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Quantified Reliability of Aerospace Optoelectronics

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ABSTRACT

The attributes of and challenges in the recently suggested probabilistic design for reliability (PDFR) concept, and the role of its major constituents - failure oriented accelerated testing (FOAT) and physically meaningful predictive modeling (PM) - are addressed, advanced and discussed. The emphasis is on the application of the powerful and flexible Boltzmann-Arrhenius-Zhurkov (BAZ) model, and particularly on its multi-parametric aspect. The model can be effectively used to analyze and design optoelectronic (OE) devices and systems with the predicted, quantified, assured, and, if appropriate and cost-effective, even maintained probability of failure in the field. The numerical example is carried out for an OE system subjected to the combined action of the ionizing radiation and elevated voltage as the major stimuli (stressors). The measured leakage current is used as a suitable characteristic of the degree of degradation. It is concluded that the suggested methodology can be accepted as an effective means for the evaluation of the operational reliability of the aerospace electronics and OE systems and that the next generation of qualification testing (QT) specifications and best practices for such systems could be viewed and conducted as a "quasi-FOAT," a sort of an "initial stage of FOAT" that adequately replicates the initial non-destructive segment of the previously conducted comprehensive "full-scale" FOAT.

INTRODUCTION

OE is finding numerous applications in aerospace engineering. Short- and especially long-term reliability of OE devices and systems is, however, the major challenge for broad application of OE and photonic products in aerospace systems, when high reliability is a must. Here are some major problems and challenges envisioned and the most often and natural questions asked in connection with the reliability of the OE products:

- Qualification testing (QT) is the major means for making a viable device into a reliable product. It is well known, however, that the today's OE devices and systems that passed the existing QT often exhibit premature operational failures. Are the existing OE QT methodologies and procedures adequate [1]?
- Since typical OE products have been employed in aerospace engineering for just several years, there are no well-established and commonly accepted QT specifications, accelerated test (AT) methodologies and best practices yet, and it is unclear whether the OE product manufacturers should be shooting for a 30 year (perhaps unrealistically) long lifetime for an OE product or might be willing to settle for a shorter, but more or less satisfactorily substantiated and predicted lifetime?
- The predicted (anticipated) reliability of an OE product should be different for different loading (stressors) and for different fabrication technologies and applications [2], even within the aerospace world. How to consider and to quantify the effect of these conditions and applications, when planning the useful and cost-effective OE product lifetime?
- OE materials degradation (aging) and failure mechanisms that have been found in actual operation were not always addressed and detected by the existing QT and other AT efforts. How to establish the minimum list of the crucial ATs and the meaningful stressors, and, since the principle of superposition does not work in reliability engineering, how to establish the most important and physically meaningful combinations of these stressors?
- There is always a long way to go from what has been obtained in a research lab (research stage) to a viable and reliable industrial product (development stage). How could this way be shortened for the OE devices for the aerospace applications?
- Since real time degradation is a slow process that might take years to manifest, could physically meaningful and cost-effective AT methodologies for measuring the degradation (aging) rates and consequences be developed and implemented?

- Predictive modeling (PM) has proven to be a highly useful and time- and cost-effective means for understanding the physics of failure and designing the most practical ATs in many areas of electronic engineering [3, 4, 5, 6]. There is certainly a need for developing such models in the OE area as well, including the aerospace field, with an emphasis on validation, if possible, of the observed field failures. Which models might be the most needed ones: thermal, environmental, mechanical, outer space ionizing radiation related, most likely combinations of these, anything else?

The above concerns are primarily industries concerns, but what should be the major reliability related worries of a particular OE product manufacturer, especially in the aerospace world, when high and predictable reliability is imperative [7]?

In the analysis that follow we do not intend, of course, to dot all the i's and cross all the t's in the new and challenging world of OE reliability engineering for aerospace applications, but rather intend to partially address and discuss some of the above problems, with an objective to show how the recently suggested PDfR concept, based on the highly focused and highly cost-effective FOAT and simple and physically meaningful PM techniques can be effectively used for making an OE device into a reliable product, with the predicted, quantified, assured, and, if appropriate and cost-effective, even maintained probability of failure (PoF) in the field.

WHEN RELIABILITY IS IMPERATIVE ABILITY TO QUANTIFY IT IS A MUST

The ultimate broad goal of the OE and photonic industries is to make their deliverables consistently robust in the field by establishing industry wide QT methodologies and practices. On the other hand, the short-term and practical goal of an OE product manufacturer is to conduct and pass the existing QT specifications and requirements without questioning if or to what extent they are adequate. QT is the major means that the industries use to make their devices into products. It brings to a "common denominator" different OE manufacturers and different OE products. Many OE products that passed the today's QTs have been known, however, to often prematurely fail in the field. Are the today's OE and photonic QT and specifications adequate? Do the OE manufacturing industries need new approaches to qualify their products? And if they do, could the existing OE specifications, procedures and practices be improved to an extent that if an OE product passed the existing QT, there is a quantifiable and sustainable way to assure that it will satisfactorily, in a failure-free fashion, perform in the field?

At the same time, there exists a perception, perhaps a substantiated one, that some products or at least some important parts of these products are highly reliable and never fail. Although, as they say, one should never say "never", the very existence of such a perception could be attributed to the superfluous and unnecessary robustness of a particular design

or a particular component for the given application and loading conditions. When failure occurs, root cause analyses are conducted, origins of failures are detected, and the appropriate corrective actions are taken, and these actions are usually aimed at strengthening the weakest link in the design, while the non-failed elements remain unchanged. As a result of such actions the product might become over-engineered and, hence, to complex and too costly. Could it be proven that a particular product or an element that never failed is indeed superfluously robust and is therefore too costly for the particular application it is intended for? Is it possible that the manufacturer spent more than necessary to produce this product, and the customer paid too much to purchase it?

If these questions make sense, and, in the authors' opinion, they sure do, to answer them one has to find a consistent and a trustworthy way to quantify the product's reliability [8]. Then it would become possible not only to assure its adequate performance in the field, but also to determine if a well understood and a well substantiated reduction in the product's superfluous reliability, if any, could be translated into considerable cost savings.

In addition, there is always an incentive to optimize reliability. Based on such an optimization, it would be possible to establish the best compromise between reliability, cost effectiveness and time-to-market (to completion) of the product of interest. OE products for aerospace applications are extremely expensive, and therefore the ability to understand the relationship between the reliability and cost, and, if possible, to bring the cost down without compromising reliability is of obvious and extraordinary importance. No optimization is possible, of course, if reliability is not quantified and evaluated vs. the expenses associated with the cost of creating a reliable product and the cost of its restoration, if it fails [8]. Last but perhaps the most important consideration in favor of an attempt to quantify operational reliability is that consistent and sustainable prediction and quantification of the operational reliability would enable one to develop the most effective QT methodologies, procedures and specifications. These should consider the expected (required) time in operation, the most likely operation conditions, and possible consequences of failure.

PROBABILISTIC DESIGN FOR RELIABILITY (PDfR)

Design for reliability (DfR) is a set of approaches, methods and best practices that are supposed to be used at the design stage of the product to minimize the risk that it might not meet the reliability requirements, objectives and expectations. "While 50% of the total actual cost of an electronic product is due to the cost of materials, 15% - to the cost of labor, 30% to the overhead costs and only 5% to the design effort, this effort influences about 70% of the total cost of the product. If reliability is taken care of at the design phase, the final cost of the product does not go up. If a reliability problem is detected

during engineering the cost of the product goes up by a factor of 10. If the problem is caught in production phase, the cost of the product increases by a factor of 100 or more" [9]. Reliability is conceived at the design stage, whether one admits that or not. If the designer does a good job, there is a good chance that a "genetically healthy" OE product will be born. If this happens, then there are also high chances that subsequent reliability oriented or reliability affecting efforts conducted at different stages of the product's lifetime, such as fabrication, testing, maintenance, diagnostics, prognostics and health monitoring (PHM), will be successful as well. When deterministic (non-probabilistic) approach is used to quantify reliability, it could be based on the concept that sufficient reliability level will be assured if a high enough safety factor (SF) is used. The deterministic SF is defined as the ratio $SF = C/D$ of the capacity ("strength") C of the product to the demand ("load") D . In a particular problem the capacity and demand could be mechanical loads, elevated or low temperatures, electrical current, resistance, voltage, light intensity, humidity, etc. Cost effectiveness is seldom associated with the reliability level, if a deterministic approach is used.

"TEN COMMANDMENTS" IN THE PROBABILISTIC DESIGN FOR RELIABILITY (PDfR) CONCEPT

PDfR concept [10, 11, 12] is central in our approach to calculate the PoF of an OE device and to use this probability as a suitable criterion of the product performance. The following ten major principles ("commandments") reflect the rationale behind the PDfR concept:

1. PDfR is an effective means for improving the state-of-the-art in the field of the OE engineering by quantifying, on the probabilistic basis, the operational reliability of OE devices. The PDfR concept is based on the recognition of the fact that nobody and nothing is perfect, and that the difference between an unreliable product and a highly reliable one is "merely" the level of their operational PoF.
2. The PoF of an OE product is never zero, but could and should be assessed (quantified) and brought to an acceptable (adequate) level.
3. The best OE product should be designed and fabricated as the best compromise between the needs (requirements) for its reliability, cost effectiveness and time-to-market (completion) [12]. These three major factors are of different importance in different applications and situations, but they are always of importance in any OE related technology. The most effective compromise can be established only if the PoF of an OE product is quantified
4. OE product's reliability cannot be low, need not be higher than necessary, but has to be adequate for the given application, considering the expected and/or remaining useful lifetime, environmental conditions and possible consequences of failure
5. Redundancy, trouble-shooting and maintenance are important factors to be considered, when adequate reliability

level has to be maintained, especially if the "genetic health" of the product is not high

6. When reliability is imperative, the ability to quantify it is highly desirable and is even a must, especially if one intends to optimize and assure reliability, as far as its level and most feasible compromise with cost-effectiveness are concerned [7].
7. One cannot design a product with quantified, optimized and assured reliability by limiting the effort to the widely used today highly accelerated life testing (HALT) [13]. HALT might detect and identify possible failure modes and even, to a limited (and unknown) extent, improve (ruggedize) reliability, but does not quantify it. One cannot quantify and assure reliability by simply following the existing qualification practices either, especially for new products and new applications, when such practices do not yet exist.
8. Reliability is conceived at the design stage, whether one admits that or not, and should be taken care of, first of all, at this stage. It is at the design stage, when an attempt should be made to create a "genetically healthy" product. Reliability evaluations and assurances cannot be delayed until the product is fabricated and installed. It is too late at this stage to change the design or the materials for improved reliability. That is why, when high reliability is critical, users like NASA, whose OE products have to perform in a failure-free fashion in operation, have to re-qualify parts in order to assess their remaining useful lifetime (RUL), to use redundancy to build a reliable enough system out of insufficiently reliable components and to employ and master the PHM technologies, instrumentations and techniques to maintain high level of operational performance of insufficiently "genetically" healthy materials, devices and systems. In addition, by adding the PHM effort to the product one might add considerably to the product's cost. It is also important to have in mind that redundancy, PHM and other auxiliary health monitoring (managing) equipment and instrumentation is not 100% reliable either.
9. Highly cost-effective and highly focused FOAT [14, 15, 16, 17] geared to a limited number of pre-determined simple, easy-to-use and physically meaningful predictive reliability models and aimed at understanding the physics of failure anticipated and quantified by these models is an important constituent part of the PDfR effort.
10. Predictive modeling (PM) [3, 4, 5, 6] is another important constituent of the PDfR approach. PM, in combination with FOAT, 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 PoF sufficiently low ("principle of practical confidence").

SAFETY FACTOR (SF)

Direct use of the PoF as an adequate criterion of the likelihood of non-failure is often inconvenient, since, for highly reliable items, this probability is expressed by a number which is very close to one, and, for this reason, even significant changes in the product design, which have an appreciable impact on its reliability, might have a minor effect on the PoF. When the

mean value, $\langle \psi \rangle$, and the standard deviation, \hat{S} , of the margin of safety $MS = \psi = C - D$ for a reliability characteristic of interest are available, the safety factor SF is computed as

$$SF = \frac{\langle \psi \rangle}{\hat{S}}$$

When the random time-to-failure (TTF) is of interest, the SF can be found as the ratio of the MTTF to the standard deviation of the TTF.

The PoF and/or the level of the SF should be chosen depending on the existing experience, anticipated operation conditions, possible consequences of failure, acceptable risks, the available and trustworthy information about the capacity and the demand, the accuracy with which the capacity and the demand are determined, possible costs and social benefits, information on the variability of materials and structural parameters, fabrication technologies and procedures, etc. Reliability is not an exact science, and sufficient or insufficient reliability is often in the eye of the beholder. Intuition and vision often play a significant role in the reliability assessments and expectations. Quantification, however, enables one to minimize the level of subjectivity in reliability assessments and judgments.

ACCELERATED TESTING (AT), ITS ROLE AND SIGNIFICANCE

Shortening of product's design and development time does not allow in the today's industrial environment, even in the aerospace field, for time consuming reliability investigations. To get maximum reliability information in minimum time and at minimum cost is the major goal of a product manufacturer. At the same time, it is impractical to wait for failures, when the lifetime of a typical today's OE device or package is hundreds

of thousands of hours. AT is therefore both a must and a powerful means in electronics and OE manufacturing. The major AT types are summarized in [Table 1](#).

Product development testing (PDT) is a crucial part of the design-for-reliability (DfR) effort. A typical example is shear-off testing when there is a need to determine the most feasible bonding material and its thickness. HALT (see, e.g., [13]) is currently widely employed, in different modifications, with an intent to determine the product's design and reliability weaknesses, assess its reliability limits, ruggedize the product by applying elevated stresses (not necessarily mechanical and not necessarily limited to the anticipated field stresses) that could cause field failures, and to provide large (although, actually, unknown) SMs over expected in-use conditions. HALT often involves step-wise stressing, rapid thermal transitions, etc. HALT is a "discovery" test. It is the QT that is the "pass/fail" one and, as such, is the major means for making a promising and viable device (package) into a reliable and marketable product. QT brings to a "common denominator" different manufacturers and different products. When it comes to manufacturing, however, mass fabrication generates, in addition to desirable-and-robust ("strong") products, also some amount of undesirable-and-unreliable ("weak") devices ("freaks"), which, if shipped to the customer, will most likely fail in the field. Burn-in testing (BIT) [12] is supposed to detect and to eliminate such "freaks". As a result, the final bathtub curve of a product that underwent BIT is not supposed to contain the infant mortality portion. In the today's practice, BIT, which is a destructive test for the "freaks" and a non-destructive test for the healthy devices, is often run within the framework of and concurrently with HALT.

Table 1. Accelerated Test Types

AT type	Product development testing (PDT)	Highly accelerated life testing (HALT)	Qualification testing (QT)	Burn-in testing (BIT)	Failure oriented accelerated testing (FOAT)
Objective	Technical feedback to assure that the taken design approach is acceptable	Ruggedize the product and to assess the reliability limits	Proof of reliability; demonstration that the product is qualified to serve in the given capacity	Eliminate the infant-mortality part of the bathtub curve	Understand the physics of failure, confirm the use of a particular predictive model, assess the probability of failure
End point	Type, time, level, and/or the number of observed failures	Predetermined number or percent of failures	Predetermined time and/or cycles, and/or excessive (unexpected) number of failures	Predetermined time and/or loading level	Predetermined number or percent (typically 50%) of failures
Follow-up activity	Failure analysis, design decision	Failure analysis	Pass/fail decision	Shipping of sound devices	Failure and probabilistic analyses of the test data
Ideal test	Specific definitions	No failures in a long time			Numerous failures in a short time

A highly focused and highly cost effective FOAT, the “heart” of the PDfR concept, should be conducted in addition to and, in some cases, even instead of HALT. FOAT is a solid experimental foundation of the PDfR approach. A prediction, based on the FOAT and subsequent PM, might not be perfect, but it is still better to pursue it, 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 OE device performance is critical. If one sets out to understand the physics of failure in an attempt to create a failure-free product, conducting a FOAT type of an experiment should be imperative, should it not? Accordingly, FOAT’s objective is to confirm usage of a particular more or less well established PM, to confirm (say, after HALT is conducted) the underlying physics of failure, and establish the numerical characteristics (activation energy, time constant, exponents, if any, etc.) of the particular FOAT reliability model of interest.

FAILURE ORIENTED ACCELERATED TESTING (FOAT) AS AN EXTENSION AND ADVANCEMENT OF THE HIGHLY ACCELERATED LIFE TESTING (HALT)

FOAT could be viewed as an extension of HALT. 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 “white box”, whose main objective is to confirm usage of a particular PM 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.

While HALT does not measure (does not quantify) reliability, FOAT does. HALT can be used for “rough tuning” of an OE product’s reliability, while FOAT 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 an OE device. HALT tries, quite often rather successfully, to “kill many unknown birds with one stone”. HALT has demonstrated over the years its ability to improve robustness through a “test-fail-fix” process, in which the applied stresses are somewhat above the specified operating limits. There is a general perception that by doing that, HALT might be able to quickly precipitate and identify failures of different origins.

Since the principle of superposition does not work in reliability engineering, both HALT and FOAT use, when appropriate, combined stressing under various stimuli (stressors). FOAT and HALT could be carried out separately, or might be partially combined in a particular AT effort.

New OE 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. [18]).

The FOAT based approach could be viewed as a “quantified and reliability physics oriented HALT”. FOAT should be implemented, whenever feasible and appropriate, in addition to HALT. In some cases FOAT could be implemented even instead of HALT, especially for new OE products, whose operational reliability is unclear and for which no experience is accumulated and no best practices exist. The FOAT approach should be geared to a particular technology and application, with consideration of the most likely stressors.

SOME MAJOR FAILURE ORIENTED ACCELERATED TEST MODELS

Here are some major FOAT models:

- Arrhenius' equation

$$\tau = \tau_0 \exp\left(\frac{U}{kT}\right) \quad (1)$$

Here τ is the lifetime, τ_0 is the time constant, U is the activation energy, T is the absolute temperature and k is Boltzmann's constant. This law and its numerous extensions and modifications are used when there is evidence or belief that the elevated temperature is the major cause of the material or the device degradation. Examples are lifetime of electrical insulations and dielectrics, solid state and semiconductor devices, inter-metallic diffusion, batteries and solar cells, lubricants and greases, thermal interface materials, plastics, certainly, OE devices, etc. Arrhenius model can be used also when evaluating reliability characteristics other than lifetime, such as, e.g., leakage current or light output.

- BAZ model [19, 20, 21, 22]

$$\tau = \tau_0 \exp\left(\frac{U_0 - \gamma\sigma}{kT}\right) \quad (2)$$

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 loading σ was a constant mechanical tensile stress, it has been recently suggested [12, 20] that any other stimulus of importance (voltage, current, thermal stress, humidity, radiation, etc.) can be used as such a stress. The effective activation energy

$$U = kT \ln \frac{\tau}{\tau_0} = U_0 - \gamma\sigma \quad (3)$$

plays in the BAZ model the role of the stress-free energy U_0 in the Arrhenius model (1). 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 [20]. It has been shown that this solution represents the worst case scenario for the Markovian process addressed and that the reliability predictions based on the BAZ model are reasonably conservative and are advisable to be used in engineering practice.

- Various and numerous crack growth models are used to assess the fracture toughness of materials in the brittle state.
- Inverse power law is used in numerous modifications of the Coffin-Manson's semi-empirical relationships aimed at the prediction of the low cycle fatigue life-time of solders that operate above the yield limit.
- Miner-Palmgren rule is used to address fatigue when the elastic limit is not exceeded.
- Weakest link models are used to evaluate the lifetime in extremely brittle materials, like Si, with highly localized defects.
- Stress-strength interference models (see, e.g., [22]) are widely used in various problems of structural (physical) design in many areas of engineering, including microelectronics.
- Peck's model

$$\tau = \tau_0 H^{-n} \exp\left(\frac{U_0}{kT}\right) \quad (4)$$

considers the combined action of elevated temperature and relative humidity H .

- Peck's power law

$$\tau = \tau_0 H^{-n} f(V) \exp\left(\frac{U_0}{kT}\right) \quad (5)$$

considers also the applied voltage.

- Eyring formula could be obtained from (4) by substituting the relative humidity H in it with the peak current I .

It is important to point out that the model (2) has a solid physical meaning, reflected by the level of the activation energy, while the formulas (4) and (5) are semi-empirical. On the other hand, if testing is carried out based on the formula (4), the results can be easily interpreted in terms of the model (2). Indeed, by putting $\sigma = H$ in the BAZ formula (2) and equating the lifetimes predicted by the formulas (2) and (4), we obtain:

$$\gamma = nkT \frac{\ln H}{H} \quad (6)$$

- Black's equation can be obtained by substituting in the Peck's model (4) the relative humidity H with the current density j . It is used to quantify the reliability in electro-

migration problems, to evaluate the lifetime of hetero-junction bipolar transistors and, in some cases, the role of humidity as well.

It is important to emphasize that all these models can be interpreted in terms of the probability of failure under the given loading conditions and after the given time in operation. A bathtub curve is a good example of a FOAT model and is a reliability "passport" of the device (system) of interest. If this curve is available, then many useful quantitative predictions could be made (see, e.g., [23]).

As another example let us 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 (this single-parametric law is characterized by the highest entropy and reflects therefore the most conservative approach) as

$$P = \exp\left[-\frac{t}{\tau_0} \exp\left(-\frac{U}{kT}\right)\right] \quad (7)$$

Solving this equation for the temperature T , we have:

$$T = -\frac{\left(\frac{U}{k}\right)}{\ln\left(-\frac{\tau_0}{t} \ln P\right)} \quad (8)$$

Addressing, e.g., surface charge accumulation failure, for which the ratio of the activation energy to the Boltzmann's constant is $U/k = 11600$ °K, assuming that the FOAT-predicted time factor τ_0 is $\tau_0 = 2 \times 10^{-5}$ hours, that the customer requires that the probability of failure at the end of the device's service time of $t = 40,000$ hours does not exceed $Q = 10^{-5}$, we obtain: $T = 352.3$ °K = 79.3 °C. Thus, the heat managing device (heat sink) should be designed accordingly, and the vendor should be able to deliver such a heat sink. More complicated examples of FOAT and design decisions based on the FOAT data could be found in Refs. [10, 22, 24].

MULTI-PARAMETRIC BOLTZMANN-ARRHENIUS- ZHURKOV (BAZ) MODEL

Let the lifetime τ in the BAZ model (2) be 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 [11]. Let us assume that the failure rate of an OE device, which characterizes the rate of propensity of the material or the device to failure, is determined

by the level of the leakage current: $\lambda = \gamma_I I$. Then, using the type (2) model, one could seek the probability of the OE product's non-failure in the form:

$$P = \exp \left[-\gamma_I I t \exp \left(-\frac{U_0 - \gamma_H H - \gamma_V V}{kT} \right) \right] \quad (9)$$

where the γ values reflect the sensitivities of the device to the corresponding stimuli (stressors). Although only two stimuli (stressors) were selected in this model - relative intensity of the ionizing radiation H and elevated voltage V - the model can be easily made multi-parametric, i.e., generalized for as many stimuli as necessary.

It should be pointed out that the sensitivity factors γ should be determined from the FOAT when the combined action of all the stimuli (stressors) of importance (interest) is considered. Because of that the structure of the multi-parametric BAZ expressed by the equation (9) should not be interpreted as a superposition of the effects of different stressors, but rather as a convenient and physically meaningful representation of the FOAT data.

The physical meaning of the distribution (9) could be seen from the following formulas

$$\begin{aligned} \frac{\partial P}{\partial I} &= -\frac{H(P)}{I}, & \frac{\partial P}{\partial t} &= -\frac{H(P)}{t}, \\ \frac{\partial P}{\partial U_0} &= \frac{H(P)}{kT}, \\ \frac{\partial P}{\partial H} &= -\frac{H(P)}{kT} \gamma_H = -\gamma_H \frac{\partial P}{\partial U_0}, \\ \frac{\partial P}{\partial V} &= -\frac{H(P)}{kT} \gamma_V = -\gamma_V \frac{\partial P}{\partial U_0}, \end{aligned} \quad (10)$$

Where $H(P) = -P \ln P$ is the entropy of the probability of non-failure. The formulas (10) can be obtained from (9) by differentiation. The following conclusions can be made based on the formulas (10):

- 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.
- The last two formulas in (10) 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 (with an opposite sign though).

The equation (9) contains four empirical parameters that characterize the OE material or device of interest: the stress-free activation energy U_0 and three sensitivity factors γ . Here is how these parameters can be obtained from the highly focused and, we believe, rather inexpensive 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 ionizing radiation 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). This enables one to obtain the following two relationships:

$$\begin{aligned} P_1 &= \exp \left[-\gamma_I I_* t_1 \exp \left(-\frac{U_0 - \gamma_H H - \gamma_V V}{kT_1} \right) \right], \\ P_2 &= \exp \left[-\gamma_I I_* t_2 \exp \left(-\frac{U_0 - \gamma_H H - \gamma_V V}{kT_2} \right) \right] \end{aligned} \quad (11)$$

Since the numerators $U_0 - \gamma_H H - \gamma_V V$ in these relationships are kept the same, the following transcendental equation must be fulfilled for the sought sensitivity factor γ_I of the leakage current:

$$f(\gamma_I) = \ln \left(-\frac{\ln P_1}{I_* t_1 \gamma_I} \right) - \frac{T_2}{T_1} \ln \left(-\frac{\ln P_2}{I_* t_2 \gamma_I} \right) = 0 \quad (12)$$

Here t_1 and t_2 are times, at which the failures were observed. It is expected that more than two series of FOAT tests and at more than two temperature levels will be conducted, so that the sensitivity parameter γ_I could be predicted with a high enough degree of accuracy and certainty.

At the second step, FOAT tests at two ionized radiation levels H_1 and H_2 should be conducted for the same temperature and voltage. This leads to the relationship:

$$\gamma_H = \frac{kT}{H_1 - H_2} \left[\ln \left(-\frac{\ln P_1}{I_* t_1 \gamma_I} \right) - \ln \left(-\frac{\ln P_2}{I_* t_2 \gamma_I} \right) \right] \quad (13)$$

Similarly, by changing the voltages V_1 and V_2 in the next set of FOAT tests one could find:

$$\gamma_V = \frac{kT}{V_1 - V_2} \left[\ln \left(-\frac{\ln P_1}{I_* t_1 \gamma_I} \right) - \ln \left(-\frac{\ln P_2}{I_* t_2 \gamma_I} \right) \right] \quad (14)$$

Finally, the stress-free activation energy can be computed as

$$U_0 = \gamma_H H + \gamma_V V - kT \ln \left(- \frac{\ln P}{I_* t \gamma_I} \right) \quad (15)$$

for any consistent ionized radiation, voltage, temperature and time values. 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.

After the sensitivity factors of the leakage current, the relative ionizing radiation and the voltage, and the loading (stressor) free activation energy are determined for the tested combinations of the input data, the [formula \(9\)](#) could be used, but should be checked (validated), of course, for other physically meaningful combinations of the FOAT parameters.

POSSIBLE NEXT GENERATION OF QUALIFICATION TESTS (QT)

The next generation OE 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 (such as “canaries”) should be concurrently tested to make sure that the safe limit is not exceeded. We believe that such an approach to qualify devices into products will enable the OE industry to specify, and the manufacturers - to assure, a predicted and adequate PoF for an OE device or a module that passed the QT and will be operated in the field under the given conditions for the given time. FOAT should be thoroughly designed and implemented, so that the QT is based on the trustworthy FOAT data.

Since FOAT cannot do without simple, easy-to-use and physically meaningful PM, the role of such modeling, both computer-aided and analytical (mathematical), in making the suggested new approach to QT practical and successful [\[31, 32, 33\]](#). 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.

NUMERICAL EXAMPLE

Let, e.g., 1) after $t_1 = 35h$ of testing at the temperature $T_1 = 60^\circ C = 333^\circ K$ at the given voltage (say, $V=600V$) and at the given ionizing radiation level (say, $H=0.85$) 10% of the tested modules reached or exceeded the critical level of the leakage current of $I_* = 3.5 \mu A$ and, hence, failed, so that the probability of non-failure is $P_1=0.9$ and 2) after $t_2 = 70h$ of testing at the

temperature $T_2 = 85^\circ C = 358^\circ K$ at the same voltage and the same relative ionizing radiation, 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 \(12\)](#) yields:

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

This equation has the solution $\gamma_I = 4926 h^{-1} (\mu A)^{-1}$. Then $\gamma_I I_* = 17241 h^{-1}$.

At the second step, tests at two radiation levels H_1 and H_2 were conducted for the same temperature and voltage levels. This leads to the relationship:

$$\gamma_H = \frac{kT}{H_1 - H_2} [\ln(-0.5800 \times 10^{-4} \frac{\ln P_1}{t_1}) - \ln(-0.5800 \times 10^{-4} \frac{\ln P_2}{t_2})]$$

Let, e.g., after $t_1=40h$ of testing at the relative radiation level of $H_1=0.5$ at the given voltage (say, $V=600V$) and temperature (say, $T = 60^\circ C = 333^\circ K$), 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 radiation level of $H_2=0.85$, 10% of the tested modules failed, so that $P_2=0.9$. Then the above equation, with $k=8.61733 \times 10^{-5} eV/^\circ K$ 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, $T = 85^\circ C = 358^\circ K$ 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

$$\gamma_V = \frac{0.02870}{400} [\ln(-0.5800 \times 10^{-4} \frac{\ln P_2}{t_2}) - \ln(-0.5800 \times 10^{-4} \frac{\ln P_1}{t_1})]$$

or $\gamma_V = 4.1107 \times 10^{-6} eV/V$

After the factors of the leakage current, the radiation and the voltage are found, the stress free activation energy can be determined for the given temperature and for any combination of loadings on the basis of the [formula \(15\)](#). Calculations indicate that the loading free activation energy in this numerical example (with rather arbitrary input data) is about $U_0=0.477 eV$. The third term in [\(15\)](#) plays the dominant role, so that, in approximate evaluations, only this term could be considered.

CONCLUSION

The application of 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 aerospace OE products reliability prediction and assurance. We believe that the existing QT specifications could be improved, using the addressed approach, to an extent that if an OE device, module

or a system passed the new generation of the QT specifications, there will be a quantifiable and consistent way to assure that the operational performance of an OE product will be satisfactory and that its projected lifetime will indeed take place with an acceptable PoF and confidence limits.

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ACRONYMS

- AT** - Accelerated testing;
- BAZ** - Boltzmann-Arrhenius-Zhurkov model;
- BIT** - Burn-in testing;
- DfR** - Design for reliability;
- FOAT** - Failure oriented accelerated testing;
- HALT** - Highly accelerated life testing;
- MTTF** - Mean time to failure;
- OE** - Optoelectronics;
- PDfR** - Probabilistic DfR;
- PDT** - Product development testing;
- PHM** - Prognostics and health monitoring;
- PM** - Predictive modeling;
- PoF** - Probability of failure;
- QT** - Qualification testing;
- SF** - Safety factor;
- SM** - Safety margin;
- TTF** - Time to failure