

Quantified Reliability of Aerospace Optoelectronics

Ephraim Suhir

Alain Bensoussan
Thales Alenia Space France

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.

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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 reliability, might have a minor effect on the PoF. When the