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Is burn-in always needed?

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ABSTRACT: It is shown that the time-derivative of the failure rate at the initial moment of time of the infant mortality portion of the bathtub curve (BTC) can be considered as a suitable criterion of whether burn-in testing (BIT) for a manufactured IC device should or does not have to be conducted. It is shown also that this derivative is, in effect, the variance of the random statistical failure rate (SFR) of the mass-produced components that the product of interest is comprised of. These components are received from numerous vendors, whose commitments to reliability were unknown, and therefore the random SFR of these components might vary in a very wide range, from zero to infinity. Based on the general formula for the non-random SFR of a product comprised of such components, the solution for the case of normally distributed random SFR of the constituent components was obtained. This information enables to answer the fundamental question "to burn-in or not to burn-in?" in electronics manufacturing. If this question is answered in affirmative, i.e., if BIT is decided upon, it is shown that physically meaningful multi-parametric Boltzmann-Arrhenius-Zhurkov (BAZ) equation can be employed for the assessment of BIT's duration and level.

Our analyses shed light on the role and significance of some important factors that affect the testing time and the stress level. These factors include: the role of the random SFR of mass-produced components that the product of interest is comprised of; the way to assess the (relatively low, compared to the healthy population) activation energy of the "freaks" from the highly focused and highly cost effective failure-oriented-accelerated-testing (FOAT); the role (contribution) of the applied stressor(s); and, most importantly, - the probabilities of the "freak" failures and the corresponding duration of the BIT. These factors should be considered when there is intent to quantify and, eventually, optimize the BIT's procedure and outcome. Future work should include experimental verifications of the suggested concepts.

I. INTRODUCTION

BIT [1–3] is an accepted practice for detecting and eliminating early failures in newly fabricated electronic products prior to shipping the "healthy" ones, i.e. those that survived BIT, to the customer(s). BIT can be based on elevated temperatures, temperature cycling, voltage, current, humidity, random vibrations, etc., and/or on the appropriate combination of these stressors. BIT is a costly undertaking: early failures are avoided and the infant mortality portion of the BTC is supposedly eliminated as the result of BIT and, certainly, at the expense of the reduced yield. But what is an even worse, elevated BIT stress might not only eliminate "freaks", but could cause permanent damage to the main population of the "healthy" products. This is particularly true for solder joint interconnections, the reliability bottle-neck of the today's electronics technologies: an appreciable and unknown portion of their lifetime could be consumed because of the BIT. This type of testing should be therefore well understood, thoroughly planned and carefully executed.

It is unclear, however, whether BIT is always needed or to what extent are the to-day's practices adequate and effective. The highly accelerated life testing (HALT) [4], which is the procedure of choice employed today as a suitable BIT vehicle, is a "black box" that tries "to kill many birds with one stone". HALT is unable to provide any trustworthy information on what it actually does. It remains unclear what could possibly be done to develop an insight into what is actually happening during and as a result of the HALT-based BIT and how to effectively eliminate "freaks", while shortening the testing time, reducing its cost and avoiding damaging the sound devices. When HALT is relied upon to

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do the job, it is not easy even to determine whether the infant mortality portion, which is characterized by the decreasing failure rate with time, exists at all. Thus, there is an obvious incentive to develop ways, in which the physics of the BIT process could be better understood, quantified, monitored and possibly even optimized.

In this paper some important BIT aspects are addressed for an electronic product comprised of numerous mass-produced components [5]. We shed some quantitative light on the BIT process, and, since nothing is perfect, such a quantification is done on the probabilistic basis, having in mind that the difference between a highly reliable process or a product and an insufficiently reliable one is merely in the level of their never-zero probability of failure. Particularly, a suitable criterion is suggested to answer the fundamental "to burn-in or not to burn-in" question in electronics manufacturing [6], and, if BIT is decided upon, - to find a way to quantify its outcome. This could be done using BAZ model [7]. This model has been recently employed in a number of electronics and photonics reliability problems as an effective constitutive equation in the probabilistic design for reliability (PDfR) [8] effort.

II. ANALYSIS

This fundamental question is addressed here using two mutually complementary and independent analyses: 1) the analysis of the configuration of the infant mortality portion of a BTC that has been obtained for a more or less well established manufacturing technology of interest; and 2) the analysis of the role of the random SFR of the mass-produced components that the product of interest is comprised of; in this analysis the effect that the random SFR of the mass-produced components is considered from the standpoint of its effect on the nonrandom initial SFR of the product.

The desirable steady-state portion of the BTC takes place at the end of the BIT process as a result of the interaction of two major irreversible time-dependent processes: the "favorable" statistical process that results in a decreasing failure rate with time, and the "unfavorable" physics-of-failure-related process resulting in an increasing failure rate. The first process dominates at the infant mortality portion of the BTC and is considered here. The BTC SFR process can be predicted for a product comprised of mass-produced components using sheer theoretical considerations. The infant mortality portion of the typical BTC, the "reliability passport" of the electronics manufacturing technology of interest and its mass-produced products, can be approximated as:

$$\lambda(t) = \lambda_0 + (\lambda_1 - \lambda_0)\left(1 - \frac{t}{t_1}\right)^{n_1}, 0 \le t \le t_1. \tag{1}$$

Here λ_0 is its steady-state minimum, λ_1 is its initial (highest) value at the beginning of the IMP, t_1 is the duration of this portion, and the exponent $n_1 = \frac{\beta_1}{1-\beta_1}$ is expressed through the "fullnesses" β_1 of the BTC's infant mortality portion. This "fullness" is defined as the ratio of the area below the BTC to the area $(\lambda_1 - \lambda_0)t_1$ of the corresponding rectangular. The exponent n_1 changes from zero to one, when the "fullness" β_1 changes from zero to 0.5.

As follows from (1), the time derivative of the failure rate at the initial moment of time ($t = 0$) is

$$\lambda'(0) = -\frac{\lambda_1 - \lambda_0}{t_1}\frac{\beta_1}{1-\beta_1}. \tag{2}$$

If this derivative is zero or next-to-zero, this means that the infant mortality portion of the BTC is parallel to the time axis, that there is, in effect, no such portion at all, the initial value λ_1 of the BTC is not different from its steady-state λ_0 value, and therefore no BIT is needed to eliminate this portion, and "not to burn-in" is the answer to basic question

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"to burn-in or not to burn-in". What is less obvious is that the same result takes place for $\frac{\beta_1}{t_1} = 0$. This means that although the BIT *is* needed, it could be very short and very low level, because there are not too many "freaks" in the manufactured population and because, although these "freaks" exist, they are characterized by very low probabilities of non-failure, so that the planned BIT process could be both low level and next-to-an-instantaneous one. No damages to the healthy population will be done.

The maximum value of the fullness β_1 is $\beta_1 = 0.5$. This corresponds to the case when the infant mortality portion of the BTC is a straight line connecting the initial, λ_1, and the steady-state, λ_0, BTC failure rate values. In this case the initial time derivative of the failure rate is

$$\lambda'(0) = \frac{d\lambda(t)}{dt} = -\frac{\lambda_1 - \lambda_0}{t_1}, \tag{3}$$

and this seems to be the case, when the BIT is mostly needed.

The non-random time-dependent SFR $\lambda_{ST}(t)$ of the product (it is this value that one sees at the BTC) can be obtained from the random SFR λ of its constituent components, whose probability density distribution function is $f(\lambda)$, as follows [5]:

$$\lambda_{ST}(t) = \frac{\int_0^\infty \lambda \exp(-\lambda t) f(\lambda) d\lambda}{\int_0^\infty \exp(-\lambda t) f(\lambda) d\lambda}. \tag{4}$$

Thus, the $\lambda_{ST}(t)$ will be different for different distributions of the random failure rate of the constituent components. Consider the situation when the failure rate λ is normally distributed:

$$f(\lambda) = \frac{1}{\sqrt{2\pi D}} \exp\left(-\frac{(\lambda - \bar{\lambda})^2}{2D}\right). \tag{5}$$

Here $\bar{\lambda}$ is the mean value of the failure rate λ and D is its variance. Then the following formula can be obtained:

$$\lambda_{ST}(t) = \sqrt{2D}\varphi[\tau(t)]. \tag{6}$$

Here the "time function" $\varphi[\tau(t)]$ depends on the dimensionless "physical" (effective) time

$$\tau = t\sqrt{\frac{D}{2}} - s, \tag{7}$$

where $s = \frac{\bar{\lambda}}{\sqrt{2D}}$ value, known in the probabilistic reliability theory as safety factor, can be interpreted as a measure of the degree of uncertainty of the random SFR. The time derivative of the non-random SFR can be found as

$$\lambda'_{ST}(t) = \sqrt{2D}\frac{d\varphi[\tau(t)]}{dt} = \sqrt{2D}\frac{d\varphi}{d\tau}\frac{d\tau}{dt} = D\varphi'(\tau). \tag{8}$$

The derivative $\varphi'(\tau)$ at the initial moment of time is -1.0, and therefore,

$$\lambda'_{ST}(0) = \lambda'_1 = -D. \tag{9}$$

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This result explains the physical meaning of the time derivative of the initial failure rate λ_1 for a product comprised of numerous components, whose failure rate changes from zero to infinity: this derivative is simply the variance (with a "minus" sign, of course: the infant mortality portion of the BTC is always a decreasing function) of the random SFR of the components that the product of interest is comprised of.

The BAZ model [7, 8] suggests a simple, easy-to-use and physically meaningful way for the evaluation of the probability of non-failure of a material or a device after the given time in testing or operation at the given temperature and under the given stress or stressors. The probability of non-failure during the BIT can be sought, using BAZ model, as

$$P = \exp\left[-\gamma_t D I_* t \exp\left(-\frac{U_0 - \gamma_\sigma \sigma}{kT}\right)\right]. \tag{10}$$

Here D is the variance of the random SFR of the mass-produced components, I is the measured/monitored signal (such as, e.g., leakage current, whose agreed-upon high value I_* is viewed as an indication of failure; or an elevated electrical resistance, suitable particularly for solder joint interconnections - the most vulnerable structural element in the today's packaged IC devices), t is time, σ is the "external" stressor, U_0 is the highest activation energy (unlike in the original BAZ model, this energy may or may not be affected by the level of the external stressor), T is the absolute temperature, γ_σ is the stress sensitivity factor and γ_t is the time/variance sensitivity factor.

The above equation makes physical sense. Indeed, the probability of non-failure decreases with an increase in the variance D, in the time t, in the level I_* of the leakage current at failure and in the environmental temperature T, and increases with an increase in the activation energy U_0 that characterizes the propensity of the material or the device to failure.

The time derivative of the probability of non-failure is

$$\frac{dP}{dt} = -\frac{H(P)}{t}, \tag{11}$$

where $H(P) = -P \ln P$ is the entropy of the distribution. These formulas explain the reliability physics underlying the accepted distribution for the probability of non-failure: this probability is proportional to the entropy of this distribution and is inversely proportional to the time of testing or operation. The entropy $H(P) = -P \ln P$ is zero for $P = 0$ and for $P = 1$, and reaches its maximum $H_{\max} = e^{-1}$ for $P = e^{-1}$. The maxima of the probability of non-failure and the entropy take place at the moment of time

$$t = \frac{1}{\gamma_t D I_*} \exp\left(\frac{U_0 - \gamma_\sigma \sigma}{kT}\right) \tag{12}$$

that is considered in the BAZ model as the mean time to failure (MTTF).

There are three unknowns in the above expressions: the product $\rho = \gamma_t D$ of the time-sensitivity factor γ_t and the variance D; the stress-sensitivity factor γ_σ and the activation energy U_0. These unknowns could be determined from a two-step FOAT.

At the first step testing should be carried out for two different temperatures, T_1 and T_2, but for the same effective activation energy $U = U_0 - \gamma_\sigma \sigma$. Then the relationships

$$P_{1,2} = \exp\left[-\rho I_* t_{1,2} \exp\left(-\frac{U_0 - \gamma_\sigma \sigma}{kT_{1,2}}\right)\right] \tag{13}$$

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can be obtained. Here $P_{1,2}$ are the measured probabilities of non-failure, $t_{1,2}$ are the corresponding times and I_* is the leakage current at failure. Since the numerator $U = U_0 - \gamma\sigma$ in these relationships is kept the same, the amount $\rho = \gamma_t D$ can be found as

$$\rho = \exp\left[\frac{1}{\theta - 1}\left(\frac{n_2^\theta}{n_1}\right)\right], \tag{14}$$

where the notations

$$n_{1,2} = -\frac{\ln P_{1,2}}{I_* t_{1,2}},\ \theta = \frac{T_2}{T_1} \tag{15}$$

are used.

The <u>second step</u> of testing aimed at the evaluation of the stress sensitivity factor γ_σ should be conducted at two stress levels σ_1 and σ_2 (say, temperatures or voltages). If the stresses σ_1 and σ_2 are thermal stresses determined for the temperatures T_1 and T_2, these stresses could be determined using a suitable analytical thermal stress model. Then

$$\gamma_\sigma = k\frac{T_1 \ln n_1 - T_2 \ln n_2 + (T_2 - T_1)\ln\rho}{\sigma_1 - \sigma_2}. \tag{16}$$

If, however, the external stress is not a thermal stress, then the temperatures at these tests should preferably be kept the same. Then the ρ value will not affect the factor γ_σ, and could be evaluated as

$$\gamma_\sigma = \frac{kT}{\sigma_1 - \sigma_2}\ln\left(\frac{n_1}{n_2}\right), \tag{17}$$

where T is the testing temperature. Finally, after the product ρ and the factor γ_σ are determined, the activation energy U_0 can be found as

$$U_0 = -kT_1 \ln\left(\frac{n_1}{\rho}\right) + \gamma\sigma_1 = -kT_2 \ln\left(\frac{n_2}{\rho}\right) + \gamma\sigma_2. \tag{18}$$

The time to failure (TTF) can be obviously determined as

$$t = \frac{-\ln P}{\rho I_*}\exp\left(\frac{U_0 - \gamma_\sigma \sigma}{kT}\right), \tag{19}$$

and the mean-time-to-failure (MTTF) as

$$t = \frac{1}{\rho I_*}\exp\left(\frac{U_0 - \gamma_\sigma \sigma}{kT}\right). \tag{20}$$

These formulas indicate particularly that the (probability-of-non-failure dependent) TTF and the (probability of non-failure independent) MTTF are related as

$$\frac{TTF}{MTTF} = -\ln P. \tag{21}$$

The TTF and the MTTF coincide for the probability of non-failure $P = e^{-1} = 0.3679$, and their ratio changes from zero to infinity, when the probability P of non-failure changes from one to zero.

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III. NUMERICAL EXAMPLE

Let, e.g., the following data were obtained at the first step of FOAT:

1) After $t_1 = 14h$ of testing at the temperature of $T_1 = 60^0 C = 333^0 K$, 90% of the tested devices reached the critical level of the leakage current of $I_* = 3.5\mu A$ and, hence, failed, so that the recorded probability of non-failure is $P_1 = 0.1$; the applied stress is elevated voltage $\sigma_1 = 380V$;

2) After $t_2 = 28h$ of testing at the temperature of $T_2 = 85^0 C = 358^0 K$, 95% of the samples failed, so that the recorded probability of non-failure is $P_2 = 0.05$.

The applied external stress is still elevated voltage of the level $\sigma_1 = 380V$. Then

$$n_1 = -\frac{\ln P_1}{I_* t_1} = -\frac{\ln 0.1}{3.5x14} = 4.6991x10^{-2}\,\mu A^{-1}h^{-1};\quad n_2 = -\frac{\ln P_2}{I_* t_2} = -\frac{\ln 0.05}{3.5x28} = 3.0569x10^{-2}\,\mu A^{-1}h^{-1};$$

$$\theta = \frac{T_2}{T_1} = \frac{358}{333} = 1.0751,\quad \rho = \exp\left[\frac{1}{\theta - 1}\left(\frac{n_2^{\theta}}{n_1}\right)\right] = \exp\left[\frac{1}{0.0751}\left(\frac{0.030569^{1.0751}}{0.046991}\right)\right] = 785.3197\,\mu A^{-1}h^{-1}.$$

At the second step of FOAT one can use, without conducting additional testing, the above information from the first step, its duration and outcome, and let the second step of testing has shown that after $t_2 = 36h$ of testing at the same temperature of $T = 60^0 C = 333^0 K$, 98% of the tested samples failed, so that the predicted probability of non-failure is $P_2 = 0.02$. If the stress σ_2 is elevated voltage $\sigma_2 = 220V$, then

$$n_2 = -\frac{\ln P_2}{I_* t_2} = -\frac{\ln 0.02}{3.5x36} = 3.1048x10^{-2}\,\mu A^{-1}h^{-1},$$

and the formula for the stress sensitivity factor γ_σ yields:

$$\gamma_\sigma = kT\frac{\ln\left(\frac{n_1}{n_2}\right)}{\sigma_1 - \sigma_2} = 8.61733x10^{-5}x333\frac{\ln\left(\frac{4.6991x10^{-2}}{3.1048x10^{-2}}\right)}{380 - 220} = 4326x10^{-5}eVxV^{-1}.$$

Then the activation energy U_0 is

$$U_0 = -kT\ln\left(\frac{n_1}{\rho}\right) + \gamma_\sigma \sigma_1 =$$

$$= -8.61733x10^{-5}x333\ln\left(\frac{4.6991x10^{-2}}{785.3197}\right) + 7.4326x10^{-5}x380 = 0.2790 + 0.0282 = 0.3072eV$$

or, to make sure that there was no calculation error, as

$$U_0 = -kT\ln\left(\frac{n_2}{\rho}\right) + \gamma_\sigma \sigma_2 = -8.61733x10^{-5}x333\ln\left(\frac{3.1048x10^{-2}}{785.3197}\right) + 7.4326x10^{-5}x220 = 0.2909 + 0.0164 =$$

$$= 0.3072eV$$

No wonder that these values are considerably lower than the activation energies of "healthy" products. Many manufacturers feel ("rule of thumb") that the level of 0.7eV can be used as an appropriate tentative number for the activation energy of

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healthy electronic products. In this connection it should be indicated that when the BIT process is monitored and the activation energy U_0 is being continuously calculated based on the number of the failed devices, the BIT process should be terminated, when the calculations, based on the FOAT data, indicate that the energy U_0 starts to increase.

The calculated data show also that this energy slightly increases with an increase in the level of loading. This increase is, however, only about 5-8%. The MTTF is

$$t = \frac{1}{\rho I_*}\exp\left(\frac{U_0 - \gamma_\sigma \sigma}{kT}\right) = \frac{1}{785.3197x3.5}\exp\left(\frac{0.3072 - 7.4326x10^{-5}}{8.61733x10^{-5}x333}\right) = 16.1835h,$$

and the TTF is $t = MTTFx(\ln P)$. The calculated BIT related TTF for different probabilities of non-failures are shown in Table 1:

Table 1. TTF vs. Probability-of-Non-Failure

P	0.0050	0.0075	0.0100	0.0500
TTF,	85.7453	79.183	74.527	48.4814

Clearly, the probabilities of non-failure for a successful BIT should be low enough. It is clear also that the BIT process should be terminated when the calculated probabilities of non-failure and the activation energy U_0 start rapidly increasing.

IV. CONCLUSION

Although our analyses do not suggest any straightforward way of how to optimize BIT, they nonetheless shed useful light on the significance of some important factors that affect the BIT time of a product comprised of mass-produced components. Future work should include experimental verification of the suggested “to burn-in or not to burn in” criterion, as well as its acceptable values, which would enable to answer the “to burn-in or not to burn-in” question. It should include also investigation of the effects of other possible distributions of the random SFR, such as, e.g., Rayleigh distribution.

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