Topic: Reliability of Biomedical Devices and Technologies

Medical Electron Device Reliability is Critical, and Therefore Ability to Quantify it is Paramount

Dr. Ephraim Suhir- Contributing Editor

Introduction

Some questions asked in connection with the today's state-of-the-art and practices in the area of reliability evaluations and assurances of microelectronics and photonics materials and devices, including medical devices, are formulated, and some references to the related published work are indicated. The emphasis is on the author's publications during his long career in the field of electronics materials and devices reliability. The substance of the recently suggested probabilistic design for reliability (PDfR) concept, the attributes of the failure-oriented-accelerated-testing (FOAT) and Boltzmann-Arrhenius-Zhurkov (BAZ) constitutive equation (model) are briefly discussed and numerical examples are provided. It is concluded that the application of the PDfR concept and its experimental basis FOAT, geared to the flexible and physically meaningful BAZ model, put the art of creating reliable electronic products on a "reliable" applied science foundation and, owing to that, enables making a viable electron device, and particularly, medical device, into a reliable product.

Today's practices and some questions asked

- Electron devices that underwent highly accelerated life testing (HALT) [1, 2], passed the existing qualification tests (QT) and survived burn-in testing (BIT) [3, 4] often exhibit nonetheless premature field failures. Are these methodologies and practices, and particularly the HALT procedures, adequate [5]?
- Do electronic industries need new approaches to qualify their products, and if they do, what should be done differently [6]?
- Could the existing practices be improved to an extent that if the product passed the reliability tests, there is a way to assure that it will satisfactorily perform in the field [7]?
- In many applications, such as, e.g., aerospace, military, long-haul communications, and, certainly medical, high reliability of electronics materials and products is particularly critical. Failures are a catastrophe and are not acceptable. Could the operational (field) reliability of an

electronic product be assured, if it is not predicted, i.e., not quantified in advance, at the design and product development stage [8-10]? It is well known that when NASA receives such products from big companies, NASA has to re-qualify these products and established their “remaining useful lives (RUL)” to make sure that these products are good enough to be installed in a, say, space shuttle. But it is too late in such a situation to change the materials, or the designs, i.e., too late to create a “genetically healthy” product. Such a practice triggered therefore the s.c. prognostics-and-health monitoring (PHM) practice. Such a practice might be good in addition to an effort of creating a “genetically healthy” product, but not instead of it. Agree?

- And if such a quantification is found to be necessary, could that be done on the deterministic, i.e., on a non-probabilistic basis, or, since nothing is perfect, and because the difference between a highly reliable product and an insufficiently reliable one is “merely” in the difference between their never-zero probabilities of failure, the probabilistic approach should be applied [11-19]?
- Should electronic product manufacturers keep shooting for an unpredictable and, perhaps, unachievable and unnecessary very long, such as, e.g., twenty years or so, product lifetime or, considering that every five years a new generation of devices appear on the market, the industries and particularly medical device manufacturers should settle for a shorter, but well substantiated, predictable and assured lifetime, with a high probability of non-failure?
- And what should be the role of predictive modeling, both computer-aided simulations, like, say, finite-element-analysis (FEA) and the “old-fashioned” analytical modeling [20-24]?
- What role could play the recently suggested Failure-Oriented-Accelerated-Testing (FOAT) and Boltzmann-Arrhenius-Zhurkov (BAZ) analytical model in predicting, on the probabilistic basis, the device’s probability of failure and its useful lifetime [25-28]?
- It is clear that higher specified probabilities of non-failure result in shorter expected lifetimes. Then how such lifetimes should be related to the acceptable (specified) probability of non-failure for particular products and applications?
- Considering that the principle of superposition does not work in reliability engineering, how to establish the adequate physically meaningful stressors, their combinations and levels for the appropriate accelerated tests?
- The best engineering product is the best compromise between the requirements for its reliability, cost effectiveness and time-to-market; it goes without saying that, in order to make the desired optimization possible, the reliability of such product should also be quantified, but how to do that[29]?
- Bathtub curve, the experimental “reliability passport” of a mass-produced device reflects the inputs of two critical irreversible processes – the statistics-of-failure process that results in a reduced failure rate with time (this is particularly evident from the infant mortality portion of the curve) and physics-of-failure (aging, degradation) process that leads to an increased failure rate with time (this trend is explicitly exhibited by the wear out portion of the bathtub diagram). Could these two critical processed be separated? The need for that is due to the obvious incentive to minimize the role and the rate of aging, and this incentive is especially significant for products like lasers, solder joint interconnections and others, which are characterized by long wear out

portions and when it is economically infeasible to restrict the product's lifetime to the steady-state situation, when the two irreversible processes in question compensate each other [30].

- A related question has to do with the fact that real time degradation is a very slow process. Could physically meaningful and cost-effective methodologies for measuring and predicting the degradation (aging) rates and consequences be developed [30]?
- Yet another related question has to do with the BIT of electron devices. It is unclear even whether such testing is always necessary, and if it is decided upon that it is, how long should it last and at what level, so that the infant mortality portion of the bathtub curve is eliminated [31-33]?

In the references to the published work below many questions asked above the outline that follow (including references) some of these questions are answered on the basis of the recently suggested PDfR concept. The next sections summarize some main features of this concept, address the attributes of the FOAT vs traditional HALT, and show some simple examples of the application of the PDfR concept, including BAZ model.

PDfR and its "ten commandments"

The PDfR concept is an effective means for improving the state-of-the-art in the electronics and photonics reliability field by quantifying, on the probabilistic basis, the operational reliability of a material or a product by predicting the probability of its likely failure under the given loading conditions and after the given service time, and to use this probability as a suitable and physically meaningful criterion of the expected product's performance. The following ten major (governing) principles ("commandments") reflect the rationale behind the PDfR concept:

1) When reliability of a product is imperative, ability to predict it is a must; reliability cannot be assured, if it is not quantified;
2) Nothing is perfect; the difference between a highly reliable and an insufficiently reliable product is "merely" in the level of their never-zero probability of failure, and therefore such a quantification should be done on the probabilistic basis;
3) Reliability evaluations cannot be delayed until the product is made and should start at the design stage; it should be taken care of, however, at all the significant stages of the product's life: at the design stage, when reliability is conceived; at the accelerated testing stage, using electrical, optical, environmental and mechanical instrumentation; at the production/manufacturing stage, when reliability is implemented; and, if necessary and appropriate, reliability should be maintained in the field during the product's operation; then there will be a reason to believe that a "genetically healthy" product is created and its "health" could be maintained by using various popular today prognostics-and-health monitoring/"management" (PHM) methods, as well as redundancy, trouble-shooting and other more or less important means that could be considered to maintain adequate reliability level, especially if the "genetic health" of the product is not as high as it could and should be;
4) Product's reliability cannot be low, of course, but need not be higher than necessary either: it has to be adequate for the given product and application, considering its lifetime, environmental conditions and consequences of failure;

5) The best product is the best compromise between the requirements for its reliability, cost effectiveness and time-to-market; it goes without saying that such a compromise cannot be achieved if reliability is not quantified;
6) One cannot design a product with quantified, optimized and assured reliability by limiting the effort to the widely used today “black box” - highly accelerated life testing (HALT); understanding the underlying physics of failure is crucial, and therefore highly cost-effective and highly focused failure-oriented-accelerated-testing (FOAT) should be considered and conducted as a possible and natural extension of HALT;
7) FOAT, unlike HALT, is a “white/transparent box” aimed at understanding the physics of failure and should be geared to a limited number of pre-determined simple, easy-to-use and physically meaningful predictive reliability models and is viewed as the experimental basis and important constituent part of the probabilistic design for reliability (PDfR) effort;
8) Physically meaningful, easy-to-use and flexible multi-parametric Boltzmann-Arrhenius-Zhurkov (BAZ) model can be used as a suitable one for the assessment of the remaining “useful” life (RUL) of an electronic product,
9) Predictive modeling, not limited to FOAT models, is a powerful means to carry out, if necessary, sensitivity analyses (SA) with an objective to quantify and practically nearly eliminate failures by making the probability of failure sufficiently low; this principle could be referred to as the “principle of practical confidence”.
10) Consideration of the role of the human factor is highly desirable in the PDfR effort: not only “nothing”, but also “nobody” is perfect, and the human role in assessing the likelihood of the adequate performance of a product,

FOAT (“transparent box”) vs HALT (“black box”)

A highly focused and highly cost effective FOAT is the experimental foundation and the “heart” of the PDfR concept. FOAT should be conducted in addition to and, in some cases, even instead of HALT, especially for new products, whose operational reliability is unclear and for which no experience is accumulated and no best practices nor HALT methodologies are not yet developed. Predictions, based on the FOAT and subsequent probabilistic predictive modeling, might not be perfect, at least at the beginning, but it is still better to pursue this effort rather than to turn a blind eye on the fact that there is always a non-zero probability of the product’s failure. Understanding the underlying reliability physics for the product performance is critical. If one sets out to understand the physics of failure in an attempt to create a failure-free product (in accordance with the “principle of practical confidence”) conducting a FOAT type of an experiment is imperative. FOAT’s objective is to confirm the usage of a particular more or less well established predictive model, to confirm (say, after HALT is conducted) the physics of failure, and establish the numerical characteristics (activation energy, time constant, sensitivity factors, etc.) of the particular FOAT modal of interest.

FOAT could be viewed as an extension of HALT. While HALT is a “black box”, i.e., a methodology which can be perceived in terms of its inputs and outputs without a clear knowledge of the underlying physics and the likelihood of failure., FOAT, on the other hand, is a “transparent box”, whose main objective is to confirm the use of a particular reliability model that reflects a specific anticipated failure mode. The major assumption is, of course, that this model should be valid in both AT and in actual operation conditions. HALT does not measure (does not quantify) reliability. FOAT does. HALT can be used for “rough tuning” of product’s reliability, and FOAT could and should be employed when “fine tuning” is needed, i.e., when there is a need to quantify, assure and even specify the operational reliability of a product. HALT tries to “kill many unknown birds with one (also not very well known) stone”. HALT has demonstrated, however, over the years its ability to improve robustness through a “test-fail-fix” process, in which the applied stresses (stimuli) are somewhat above the specified operating limits. This “somewhat above” is based, however, on an intuition, rather than on a calculation. There is a general perception that HALT might be able to quickly precipitate and identify failures of different origins. FOAT and HALT could be carried out separately, or might be partially combined in a particular AT effort. Since the principle of superposition does not work in reliability engineering, both HALT and FOAT use, when appropriate, combined stressing under various stimuli (stressors).

New products present natural reliability concerns, as well as significant challenges at all the stages of their design, manufacture and use. An appropriate combination of HALT and FOAT efforts could be especially useful for ruggedizing and quantifying reliability of such products. It is always necessary to correctly identify the expected failure modes and mechanisms, and to establish the appropriate stress limits of HALTs and FOATs with an objective to prevent “shifts” in the dominant failure mechanisms. There are many ways of how this could be done (see, e.g., [8]). The FOAT based approach could be viewed as a quantified and reliability physics oriented HALT. The FOAT approach should be geared to a particular technology and application, with consideration of the most likely stressors.

Some simple PDfR examples

Adequate heat sink

Consider a device whose steady-state operation is determined by the Arrhenius equation (1). The probability of non-failure can be found using the exponential law of reliability as $P = \exp\left[-\frac{t}{\tau_0}\exp\left(-\frac{U}{kT}\right)\right]$. Solving this equation for the absolute temperature T, we have: $T = -\frac{U/k}{\ln\left(-\frac{\tau_0}{t}\ln P\right)}$. Addressing, e.g., surface charge accumulation failure, for which the ratio of the activation energy to the Boltzmann’s constant is $\frac{U}{k} = 11600^0 K$, assuming that the FOAT- predicted time factor τ_0 is $\tau_0 = 2x10^{-5}$ hours, that the customer requires that the probability of failure at the end of the device’s service time of $t = 40{,}000$ hours is only $Q = 10^{-5}$, the above formula yields: $T = 352.3^0 K = 79.3^0 C$. Thus, the heat sink should be designed accordingly, and the vendor should be able to deliver such a heat sink. The situation changes to the worse, if the temperature of the device changes, especially in a random fashion, but this situation can also be predicted by a simple probabilistic analysis, which is, however, beyond the scope of this article.

Reliable seal glass

The maximum interfacial shearing stress in the thin solder glass layer can be computed by the formula: $\tau_{\max} = kh_g\sigma_{\max}$.

Here $k = \sqrt{\frac{\lambda}{\kappa}}$ is the parameter of the interfacial shearing stress, $\lambda = \frac{1-\nu_c}{E_c h_c} + \frac{1-\nu_g}{E_g h_g}$ is the axial compliance of the assembly, $\kappa = \frac{h_c}{3G_c} + \frac{h_g}{3G_g}$ is its interfacial compliance, $G_c = \frac{E_c}{2(1+\nu_c)}$, $G_g = \frac{E_g}{2(1+\nu_g)}$ are the shear moduli of the ceramics and glass materials, $\sigma_{\max} = \frac{\Delta\alpha\Delta t}{\lambda h_g}$ is the maximum normal stress in the midportion of the glass layer, Δt is the change in temperature from the soldering temperature to the low (room or testing) temperature, $\Delta\alpha = \overline{\alpha}_c - \overline{\alpha}_g$ is the difference in the effective coefficients of thermal expansion (CTEs) of the ceramics and the glass, $\overline{\alpha}_{c,g} = \frac{1}{\Delta t}\int_t^{t_0} \alpha_{c,g}(t)dt$ are these coefficients for the given temperature t, t_0 is the annealing (zero stress, setup) temperature, and $\alpha_{c,g}(t)$ are the time dependent CTEs for the materials in question. In an approximate analysis one could assume that the axial compliance λ of the assembly is due to the glass only, so that $\lambda \approx \frac{1-\nu_g}{E_g h_g}$ and therefore the maximum normal stress in the solder glass can be evaluated as $\sigma_{\max} = \frac{E_g}{1-\nu_g}\Delta\alpha\Delta t$. While the geometric characteristics of the assembly, the change in temperature and the elastic constants of the materials can be determined with high accuracy, this is not the case for the difference in the CTEs of the brittle materials of the glass and the ceramics. In addition, because of the obvious incentive to minimize this difference, such a mismatch is characterized by a small difference of close and appreciable numbers. This contributes to the uncertainty of the problem in question justifies the application of the probabilistic approach. Treating the CTEs of the two materials as normally distributed random variables, we evaluate the probability P that the thermal interfacial shearing stress is compressive (negative) and, in addition, does not exceed a certain allowable level [9]. This stress is proportional to the normal stress in the glass layer, which is, in its turn, proportional to the difference $\Psi = \alpha_c - \alpha_g$ of the CTE of the ceramics and the glass materials, one wants to make sure that the requirement $0 \le \Psi \le \Psi_* = \frac{\sigma_a}{E_g}\frac{1-\nu_g}{\Delta t}$ takes place with a very high probability.. For normally distributed random variables α_c and α_g the variable Ψ is also distributed in accordance with the normal law with the mean value and standard deviation as $\prec \psi \succ = \prec \alpha_c \succ - \prec \alpha_g \succ$ and $\sqrt{D_\psi} = \sqrt{D_c + D_g}$, where $\prec \alpha_c \succ$ and $\prec \alpha_g \succ$ are the mean values of the materials' CTEs, and D_c and D_g are their variances. The probability that the above condition takes place is $P = \int_0^{\psi_*} f_\psi(\psi)d\psi = \Phi_1(\gamma^* - \gamma) - [1 - \Phi_1(\gamma)]$, where $\Phi_1(t) = erft = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{t} e^{-t^2/2}dt$ is the error function, $\gamma = \frac{\prec \psi \succ}{\sqrt{D_\psi}}$ is the SF for the CTE difference and $\gamma^* = \frac{\psi^*}{\sqrt{D_\psi}}$ is the SF for the acceptable level of the allowable stress. If, e.g., the elastic constants of the solder glass are $E_g = 0.66x10^6 kg/cm^2$ and $\nu_g = 0.27$, the sealing (fabrication) temperature is $485^0 C$, the lowest (testing) temperature is $-65^0 C$ (so that $\Delta t = 550^0 C$), the computed effective CTE's at this temperature are $\bar{\alpha}_g = 6.75x10^{-6} 1/^0 C$ and $\bar{\alpha}_c = 7.20x10^{-6} 1/^0 C$, the standard deviations of these STEs are $\sqrt{D_c} = \sqrt{D_g} = 0.25x10^{-6} 1/^0 C$ and the (experimentally obtained) ultimate compressive strength for the glass material is $\sigma_u = 5500 kg/cm^2$. With the acceptable SF of, say, 4, we have $\sigma^* = \sigma_u / 4 = 1375 kg/cm^2$. The allowable level of the parameter ψ is therefore

$$\psi_* = \frac{\sigma_a}{E_g}\frac{1-\nu_g}{\Delta t} = \frac{1375}{0.66x10^6}\frac{0.73}{550} = 2.765x10^{-6} 1/^0 C.$$

The mean value $\prec \psi \succ$ and variance D_ψ of the parameter ψ are $\prec \psi \succ = \prec \alpha_c \succ - \prec \alpha_g \succ = 0.450x10^{-6} 1/^0 C$ and $D_\psi = D_c + D_g = 0.25x10^{-12} (1/^0 C)^2$, respectively. Then the predicted SFs are $\gamma = 1.2726$ and $\gamma^* = 7.8201$, and the corresponding probability of non-failure of the seal glass material is $P = \Phi_1(\gamma^* - \gamma) - [1 - \Phi_1(\gamma)] = 0.898.$ Note that if the standard deviations of the materials CTEs were only $\sqrt{D_c} = \sqrt{D_g} = 0.1x10^{-6} 1/^0 C$, then the SFs would be much higher: $\gamma = 3.1825$ and $\gamma^* = 19.5559$, and the probability of non-failure would be as high as $P = 0.999.$

Extreme response in temperature cycling

Let an electronic device be operated in temperature cycling conditions, and th random amplitude of the induced stress, when a single cycle is applied is distributed in accordance with the Rayleigh law, so that the probability density function of this amplitude is $f(r) = \frac{r}{D_x}\exp\left(-\frac{r^2}{2D_x}\right)$. Our objective is to assess the most likely extreme value of the stress amplitude for a large number n of cycles. The probability distribution density function and the probability distribution function for the extreme value Y_n of the stress amplitude can be found as $g(y_n) = n\{f(x)[F(x)]^{n-1}\}_{x=y_n}$ and $G(y_n) = \{[F(x)]^n\}_{x=\varsigma_n}$, respectively. Then the following expression for the probability density distribution function $g(y_n)$ can be obtained: $g(y_n) = n\varsigma_n^2 \exp\left(-\frac{\varsigma_n^2}{2}\right)\left[1-\exp\left(-\frac{\varsigma_n^2}{2}\right)\right]^{n-1}$, where $\varsigma_n = \frac{y_n}{\sqrt{D_x}}$ is the sought dimensionless amplitude. Its maximum value could be determined from the equation $g'(y_n) = 0$, which yields: $\varsigma_n^2\left[n\exp\left(-\frac{\varsigma_n^2}{2}\right)-1\right] - \left[\exp\left(-\frac{\varsigma_n^2}{2}\right)-1\right] = 0$. If the number n is large, the second term in this expression is small and can be omitted, so that $n\exp\left(-\frac{\varsigma_n^2}{2}\right)-1 = 0$, and $y_n = \varsigma_n\sqrt{D_x} = \sqrt{2D_x \ln n}$. As evident from this result, the ratio of the extreme response y_n, after n cycles are applied, to the maximum response $\sqrt{D_x}$, when a single cycle is applied, is $\sqrt{2\ln n}$. This ratio is 3.2552 for 200 cycles, 3.7169 for 1000 cycles, and 4.1273 for 5000 cycles.

Quantifying reliability using BAZ model

BAZ model $\tau = \tau_0 \exp\left(\frac{U_0 - \gamma\sigma}{kT}\right)$ can be used when the material or the device experience combined action of elevated temperature T

and external loading σ (not necessarily mechanical). Although in Zhurkov's tests the loading σ was a constant mechanical tensile stress, it has been recently suggested that any other stimulus of importance (voltage, current, thermal stress, humidity, radiation, etc.) can be used as such a stress. The effective activation energy $U = kT\ln\frac{\tau}{\tau_0} = U_0 - \gamma\sigma$ plays in the BAZ model the role of the stress-free energy U_0 in the Arrhenius model ($\sigma = 0$). The BAZ model and the Arrhenius equation can be obtained as the steady-state solution to the Fokker-Planck equation in the theory of Markovian processes. This solution represents the worst case scenario, so that the reliability predictions based on the BAZ model are conservative and advisable in engineering practice [12]. Let the lifetime τ in the BAZ model is viewed as the MTTF. Such an assumption suggests that if the exponential law of probability $P = \exp(-\lambda t)$ of non-failure is used, the MTTF corresponds to the moment of time when the entropy of this law reaches its maximum value. Indeed, from the formula $H(P) = -P\ln P$ we obtain that the maximum value of the entropy $H(P)$ is equal to e^{-1} and takes place for $P = e^{-1.} = 0.3679.$ With this probability of non-failure, the BAZ model yields: $t = \tau_0\exp\left(\frac{U}{kT}\right).$ Comparing this result with the original Arrhenius equation we conclude that the MTTF expressed by this equation corresponds to the moment of time when the entropy of the time-depending process $P = P(t)$ is the largest.

Multi-parametric BAZ model

Let us elaborate on the substance of the multi-parametric BAZ model [27] using as an example a situation when the product of interest is subjected to the combined action of the elevated relative humidity H and elevated voltage *V.* Let us assume that the failure rate of a product is determined by the level of the leakage current: $\lambda = \gamma_I I.$ Then one can seek the probability of the product's non-failure as $P = \exp\left[-\gamma_I It\exp\left(-\frac{U_0 - \gamma_H H - \gamma_V V}{kT}\right)\right].$ Here the γ factors reflect the sensitivities of the device to the change in the corresponding stressors. Although only two stressors are selected – the relative humidity H and the elevated voltage V - the model can be easily made multi-parametric, i.e., generalized for as many stimuli as necessary. The sensitivity factors γ should be determined from the FOAT when the combined action of all the stimuli (stressors) of importance is considered. Because of that the structure of the multi-parametric BAZ should not be interpreted as a superposition of the effects of different stressors (as is known, superposition principle does not work in reliability engineering), but rather as a convenient and physically meaningful representation of the FOAT data. The physical meaning of the above distribution could be seen from the formulas

$$\frac{\partial P}{\partial I} = -\frac{H(P)}{I},\quad \frac{\partial P}{\partial t} = -\frac{H(P)}{t},\quad \frac{\partial P}{\partial U_0} = \frac{H(P)}{kT},$$

$$\frac{\partial P}{\partial H} = -\frac{H(P)}{kT}\gamma_H = -\gamma_H\frac{\partial P}{\partial U_0},$$

$$\frac{\partial P}{\partial V} = -\frac{H(P)}{kT}\gamma_V = -\gamma_V\frac{\partial P}{\partial U_0},$$

where $H(P) = -P\ln P$ is the entropy of the probability $P = P(t)$ of non-failure. The following conclusions can be made based on these formulas:

1) The change in the probability of non-failure always increases with an increase in the entropy (uncertainty) of the distribution.

This probability decreases with an increase in the leakage current and with time, which certainly makes physical sense.

2) The last two of the above formulas show the physical meaning of the sensitivity factors γ: they can be found as the ratios of the change in the probability of non-failure with respect to the corresponding stimuli to the change of this probability with the change in the stress-free activation energy.

The equation for the probability of non-failure contains four empirical parameters: the stress-free activation energy U_0 and three sensitivity factors γ: leakage current factor, relative humidity factor and elevated voltage factor. Here is how these factors could be obtained from the highly focused and highly cost effective FOAT data. *First* one should run the FOAT for two different temperatures T_1 and T_2, keeping the levels, low or high, of the relative humidity H and elevated voltage V the same in both tests; recording the percentages (values) P_1 and P_2 of non-failed samples (or values $Q_1 = 1 - P_1$ and $Q_2 = 1 - P_2$ of the failed samples); assuming a certain criterion of failure (say, when the level of the measured leakage current exceeds a certain level I_*), we obtain:

$$P_{1,2} = \exp\left[-\gamma_I I_* t_{1,2} \exp\left(-\frac{U_0 - \gamma_H H - \gamma_V V}{kT_{1,2}}\right)\right].$$

Since the numerators in these relationships are kept the same, the following equation must be fulfilled for the sought sensitivity factor γ_I of the leakage current:

$$f(\gamma_I) = \ln\left(-\frac{\ln P_1}{I_* t_1 \gamma_I}\right) - \frac{T_2}{T_1}\ln\left(-\frac{\ln P_2}{I_* t_2 \gamma_I}\right) = 0.$$

Here t_1 and t_2 are the times, at which the failures were detected. It is expected that more than just two series of FOAT tests and at more than two temperature levels are conducted, so that the sensitivity parameter γ_I could be predicted with a high enough degree of accuracy (certainty). *At the second step*, FOAT tests at two relative humidity levels H_1 and H_2 should be conducted for the same temperature and voltage. This leads to the relationship:

$$\gamma_H = \frac{kT}{H_1 - H_2}\left[\ln\left(-\frac{\ln P_1}{I_* t_1 \gamma_I}\right) - \ln\left(-\frac{\ln P_2}{I_* t_2 \gamma_I}\right)\right]$$

.Similarly, at the *next step* of FOAT tests, by changing the voltages V_1 and V_2, the following expression for the sensitivity factor γ_V can be obtained:

$$\gamma_V = \frac{kT}{V_1 - V_2}\left[\ln\left(-\frac{\ln P_1}{I_* t_1 \gamma_I}\right) - \ln\left(-\frac{\ln P_2}{I_* t_2 \gamma_I}\right)\right].$$

Finally, the stress-free activation energy can be computed as $U_0 = \gamma_H H + \gamma_V V - kT\ln\left(-\frac{\ln P}{I_* t \gamma_I}\right)$ for any consistent humidity, voltage, temperature and time. The above relationships could be obtained particularly also for the case of zero voltage, i.e., without a high-voltage bias. This will provide additional information of the materials and device reliability characteristics. Let, e.g., the following input information is available: 1) After $t_1 = 35h$ of testing at the temperature $T_1 = 60^0 C = 333^0 K$, the voltage V=600V and the relative humidity H=0.85, 10% of the tested modules exceeded the allowable (critical) level of the leakage current of $I_* = 3.5\mu A$ and, hence, failed, so that the probability of non-failure is $P_1 = 0.9$; 2) After $t_2 = 70h$ of testing at the temperature $T_2 = 85^0 C = 358^0 K$ at the same voltage and the same relative humidity, 20% of the tested samples reached or exceeded the critical level of the leakage current and, hence, failed, so that the probability of non-failure is $P_2 = 0.8$. Then the equation (12) results in the following transcendental equation for the leakage current sensitivity factor γ_I:

$$f(\gamma_I) = \ln\left(\frac{0.10536}{\gamma_I}\right) - 1.075075\ln\left(-\frac{.0.22314}{\gamma_I}\right) = 0\cdot$$

This equation yields: $\gamma_I = 4926\, h^{-1}(\mu A)^{-1}$. Thus,

$\gamma_I I_* = 17241 h^{-1}$. This concludes the *first step of testing.* At the *second step*, tests at two relative humidity levels H_1 and H_2, were conducted for the same temperature and voltage levels. This led to the relationship:

$$\gamma_H = \frac{kT}{H_1 - H_2}\left[\ln\left(-0.5800x10^{-4}\frac{\ln P_1}{t_1}\right) - \ln\left(-0.5800x10^{-4}\frac{\ln P_2}{t_2}\right)\right].$$

Let, e.g., after $t_1 = 40h$ of testing at the relative humidity of $H_1 = 0.5$ at the given voltage (say, V=600V) and temperature (say, $T = 60^0 C = 333^0 K$), 5% of the tested modules failed, so that $P_1 = 0.95$, and after $t_2 = 55h$ of testing at the same temperature and at the relative humidity of $H_2 = 0.85$, 10% of the tested modules failed, so that $P_2 = 0.9$. Then the above equation for the γ_H value, with the Boltzmann constant $k = 8.61733x10^{-5} eV/K,$ yields: $\gamma_H = 0.03292 eV$. At the *third step*, FOAT at two different voltage levels $V_1 = 600V$ and $V_2 = 1000V$ have been carried out for the same temperature-radiation bias, say, $T = 85^0 C = 358^0 K$ and $H = 0.85$, and it has been determined that 10% of the tested devices failed after $t_1 = 40h$ of testing ($P_1 = 0.9$) and 20% of devices failed after $t_2 = 80h$ of testing ($P_2 = 0.8$). The voltage sensitivity factor can be found then as follows:

$$\gamma_V = \frac{0.02870}{400}\left[\ln\left(-0.5800x10^{-4}\frac{\ln P_2}{t_2}\right) - \ln\left(-0.5800x10^{-4}\frac{\ln P_1}{t_1}\right)\right] = 4.1107x10^{-6} eV/V$$

.

After the sensitivity factors of the leakage current, the humidity and the voltage are found, the stress free activation energy can be determined for the given temperature and for any combination of loadings (stimuli). The third term in the equation for the stress-free activation energy plays the dominant role, so that, in approximate evaluations, only this term could be considered. Calculations indicate that the loading free activation energy in the above numerical example (even with the rather tentative, but still realistic, input data) is about $U_0 = 0.4770 eV$. This result is consistent with the existing experimental data. Indeed, for semiconductor device failure mechanisms the activation energy ranges from 0.3 to 0.6eV, for metallization defects and electro-migration in Al it is about 0.5eV, for charge loss it is on the order of 0.6 eV, for Si junction defects it is 0.8 eV.

Possible next generation QT

The next generation QT could be viewed as a “quasi-FOAT,” “mini-FOAT”, a sort-of an “initial stage of FOAT” that more or less adequately replicates the initial non-destructive, yet full-scale, stage of FOAT. The duration and conditions of such a “mini-FOAT” QT could and should be established based on the observed and recorded results of the actual FOAT, and should be limited to the stage when no failures, or a predetermined and acceptable small number of failures in the actual full-scale FOAT, were observed. PHM technologies (“canaries”) could be concurrently tested to make sure that the safe limit is established correctly and is not exceeded. Such an approach to qualify electronic devices into products will enable the industry to specify, and the manufacturers - to assure, a predicted and adequate PoF for an electronic product that passed the QT and is expected to be operated in the field under the given conditions for the given time. FOAT should be thoroughly designed, implemented, and analyzed, so that the QT is based on the trustworthy FOAT data.

Conclusion

The application of FOAT, the PDfR concept and particularly the multi-parametric BAZ model enables one to improve dramatically the state of the art in the field of the electreonic products reliability prediction and simple, easy-to-use and physically meaningful predictive modeling, the role of such modeling, both computer-aided and analytical (mathematical), in making the suggested new approach to QT practical and successful. It is imperative that the reliability physics that underlies the mechanisms and modes of failure is well understood. Such an understanding can be achieved only provided that flexible, powerful and effective PDfR efforts are implemented.

References:

1. Suhir, E., Bensoussan, A., Nicolics, J., Bechou, L., “Highly Accelerated Life Testing (HALT), Failure Oriented Accelerated Testing (FOAT), and Their Role in Making a Viable Device into a Reliable Product”, IEEE Aerospace Conference, Big Sky, Montana, March 2014
2. Suhir, E Accelerated Life Testing (ALT) in Microelectronics and Photonics: Its Role, Attributes, Challenges, Pitfalls, and Interaction with Qualification Tests”, Keynote address, SPIE’s 7-th Annual Int. Symp. on Nondestructive Evaluations for Health Monitoring and Diagnostics, 17-21 March, San Diego, CA, 2002
3. Jordan J., Pecht, M. and J. Fink, “How Burn-in Can Reduce Quality and Reliability,” *Int’l. Journal of Microcircuits and Electronic Packaging*, Vol. 20, No. 1, pp. 35–40, 1997
4. E.Suhir, “To Burn-In, or Not to Burn-in: That’s the Question”, Aerospace , vol.6, No.3,2019
5. Suhir, E., Mahajan, R., “Are Current Qualification Practices Adequate?“, Circuit Assembly, April 2011
6. E.Suhir, “What Could and Should Be Done Differently: Failure-Oriented-Accelerated-Testing (FOAT) and Its Role in Making an Aerospace Electronics Device into a Product”, Journal of Materials Science: Materials in Electronics, vol.29, No.4, 2018

assurance. Since FOAT cannot do without

7. Suhir, E “Reliability and Accelerated Life Testing”, Semiconductor International, February1, 2005
8. Suhir, E.“When Reliability is Imperative, Ability to Quantify It is a Must”, IMAPS Advancing Microelectronics, July-Aug. 2012
9. Suhir, E.,“Could Electronics Reliability Be Predicted, Quantified and Assured?” Microelectronics Reliability, No. 53, April 15, 2013
10. E.Suhir, J.Nicolics, “Aerospace Electronics-and-Photonics (AEP) Reliability Has to be Quantified to be Assured”, AIAA SciTech Conf., San Diego, CA, January 2016
11. Suhir, E. and Yi, S. “Probabilistic Design for Reliability (PDfR) of Medical Electronic Devices (MEDs): When Reliability is Imperative, Ability to Quantify it is a Must”, Journal of SMT, 30 (1), 2017
12. Suhir, E “Predictive Modeling is a Powerful Means to Prevent Thermal Stress Failures in Electronics and Photonics”, Chip Scale Reviews, 15 (4), July-August, 2011
13. E. Suhir, and S. Yi, “Probabilistic Design for Reliability (PDfR) of Medical Electronic Devices (MEDs): When Reliability is Imperative, Ability to Quantify it is a Must”, Journal of SMT, v. 30, Issue 1, 2017
14. Suhir, E and Poborets, B., “Solder Glass Attachment in Cerdip/Cerquad Packages: Thermally Induced Stresses and Mechanical Reliability”, Proc. of the 40th Elect. Comp. and Techn. Conf., Las Vegas, Nevada, May 1990;

15. Suhir, E, “Applied Probability for Engineers and Scientists”, McGraw-Hill, New York, 1997
16. Suhir, E “Thermal Stress Modeling in Microelectronics and Photonics Packaging, and the Application of the Probabilistic Approach: Review and Extension”, IMAPS Int. J. of Microcircuits and Electr. Pack., 23 (2), 2000
17. Suhir, E, “Probabilistic Design for Reliability”, Chip Scale Reviews, vol.14, No.6, 2010
18. Suhir, E Mahajan, R., Lucero, A., Bechou, L., “Probabilistic Design for Reliability (PDfR) and a Novel Approach to Qualification Testing (QT)”, IEEE/AIAA Aerospace Conf., Big Sky, Montana, 2012
19. E.Suhir, “Aerospace Electronics Reliability Prediction: Application of Two Advanced Probabilistic Techniques”, ZAMM, vol.1, No.16, 2017
20. Suhir, E “Thermal Stress Failures: Predictive Modeling Explains the Reliability Physics Behind Them”, IMAPS Advancing Microelectronics, 38 (4),July/August, 2011
21. Suhir, E “Analytical Thermal Stress Modeling in Electronic and Photonic Systems”, ASME Appl. Mech. Reviews, 62 (4), 2009.
22. Suhir,E. “Analytical Modeling Enables One to Explain Paradoxical Situations in the Behavior and Performance of Electronic Materials and Products: Review”, Journal of Physical Mathematics 07(01) · Dec. 2015
23. Suhir, E., “Analytical Modeling Occupies a Special Place in the Modeling Effort”, Short Comm., J.Phys.Math., 7(1), 2016
24. Suhir, E, “Failure-Oriented-Accelerated-Testing (FOAT) and Its Role in Making a Viable IC Package into a Reliable Product”, Circuit Assembly, June 2013
25. Zhurkov, S.N., “Kinetic Concept of the Strength of Solids”, Int. J. of Fracture Mechanics, vol.1, No.4, 1965
26. Suhir, E, and Kang, S., “Boltzmann-Arrhenius-Zhurkov (BAZ) Model in Physics-of-Materials Problems”, Modern Physics Letters B (MPLB), vol.27, April 2013
27. Suhir, E., and Bensoussan, A., “Application of Multi-Parametric BAZ Model in Aerospace Optoelectronics”, IEEE Aerospace Conference, Big Sky, Montana, March 2014
28. Suhir, E “Three-Step Concept in Modeling Reliability: Boltzmann-Arrhenius-Zhurkov Physics-of-Failure-Based Equation Sandwiched Between Two Statistical Models”, Microelectronics Reliability, Oct. 2014
29. Suhir, E, Bechou, L., “Availability Index and Minimized Reliability Cost”, Circuit Assemblies, February 2013
30. Suhir, E., “Statistics- and Reliability-Physics-Related Failure Processes”, Modern Physics Letters B (MPLB), Vol. 28, No. 13, 2014
31. Suhir, E., “Analytical Modeling Enables Explanation of Paradoxical Behaviors of Electronic and Optical Materials and Assemblies”, Advances in Materials Research, vol.6, No.2, 2017
32. Suhir E. and Ghaffarian, R., “Electron Device Subjected to Temperature Cycling: Predicted Time-to-Failure”, Journal of Electronic Materials, vol.48, No.2, 2019
33. Suhir, E., “Making a Viable Medical Electron Device Package into a Reliable Product”, IMAPS Advancing Microelectronics, 2019, in print

Author’s Biography

Dr. Ephraim Suhir is on the faculty of the Portland State University, Portland, OR, USA, and Technical University, Vienna, Austria. He is also CEO of the Small Business Innovative Research (SBIR) ERS Co. in Los Altos, CA, USA. Ephraim is Foreign Full Member (Academician) of the National Academy of Engineering, Ukraine (he was born in that country); IEEE Life Fellow of the Institute of Electrical and Electronics Engineers (IEEE), the American Society of Mechanical Engineers (ASME), the Society of Optical Engineers (SPIE), and the International Microelectronics and Packaging Society (IMAPS); and Fellow of the American Physical Society (APS), the Institute of Physics (IoP), UK, and the Society of Plastics Engineers (SPE). He is Associate Fellow of the American Institute of Aeronautics and Astronautics (AIAA).

Ephraim has authored 400+ publications (patents, technical papers, book chapters, books), presented numerous keynote and invited talks worldwide, and received many professional awards, including 1996 Bell Laboratories Distinguished Member of Technical Staff (DMTS) Award (for developing effective methods for predicting the reliability of complex structures used in AT&T and Lucent Technologies products), and 2004 ASME Worcester Read Warner Medal for outstanding contributions to the permanent literature of engineering and laying the foundation of a new discipline “Structural Analysis of Electronic Systems”. Ephraim is the third “Russian American”, after S. Timoshenko and I. Sikorsky, who received this prestigious award. This year Ephraim received the 2019 IEEE Electronic Packaging Society (EPS) Field award for seminal contributions to mechanical reliability engineering and modeling of electronic and photonic packages and systems.