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Editorial

Probabilistic design for reliability of aerospace electronics and photonics: role, significance, attributes, challenges

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"Do not go where the path may lead, go instead where there is no path and leave a trail"
Ralph Waldo Emerson (1803–1882), American essayist, philosopher and poet

"A pinch of probability is worth a pound of perhaps"
James G. Thurber (1894–1961), American cartoonist, journalist, and playwright

"Probability theory is nothing but common sense reduced to calculation", said Pierre-Simon Laplace (1749–1827), the famous French mathematician, founder of the science of applied probability. This statement has been and is true for almost any area of engineering and science (see, e.g., [1]), including aerospace electronics and photonics, micro-electromechanical-systems (MEMS), and their optical modifications (MOEMS). The author of this write-up, being in the mid-eighties for about two decades with the Bell Labs Basic Research, Physical Sciences and Engineering Division, as its Distinguished Member of Technical Staff (DMTS), dealt with the reliability of AT&T and then Lucent Technologies designs, technologies, and products and applied his experience in reliability physics and risk analyses to the challenging field of semiconductor packaging. He suggested particularly [2–5] that the probabilistic design for reliability (PDfR) concept be considered in "physical design" of electronic and photonic products ("electrical design" is the other major part of electronic and photonic engineering). The effort is aimed at making a viable IC device into a reliable product and focuses on the applications, in which high reliability is critical, such as, e.g., aerospace, military, or long-haul-communications. Bell Labs electronic engineers used to say at that time that "nothing might possibly happen to an electron or a photon, but if you attach the best IC device (first level of interconnections) or the best package (second level) to a piece of junk known as a substrate, you will end up with a piece of junk". That is why physical design-for-reliability (DfR) of electronics and photonics devices, packages, and systems has been important in the past, is important today, and will remain important in the future [6]. This is particularly true also in the important case of various "human-in-the-loop" (HITL) missions and situations, when the reliability of the equipment and instrumentation (both its hard- and software) and human(s) performance contribute jointly to the outcome of a critical undertaking [7].

It is noteworthy that an always expensive and always time-and-labor consuming DfR effort (reliability, if understood, costs money to be implemented and assured, does it not?) might not be needed for many commercial applications: it is low cost and short time to market, and not reliability, that is of primary importance for commercial products. The satisfactory and sufficient reliability is defined for such products, only, perhaps, partially in jest, as a situation "when the customer comes back, not the product". Things are, however, completely different in the aerospace world, and it is in this world where, because of numerous intervening uncertainties, "chance governs all" (John Milton, "Paradise Lost"). The difference between a highly reliable and an insufficiently reliable electronic or a photonic product or a system in the aerospace engineering domain is "merely" the difference in their never-zero probabilities of failure. The reliability of an aerospace system cannot be assured, nor even effectively improved, if it is not quantified, and if, because of the inevitable uncertainties in materials' properties, type and level of loadings, environmental conditions, human performance, etc., such a quantification is not done on the probabilistic basis. It would not be an exaggeration to say that the application of the PDfR concept makes a difference in the state-of-the-art in the field of electronics and photonics reliability engineering for critical applications by putting this body of knowledge on a "reliable" probabilistic foundation and establishing adequate probabilities of failures. This should be done, of course, by predicting these probabilities and considering the consequences of the particular failures.

The PDfR effort could be based particularly on the recently suggested multi-parametric Boltzmann-Arrhenius-Zhurkov (BAZ) flexible and physically meaningful constitutive model [8,9] whose experimental basis is failure-oriented accelerated testing (FOAT) [10–12] at the design stage.

There are (chronologically, when making a viable IC design into a reliable product) three types of FOAT: 1) some product development tests (such as, e.g., temperature cycling or shear-off tests); 2) FOATs at the design stage (these, as has been indicated, highly focused and highly cost-effective tests are part of the PDfR effort and should be applied when a new technology, a new design, or a new application of an existing product is considered and when there are no suitable and trustworthy HALTs [13], nor suitable best practices yet; and 3) burn-in-tests (BITs) [14] that are always failure-oriented: their objective is, as is known, to, hopefully, get rid of the infant-mortality portion of the bathtub curve. As far as the FOAT-oriented temperature cycling tests are concerned (these are widely used and could be part of each of the three FOAT types), it has been recently shown [15] and even "reduced to practice" under a research project with NASA (conducted in collaboration with R.

Ghaffarian) that there is an obvious incentive to replace these expensive, time-and-labor consuming and possibly misleading tests with other, more physically meaningful ones, such as, e.g, low-temperature/random-vibrations bias.

The appropriate PDfR/FOAT/BAZ stressors could be, in effect, any more or less realistic “stimuli” that shorten the useful lifetime and increase the probability of failure of a device, package, module, or a system: mechanical, thermal, or dynamic stresses, elevated voltage or current, high humidity, temperature extremes (high temperatures affect, as is known, the materials' degradation and aging, i.e., its long-term performance, while low temperatures result in elevated thermal stresses affecting its short-term reliability), interfacial charge accumulation, charge injection, corrosion, light intensity, ionizing radiation, etc., or, of course, a possible and physically meaningful combination of these stressors. It has been recently demonstrated, with an emphasis on aerospace safety applications (see, e.g., [7]), that the suggested PDfR concept could be applied also in various “human-in-the-loop” (HITL) situations, when the equipment's reliability and human(s) performance contribute jointly to the outcome of a mission or an off-normal situation, and that such applications might include also medical and clinical [16,17] systems.

The incentive for the application of the probabilistic approach (actually, considering “uncertainties”) in ergonomics has been first indicated, most likely, by Tversky and Kahneman [18] back in 1947 (see also their 1982 book [19]). These authors addressed cognitive “heuristics and biases” when considering various uncertainties in human psychology in association with decision making tasks in economics (2002 Nobel Memorial Prize in Economic Sciences). Being top-notch, but traditional, psychologists, these authors discussed problems containing “uncertainties” from the qualitative viewpoint. The need for a broader application of the quantitative risk assessments in ergonomics engineering was indicated later on in application to risk analyses in various complex systems (see, e.g. [20]). In conclusion, we would like to emphasize that while predictive modeling should always precede any type of accelerated testing, the “old-fashioned” analytical (“mathematical”) modeling, considered in the above analyses [21], should complement, whenever possible, computer simulations: these two major modeling tools are based on different assumptions and use different calculation techniques, and if the results obtained using these tools are in agreement, then there is a good reason to believe that they are sufficiently accurate and, hence, trustworthy. Future work should be focused on the experimental verification of the developed models, the obtained results, the drawn conclusions, and the suggested recommendations.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

Conflict of interest

All authors declare no conflicts of interest in this paper.

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