

Complex Software Systems: Two Non-Software Reliability Concerns

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Abstract

The objective of this write-up is to draw attention of reliability engineers working in the field of highly popular today complex software systems (CSS), like, e.g., artificial intelligence (AI), large language models (LLM) and robotics engineering (RE), that when it comes to assuring success and safety of such systems, non-software reliability, such as the reliability of the systems' hardware and human performance, are equally, if not even more, important. Two more or less typical problems are addressed here as suitable examples: 1) the hardware reliability of PN junctions employed in semiconductor electronics for almost a century and 2) the ergonomics-engineering human-in-the-loop (HITL) role in critical undertakings, when the hardware reliability of the electronic-and-photonics materials-and-structures and human performance contribute jointly to the success and safety of an undertaking of importance. The emphasis is on the need for quantifying, preferably on the probabilistic basis, the possible role, significance, attributes, and challenges, associated with the application of the "old-fashioned" analytical ("mathematical") predictive modeling (APM) technique, as well as on the experimental foundation of this technique – failure oriented accelerated testing (FOAT).

Keywords: Artificial Intelligence (AI), Complex-Software-Systems (CSS), Double-Exponential-Probability-Distribution-Function (DEPDF), Failure-Oriented-Accelerated-Testing (FOAT), Human-Capacity-Factor (HCF), Human Error (HE), Human Factor (HF), Probabilistic Analytical ("mathematical") Modeling (PAM), Probabilistic Design for Reliability (PDFR), Robotics Engineering (RE), Stress-Free-Activation-Energy (SFAE), Space Safety Engineering (SSE), State-of-Health (SoH), State-of-Mind (SoM)

Introduction

Incentive Perspective

The current effort in assuring the reliable performance of complex software systems (CSS's) is naturally and primarily focused on the systems software reliability (see, e.g., [1]). In our analysis, however, two critical non-software reliability concerns related to the successful performance of such systems are addressed, with an emphasis on their role in space safety engineering (SSE): 1) the hardware reliability of PN junctions used in semiconductor engineering for about a century [2-9] and 2) the ergonomics human-in-the-loop (HITL) role [10-

59], when reliability of materials-and-structures and human-performance contribute jointly to the outcome of various critical CSS HITL undertakings. While the PN junction has been known for many years as an exceptionally reliable structural element of a semiconductor device, it is well known also that human intervention can bring down dramatically the overall performance of a HITL system of any nature. This is true even in the case of its functioning for a short time, when no human error (HE) is likely to occur, not to mention the system's long-term, such as, e.g., space travel, performance. The emphasis of our analyses is on quantifying, preferably on the probabilistic basis, the possible role, significance, attributes, and challenges, using analytical ("mathematical") predictive modeling (PAM) technique. The practical implementation of this technique could be done based on the recently suggested physically meaningful and highly flexible multi-parametric Boltzmann-Arrhenius-Zhurkov (BAZ) constitutive equation [60-74] and on the more general, double-exponential-probability-distribution-function (DEPDF) [75] that should be employed when no thermal loading takes place. The multi-parametric BAZ's and the DEPDF's experimental foundation are of failure-oriented-

accelerated-testing (FOAT) [76-78] type. Such testing is or could be carried out at one or more of the following three major stages of the product's design-and-manufacturing process (put here in chronological order): 1) product development stage (e.g., temperature cycling, thermal shock, shear-off or drop testing), 2) design stage (suggested recently for new products, new technologies, or new applications of the existing products and technologies, when no trustworthy and effective highly accelerated life testing (HALT) (see, e.g., [79, 80]), nor acceptable "best practices" have been developed and agreed upon yet) and 3) burn-in testing (BIT). This type of testing is always of the FOAT type: its objective is to get rid of the highly unreliable products ("freaks") that almost always exist in a just-manufactured IC product population. A successful BIT is supposed to get rid of the infant-mortality-portion (IMP) of the bathtub curve (BTC), without, hopefully, causing damage to the remaining, healthy, population. The multi-parametric BAZ constitutive equation, originally suggested in application to microelectronic, photonic, micro-electronics-mechanical-systems (MEMS) and MOEMS (optical MEMS) products and then modified and extended in application to various HITL, medical, biological, aerospace, and vehicular missions and situations, is employed here to predict, from the FOAT data, the probability of failure of CSS chips and when considering the role of the human factor (HF) in an HITL mission or an extraordinary situation of importance. Application of the BAZ equation enables accounting for the impact of physical defects and process variations on the semiconductor stress-free activation energy (SFAE). This energy is viewed, following Arrhenius, as the critical reliability-physics related property of an IC device in general and its PN junction in particular. It is shown also, using BAZ equation, how the probability of non-failure (reliability) and the corresponding mean-time-to-failure (MTTF) of a PN junction can be evaluated from the appropriate designed and correctly interpreted FOAT. The general concepts are illustrated by experimental data. As to the role of the human factor (HF) in the performance of CSS systems, it is shown that the HITL's long-term performance is affected, for the given level of the mental (cognitive) workload (MWL), by the human capacity factor (HCF), and that the HITL short-term performance might depend, in addition to the long-term HFs, also on the current, temporary, short-term states of the human health (SoH) and mind (SoM). These could possibly lead to disastrous human failure. The roles of these factors are quantified using the double-exponential-probability-distribution function (DEPDF) [75], a generalization of the multi-parametric BAZ equation, when no thermal loading is applied. The general concept is illustrated by a detailed numerical example. It is concluded, particularly, that while some kind of predictive modeling should always be considered and conducted prior to and, when possible and appropriate, also during HALT or FOAT of a CSS of importance, the "old-fashioned" analytical ("mathematical") modeling, and, preferably, the one of the probabilistic-design-for-reliability (PDFR) type, should always complement computer simulations: these two major available modeling tools are based on different assumptions and use different calculation techniques, and if the results obtained using these tools agree, then there is a good reason to believe that the obtained data are sufficiently accurate and, hence, trustworthy. Future work should address other suitable applications of the concepts and

approaches described in this write-up, and should include, particularly, the development of practical methodologies for evaluating the probabilities of the expected field failures and for establishing the ultimate acceptable risks for critical products, technologies and applications, even beyond the CSS fields, with consideration, in addition to the predicted probabilities of the possible failures, and the corresponding useful life times, also the likelihoods of the consequences of such failures, having in mind that although the probabilities of the field failures cannot be high, they should not be lower than necessary either, but should be adequate for the given system, product and application: products that "never fail" are, as a rule, much more expensive than they could and should be. Numerous additional examples (case studies) could be found in the referenced publications.

Analytical ("Mathematical") Predictive Modeling, Its Role and Significance

Although some kind of predictive modeling should always be carried out in an engineering analysis, it is highly desirable that analytical ("mathematical") modeling (see, e.g., [13]) complements computer simulations for critical applications: computer simulations and analytical ("mathematical") modeling are based on different assumptions, use different calculation techniques, present differently the output data, and if the results obtained using these two major independent modeling tools are in agreement, then there is a good reason to believe that the obtained information is accurate and trustworthy. Today's powerful and flexible computer programs enable us to obtain, within a reasonable time and at a reasonable cost, a solution to almost any modeling problem, but should not an independent modeling technique be also considered and employed to make sure that it is also the solution? The "old-fashioned" analytical ("mathematical") modeling that has existed in applied science and engineering for hundreds of years still occupies, in today's computer simulation era, a very special and important place: it often enables obtaining relationships that explain the physics of phenomena and, particularly, various paradoxical situations better than computer simulations or even experimentation could. As Heinrich Hertz (1857-1894), the famous German physicist, had put it, "mathematical formulas have their own life, they are smarter than we, even smarter than their authors, and often provide more than what has been expected from them." A good analytical model should be based on simple relationships, clearly indicating the role of the major factors affecting the design, the technology, the object, the structure or the system of interest. Critical requirements for an effective analytical model are simplicity, clear physical meaning. As Einstein had indicated, "it can scarcely be denied that the supreme goal of all theory is to make the irreducible basic elements as simple and as few as possible without having to surrender the adequate representation of a single datum of experience." He also indicated that "external justification and internal perfection", i.e., suitability for being verified experimentally and, in addition, possess attractive mathematical appearance. One authority in applied physics remarked, also in jest, of course, that "the degree of understanding a physical phenomenon is inversely proportional to the number of variables used for its description" and that "a formula longer than an inch is most likely wrong". These funny statements are exaggerations, of course, but the well-known Hooke's law $\sigma = E\epsilon$ (1678) in the strength-of-materials, second

Newton's law $F=ma$ in dynamics and his law $F=G\frac{m_1m_2}{r^2}$ (1687)) in universal gravitation, Ohm's law $V=IR$ (1827) in electrical engineering, Lorentz' factor $\gamma=\left(\sqrt{1-\frac{v^2}{c^2}}\right)^{-1}$ (1892) in astrophysics, and the famous Einstein's equation $E=mc^2$ (1905) in the relativity theory and nuclear physics are, probably, the best illustrations to these statements. In this connection we would like to indicate also a much more modest, of course, simple and physically meaningful formula $t_r=\frac{1}{k}\left(\frac{\tau_{max}}{\tau_0}-1\right)$ (2021) for the expected sizes of the thermally induced inelastic zones, if any, at the end portions of long-and-stiff enough soldered interfaces in bi-material assemblies experiencing thermally induced loading in shear: solder joint interconnections, especially lead-free, are, as is known, the bottleneck of the reliability of materials and structures in modern electronics and photonics reliability engineering. The predictions based on this formula are in excellent agreement with the experimental and finite-element-analyses (FEA) data. Empirical relationships, such as the numerous experimental Coffin-Manson's type ones, widely employed today in electronics and photonics reliability engineering practice to assess the useful lifetime of solder-joint interconnections, are certainly helpful, but their structure and particularly the non-integer exponents in the experimentally obtained expressions for the time and/or the number-of-cycles-to-failure clearly indicate on the lack of understanding the underlying reliability physics in this field of microelectronics and photonics engineering.

PN Junction in IC Devices: Predicted Reliability

Modified Boltzmann-Arrhenius-Zhurkov (BAZ) constitutive model (see, e.g., [67]) is applied in this analysis to predict the reliability of the PN junction in integrated circuits (ICs). The BAZ model accounts for the impact of physical defects and process variations on the stress-free activation energy. This energy is viewed here as the semiconductor material's critical reliability property. The probability of non-failure and the corresponding mean-time-to-failure (MTTF) can be evaluated from the failure-oriented-accelerated-testing (FOAT) whose experimental data are interpreted using the multiparametric BAZ model obtained as a generalization of the model

$$\tau = \tau_0 \exp\left(\frac{U_0 - \gamma\sigma}{kT}\right) \quad (1)$$

suggested about sixty years ago by Zhurkov and his associates in the experimental fracture mechanics. This model is an extension of the Arrhenius' model

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

in the theory of chemical reactions. Model (2) is formally similar to Boltzmann's equation in the thermodynamic theory of gases. The following notation is used in these equations: τ is the mean-time-to-failure (MTTF), τ_0 is the time constant, $k = 8.617333 \times 10^{-5}$ eV/K is the Boltzmann constant, T is the absolute temperature, kT is the thermal energy, U_0 is the activation energy (the term was introduced by Arrhenius), and γ is the stress sensitivity factor. In Zhurkov's tests, the loading σ was always a constant mechanical tensile stress applied to notched specimens. The effective activation energy

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

in Zhurkov's model (1) decreases with an increase in the applied stress σ . Zhurkov and his associates used this model to determine fracture toughness of numerous materials experiencing combined action of an elevated temperature and external mechanical loading. In their interpretation, while the elevated temperature affects the degradation process (long-term strength), the external loading affects fracture toughness (short-term strength) of the material. Zhurkov's model was recently extended and modified in application to various electronics and optical materials, assemblies, packages, and systems. It has been suggested that various stressors (stimuli) of importance, such as voltage, current, thermal stress, humidity, vibrations, ionizing radiation, light output, etc., and their relevant combinations could be considered as appropriate stressors. It has been suggested also that such a modified and an extended multi-parametric BAZ model are employed to quantify the outcome of a failure-oriented-accelerated-testing (FOAT). This highly focused and highly cost-effective testing is aimed, first, on understanding the physics of failure, but enables also, using the multi-parametric BAZ model and the well-known exponential law of reliability, to assess the probability

$$P = \exp\left[-\frac{\tau}{\tau_0} \exp\left(-\frac{1}{kT}\left(U_0 - \sum_{i=1}^n \gamma_i \sigma_i\right)\right)\right] \quad (4)$$

of non-failure of the devices under test. In this formula, γ_i are the sensitivity factors for stressors. In addition, having in mind FOAT applications, it has been suggested that the time ratio τ/τ_0 in the above formula is replaced by an expression that considers the role of time and an appropriate measurable physical quantity that could be considered as a suitable characteristic of the degree of degradation of the material or the device under test and monitored during the FOAT process. If, e.g., leakage current is employed in this capacity, then the equation (4) could be written as

$$P = \exp\left[-\gamma_I I_{*} t \exp\left(-\frac{1}{kT}\left(U_0 - \sum_{i=1}^n \gamma_i \sigma_i\right)\right)\right] \quad (5)$$

Here t is time, I_{*} is the level of the leakage current considered as an indication of degradation and failure and γ_I is the sensitivity factor of the current-time product. In the analysis that follows, the BAZ model is used to assess the reduction in the stress-free activation energy. The analysis is conducted in application to the integrated circuit (IC) failures caused by physical defects and process variations (Fig. 1). The IC yield in such an effort could be measured using the existing yield models. The BAZ model is further modified here for the application of interest. It is considered that the stress-free energy U_0 is affected by physical defects and process variations that reduce this energy and, hence, the IC yield ($0 \leq Y \leq 1$). Then, the expression for the effective activation energy is assumed as

$$U = kT \ln \frac{\tau}{\tau_0} = YU_0 - \gamma\sigma. \quad (6)$$

If the applied voltage V is considered as a physically meaningful stressor, then the equation (5) for the probability of non-failure can be presented as

$$P = \exp \left[-\gamma_I I_* t \exp \left(-\frac{YU_0 - \gamma_V V}{kT} \right) \right] \quad (7)$$

The equation makes physical sense. Indeed, the probability of non-failure decreases with time, temperature, leakage current, and the applied voltage and is higher for a larger stress-free activation energy. The yield loss associated with

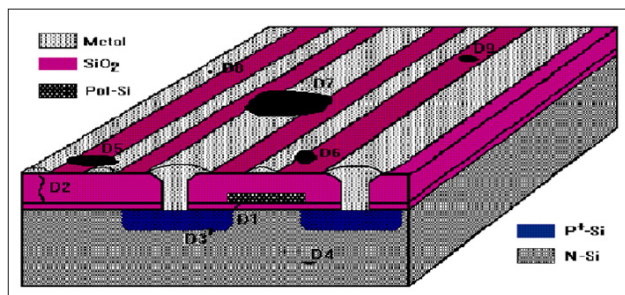


Figure 1: Point and lithographic Defects in an Integrated Circuit Chip

Each physical defect or process variation type can be estimated, particularly, by the yield model suggested by Stamenkovic and Stojadinovic [6]. The equation (7) for the probability of non-failure contains three unknowns: two sensitivity factors, γ_I and γ_V , and the activation energy U_0 . These unknowns could be found from the FOAT equation. Testing should be conducted in two steps. At the first step, testing should be carried out for two temperature levels, T_1 and T_2 , while keeping unchanged the effective energy (6) in the numerator of the equation (7). Then this equation yields:

$$P_{1,2} = \exp \left[-\gamma_I I_* t_{1,2} \exp \left(-\frac{YU_0 - \gamma_V V}{kT_{1,2}} \right) \right] \quad (8)$$

where P_1 and P_2 are the percentages of non-failed specimens at the testing times t_1 and t_2 , respectively. The following formula

$$\gamma_I = n_2 \exp \left[\frac{1}{\theta - 1} \ln \left(\frac{n_2}{n_1} \right) \right] \quad (9)$$

can be obtained for the sensitivity factor γ_I . Here

$$n_{1,2} = \frac{-\ln P_{1,2}}{I_* t_{1,2}}, \theta = \frac{T_2}{T_1} \quad (10)$$

At the second step of FOAT, the temperature T should be kept the same, but the voltage V should be changed. Then the formula

$$\gamma_V = \frac{kT}{V_2 - V_1} \ln \left(\frac{n_2}{n_1} \right) \quad (11)$$

can be obtained for the sensitivity factor γ_V . Clearly, the n values are different at these two FOAT steps. After the sensitivity factors γ_I and γ_V are determined, the reduced activation energy YU_0 can be evaluated from the second step of the FOAT as

$$YU_0 = -\ln \left(\frac{n_1}{\gamma_I} \right) kT + \gamma_V V_1 = -\ln \left(\frac{n_2}{\gamma_I} \right) kT + \gamma_V V_2, \quad (12)$$

and the change in the probability of non-failure (PnF) with time can be found from (7) as

$$\frac{dP}{dt} = -\frac{H(P)}{t}, \quad (13)$$

Where

$$H(P) = -P \ln P \quad (14)$$

is the entropy of the distribution (7). The formula (13) explains the reliability physics underlying this distribution: the time derivative of the probability P of non-failure increases with an increase in the entropy (degree of uncertainty) of this distribution and decreases with time. The MTTF takes place, when the entropy (14) reaches its maximum value e^{-1} . As evident from (14), this corresponds to the probability P of non-failure value, which is also $P = e^{-1}$. The mean-time-to-failure (MTTF) is

$$MTTF = \frac{1}{\gamma_I I_*} \exp \left(\frac{YU_0 - \gamma_V V}{kT} \right) \quad (15)$$

As a suitable experimental verification of the above model, we consider six critical processes typically responsible for the yield loss in the semiconductor technology practice: P+ diffusion, N+ diffusion, silicon-dioxide formation, contact formation, via formation, and metal layer formation. In-line yield measurements made on the corresponding test structures are presented in Table 1.

Table 1: Yield Measurement Results

Critical process	Yield (Y)
P+ diffusion	0.994
N+ diffusion	0.993
Silicon-dioxide formation	0.988
Contact formation	0.992
Via formation	0.989
Metal layer formation	0.995

Let, e.g., the leakage current of $I_* = 0.5 \mu A$ be considered as definition of failure. Having in mind that the proposed model uses two stressors (temperature and voltage), we select two temperature and two voltage values to be applied (stressing the test structures) in two consecutive FOAT steps. The first FOAT step was conducted at the temperatures $T_1 = 25^\circ C = 298 K$ and $T_2 = 50^\circ C = 323 K$, until a half of the measured test structures failed, so that $P_1 = 0.5$ and $P_2 = 0.5$. Now, the θ parameter can be calculated and is $\theta = \frac{T_2}{T_1} = \frac{323}{298} = 1.0839$. The times necessary for the failure of a half of the measured test structures (a hundred samples) and the corresponding temperature sensitivity factor are shown in Table 2.

Table 2: Testing Times and Temperature Sensitivity Factor

Critical process	t1 for T1 (h)	t2 for T2 (h)	γ_I (h-1 μA^{-1})
P+ diffusion	2880	1072	168.7513

N+ diffusion	2752	1024	177.3940
Silicon-dioxide formation	2008	752	223.6748
Contact formation	2600	960	207.4625
Via formation	2216	832	196.1586
Metal layer formation	2176	816	202.8924

Table 3: Testing Times and Voltage Sensitivity Factor

Critical process	t1 for V1 (h)	t2 for V2 (h)	γV (eV/V)
P+ diffusion	36	2.5	0.18560
N+ diffusion	29	2	0.18608
Silicon-dioxide formation	15	1	0.18844
Contact formation	24	1.5	0.19293
Via formation	22	1.5	0.18688
Metal layer formation	23	1.5	0.18997

At the second FOAT step, testing was conducted at a temperature of $T=50^{\circ}C=323^{\circ}K$, first at a voltage of $V_1 = 2.8 V$ and then at a voltage of $V_2 = 3.2 V$. Testing was conducted until a half of the measured test structures (a hundred samples) failed ($P_1 = P_2 = 0.5$). The times necessary for the failure of a half of the measured test structures and the corresponding voltage sensitivity factor are shown in Table 3. Then the equation (12) can be used to calculate the reduced and defect-free failure activation energies. These results are based on the measurement data and can be used for reliability predictions. The activation energies and mean-time-to-failure for two voltage values are shown in Table 4. Thus, a modified BAZ model that establishes the link between the yield and reliability (probability of non-failure) has been suggested. The proposed modification of the model considers the reduction of the stress-free failure activation energy caused by physical defects and process variations defining the yield as a correction parameter. The presented application example shows the first promising results. The next step will be to compare the model predictions with reliability test data from the field.

Table 4: Activation Energies and MTTF for Nominal and High Voltages

Critical process	YU0 (eV)	U0 (eV)	MTTF for 1.5 V (h)	MTTF for 2.8 V (h)
P+ diffusion	0.7531	0.7576	302103	52
N+ diffusion	0.7498	0.7551	248896	42
Silicon-dioxide formation	0.7445	0.7535	143735	22
Contact formation	0.7681	0.7743	283645	35
Via formation	0.7471	0.7554	195963	32
Metal layer formation	0.7580	0.7618	236712	33

Human-in-The-Loop (Hitl) Concept, Its Role, Significance, Attributes

Probabilistic Predictive Modeling (PPM) Approach

The outcome of a space mission must be quantified to assure its success and safety, and since nobody and nothing is perfect, and the probability of human and the equipment/instrumentation

failure is therefore never zero, such quantification should be done on a probabilistic basis. Probabilistic predictive modeling (PPM) enables evaluating, assuring and, when necessary and appropriate, even specifying the adequate (low enough) probability of failure of a mission or an off-normal situation, when the performance of the never-perfect human, never-100% - reliable equipment/instrumentation (both its hard- and software), not always 100% -predictable response of the object of control- the spacecraft-, usually uncertain and often harsh environment, and the interactions (interfaces) of these uncertainties contribute jointly to the outcome of a mission or of an extraordinary situation. An important aspect of the role of HF in making an outer space mission successful and safe is considered in this analysis: the effect of the astronaut's HCF and his/her SoH on his/her performance, such as, say, the likelihood of making a human error (HE). Our objective is to show that the suggested DEPDF can be effectively employed to do that. The "old fashioned" analytical ("mathematical") modeling is used in our PPM. Analytical modeling occupies a special place in today's modeling effort, when most quantitative analyses use computer simulations. In the author's opinion and experience, analytical modeling should always be considered, whenever possible, in addition to computer simulations, in every critical modeling effort: these two modeling approaches are based, as a rule, on different assumptions and employ different calculation techniques, and if the results obtained using these two approaches in the problem of interest agree, then there is a good reason to believe that these results are sufficiently accurate and trustworthy.

Double-Exponential-Probability-Distribution-Function (Depdf) as the Governing Equation of the Hitl Concept

The DEPDF [75] could be introduced in many ways, depending on the attributes of the problem of interest. In this analysis we suggest a DEPDF that enables evaluating the impact of three major factors, the MWL G , the HCF F and the time t (always affecting the astronaut's performance and sometimes even his/her health), on the probability of human non-failure (HnF). With this objective in mind, this probability is sought as follows:

$$P^h(F, G, S_*) = P_0 \exp \left[\left(1 - \gamma_S S_* t - \frac{G^2}{G_0^2} \right) \exp \left(1 - \gamma_T T_* - \frac{F^2}{F_0^2} \right) \right] \quad (16)$$

Here P_0 is the probability of the human non-failure (HnF)) at the initial moment of time and at a sufficiently low level of the MWL ($G=G_0$) S_* is the threshold (acceptable level) of the supposedly continuously monitored/measured and possibly cumulative, effective, indicative, even multi-parametric human health characteristic ("symptom"), such as, e.g., body temperature, arterial blood pressure, oxyhemometric determination of the level of saturation of blood hemoglobin with oxygen, electrocardiogram measurements, pulse frequency and fullness, frequency of respiration, measurement of skin resistance that reflects skin covering with sweat, etc. (since the time t and the threshold S_* enter the above expression as a product $S_* t$, each of these parameters has a similar cumulative impact on the sought probability); γ_S is the sensitivity factor for the symptom S_* and/or the time t and/or their product $S_* t$; the $G \geq G_0$ is the actual (elevated, off-normal, extraordinary, possibly time-dependent) MWL; G_0 is the MWL in ordinary (normal) operation conditions; T_* is the mean time to error/failure (MTTF/MTTE); γ_T is the

sensitivity factor for this time; $F \geq F_0$ is the actual human-capacity-factor (HCF) exhibited or required in a particular condition of importance; and F_0 is the most likely (normal, specified, ordinary) HCF. There is a certain overlap between the levels of the HCF F and the T_* value, which has also to do with human quality and performance. The difference is that the time T_* is viewed here as a short-term characteristic of the astronaut's performance that might be affected, first of all, by his/hers personality and susceptibility to various influences, while the HCF is a long-term human characteristic, such as education, age, experience, ability to think and act independently, or, if necessary, as a team player, etc. (see the HCF dedicated section below). The MTTF might be determined for the particular individual by using a highly focused failure oriented accelerated testing (FOAT) on a flight simulator (whatever the appropriate definition of failure in such testing might be decided upon), while the factor F , which should also be quantified, cannot be evaluated experimentally on a flight simulator, and special methodologies and specifications should be developed to establish the adequate HCF nomenclature, levels and even the appropriate units. It goes without saying that MWL and HCF should be expressed in the same, preferably, dimensionless, units. It is noteworthy that while the P_0 value is defined in this analysis as the probability-of-nonfailure (PnF) at a very low MWL level G , it could be determined and evaluated also as the probability-of-nonfailure PnF for a hypothetical situation, when the HCF F is extraordinarily high, i.e., for an astronaut who is exceptionally highly qualified (like, say, Captain "Sully" in the famous "miracle-on-the-Hudson" event), while the MWL G is still finite, and so is the operational time t .

The function (16) has a "nice" symmetric form. It reflects, in effect, the role of the "objective", "external", short-term "mental-workload (MWL) + state-of-health (SoH)" impact $E = \left(1 - \gamma_s S_d - \frac{G^2}{G_0^2}\right)$ as well as the role of the "subjective", "internal", long-term "human-capacity-factor (HCF)," human-error" (HE)" impact factor $I = \left(1 - \gamma_f T_* - \frac{F^2}{F_0^2}\right)$. The rationale behind the structures of these expressions is that the level of the MWL could be affected by the human's "state-of-health (SoH) symptom" S_* . The same individual might experience a higher MWL, which is not only different for different individuals (it is well known that highly qualified and highly experienced individuals experience considerably lower subjective MWLs), but might be quite different depending on the particular astronaut's current, short-term, SoH, while the HCF, although could also be affected by the state of his/her SoH, affects indirectly the likelihood of a human error (HE) occurrence. In our approach the role of a possible HE in the long run is considered by the mean time to error (MTTE) T_* , since HE is, in effect, a failure in his/her error-free performance process, and the MTTE is, in effect, the mean-time-to-failure (MTTF) in this process. When the human's qualification is exceptionally high, the likelihood of an error is still and most likely low, regardless of the objective external conditions reflected by the MWL. Thus, in this analysis the "external" $E = \text{MWL} + \text{SoH}$ factor is viewed as a short-term characteristic of the human performance, while the "internal" factor $I = \text{HCF} + \text{HE}$ is a more permanent, a long-term characteristic of the human capacity factor HCF and its role. It is also noteworthy that the human mind that has to do, of course, with MWL and his/her body are closely linked and that such links are different for different individuals and circumstances. At present this link and the role of state-of-health (SoH) are far from

being well defined and understood. The suggested formalism to consider this circumstance is therefore just a possible and a tentative way to account for such a link. Difficulties may arise on some occasions when the MWL and the SoH factors overlap. It is anticipated therefore that the MWL impact in the suggested formalism considers, to an extent possible, various most important influences other than the direct SoH related one.

Mental (Cognitive) workload (MWL)

Measuring MWL has become, as is known, a key method of improving aerospace safety, and there is extensive published work devoted to the measurement of the MWL in aviation, both military and commercial. Similar approaches could be, of course, and are applied to astronauts. Navigator's MWL can be measured using subjective ratings and/or objective measures. The subjective ratings during FOAT (simulation tests) can be, e.g., after the expected failure is defined, in the form of periodic inputs to some kind of data collection device that prompts the pilot to enter, say, a number between 1 and 10 to estimate the MWL every few minutes. There are also some objective MWL measures, such as, e.g., heart rate variability. Another possible approach uses post-flight questionnaire data: it is usually easier to measure the MWL on a flight simulator than in actual flight conditions. In a real aircraft, one would probably be restricted to using post-flight subjective (questionnaire) measurements, since a human psychologist would not want to interfere with the pilot's work. Given the multidimensional nature of MWL, no single measurement technique can be expected to account for all the important aspects of it. In modern military aircraft, complexity of information, combined with time stress, creates significant difficulties for the pilot under combat conditions, and the first step to mitigate this problem is to measure and manage the MWL. Current research efforts in measuring MWL use psychophysiological techniques, such as electroencephalographic, cardiac, ocular, and respiration measures to identify and predict MWL levels. Measurement of cardiac activity has been also a useful physiological technique employed in the assessment of MWL, both from tonic variations in heart rate and after treatment of the cardiac signal. Such an effort belongs to the fields of astronautic medicine and aerospace human psychology.

Human Capacity Factor (HCF)

HCF, unlike MWL, is a relatively new notion. HCF plays with respect to the MWL approximately the same role as strength/capacity plays with respect to stress/demand in structural analysis and in some economics problems. HCF includes, but might not be limited to, the following major qualities that would enable a professional human to successfully cope with an elevated off-normal MWL: age; fitness; health; personality type; psychological suitability for a particular task; professional experience and qualifications; education, both special and general; relevant capabilities and skills; level, quality and timeliness of training; performance sustainability (consistency, predictability); independent thinking and independent acting, when necessary; ability to concentrate; awareness and ability to anticipate; ability to withstand fatigue; self-control and ability to act in cold blood in hazardous and even life threatening situations; mature (realistic) thinking; ability to operate effectively under pressure, and particularly under time pressure; leadership ability; ability to operate effectively, when necessary, in a tireless fashion, for a long period of time (tolerance to

stress); ability to act effectively under time pressure and make well substantiated decisions in a short period of time and in an uncertain environmental conditions; team-player attitude, when necessary; swiftness in reaction, when necessary; adequate trust (in humans, technologies, equipment); ability to maintain the optimal level of physiological arousal. These and other qualities are certainly of different importance in different HITL situations. It is clear also that different individuals possess these qualities to different degrees. Long-term HCF could be time dependent. To come up with suitable figures-of-merit for the HCF, one could rank, similarly to the MWL estimates, the above and perhaps other qualities on the scale from, say, one to ten, and calculate the average figure of merit for each individual and for a particular task. Clearly, MWL and HCF should use the same measurement units, which could be particularly non-dimensional. Special psychological tests might be necessary to develop and conduct to establish the level of these qualities for individuals of significance. Human capacity factor (HCF), unlike mental/cognitive workload (MWL), is a relatively new notion in ergonomics engineering. HCF plays with respect to the MWL approximately the same role as strength/capacity plays with respect to stress/demand in structural analysis and in some economics problems. HCF includes, but might not be limited to, the following major qualities that would enable a professional human to successfully cope with an elevated off-normal MWL: age; fitness; health; personality type; psychological suitability for a particular task; professional experience and qualifications; education, both special and general; relevant capabilities and skills; level, quality and timeliness of training; performance sustainability (consistency, predictability); independent thinking and independent acting, when necessary; ability to concentrate; awareness and ability to anticipate; ability to withstand fatigue; self-control and ability to act in cold blood in hazardous and even life threatening situations; mature (realistic) thinking; ability to operate effectively under pressure, and particularly under time pressure; leadership ability; ability to operate effectively, when necessary, in a tireless fashion, for a long period of time (tolerance to stress); ability to act effectively under time pressure and make well substantiated decisions in a short period of time and in an uncertain environmental conditions; team-player attitude, when necessary; swiftness in reaction, when necessary; adequate trust (in humans, technologies, equipment); ability to maintain the optimal level of physiological arousal. These and other qualities are certainly of different importance in different human-in-the-loop (HITL) situations. It is clear also that different individuals possess these qualities in different degrees. Long-term HCF could be time dependent. To come up with suitable figures-of-merit (FoM) for the HCF, one could rank, similarly to the MWL estimates, the above and perhaps other qualities on the scale from, say, one to ten, and calculate the average FoM for each individual and task. Clearly, MWL and HCF measurements should use the same units, which could be particularly non-dimensional. Special psychological tests might be necessary to develop and conduct to establish the level of these qualities for the individuals of significance.

Strange as it may sound, but the first person, who addressed what is known today as ergonomics science and even suggested the application of analytical (“mathematical”) predictive modeling in this body of knowledge, was the great Russian writer, count Leo Tolstoy [84]. In his November 5, 1910, letter (written just 15

days before his death) to Russian Orthodox priest Father Dimitri Yegorovich Troitsky Tolstoy wrote: “I perfectly agree with you that humility is the greatest and most needful virtue. As I always say, man is like a fraction, in which the denominator indicates his opinion about himself. It is best for this denominator to be zero (complete humility), and it is terrible when it is augmented to infinity. In the first case, man has a true significance, whatever the denominator, but in the second case — none.” This definition is based, using today’s ergonomics terminology, on the HCF/MWL ratio of the human capacity factor HCF to his/her mental (cognitive) workload MWL. This ratio can be considered even when human performance is viewed as a random variable and is a time dependent characteristic of a HITL random process characterized by its meantime-to-failure (MTTF) $\tau = \frac{HCF}{MWL}$ and its failure rate $\lambda = \frac{1}{\tau} = \frac{MWL}{HCF}$. Then the well-known exponential law of reliability $p = e^{-\lambda t}$ can be applied to determine the probability of non-failure of a critical random HITL process [85].

Conclusions and Future Work

While some kind of predictive modeling should always be considered and conducted prior to and, when possible and appropriate, also during HALT or FOAT of an CSS of importance, the “old-fashioned” analytical modeling, and, preferably, the one of the probabilistic-design-for-reliability (PDfR) type, should always complement computer simulations: these two major available modeling tools are based on different assumptions and use different calculation techniques, and if the results obtained using these tools agree, then there is a good reason to believe that the obtained data are sufficiently accurate and trustworthy. In connection with the approach taken it is noteworthy also that not every model needs prior or even posterior experimental validation. In the author’s view, the structure of our governing models does not. Just the opposite: this model should be used as the basis of the FOAT to establish the MWL, HCF, and various human errors (HE) through the corresponding observed and recorded MTTF and his/hers SoH at normal operation conditions and for a navigator with regular skills and of ordinary human capacity. These experiments could be conducted, e.g., on a flight simulator using various specially developed testing methodologies. Being a probabilistic, not a statistical model, the approach should be used to obtain, interpret and accumulate relevant statistical information. Future work should address other suitable and possible applications of the concepts and approaches addressed, and should include, particularly, the development of practical methodologies for evaluating, in addition to the probabilities of the field failures, also, when possible and appropriate, the ultimate acceptable (specified) risks of such failures for critical products, technologies and applications, both within and even beyond the CSS fields. This should be done considering, in addition to the predicted probabilities of the possible field failures, also the likelihoods of the consequences of such failures, times to market and cost effectiveness, having in mind that although the never-zero probabilities of the field failures cannot be high, of course, such probabilities should not be lower than necessary, but should be adequate for the given critical system, product and application: products that “never fail” are, as a rule, much more expensive than they could and should be.

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References

1. N Leveson. "The Role of Software in Recent Aerospace Accidents", Proc. of the 19-th Int. Systems Safety Conf., System Safety Society, Unionville, VA. 2001.
2. C H Stapper. "Modelling of Integrated Circuit Defect Sensitivities", IBM J. Research and Development. 1983. 27.
3. Z Stamenkovic, S Dimitrijevic, N Stojadinovic. "Integrated Circuit Production Yield Assurance Based on Yield Analysis", Microelectronics Journal. 1993. 24.
4. Z Stamenkovic, N Stojadinovic, S Dimitrijevic. "Modelling of Integrated Circuit Yield Loss Mechanisms", IEEE Trans. Semiconductor Manufacturing. 1996. 9.
5. W Kuo, T Kim. "An Overview of Manufacturing Yield and Reliability Modelling for Semiconductor Products", Proceedings of the IEEE. 1999. 87.
6. Z Stamenkovic, N Stojadinovic. "The Computer Engineering Handbook: Computer-Aided Analysis and Forecast of Integrated Circuit Yield" (edited by V. Oklobdzija), CRC Press, Boca Raton. 2002.
7. M Sachdev, JP de Gyvez. Defect-Oriented Testing for Nano-Metric CMOS VLSI Circuits: Yield Engineering, Springer US. 2007.
8. A Boogaard, I Smith, O Mouraille, T Knaapen, R Stegen. "Improving Equipment Defectivity Specifications through Chip Yield Modelling: A Case Study for Immersion Lithography", IEEE Trans. Semiconductor Manufacturing. 2013. 26.
9. E Suhir, Z Stamenkovic. "Using Yield to Predict Long-Term Reliability of Integrated Circuits: Application of Boltzmann-Arrhenius-Zhurkov Model", Solid-State Electronics. 2020. 164.
10. F Restle, J Greeno. Introduction to Mathematical Psychology, Reading, MA, Addison Wesley. 1970.
11. A Tversky, D Kahneman. Judgment Under Uncertainty: Heuristics and Biases. Science. 1974. 185.
12. LM Faller, S Mühlbacher-Karrer, R Hamid, H Zangl. "Employment of Capacitive Sensors to Enhance Safety by Non-Invasive Pilot and Crew Monitoring in Human-in-the-Loop (HITL) Related Aerospace Missions", Special NDA Session at the AIAA SciTech Conf., Gaylord Texan Resort & Convention Center. 2017. 9-13.
13. E Suhir. Human-in-the-Loop: Probabilistic Modeling of an Aerospace Mission Outcome, CRC Press. 2019.
14. D Kahneman, P Slovic, A Tversky (Eds.). Judgment Under Uncertainty: Heuristics and Biases. Cambridge University Press, Cambridge. 1982.
15. LP Goodstein, H.B. Andersen and S.E. Olsen, Tasks, Errors, and Mental Models. Taylor and Francis. 1988.
16. J Reason. Human Error, Cambridge University Press, Cambridge, 1990.
17. S Baron, DS Kruser, B Huey (eds). Quantitative Modeling of Human Performance in Complex Dynamic Systems, National Academy Press, Washington, DC, 1990.
18. D Hamilton, C Bierbaum. "Task Analysis/Workload (TAWL)-A Methodology for Predicting Operator Workload", Proc. of the Human Factors and Ergonomics Soc. 34-th Annual Meeting, Santa Monica, CA. 1990.
19. AD Baddeley. "Working Memory", Science. 1992. 255.
20. E Hollnagel. Human Reliability Analysis: Context and Control, Academic Press, London 1993.
21. PA Hancock, JK Caird. "Experimental Evaluation of a Model of Mental Workload: Human Factors", The J. of the Human Factors and Ergonomics Society. 1993. 35.
22. R Amalberti. "Anticipation" in M. de Montmollin, ed., Vocabulaire de l'Ergonomie, Octares. (in French). 1995.
23. MR Endsley. "Toward a Theory of Situation Awareness in Dynamic Systems", Human Factors. 1995. 37.
24. KA Ericsson, W Kintsch. "Long-Term Working Memory", Psychological Review. 1995. 102.
25. PC Cacciabue, E Hollnagel. "Human Factors Methods for Safety Assessment in Highly Automated Environments: Task Analysis, Modeling, and Data", PSAM-4 Int. Conf. on Probabilistic Safety Assessment and Management, New York, USA: Sept. 1998. 13-18.
26. J Orasanu, L Martin, J Davison. "Errors in Aviation Decision Making: Bad Decisions or Bad Luck?", Proc. of the 4-th Conf. on Naturalistic decision Making, Warrington, VA. 1998.
27. MR Endsley, DJ Garland eds. Situation Awareness Analysis and Measurement, Lawrence Erlbaum Associates, Mahwah, NJ. 2000.
28. C Lebiere. "A Theory Based Model of Cognitive Workload and its Applications", Proc. of the Interservice/Industry Training, Simulation and Education Conf., Arlington, VA: NDIA. 2001.
29. SG Archer, L Allender. "New Capabilities in the Army's Human Performance Modeling Tool", Proc. of the Advanced Simulation Technologies Conf., Seattle, WA. 2001.
30. NA Taatgen, "A Model of Individual Differences in Learning Air Traffic Control", Proc. 4-th Int. Conf. on Cognitive Modeling, Lawrence Erlbaum Ass. Mahwah, NJ. 2001.
31. K Leiden, JW Keller, JW French. Context of Human Error in Commercial Aviation, Tech. Report, MicroAnalysis and Design, Boulder, CO. 2001.
32. SJ Hoffman ed, The Mars Surface Reference Mission: A Description of Human and Robotic Surface Activities, NASA/TP. 2001. 209371.
33. TA Polk, CM Seifert. Cognitive Modeling, MIT Press, Cambridge, Mass. 2002.
34. CD Wickens. "Multiple Resources and Performance Prediction", Theoretical Issues in Ergonomic Science. 2002. 3.
35. A Kirlik. "Human Factors Distribute Its Workload: Review," E. Salas (ed), Advances in Human Performance and Cognitive Engineering Research, vol.1, Contemporary Psychology. 2003. 48.
36. A Hobbs. "Human Factors: The Last Frontier in Aviation Safety", Int. J. of Aviation Psychology. 2004. 14.
37. KA Gluckand, RW Pew (eds.). Modeling Human Behavior with Integrated Cognitive Architectures, Lawrence Erlbaum Associates, Mahwah, NJ. 2005.
38. BF Gore, JD Smith. "Risk Assessment and Human Performance Modeling: Need for an Integrated Approach", Int. J. of Human Factors Modeling and Simulation. 2006. 1.
39. MR Lehto, JR Buck. Introduction to Human Factors and Ergonomics for Engineers, Lawrence Erlbaum Associates, Taylor and Francis Group, New-York-London. 2008.

40. NASA, International Space Station Human Behavior and Performance Competency Model, NASA/TM. 2008. 2: 214775.
41. E Suhir. "Helicopter-Landing-Ship: Undercarriage Strength and the Role of the Human Factor", ASME Off-Shore Mechanics and Arctic Engineering (OMAE) Journal. 2009. 132.
42. Drake BG. Ed Mars Architecture Steering Group, Human Exploration of Mars, Design Reference Architecture 5.0, NASA Johnson Space Center. 2009.
43. A Kaddoussi, N Zoghalmi, H Zgaya, S Hammadi, F Bretaudeau. "A Preventive Anticipation Model for Crisis Management Supply Chain," IEEE Int. Conf. on Systems, Man, and Cybernetics. 2011.
44. E Suhir. "Human-in-the-Loop": Likelihood of a Vehicular Mission-Success-and-Safety, and the Role of the Human Factor", Paper ID 1168, 2011 IEEE/AIAA Aerospace Conf., Big Sky, Montana. 2011. 5-12.
45. M Stamatelatos, H Dezfuli. "Probabilistic Risk Assessment Procedures Guide for NASA Managers and Practitioners", NASA, USA 2011.
46. JM Salotti. "Revised Scenario for Human Missions to Mars", Acta Astronautica. 2012. 81.
47. E Suhir. "Miracle-on-the-Hudson": Quantified Aftermath", Int. J. Human Factors Modeling and Simulation, April 2013.
48. J-M Salotti, E Suhir. "Manned Missions to Mars: Minimizing Risks of Failure", Acta Astronautica. 2014. 93.
49. J-M Salotti, E Suhir. "Some Major Guiding Principles for Making Future Manned Missions to Mars Safe and Reliable", IEEE Aerospace Conf., Big Sky, Montana 2014.
50. J-M Salotti, R Hedmann, E Suhir. "Crew Size Impact on the Design, Risks and Cost of a Human Mission to Mars", IEEE Aerospace Conference, Big Sky, Montana 2014.
51. E Suhir. "Human-in-the-loop (HITL): Probabilistic Predictive Modeling (PPM) of an Aerospace Mission/Situation Outcome", Aerospace. 2014.
52. E Suhir. "Mental Workload (MWL) vs. Human Capacity Factor (HCF): A Way to Quantify Human Performance": in Gregory and Inna Bedny, eds., Applied and Systemic-Structural Activity Theory, CRC Press. 2019.
53. E Suhir. "Failure-Oriented-Accelerated-Testing and Its Possible Application in Ergonomics", Ergonomics International Journal. 2019. 3.
54. J.-M. Salotti. "Minimum Number of Settlers for Survival on Another Planet", Sci.Rep. 2020. 10: 9700.
55. E Suhir. Quantifying Unquantifiable" in Aerospace Electronics and Ergonomics Engineering: Review", Journal of Aerospace Engineering and Mechanics (JAEM)2020. 4.
56. E Suhir, G Paul. "Avoiding Collision in an Automated Driving Situation." Theoretical Issues in Ergonomics Science (TIES). 2020.
57. E Suhir, G Paul, H Kaindl. "Towards Probabilistic Analysis of Human-System Integration in Automated Driving." In: T. Ahram, W. Karwowski, A. Vergano, F. Leali and R. Taiar (eds), Intelligent Human Systems Integration, IHSI 2020, Advances in Intelligent Systems and Computing. Springer. 2020. 1131.
58. E Suhir. "Risk-Analysis in Aerospace Human-Factor-Related Tasks: Review and Extension." Journal of Aerospace Engineering and Mechanics (JAEM). 2020. 4.
59. E Suhir. "Head-on Railway Obstruction: A Probabilistic Model." Theoretical Issues in Ergonomic Science (TIES). 2020.
60. L Boltzmann. "The Second Law of Thermodynamics. Populare Schriften." Essay 3, Address to a Formal Meeting of the Imperial Academy of Science. 1886.
61. S Arrhenius. "Recherches sur la conductivité galvanique des électrolytes" ("Research on the Galvanic Conductivity of Electrolytes"). Doctoral Dissertation. Stockholm, Royal Publishing House, P. A. Norstedt & Söner. 1884.
62. S N Zhurkov. "Проблема прочности твёрдых тел" ("The Problem of the Strength of Solids"). Vestnik Akad. Nauk SSSR (Bulletin of the USSR Academy of Sciences). 1957. 11.
63. S N Zhurkov. "Kinetic Concept of the Strength of Solids." Int. J. of Fracture. 1965. 1.
64. L Boltzmann. "Studien über das Gleichgewicht der lebendigen Kraft zwischen bewegten materiellen Punkten." Wiener Berichte. 1868. 58.
65. SA Arrhenius. "Über die Dissociationswärme und den Einfluß der Temperatur auf den Dissociationsgrad der Elektrolyte." Z. Phys. Chem. 1889. 4.
66. E Suhir, L Bechou, A Bensoussan. "Technical Diagnostics in Electronics: Application of Bayes Formula and Boltzmann-Arrhenius-Zhurkov BAZ Model." Printed Circuit Design & Fab/Circuits Assembly. 2012. 29.
67. E Suhir, S Kang. "Boltzmann-Arrhenius-Zhurkov BAZ Model in Physics-of-Materials Problems." Modern Physics Letters B MPLB. 2013. 27.
68. E Suhir. "Three-Step Concept in Modeling Reliability: Boltzmann-Arrhenius-Zhurkov Physics-of-Failure-Based Equation Sandwiched Between Two Statistical Models." Microelectronics Reliability. 2014.
69. E Suhir. "Static Fatigue Lifetime of Optical Fibers Assessed Using Boltzmann-Arrhenius-Zhurkov BAZ Model." Journal of Materials Science: Materials in Electronics. 2017. 28.
70. A Ponomarev, E Suhir. "Predicted Useful Lifetime of Aerospace Electronics Experiencing Ionizing Radiation: Application of BAZ Model." Journal of Aerospace Engineering and Mechanics JAEM. 2019. 3.
71. E Suhir. "Boltzmann-Arrhenius-Zhurkov Equation and Its Applications in Aerospace Electronic-and-Photonic Reliability-Physics Problems." Int. Journal of Aeronautical Science and Aerospace Research IJASAR. 2020. 7.
72. E Suhir. "Survivability of Species in Different Habitats: Application of Multi-Parametric Boltzmann-Arrhenius-Zhurkov Equation." Acta Astronautica. 2020. 175.
73. E Suhir. "Predicted Low-Cycle Fatigue Lifetime of Solder Joint Interconnections: Application of Hall's Approach and Boltzmann-Arrhenius-Zhurkov BAZ Model." Journal of Aerospace Engineering and Mechanics JAEM. 2022. 6.
74. E Suhir. "Boltzmann-Arrhenius-Zhurkov BAZ Constitutive Equation Enables Quantifying Reliability Physics in Electronics Engineering." Editorial, Acta Scientific Applied Physics. 2023. 3.
75. E Suhir. "The Double-Exponential-Probability-Distribution-Function and Its Applications in Reliability-Physics, Ergonomics-Science and Aerospace-Safety Problems: Perspective." Microelectronics Reliability. 2024.

76. 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*. 2018. 29.
77. E Suhir. "For How Long Should Burn-in Testing Last?" *J. of Electrical & Electronic Systems*. 2019. 8.
78. E Suhir. "A Tale of Three Types of Failure-Oriented-Accelerated-Tests and Their Roles in Assuring Aerospace Electronics and Photonics Reliability: Perspective." *J. of Space Safety Engineering*. 2024.
79. M Silverman. "40 Years of HALT: What Have We Learned?" *Ops A La Carte LLC, IEEE EPS Seminar, ASTR*. 2012.
80. A Kleyner, ed. *Next Generation HALT and HASS: Robust Design of Electronics and Systems*. John Wiley and Sons. 2016.
81. E Suhir. "Is Temperature Cycling an Adequate Accelerated Test in Reliability Physics of IC Products?" *Acta Scientific Applied Physics*. Editorial. 2023.
82. E Suhir, R Mahajan. "Are Current Qualification Practices Adequate?" *Circuit Assembly*. 2011.
83. E Suhir. "Analytical Modeling Occupies a Special Place in Reliability-Physics." *Acta Scientific Applied Physics*. Editorial. 2023.
84. P Johnson. *Intellectuals: From Marx and Tolstoy to Sartre and Chomsky*. Harper & Row, New-York. 1988.
85. E Suhir. "Exponential Law of Reliability and Its Applications in Some Critical Aerospace Safety Problems: Perspective." *J. of Space Safety Engineering*. 2025. 12.