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A Comparative Overview of Electronic Devices Reliability Prediction Methods-Applications and Trends

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ABSTRACT:
Reliability prediction is vital in the conception, definition, design, development, operation and maintenance phase of electronic devices. It is needed at various system levels and degrees of detail, in order to evaluate, determine and improve the dependability measures of an item when designing electronic devices in view of the high level competition among device manufacturers. Different reliability prediction methods or models are available for electronic devices. This paper comparatively examined the commonly used methods such as empirically based failure rate modeling methodologies used in reliability prediction handbooks, and physics of failure (PoF) based models. Three empirical approaches such as MIL-HDBK-217F – a conservative standard applicable principally to military equipment, and Bellcore TR-332/Telcordia SR-332, which are applicable to commercial devices are reviewed in closer details. Also reviewed is Recueil de Donnes de Fiabilite (RDF) 2000, used in Telecom industry. Some PoF based methods such as Arrhenius law; Eyring model, Black Model for Electromigration, and Coffin Manson Model for fatigue are also examined. Additionally, the respective merits and demerits of the prediction methods which provide the basis for use are noted. The paper also attempts to highlight future trends and challenges in RP of electronic devices.

KEYWORDS: Bellcore TR-332, Empirical Methods, Life Test, MIL-HDBK-217F, Physics of Failure, RDF 2000, Reliability Prediction, and Telcordia SR-332.

1. INTRODUCTION

In today's competitive electronic components and devices environment, having higher reliability than competitors is crucial if a manufacturer of such electronic devices will be successful, and maintain sustainable business in terms of patronage and profitability. Reliability prediction (RP) are conducted during the concept and definition phase, design and development phase, and the operation and maintenance phase, at various system levels and degrees of detail, in order to evaluate, determine and improve the dependability measures of an item [1].

Over the years, RP has been used to denote the process of applying mathematical models and components data for the purpose of estimating the field reliability of a system before failure data are available for the system. However, the objectives of RP are not limited to predicting whether reliability goals, such as mean time between failures (MTBF), mean time to failures (MTTF) can be reached. RP methods have been used to:

- ~ Identify potential design weaknesses
- ~ Evaluate the feasibility of a design
- ~ Compare alternative designs and life-cycle costs
- ~ Provide models for system reliability and availability analysis
- ~ Establish goals for reliability tests
- ~ Aid in business decisions such as budget allocation and scheduling and other logistic support strategies

Once the prototype of a product is available, lab tests can be utilized to obtain more accurate RPs.

Accurate prediction of the reliability of electronic products requires knowledge of the components, the design, the manufacturing process and the expected operating conditions. The rest of this paper is divided into the following section: section II reviews RP tools, while discussion of the merits and demerits of these methods are presented in section 3. We subsequently present challenges, limitation and future trends in section 4 and finally, conclusions reached are presented in section 5.

2. REVIEW OF RELIABILITY PREDICTION TOOLS

Several approaches have been developed to predict the reliability of electronic systems and components [2]. Each approach has its unique advantages and disadvantages. Among these approaches, three main categories are often used within government agencies and industries: empirical (standards based), physics of failure (PoF) and life testing. In this article, we provide an overview of these three approaches.

First, we discuss empirical prediction methods, which are based on the experiences of engineers and on historical data, such as MIL-HDBK-217, Bellcore/Telcordia, RDF 2000 and China 299B that are widely used for RP of electronic products. Next, we discuss PoF methods, which are based on root-cause analysis of failure mechanisms, failure modes and stresses. This approach is based upon an understanding of the physical properties of the materials, operation processes and technologies used in the design. Finally, we discuss life testing methods, which are used to determine reliability by testing a relatively large number of samples at their specified operation stresses or higher stresses and using statistical models to analyze the data [3].

2.1. Empirical Prediction Methods

Empirical prediction methods are based on models developed from statistical curve fitting of historical failure data, which may have been collected in the field, in-house or from manufacturers. These methods tend to present good estimates of reliability for similar or slightly modified parts. Some parameters in the curve function can be modified by integrating engineering knowledge. It is assumed that system or equipment failure causes are inherently linked to components whose failures are independent of each other. In this case of complex systems, especially, this assumption may not hold.

There are many different empirical methods that have been created for specific applications. Table 1 lists some of the available prediction standards [3] and the following sub-sections describe three of the most commonly used methods in a bit more detail.

Table 1: Reliability Prediction Methods.

Prediction Method	**Industry of Application**
PRISM	Military and commercial
MIL-HDBK-217F and notice 1 and 2	Military
Chinese 299B	Chinese military
Bellcore TR332 or Telcordia SR332	Telecommunication
NTT Procedure	Telecommunication
Siemens SN295000	Siemens products
RDF 2000	Telecommunication
British Telecom HRD4 and HRD5	Telecommunication
SAE Reliability	Automotive

2.1.1 MIL-HDBK-217 Predictive Method

MIL-HDBK-217 is very well known in military and commercial industries. The latest version is MIL-HDBK-217F, which was released in 1991 and had two revisions: Notice 1 in 1992 and Notice 2 in 1995. It is probably by far the most internationally recognized empirical RP method, having been applied to various systems [4]-[10].

The MIL-HDBK-217F predictive method consists of part count and part stress analyses [11]. The parts count method assumes typical operating conditions of part or components complexity, ambient temperature, various electrical stresses, operation mode and environment (called reference conditions). For failure rate under reference conditions, $\left(\lambda_r\right)$ and number of components or parts, $\left(i \in I\right)$, the failure rate for a part under the reference conditions is calculated by equation 1 as given by [12]:

$$\lambda_{b,i} = \sum_{i=1}^{n} (\lambda_r)_i \qquad (1)$$

Since the parts may not operate under the specified reference conditions, the real operating conditions will result in failure rates or reliabilities that are different from those given by the handbook method, hence, the part stress method requiring the specific part's complexity, application stresses, environmental factors, and so on is more realistic. These conditions are called π- factors (such as stress factor (π_S), environment factor (π_E), temperature factor (π_T), the quality factor (π_Q), adjustment factor (π_A) and learning factor (π_L)).

The failure rate for parts under specific operating conditions can be determine using equation 2 as given by [11]:

$$\lambda = \sum_{i=1}^{I} \left(\lambda_{r,i} \pi_S \pi_E \pi_T \pi_Q \pi_A \pi_L \right) \qquad (2)$$

2.1.2 Bellcore/Telcordia Predictive Method

Due to dissatisfaction with MIL-HDBKs for its AT&T commercial products, Bellcore designed its own RP standard for commercial telecommunication products. After acquisition of Bellcore and subsequent name change to Telcordia, other versions of the standard have been releases such as SR-332 Issue 1 and SR-332 Issue 2, both called "Reliability Prediction Procedure for Electronic Equipment" [13], [14].

The Bellcore/Telcordia standard assumes a serial model for electronic parts and it addresses failure rates at the infant mortality stage, in contrast to MIL-HDBK-217, and at the steady-state stage with 'Methods I, II and III' [13], [14].Method I is similar to the MIL-HDBK-217F parts count and part stress methods. The standard provides the generic failure rates and three part stress factors: device quality factor (π_Q), electrical stress factor π_S and temperature stress factor π_T. Method II is based on combining Method I predictions with data from laboratory tests performed in accordance with specific SR-332 criteria. Method III is a statistical prediction of failure rate based on field tracking data collected in accordance with specific SR-332 criteria. Here, the predicted failure rate is a weighted average of the generic steady-state failure rate and the field failure rate.

However, there are variations in the results obtained from MIL-HBK-217 and Bellcore SR-332, because MIL-HDBK-217, meant for military is more conservative than SR-332, a commercial standard. Moreover, the underlying methods are different and more factors that may affect the failure rate are considered in MIL-HDBK-217 than in SR-332. While applying SR-332 to Single Phase Fischer-controlled smart meter [15] highlighted the merits and demerits of the SR-332, which are highlighted in section IV of this paper. Other applications of the Telcordia predictive method are reported in [16], [17].

2.1.3 RDF 2000 Predictive Method

Recueil de Donnes de Fiabilite (RDF) 2000 is a reliability data handbook developed by French telecommunications industry. This standard provides reliability prediction models for a range of electronic components using cycling profiles and applicable phases as a basis for failure rate calculations in constrast to the approaches of MIL-HNDBK-217 and Telcordia SR-332 [18]. RDF 2000 provides a unique approach to handle mission profiles in the failure rate prediction. Component failure is defined in terms of an empirical expression containing a base failure rate that is multiplied by factors influenced by mission profiles.

These mission profiles contain information about how the component failure rate may be affected by operational cycling, ambient temperature variation and/or equipment switch on/off. Unlike Telcordia SR-332, which considers infant mortality stage, RDF 2000 only focusses on the useful life stage of product life. It is assumed that, for most electronic components, the wear-out period is never reached because new products will replace older ones before the wear out phase is reached. For components whose wear-out period is not very far in the future, the normal life period has to be determined.

Conceptually, infant mortality stage failure rate is caused by a wide range of factors, such as manufacturing processes and material weakness, but can be eliminated by improving the design and production processes (e.g. by performing burn-in). As an example of RDF 2000, the empirical expression formula for a ceramic capacitor of class I is given by [18] as expressed in equation 3. Additionally, [19] reported an application of the MIL-HDBK-217F and RDF 2000 in predicting the reliability of inverters in hybrid electrical vehicles (HEV).

$$\lambda = 0.05 \left(\left[\frac{\sum_{i=1}^{n} (\pi_t)_i \times \tau_i}{\tau_{ON} + \tau_{OFF}} \right] \right) + 3.3 \times 10^{-3} \times \left[\sum_{i=1}^{j} (\pi_n)_i \times \left(\Delta T_i \right)^{0.68} \right] \times 10^{-9} \qquad (3)$$

Where:

$(\pi_t)_i$ = the temperature factor related to the ith junction temperature of the capacitor mission profile

τ_i = the working time ratio of the capacitor for the ith junction temperature of the mission profile

τ_{ON} = the total working time ratio of the capacitor

τ_{OFF} = the total downtime time ratio of the capacitor, with $\tau_{ON} + \tau_{OFF} = 1$

$(\pi_n)_i$ = the ith influence factor related to the annual cycles number of thermal variations seen by the package, with the amplitude ΔT

(ΔT_i) = the thermal amplitude variation of the ith mission profile

2.2 Physics of Failure Methods

In contrast to empirical RP methods, which are based on the statistical analysis of historical failure data, a PoF approach is based on the understanding of the failure mechanism and application of PoF model to failure data. Assessment of the reliability of systems using PoF or its relevant modifications are presented in [20]-[22]. Commonly used models which include; the Arrhenius's, Eyring models, corrosion model, hot-carrier injection model and so on are next discussed.

2.2.1 Arrhenius's Law

Arrhenius's Law is one of the earliest and most successful acceleration models used to predicts how the time-to-failure of a system varies with temperature. It is based on the principle that chemical reactions can be accelerated by increasing the system temperature. An application of this model is in evaluating the aging of a capacitor (such as an electrolytic capacitor) accelerated by increasing operating temperature. The model takes the form of equation 4 [2]. If $L(T)$ is the life characteristic related to temperature, A is the scaling factor, E_a is the activation energy (eV), tf_1 is time to failure at temperature T_1 and tf_2 is time to failure at temperature T_2, then;

$$L(T) = A\exp\left(\frac{E_a}{kT}\right) \tag{4}$$

Where:

k = Boltzmann constant $\left(eV/{}^0K\right)$

Equation 5 is the expression for Acceleration Factor (AF).

$$AF = \frac{tf_1}{tf_2} = \exp\left(\frac{E}{k}\left[\frac{1}{T_1} - \frac{1}{T_2}\right]\right) \tag{5}$$

2.2.2 Eyring Model

Whereas the Arrhenius model emphasizes the dependency of reactions on temperature, the Eyring model is commonly used for demonstrating the dependency of reactions on stress factors other than temperature, such as mechanical stress, humidity or voltage. Applications of the Eyring model are reported in [20], [23] and [24]. For life characteristic related to temperature and another stress $L(T,S)$ with constants A, α, B and C, stress factor (S) other than temperature, and absolute temperature (T).

The standard expression for the Eyring model [25] is equation 6.

$$L(T,S) = AT^{\alpha}\exp\left(\frac{E_a}{kT} + \left[B + \frac{C}{T}\right]S\right) \tag{6}$$

According to different PoF mechanisms, one more term (i.e., stress) can be either removed or added to the above standard Eyring model. Two temperature/voltage model and three stress model with parameters; temperature, voltage and humidity (relative humidity, RH) is shown in equation 7 and 8. The parameters in the equation take their already defined meaning [19].

$$L(T,V) = A\exp\left(\frac{E_a}{kT}\right)V^{-\beta} \tag{7}$$

$$L(T,V.H) = A\exp\left(\frac{\Delta H}{kT}\right)V^{-\beta}RH^{-\gamma} \tag{8}$$

2.2.3 Corrosion Model

Electronic devices with aluminum or aluminum alloy with small percentages of copper and silicon metallization are subject to corrosion failures and therefore can be described with the following model, when an arbitrary scale factor (B_0) is chosen and α, whose value is between 0.1 - 0.15 per % RH for an unknown function of applied voltage $f(V)$, with empirical value of 0.12 to 0.15, then the life characteristics dependent on humidity, voltage and temperature was given by [19] as shown in equation 9:

$$L(RH,V,T) = B_0\exp([-\alpha]RH)\,f(V)\exp\left(\frac{E_a}{kT}\right) \tag{9}$$

2.2.4 Hot Carrier Injection Model

Hot carrier injection describes the phenomena observed in MOSFETs by which the carrier gains sufficient energy to be injected into the gate oxide, generate interface or bulk oxide defects and degrade MOSFETs characteristics such as threshold voltage, transconductance, and so on [25-27].

For n-channel devices, the model is given by equation 10:

$$L(I,T) = B\left(I_{substrate}\right)^{-N} \exp\left(\frac{E_a}{kT}\right) \qquad (10)$$

Where:

B = an arbitrary scale factor.

$I_{substrate}$= the peak substrate current during stressing.

N = equal to a value from 2 to 4, typically 3.

$E_a = -0.1eV\ to -0.2eV$.

For p-channel devices with the peak gate current during stressing I_{gate} and a factor M , the model is given by:

$$L(I,T) = B\left(I_{gate}\right)^{-M} \exp\left(\frac{E_a}{kT}\right) \qquad (11)$$

Since electronic devices usually have a long time period of useful life (i.e. the constant line of the bathtub curve) and can often be modeled using an exponential distribution. If the life characteristic is not constant, then, the PoF model can be replaced by Weibull distribution or lognormal distribution.

2.2.5 Black Model for Electromigration

Electromigration is a failure mechanism that results from the transfer of momentum from the electrons, which move in the applied electric field, to the ions, which make up the lattice of the interconnect material. The most common failure mode is "conductor open." With the decreased structure of Integrated Circuits (ICs), the increased current density makes this failure mechanism very important in IC reliability.

When a constant $\left(A_0\right)$ based on the cross-sectional area of the interconnection is chosen and a scaling factor N, with values between 2 - 3.3 with current density $\left(J\right)$ having a threshold current density $\left(J_{threshold}\right)$; then Black model employing external heating and increased current density is given by equation 12 [3]:

$$MTTF = A_0\left(J - J_{threshold}\right)^{-N} \exp\left(\frac{E_a}{kT}\right) \qquad (12)$$

The current density (J) and temperature (T) are factors in the design process that affect electromigration. E_a is between 0.5 - 1.1eV. The lower the values of E_a and N, the more conservative the estimation will be. Preference for electromigration simulation and Eyring model was presented in [28]. Reports of the applications of the Black model or its modifications in reliability prediction were presented in [29-34].

2.2.6 Coffin-Manson Model for Fatigue

Fatigue failures can occur in electronic devices due to temperature cycling and thermal shock. Permanent damage accumulates each time the device experiences a normal power-up and power-down cycle. These switch cycles can induce cyclical stress that tends to weaken the material used in fabricating the devices and may cause different types of failures, such as dielectric/thin-film cracking, lifted bonds, solder fatigue, and so on.

The modified Coffin-Manson model developed by [19] has been used to model crack growth in solder due to repeated temperature cycling as the device is switched on and off. For number of cycles to failure N_f, cycling frequency f, having a cycling frequency exponent α and temperature range during a cycle of ΔT with a temperature exponent β. If A is a coefficient, then the model takes the form equation 13:

$$N_f = Af^{-\alpha}\Delta T^{-\beta}G\left(T_{\max}\right) \qquad (13a)$$

Where:

$G\left(T_{\max}\right)$= an Arrhenius term evaluated at the maximum temperature in each cycle.

$$G\left(T_{\max}\right) = \exp\frac{E_a}{kT_{\max}} \qquad (13b)$$

Three factors are usually considered for testing: maximum temperature $T_{\max}$, temperature range (ΔT) and cycling frequency (f). E_a is related to certain failure mechanisms and failure modes, and can be determined by correlating thermal cycling test data and the Coffin-Manson model. Application of the Coffin-Manson model or its modification is reported in [35-40]. An improvement to the model for a more accurate prediction of the reliability of mid-power LED wire-bonding was proposed in [41].

2.3 Life Testing Method

As mentioned above, time-to-failure data from life testing may be incorporated into some of the empirical prediction standards (such as in Bellcore/Telcordia Method II) [14]. It may also be necessary to estimate the parameters for some of the PoF models.

However, in this section of the article, we are using the term life testing method to refer specifically to a third type of approach for predicting the reliability of electronic products. With this method, a test is conducted on a sufficiently large sample of units operating under normal usage conditions. Times-to-failure are recorded and then analyzed with an appropriate statistical distribution in order to estimate reliability metrics. This type of analysis is often referred to as life data analysis or Weibull analysis [3]. Applications of this method are reported in [42], [43].

3 DISCUSSION OF RELIABILITY PREDICTION METHODS

Although empirical prediction standards have been used for many years, they are to be used with caution. The advantages and disadvantages of empirical methods have been subject of many discussions in the past three decades [44], [45]. Hence, the following can be concluded; that empirical methods are easier to use, with a lot of predictive models in existence and provide estimates of field failure rates. However, the following short comings are observed: a large part of the data used by the traditional models are out-of-date, failure of the components is not always due to component-intrinsic mechanisms but can be caused by the system design, which is not considered, the RP models are based on industry-average values of failure rate, which are neither device-specific nor vendor-specific, and it is hard to reliable field and manufacturing data, which are essential in defining adjustment factors, such as the Pi factors discussed in [11].

A given electronic component will have multiple failure modes and the component's failure rate is equal to the sum of the failure rates of all modes (i.e. humidity, voltage, temperature, thermal cycling and so on). In using the PoF models, the parameters can be determined from the design specifications or operating conditions. If the parameters cannot be determined without conducting a test, the failure data obtained from the test can be used to get the model parameters. Software can be used to analyze the failure data [3].

The observed merits of PoF methods are accurate prediction of wearout using known failure mechanisms, modeling of potential failure mechanisms based on the PoF. Additionally, during the design process, the variability of each design parameter can be determined. However, the method needs detailed component manufacturing information (such as material, process and design data), analysis is complex and could be costly to apply. Furthermore, it is difficult to assess the entire system.

The life testing method can provide more information about the product than the empirical prediction standards. Therefore, the prediction is usually more accurate, given that enough samples are used in the testing. The life testing method may also be preferred over both the empirical and PoF methods when it is necessary to obtain realistic predictions at the system (rather than component) level. This is because the empirical and physics of failure methods calculate the system failure rate using the sum of the component failure rates if the system is considered to be a serial configuration. This assumes that there are no interaction failures between the components but, in reality, due to the design or manufacturing, components are not independent.

Therefore, in order to consider the complexity of the entire system, life tests can be conducted at the system level, treating the system as a "black box," and the system reliability can be predicted based on the obtained failure data. From the review of RP methods, we summarize our assessment of researchers' preferences in Figure 1, which show our ratings of the three prediction methods reviewed using the following metrics: computational time required, simplicity of the method, accuracy, the extent of the method being component based and how popular the method is among researchers. We rate the methods on a scale of 0 – 1.

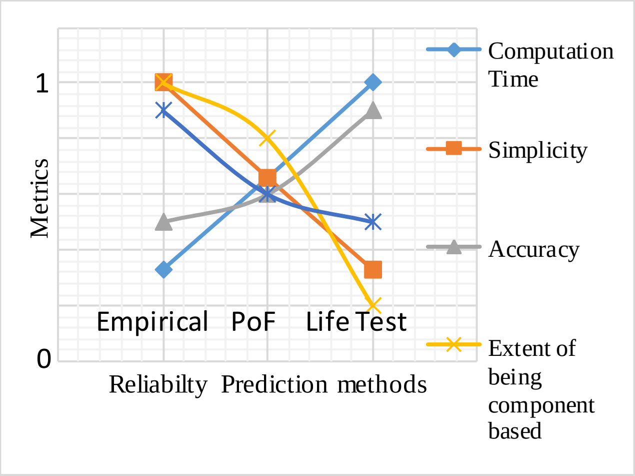

Fig. 1: Comparison of RP methods

4 CHALLENGES, LIMITATIONS AND TREND OF RELIABILITY PREDICTION

The methods cost and time needed to predict the reliability of complex systems still need further research as the results obtained thus far, are not satisfactory. A reason for this is that data needed for the reliability assessment of complex systems are not easily available. Such complex systems include electronics devices at Nano scale. Plans to update the MIL-HDBK-217F and incorporate reliability physics and system's design considerations need to be hastened. Although, applications were a combination of prediction models are used as reported in [19], future trends may see more of these approach at least in different sections of a system so as to optimize the merits of RP methods. Typically, the current prediction techniques assumes that the components failure are independent, which tends to over-predict improvements in reliability values. However, the trend is towards the common cause failure approaches which incorporate failure rates that vary with time, in predicting the reliability of systems with dependent component failure rate.

The reviewed approaches are deterministic in nature, even though stochastic approach have been used to model uncertainty, we expect more of this probabilistic approaches in the immediate future because electronic systems are rapidly becoming more complex, and field data may not readily be available.

5 CONCLUSION

In this article, we discussed three approaches for predicting the reliability of electronics. The empirical (or standards based) methods can be used in the design stage to quickly obtain a rough estimation of product reliability. The PoF and life testing methods can be used in both design and production stages. In PoF approaches, the model parameters can be determined from design specs or from test data. On the other hand, with the life testing method, since the failure data from the particular products are obtained, the prediction results usually are more accurate than those from general standards or models.

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