Temperature Acceleration Models in Reliability Predictions: Justification & Improvements

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SUMMARY & CONCLUSIONS

Reliability predictions have been for a long time a difficult task, due to the conflict between high reliability requirements and the lack of component manufacturer data. As the data available during the development phase is the product bill of materials, reliability prediction methods have developed component reliability models based on in-service field return data and/or physics of failure. The repartition of these two approaches has changed over time, where predictions were mainly based on empirical data at the beginning (MIL-HDBK-217), but more recently attempts have been made to incorporate some form of physics of failure (MIL217+, FIDES). Note, that even in these attempts the acceleration factor coefficients are still based on empirical data.

For our aeronautic applications, with the recent reliability prediction methods, steady-state temperature is the main reliability driver and any wrong assumption in the model can be catastrophic. Our methodology is based on several recent works such as Pecht's model, new mechanisms of failure (hot carrier, delamination, etc) due to greater component integration, and physics of failure simulations (Bernstein).

We propose some improvements on this model in order to have some more realistic reliability predictions. For example, we introduce a non Arrhenius model for steady-state temperature for active electronic components and explain in detail why these formulations don't match correctly to real data.

1 NOTATION

AF: Acceleration factor
Ea: activation energy
f(t): Probability density
F(t): Cumulated probability density
FIT: Failure In Time
GLL: General Log Linear
HTOL: High Temperature Life Test
Kb: Boltzman's constant
MOS: Metal Oxide Semi-conductor
MTBF: Mean Time Between Failure
MTTF: Mean Time To Failure
T: Temperature in degrees Kelvin
Topt: Minimal Temperature value for failure rate versus steady-state temperature
To: reference temperature
β: Shape parameter of the Weibull distribution
η: Scale parameter of the Weibull distribution
λ: Failure rate

2 ACCELERATION MODEL JUSTIFICATION

2.1 *Introduction*

Generally, in well known reliability prediction methodologies such as the MIL-HDBK-217 [MIL-01] or the French RDF 2000 [RDF-00], no justifications on acceleration models are provided. Even in more recent MIL217+ or FIDES methodologies, the coefficients of the acceleration models are built from empirical data (e.g. the activation energy of the Arrhenius model for temperature acceleration). Reliability standards such as the JEDEC [JED-01] or [JED-02] can also be used, but often a global activation energy is considered without more information.

Test data can also be used to determine these coefficients; however, for an acceleration model with even one parameter, data in least 2 stress levels are needed. Reliability component manufacturer data for steady-state temperature for example (HTOL tests) are based on only one stress level, thus an activation energy cannot be determined solely on these data.

In this section we will review the different acceleration models used in life-stress predictions. We shall illustrate our work with the FIDES methodology since it is the most recent, and in addition, all physical stresses are present in it (i.e. more general than other prediction standards, such as MIL-217).

2.2 *FIDES Reliability prediction MODELS*

The FIDES methodology [FID-01] is mainly based on physics of failure. The generic model has the following form :

$$\lambda = \lambda_{physic} \cdot \Pi_{induced} \cdot \Pi_{part} \cdot \Pi_{process} \qquad (1)$$

where,

λ_{physic} is the failure rate due to different failure mechanisms.

$\Pi_{induced}$ is the contribution of induced factors (overstress) inherent to a field application

Π_{part} is the quality and technical control of the component manufacturer

Πprocess is the quality and technical control of the

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processes of development, manufacturing and maintenance

In this paper, just the physical part of the failure rate is of interest. This metric is built on Cox's model and has the following form, assuming no interactions:

$$\lambda_{physic} = \sum_{i=1}^{s} \lambda o_i \cdot AF_i(X_i) \tag{2}$$

where

λo_i is the reference failure rate of the i^{th} stress

AF_i is the acceleration factor

X_i is a vector of stresses (possibly transformed)

s is the number of stresses

The reference failure rate and acceleration factor are built on GLL models [MET-02] which propose a general log-linear relationship which describes the life characteristic, here the physical failure rate, as a function of stress, X, as follows:

$$L(X) = \exp\left(\alpha_o + \sum_{i=1}^{s} \alpha_i \cdot X_i\right) \tag{3}$$

where α are model parameters.

In the case of reliability prediction, we consider the system failure rate as a constant. This assumption can be used as shown by Drenick's theorem [DRE-60]. Therefore, the failure rate in this case is the inverse of the mean life, the MTTF (assuming a system with all components in series).

2.3 *Steady-state temperature*

The Arrhenius life-stress model (or relationship) is probably the most common life-stress relationship utilized in accelerated life testing. It has been widely used when the stimulus or acceleration variable (or stress) is thermal (*i.e.* temperature). It is derived from the Arrhenius reaction rate equation [ARR-01] proposed by the Swedish physical chemist Svandte Arrhenius in 1887.

The Arrhenius reaction rate equation is given by:

$$\mathrm{Re}(T) = \gamma 0 \cdot \exp\left(\frac{Ea}{Kb \cdot T}\right) \tag{4}$$

where

Kb is the Boltzmann's constant

T is the ambient temperature in °K

Ea is the activation energy

γ_0 is a constant depending on material characteristic

The activation energy represents the minimum energy that a molecule must have to participate in a reaction that produces the failure mechanism. A negative activation energy indicates that the reaction is accelerated by temperature lower than ambient temperature.

For the steady-state temperature , equation (3) leads to

$$\lambda(X) = \exp\left(\alpha_o + \frac{\alpha_1}{T}\right)$$

If we compare this equation with equation (4), we can write:

$$\lambda(X) = \exp\left(-\alpha_o - \frac{\alpha_1}{T}\right) = \gamma 0 \cdot \exp\left(\frac{Ea}{Kb \cdot T}\right)$$

which leads to :

$$AF(T) = \exp\left[\frac{Ea}{Kb} \cdot \left(\frac{1}{T_0} - \frac{1}{T}\right)\right]$$
$$\lambda 0 = \exp\left(-\alpha_0 + \frac{Ea}{Kb \cdot T_0}\right) \tag{5}$$

where T_0 is the reference temperature.

The activation energy is an indication of effect that the covariate (temperature, humidity, etc.) has on the life of the product.

Semiconductors manufacturers performed some quality tests at high temperature (HTOL tests). From them, they estimate the component failure rate with the Arrhenius acceleration factor in use conditions. The activation energy for this calculation is generally based on the value indicated in reference [JED-02], i.e. 0.7 eV. In other words, samples are only tested at a single high level, and an activation energy is assumed in order to extrapolate to use conditions.

It is obvious that this approach greatly depends on the assumed value of the activation energy, and different standards provide different values. Originally, this method was developed at the end of 1960 by the U.S. army [MIL-01] for reliability prediction methodology and was based on their in-service field return data (MIL-HDK-217). In there, activation energy depends on component family but generally is near 0.4eV, a value also met in a more recent French methodology [RDF-01].

	MIL-HDBK-217F notice 1	MIL-HDBK-217F notice 2	RDF 2000	MIL 217 plus	FIDES
Update year	1995	1996	2000	2007	2009
Bipolar logic	0,4 eV	0,4 eV	0,4 eV	0,8 eV	0,7 eV
CMOS logic	0,35 eV	0,35 eV	0,3 eV	0,8 eV	0,7 eV
BiCmos logic	0,5 eV	0,5 eV	0,4 eV	0,8 eV	0,7 eV
Linear	0,65 eV	0,65 eV		0,8 eV	0,7 eV
Memories	0,6 eV	0,6 eV		0,8 eV	0,7 eV
VHSIC	0,4 eV	0,4 eV		0,8 eV	0,7 eV

Table1: Activation Energies in Different Prediction Standards

More recently, some new methodologies have emerged [FID-01] or [MIL-02] with some greater activation energies, i.e. 0.7 eV and 0.8 eV respectively, as shown in Table 1. Note, that these values can not be directly compared because reliability prediction models are sometimes multiplicative and sometimes additive. Regardless, different values will yield different results, and the questions of which value to use, and if this value represents the specific design, remain.

3 *KNOWN ACCELERATION MODEL WEAKNESSES*

In this section we review the assumptions and weaknesses associated with the acceleration model described in the previous section as they pertain in the different prediction standards, but more focused on the FIDES standard.

Most prediction standards assume a value for the Activation Energy in modeling life as a function of steady-state temperature. However, an incorrect assumption on the value of the activation energy can lead to an incorrect deduction regarding the effect that the covariate has on the product, as well as an erroneous calculation of the acceleration factor [JEP-02]. Figure 1 clearly shows the influence of activation energy on the acceleration factor

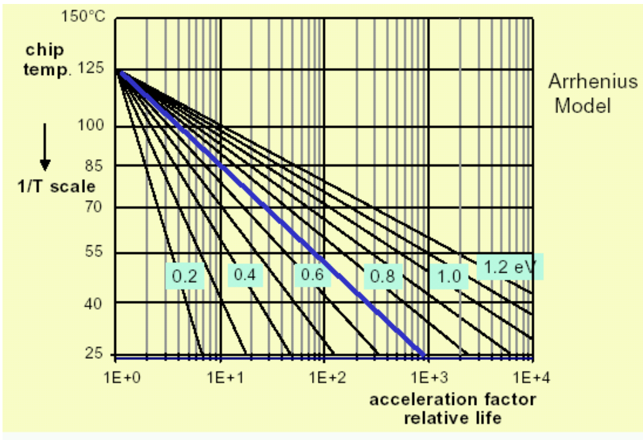

Figure 1: Effect of the activation energy on the acceleration factor.

The values of the activation energy are constant for a particular stress or failure mode, but in reality the activation energy may actually vary from one production lot to another, from one version of the product to another and from one failure mechanism to another.

FIDES reliability prediction methodology is based on COX model and more precisely on GLL models. The reference failure rate is estimated for an active component based on manufacturer reliability data and Bayesian techniques with in-service field return data as prior information. Acceleration factors are based on physics of failure and established from accelerated tests [GUE-06] for all stresses except steady state temperature. Activation energy and thus the acceleration factor is no longer demonstrated by manufacturer tests.

In addition to the assumption of a value for the activation energy in most prediction standards, there is also the question of how relevant these values are, since some standards are quite old. Case in point is the observation that time-to-failure of semiconductor components has doubled every 15 months since 1973, leading to a notable increase in effective activation energy [PEC-01]. This suggests it is no longer justifiable to regard activation energy as a stable physical constant.

Recent data also show the acceleration factor used for test-to field analysis is doubling every five years. Taking these trends into account in testing strategies will improve reliability while reducing accelerated life testing times and expense.

Activation-energy-based reliability models have been used to statistically correlate TTF to environmental conditions using an activation energy. The higher the activation energy of a component, the longer the TTF at a given operating condition. Empirical activation-energy-based reliability models do not account for the physics of failure including component details such as structure and material properties, but have been used to roughly estimate reliability.

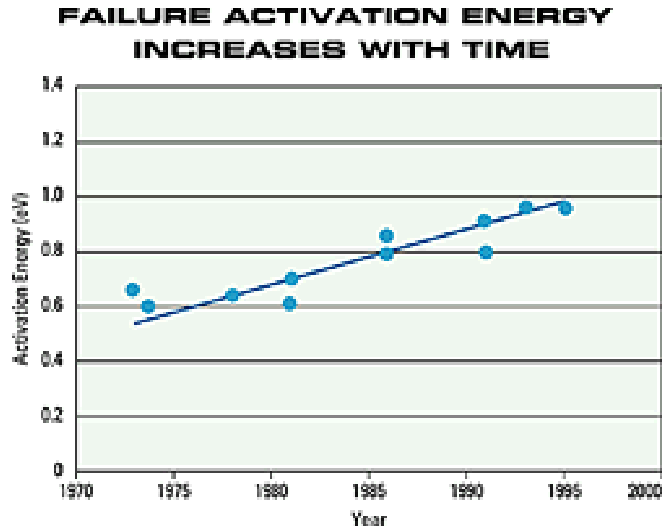

Figure 2: Progress of Activation Energy over the years.

Most activation-energy-based reliability models focus on temperature and moisture-related failure mechanisms. Reliability data presented in the literature (Figure 2) indicate that activation energy increases with time, by about 0.42 eV from 1973 to 1995.

Higher activation energy means higher stress is needed to precipitate failures. Because some reports do not state the production date of components under test, we assumed the publication date was the production date, a difference that may move data points by a couple of years, but does not change the general trend.

Another problem exists for cold temperature. Specifically, when the exponential argument tends to -∞, the exponential function is near 0. So the colder the temperature, the lower the acceleration factor will be. Nothing demonstrates this trend in actual applications. On the contrary, the presence of failure mechanism called “hot electrons" [PEC-02], which takes place for temperatures lower than 20°C, results in an acceleration factor behavior that would resemble the shape of a bathtub curve.

Indeed, in modern integrated circuits, the size reduction of transistors, 40 years ago predicted by G. Moore [MOO-01] and known as Moore’s law, allows designers to create more and more complex devices. Unfortunately, this decrease has some negative consequences. One of the most important is the apparition of hot carriers, very energetic, which perturbed and then modify slowly the electrical characteristics due to injection of charge in the oxide. This phenomenon is due to the presence of intensive electrical field creating by differential voltages on very short distances. This failure mode, characterized by negative activation energy, is accelerated by low temperatures from 20°C to -200°C.

4 IMPROVEMENTS

The weaknesses discussed in the previous section were the motivation for the suggested improvements to these models which are presented next.

4.1 *Activation energy temperature dependence*

Steady-state temperature dependant models like the Arrhenius model are largely applied to model electronic components reliability influence. These models are often used to show the effect of temperature on component failure rate with the assumption that the dominant failure mechanisms depend on the junction temperature of the active components.

This assumption allows the estimation of the activation energy or the acceleration factor by using a methodology based on a weighted average of different activation energy failure mechanisms, characterizing the component failure rate as an exponential function of temperature. As we mentioned previously, most prediction standards assume a constant value for the activation energy, which could be incorrect, given the rapid change in technology and the presence of "hot carriers."

One possible method to alleviate the problem of selecting the most representative activation energy is to estimate the value based on collected data. Utilizing maximum likelihood theory, the parameters of the Arrhenius model are solved while using the Weibull distribution as the underlying life distribution. Once the parameters have been estimated, the activation energy and acceleration factor can easily be calculated.

In addition, when multiple failure mechanisms are present (e.g. the presence of "hot carriers"), the overall activation energy, for a given temperature T, corresponds to the minimum energy required to activate the weakest failure mechanism. Therefore, the mixed life distribution can be used to describe the combined effect of multiple failure mechanisms [MET-01].

Under the Mixed Weibull distribution, the MTTF is obtained from:

$$MTTF_{eq} = \sum_{i=1}^{n} \left[p_i \cdot MTTF_i \right] \quad (6)$$

where p_i is the portion of each subpopulation..

Each failure mechanism can be characterized by a Weibull distribution with inherent shape and scale parameters. So, for a given failure mechanism "i", the acceleration factor can be written for any temperature T:

$$AF_i(T) = \frac{\eta_i(T_0)}{\eta_i(T)} = \frac{\left[MTTF(T_0)\right]_i}{\left[MTTF(T)\right]_i} = \exp\left[\frac{Ea_i}{K} \cdot \left(\frac{1}{T_0} - \frac{1}{T}\right)\right]$$

Let

$$\varepsilon = \exp\left[\frac{1}{K} \cdot \left(\frac{1}{T_0} - \frac{1}{T}\right)\right]$$

then:

$$AF_i(T) = \varepsilon^{Ea_i}$$

Therefore,

$$MTTF_i(T) = MTTF(T_0) \cdot \varepsilon^{-Ea_i}$$

Substituting this result into Eqn. (8), we get:

$$\left[MTTF(T_0)\right]_{eq} = \sum_{i=1}^{n} \left[p_i \cdot \left[MTTF(T_0)\right]_i \right]$$

$$= \sum_{i=1}^{n} \left[p_i \cdot \left[MTTF(T_{acc})\right]_i \cdot \varepsilon^{Ea_i} \right]$$

This can also be written as:

$$\left[MTTF(T_0)\right]_{eq} = \left[MTTF(T_{acc})\right]_{eq} \cdot \varepsilon^{Ea_{eq}}$$

Finally,

$$\left[MTTF(T_{acc})\right]_{eq} = \sum_{i=1}^{n} \left[p_i \cdot \varepsilon^{Ea_i - Ea_{eq}} \cdot \left[MTTF(T_{acc})\right]_i \right] \quad (7)$$

Equation (7) indicates that the subpopulation proportion "p_i ", after being exposed to high temperature, changes to proportion "p'_i " with :

$$p_i' = p_i \cdot \varepsilon^{Ea_i - Ea_{eq}} \quad (8)$$

The new proportion must also verify that $\sum_{i=1}^{n} p_i' = 1$. This leads to:

$$\sum_{i=1}^{n} p_i \cdot \varepsilon^{Ea_i - Ea} = 1 \qquad \ln\left(\sum_{i=1}^{n} p_i \cdot \varepsilon^{Ea_i}\right) = Ea \cdot \ln(\varepsilon)$$

and finally

$$Ea = \frac{\ln\left(\sum_{i=1}^{n} p_i \cdot \varepsilon^{Ea_i}\right)}{\ln(\varepsilon)} \quad (9)$$

This relation clearly shows that the overall activation energy of the mixed distribution is temperature dependant and cannot be considered as a constant because ε is temperature dependant.

Groebel, Sun and Mettas [MET-01] have proposed a complete methodology to determine the activation energy using accelerated-test data. Utilizing maximum likelihood theory, the parameters of the Arrhenius model are solved while using the Weibull distribution as the underlying life distribution.

This methodology is based on GLL models and leads to the following relationship:

$$f(t,T) = \frac{\beta}{C \cdot e^{\frac{Ea}{Kb \cdot T}}} \cdot \left(\frac{T_{F,i}}{C \cdot e^{\frac{Ea}{Kb \cdot T}}}\right)^{\beta - 1} \cdot e^{-\left(\frac{T_{F,i}}{C \cdot e^{\frac{Ea}{Kb \cdot T}}}\right)^{\beta}} \quad (10)$$

Equation (10) has made the hypothesis that there is only one failure mechanism activated and the shape parameter can be considered as a constant. So, Arrhenius model has just two unknown parameters C and Ea. So the accelerated tests must be conducted with at least 2 different temperature levels and, in this case, a constant value for Ea is found. These unknown parameters, Ea, β and C are determined by maximizing Λ with respect to these parameters.

These models have been successfully used in [PIE-01] when there was only one failure mechanism present (shape parameter is stress independent). However, reliability prediction models based on this approach are provided for components which often have different failure mechanisms even for a given stress.

4.2 *Equivalent activation energy model*

This evolution of activation energy has a physical meaning. Indeed, it represents the minimal necessary energy to create a particular failure mechanism. So, it's normal that failure mechanisms with low activation energies were induced before a failure mechanism with a high activation energy.

We are searching for a failure rate with a bathtub shape. This is the case if the 2 following conditions are satisfied:

- the first derivative with respect to temperature of the acceleration factor is null for T = Topt.
- the second derivative is non-negative for any T

$$\frac{d}{dT}\left[e^{\frac{E_a(T)}{Kb}\left(\frac{1}{T_0}-\frac{1}{T}\right)}\right]=0$$

Thus,

$$\left(\frac{dEa(T)}{dt}\right)\cdot T^2\cdot\left(\frac{1}{To}-\frac{1}{T}\right)+Ea(T)=0 \qquad (11)$$

The bathtub shape can be simply approach by a second order polynomial. This is the case if, with the form of equation (11), the function Ea(T) is an affine expression given by:

$$Ea(T)=a\cdot T+b$$

which leads to:

$$a\cdot T^2+b\cdot To=0$$

and finally:

$$Topt=\sqrt{\frac{-b\cdot To}{a}} \qquad (12)$$

This linear model is easily obtained since a line is completely defined by 2 points. The first one is found from manufacturer accelerated tests from which we have (Thtol , EaHtol).

The second one is obtained for the minimum acceleration factor value (Topt , EaMin). We can now find the analytic value of a and b parameters of the linear function Ea(T):

$$Ea(T)=Ea\min\cdot+\left(\frac{EaHtol-EaMin}{Thtol-Topt}\right)\cdot(T-Topt)$$

which leads to:

$$a=\left(\frac{EaHtol-EaMin}{Thtol-Topt}\right)$$

and

$$b=EaMin\cdot-\left(\frac{EaHtol-EaMin}{Thtol-Topt}\right)\cdot Topt$$

And finally from (12)

$$Topt=\sqrt{\frac{-EaMin\cdot-\left(\frac{EaHtol-EaMin}{Thtol-Topt}\right)\cdot Topt\cdot To}{\left(\frac{EaHtol-EaMin}{Thtol-Topt}\right)}} \qquad (13)$$

We can now just solve for the value of EaMin knowing Topt, EaHtol, Thtol and To:

$$EaMin=\frac{Topt\cdot EaHtol\cdot(Topt-To)}{Topt^2-To\cdot Thtol} \qquad (14)$$

We easily check that it's a minimum because the second derivative of the acceleration factor with respect to T is always positive.

It can also be shown that, with the new expression of the activation energy, the failure rate formula has always a GLL expression.

If we write the corresponding acceleration factor, we have:

$$AF(T)=\exp\left[\left(\frac{a\cdot T+b}{Kb}\right)\cdot\left(\frac{1}{To}-\frac{1}{T}\right)\right]$$

After some basic calculations, it can be rewritten in the following form:

$$AF(T)=\exp[\alpha_0+\alpha_1\cdot X_1+\alpha_2\cdot X_2]$$

with,

$$\alpha_0=\exp\left(\frac{\frac{b}{To}-a}{Kb}\right) \qquad \alpha_1=\exp\left(\frac{-b}{Kb}\right)$$

$$\alpha_2=\exp\left(\frac{a}{Kb\cdot To}\right) \qquad X_1=\frac{1}{T} \qquad X_2=T$$

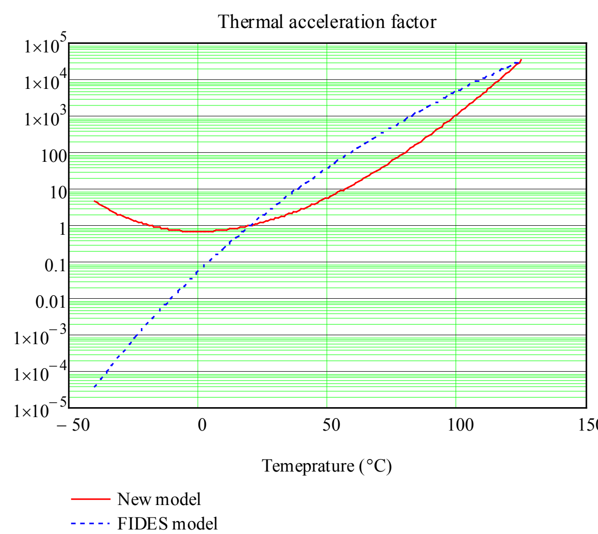

Figure 3: Comparison between Proposed Acceleration Factor model and the basic Arrhenius.

From Berstein [BER-07], we obtain approximately a linear shape for the activation energy versus temperature which confirms our model.

5 CONCLUSIONS & FUTURE WORK

Multiple evidence has been presented in this paper which supports that the assumption of a constant value for the activation energy of the Arrhenius model can lead to wrong predictions. Changes in technology and manufacturing processes render activation energy values found in different standards outdated. In addition, such values represent an average behavior of possible component families and failure modes, thus they may not be valid for a specific design. Therefore, life-stress predictions should be based on test data. The second point deals with the presence of "hot carriers" in electronics, where even the basic Arrhenius model does not adequately represent the true behavior of the acceleration factor as a function of temperature, much more so if the activation energy is considered to be a constant value. The basic Arrhenius model should thus be modified to consider the cold temperature behavior. Such a modification was presented in this paper.

Inconsistencies in the models used for other types of stress based predictions have been observed by the authors as well, and are currently investigated. For example, vibration is typically assumed to be independent of temperature for electronic equipment, even though components become more brittle at lower temperatures. In the interest of performing more realistic predictions such inconsistencies need be investigated, and the models currently used be revised.

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