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Reliability Climatic Test for Composite based on Probabilistic Arrhenius model

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Abstract – **This paper proposes a methodology to verify composite products reliability through its life time using a probabilistic Arrhenius model. It will present the challenge that automotive industry faces and study the potential improvement to be considered in order to improve the reliability during the design and validation phases. The formulas developed in this research permit to set up an accelerated test at the strict necessary needs. The goal is the integration of the variability from Energy of activation (E_a), Test Conditions (Test Bench Temperature T_b) and a dispersion from usage temperatures (T_u)**

Keywords – Polymers, Glass-Fiber, Arrhenius, Statistic, Probabilistic, Automotive reliability, Accelerated test, Climatic test

We propose a paper structured in 3 sections:

1_Automotive Reliability Context
- Reliability: needs and constraints
- Arrhenius model presentation

2_Probabilistic Arrhenius model
- Statistic on Ea parameter
- Statistic on Tu (usage) parameter
- Statistic on Tb (bench) parameter

3_Concrete case application
- Automotive application

The conclusion proposes an analysis of limits and perspectives on this subject.

INTRODUCTION : NEEDS & CONSTRAINTS OF THE AUTOMOTIVE RELIABILITY

Reliability and the automotive world are intimately linked by their histories [DEL 17] [HEN 17], their current challenges, and their futures. This section will highlight these three aspects taking into account the global context of this ever-changing industry.

There are many publications on Reliability with each one casting a different light on the theme [BER 08] [DEL 17] [HEN 17] [VER 10]. Nonetheless, the automotive world is in a permanent search for innovation, production, mobility, autonomy, and speed. In 1900, the United States had only 8,000 cars and a few hundred kilometers of road. Currently, there are more than one and a half billion motor vehicles and millions of kilometers of good roads worldwide. This economy uses and develops techniques and methods, increasingly important to the assurance of vehicle owners, in terms of total safety and comfort.

The methods of reliability testing, which estimate the probability of a system to survive under certain conditions, have in particular drawn upon the statistical theories of the eighteenth, nineteenth and twentieth centuries. There are probabilistic approaches according to the stochastic diffusion [PRA 65] (the Normal Law) in 1777 by Pierre-Simon Laplace and in 1809 by Carl Friedrich Gauss, the approach of an exponential distribution in explicit forms, among others, by Leonhard Euler in 1748 in his book Introductio in analysin infinitorum or the proportional effect extolled by R. Gibrat in 1930 [GIB 30] [AIT 57] (Log-Normal Law).

The probabilistic formulations of the estimate reappear in the movement of Karl Peasron's school with Ronald Aymler Fisher (1890-1962) and William Sealy Gosset – alias Student – (1876-1937), who were all confronted with statistical studies based on insufficient data sample size. Ronald Fisher is generally presented as the father of Estimation Theory according to the principle of "maximum likelihood" (introduced in 1912 and developed until 1922-1925) [DOD 93] [ROD 18] .

Much later in 1939 and then again in 1951, professor and engineer Waloddi Weibull published [WEI 51] [NOS 17] a statistical formulation that would surely become the most popular probabilistic distribution estimation for the processing of survival data, namely the Weibull distribution. It is not surprising to note that this statistical tool is still widely used in the automotive world, given the fact that Professor Weibull worked for major industrials like SAAB, the car manufacturer.

It was noted that the purpose of professor Weibull's work was not to develop a theoretical statistical model or basic research, he sought to solve real physical problems, such as problems related to the resistance of materials, fatigue, and breaking points [LAN 08]. Here we find the very nature of reliability, namely a multiple overlap of various sciences such as chemistry, physics, electrics, electronics, fatigue, thermo-mechanics, electromagnetism, pyrotechnics, etc.

In the automotive world the evolution of methods and statistical tools dedicated to reliability, as in other industries, was at the same time followed in parallel by an evolution of test methods to demonstrate the performance of the experimental reliability of the vehicle. Figure 1 illustrates the various and extreme applications of the first Model T Ford in 1915 and 1926.

Figure 1 Model T Ford in a forest in 1915 and on the snow in 1926 [FOR 15]

The complexity of the modern car adds a new challenge about Reliability.

Mercedes concept car shown in figure 2, known by its codename F015, unveiled in 2015 in Los Angeles, is a fine example of ultra "electronized" and computerized high technology. This concept would allow for an all-electric propulsion system with a range of 1000 km and driven autonomously.

Figure 2 F015 Mercedes Concept car of 2015 [MER 16]

The vehicles currently offered (2014–2018) offer a truly impressive system of complexity. For example, most current models have no less than 100 Electronic Control Units (ECUs), each with a computing power of more than 20 computers. The ECUs manage the entire vehicle, such as its comfort (e.g.: air conditioning, lighting) to the management of the engine (e.g.: fuel consumption, pollution) as well as certain safety features (e.g.: ESP, airbags).

The number of ECUs in modern cars is equivalent to the number found in the first airbus [CHA 09] !

According to a study by Toyota [TOY 04], it is estimated that there are more than 30,000 components in a standard vehicle these days.

As said Automakers Turn to Plastics for Lighter Vehicles [AUT 15], « modern-day plastics account for roughly 50 percent of the volume of a typical vehicle, but only 10 percent of its weight." Composites, especially short glass fiber-reinforced polymers like Polyamide 6 with 30 % glass fibers (PA6 GF30) are relevant materials more and more used in our vehicle. Figure 3 illustrates several processes of aging which impact this kind of material.

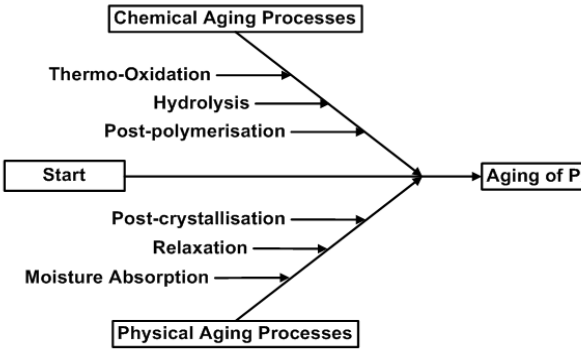

Figure 3 PA6 : relevant aging processes [ILL 01]

One way to assess the reliability performance of complex systems in composite material is the environmental climatic tests. To accelerate this environment, reliability engineers use the Arrhenius model.

Body paragraphs (like this one) should be set in Times New Roman 10pt, full justification, in two column format. Line spacing is single-spacing. The title should be set in Times New Roman, 10 pt size centered. The authors' names must also be centered, (Times New Roman 12pt font). The name of the affiliation should be written using Times New Roman Italics 12pt. Subsection titles are written in Times New Roman 10 pt italics (see Section II.). References should be numbered by the order in which they are called in the text. Their format is presented at the end of the text. Equations should be set in Times New Roman 10pt and horizontally and vertically centered. The numbering should be set at the right hand side and bracketed; all of them have to be referred in the related paragraph individually. Figure captions in Times New Roman 9 pt centered, like in Fig. 1. Table captions in Times New Roman 10 pt centered. See next sections for examples and patterns.

I. PROPOSITION OF A NEW PROBABILISTIC MODEL OF ARRHENIUS

I.1 Constant Arrhenius model

Svante Arrhenius, Nobel Prize of Chemistry in 1903, proposed a new formulation in his article called "On the velocity of the inversion of cane sugar by acids » in 1889 [ARR 89]. This formulation gave the famous Arrhenius Equation.

The Arrhenius relationship models the effect of temperature on the rate of a first-order chemical reaction and can be written as [GUA 07] :

$$\nu = A_0 \exp\left(-\frac{E_a}{\mathrm{kT}}\right) \quad (1)$$

where ν is the chemical reaction rate in moles per second, Ea the effective activation energy in electron-volts (eV), k is Boltzmann's constant (k = 8.61733x10−5 eV/◦C), T the absolute temperature (the Celsius temperature plus 273.15 degrees), and A0 is a constant related to material characteristics.

This speed expresses the amount of reaction per unit time [ALI 04] . One can consider that a failure occurs when a critical amount (in moles) of reactant is reached. Therefore, the time to reach the critical amount is called "time to failure". Since the time to failure is proportional to the reciprocal of the reaction rate, (1) it can be written as

$$\mathrm{L} = \mathrm{A} \exp\left(\frac{E_a}{\mathrm{kT}}\right) \quad (2)$$

where L is the life and A is a constant that depends on material properties, failure criteria, product design, and other factors. Equation (2) is called the Arrhenius life relationship.

Activation energy is an important concept associated with the Arrhenius relationship. It is understood that a chemical reaction is the result of the collisions between the reactant molecules. The collisions take place very frequently, but only a small fraction of the collisions convert reactants into products of the reaction. The necessary condition for the collision to cause a reaction is that the molecules must carry a minimum amount of energy to break bonds and form products. The minimum amount of energy is called the activation energy; it poses a barrier for molecules to climb over. The higher the activation energy, the lower the reaction rate and the longer the life. The activation energy is unique to a reaction, which determines the failure mechanism leading to failure. Therefore, each failure mechanism usually has different activation energy even for the same component. For example: the polyamide PA6 or PA66 are sensitive to thermal oxidation, post-crystallization and absorption with an unique Ea between 0.73 eV and 0.97 eV for each type of reaction [ILL 01] [ERI 98].

For composite materials like polymers, the effective energy of activation is expressed in kJ/mol. In this paper, eV is used as the base.

The conversion is defined by:

$$1\ eV = 96.4869\ kJ/mol$$

The graph Fig. 4 represents the Ea dispersion for different composite material obtained with 56 Ea values compiled in 11 publications like [BER 10] [GIL 04] [GIL 06] .

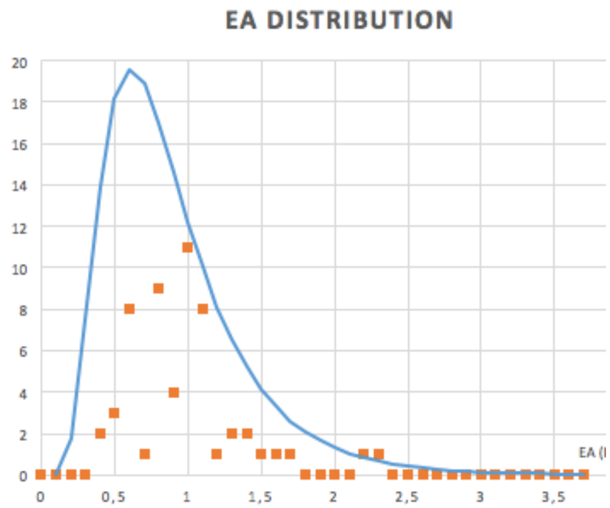

Figure 4 Ea (eV) dispersion

The median of this log-Normal distribution shows a probability of 0.85 eV with a coefficient of variation of 42 % (statistical indicator based on ratio of mean and standard deviation).

The coefficient of variation is defined as [KOO 64] :

$$CV_{ln} = \sqrt{e^{\sigma_{ln}^2} - 1} \quad (3)$$

σ_{ln} is the standard deviation of Log-normal distribution.

Since the Arrhenius life can represent a percentile, the acceleration factor Af between the life L at temperature T and the life L' at temperature T' is

$$A_f = \frac{L}{L'} = \exp\left[\frac{E_a}{k}\left(\frac{1}{T} - \frac{1}{T'}\right)\right] \quad (4)$$

The acceleration factor increases with the activation energy. If Ea is equal to 0.5 eV, as the temperature increases every 10 °C, the life would reduce approximately one-half. This fact is known as the 10◦°C rule [TOU 15].

I.2 Probabilistic Arrhenius model

a) <u>Statistic on Ea parameter</u>

The Energy of Activation (Ea) impact dramatically the acceleration factor in the Arrhenius equation (3).
If one imposes a T equal to 80 °C and T' as 30 °C (delta of 50 K), the figure 5 demonstrates the point expressed before.

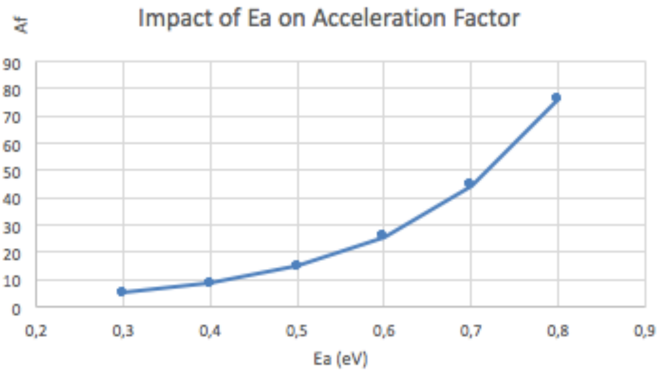

Figure 5 Ea vs acceleration factor

If the real Ea value of the composite material is 0.6 eV for a specific process then the real acceleration factor (Af) is 25.8. In other words, an increase of 50°K divided by almost 26 the life time. Nevertheless, if a wrong assumption is used, for instance 0.79 eV is taken in the Arrhenius law, the Af amounts 72. It underestimates the life time under stress of the product by a factor of 2.8. On the contrary, if 0.4 eV is taken the Af amounts 8.7. It overestimates the life time and over stress the product by a factor of 3. That is why the choice of Ea is really important and based on a good knowledge of the material and the mechanism observed in the climatic test.

Even if the Ea is relatively well chosen, an intrinsic variability of the composite material exists. This cannot be avoided. What will be the impact of a small variation on the Ea ? The figure 2.2 exposes the impact.

If the real Ea is 0.6 eV, a small variation of +/- 0.04 eV gives a variation of Af from 21 to 32 (real Af is 26). In other words, 7 % of variation on Ea introduce 20 % of variability on Af. It can be seen in the figure 6.

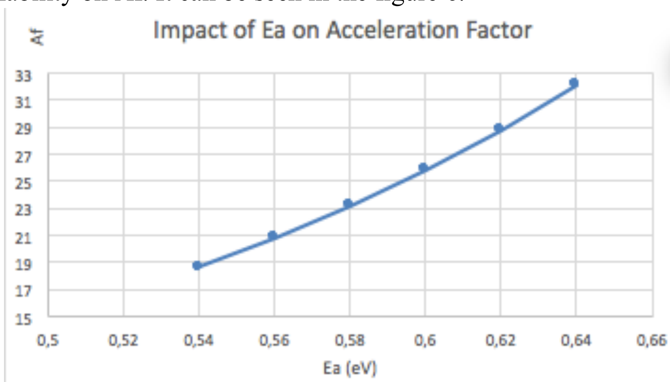

Figure 6 Small variation of Ea versus Af- Origin Lab software

Clearly, a very small variation can introduce a large impact on the acceleration factor. Let's take the example in the figure 2.2.

The point demonstrates the utility to integrate a variability of Ea directly in the Arrhenius equation (4).

Let's apply the Arrhenius equation in an accelerated climatic test set-up for an automotive usage. The equation (4) can be written differently as:

$$A_f = \exp\left[-\frac{E_a}{k}\left(\frac{1}{T_b} - \frac{1}{T_u}\right)\right] \quad (4)$$

with Tb as Temperature in the test bench (K); Tu as Temperature in public road usage (K).
Te is the equivalent temperature defined by

$$T_e = \frac{T_u - T_b}{T_u . T_b}$$
(5)

In order to simplify the relation (4), W is

$$W = -\frac{T_e}{k}$$
(6)

Then (4) becomes

$$A_f = \exp(E_a . W)$$
(7)

A logarithmic transformation gives

$$Log\left(A_f\right) = E_a . W$$
(8)

Suppose Ea is a random variable distributed by a normal law [LAM 01] defined by:

$$\sigma = \Delta_{E_a} \qquad \mu = \overline{E_a}$$
(9)

the probability density function of Ea

$$f\left(E_a\right) = \frac{1}{\sqrt{2.\pi.\Delta_{E_a}}} . exp\left[-\frac{(E_a - \overline{E_a})^2}{2\Delta_{E_a}{}^2}\right]$$
(10)

with in theory: $-\infty < E_a < +\infty$

Physically, Ea is necessarily positives.

This assumption of (10) can be coherent if the variation ΔEa is small as:

$$\frac{\Delta_{E_a}}{E_a} < 30\%$$
(11)

If Ea is randomly distributed (10) then Af (7), weighted by a W constant, is a random variable distributed by a Log-Normal law defined by the probability density function:

$$f\left(A_f\right) = \frac{1}{E_a . \Delta E_a . \sqrt{2.\pi}} . exp\left[-\frac{(\ln(E_a) - \overline{E_a})^2}{2\Delta E_a{}^2}\right]$$
(12)

The most probable value, also called mode (point of global maximum of the probability density function), is:

$$Mode\left(A_f\right) = \widehat{A_f} = exp[\mu . W - (\sigma . W)^2] \quad (13)$$
(13)

This formula can be interpreted as:
If $\Delta E_a = 0$, (13) is equivalent to (7)
If $\Delta E_a > 0$, the acceleration factor Af decrease. Of course, (13) decrease if W is lower or Te is high (Tb-Tu increase).
Therefore, the acceleration factor Af decreases with the uncertainty of Ea. This phenomenon is more visible if the temperature range of exploration is high.

Numerical example #1:

Road public usage: Tu = 40 °C (313.15 K)
Bench Temperature: Tb = 120 °C (393.15 K)
Ea = 0.85 eV

The original Arrhenius formula (4) gives :
$A_f = 607.6$
(14)

If one introduces a variability of $\Delta E_a = 0{,}1\ eV$ with a coefficient of variation of 12 % (11), the relation (13) gives
$\widehat{A_f} = 344.1$
(15)

What is the real value? It is difficult to define where is the reality between (14) and (15). Both value are supposed to describe the real world.
We can prove what is the real value based on experiments on real specimen or on warranty returns analysis.

But if (15) is considered as closer to the real value, the equation (14) does not take into account the variability of Ea and under estimate the stress by 57% (ratio (15)/(14)).

This simple example proves the added value to introduce the variability of Ea in Arrhenius model.

b) <u>Statistic on Tu (usage) parameter</u>

The usage means here the mission profile of the product, considering all stress conditions in the real life.

Equation (4) can be written as

$$A_f = \exp\left[-\beta\left(\frac{1}{T_b}-\frac{1}{T_u}\right)\right] \qquad with\ \beta = \frac{E_a}{k}$$

$$\alpha = \exp\left(\frac{-\beta}{T_b}\right) \quad \text{then } A_f = \alpha \exp\left[\frac{\beta}{T_u}\right] \qquad (16)$$

Normally, Tu is a deterministic value which characterizes the ambient temperature stressing the composite in real usage. But this temperature changes in a specific band width.

The figure 7 illustrates the random variability of temperature measured on vehicle closed to polymers water tank (inlet radiator).

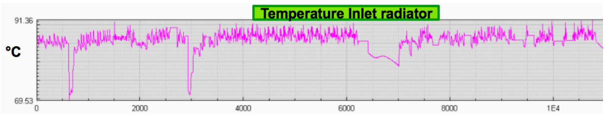

Figure 7 Evolution of temperature inlet radiator with plastic tanks.

One have to consider Tu as a random variable. To simplify the computation, Tu is considered as a random variable distributed by an uniform law (figure 8) limited in this range [Ta;Tb] where Ta<Tb (in K). The random variable Tu has got the same probability in the range [Ta;Tb].

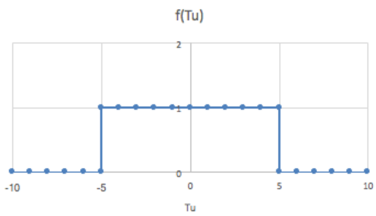

Figure 8 Density function f(Tu)

$$f_{(T_u)} = \frac{1}{\Delta T} \qquad (17)$$

with $\Delta T = T_b - T_a$ (K)

(16) becomes $\widehat{A_f} = \alpha \exp\left[\frac{\beta}{\overline{T_u}}\right]$ (18) with $\overline{T_u}$ the statistical average of the usage temperature. How to calculate $\overline{T_u}$?

It can be deduced to use a simple arithmetic mean as:

$$\overline{T_u} = \frac{T_b - T_a}{2}$$

This approach introduces an important bias of over estimation on the acceleration factor.

Based on the life time relationship (4), it must be solved:

$$\overline{L} = A\exp\left(\frac{\beta}{\overline{T_u}}\right) \qquad (19)$$

equivalent to $\frac{\overline{L}}{A} = \overline{\gamma} = \exp\left(\frac{\beta}{\overline{T_u}}\right)$ (20)

$\overline{\gamma}$ representing the statistical average of life for a composite at the statistical usage temperature $\overline{T_u}$ moving between Ta and Tb.

Based on (18), $\overline{T_u}$ can be deduced as $\overline{T_u} = \frac{\beta}{\ln(\overline{\gamma})}$ (21)

By solving (18), the integral defined on [Ta;Tb] :

$$\overline{\gamma} = \int_{T_a}^{T_b} \gamma . f(T_u) . dT_u$$

$$\overline{\gamma} = \int_{T_a}^{T_b} \exp\left(\frac{\beta}{T_u}\right) . \frac{1}{\Delta T} . dT_u$$

with the formula $\int \exp\left(\frac{a}{z}\right) dz = z.e^{\frac{a}{z}} - a.E_i\left(\frac{a}{z}\right)$

$$\overline{\gamma} = \frac{1}{\Delta T}\left[T_b.\exp\left(\frac{\beta}{T_b}\right) - T_a.\exp\left(\frac{\beta}{T_a}\right) - \beta.E_i\left(\frac{\beta}{T_b}\right) + \beta.E_i Ei\left(\frac{\beta}{T_a}\right)\right] \qquad (22)$$

Ei is the exponential integral defined in the graph 9

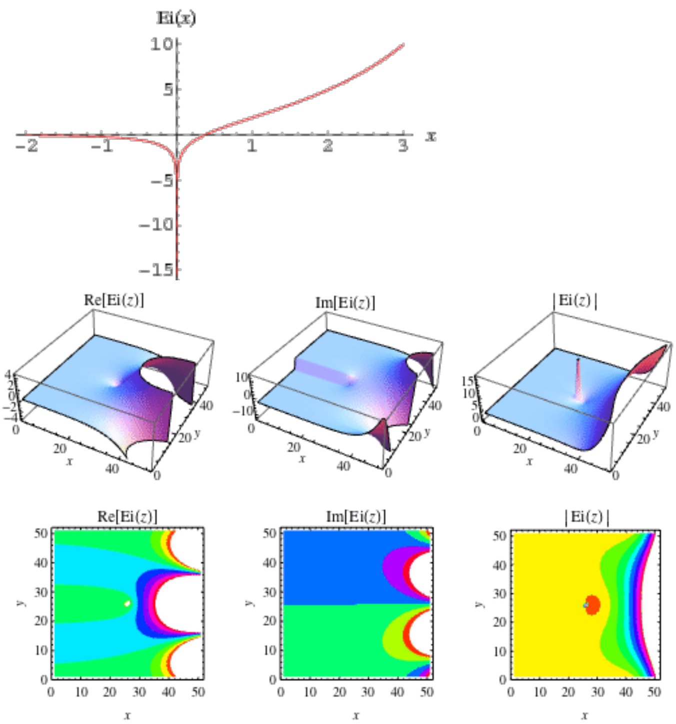

Figure 9 Integral Exponential [MAT 17]

Ei can be estimated by a Taylor series from the asymptotic expansion at z>>0 [ABR 64]

$$E_i \approx e^z.\left[\frac{1}{z}+\left(\frac{1}{z}\right)^2+\frac{2}{z^3}+\frac{6}{z^4}+\frac{24}{z^5}+\frac{120}{z^6}+O\left\{\left(\frac{1}{z}\right)^7\right\}\right]$$

The third order obtain a reasonable error (graph), less than 2% (figure 10) for almost all composite applications $\left[E_a \in (0{,}4-2{,}3 \text{ eV}) \text{ and Temperature range } (0^\circ\ C - 250^\circ\ C)\right]$.

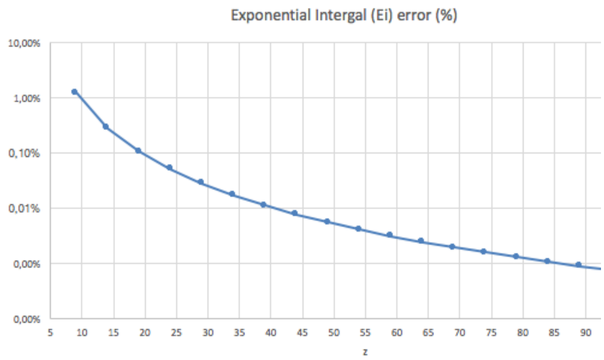

Figure 10 Exponential Integral (Ei)

$$\bar{\gamma} = \frac{1}{\Delta T}\left[\exp\left(\frac{\beta}{T_a}\right)\left\{\frac{T_a^2}{\beta}+\frac{2.T_a^3}{\beta^2}\right\} - \exp\left(\frac{\beta}{T_b}\right)\left\{\frac{T_b^2}{\beta}+\frac{2.T_b^3}{\beta^2}\right\}\right]$$

If (22) is injected in (21), $T_u$is analytically defined.

Numerical example #2:

Bench Temperature : Tb = 120°C (393.15°K)
Ea = 0.85 eV (supposed fix)

Road public usage : Tu can evaluate with the same probability in this range [Ta;Tb] = [20 °C; 60 °C] (293.15 K; 333.15 K)

The statistical average value $\overline{T_u}$ is 34 °C (306.73 K). This value is lower than the simple arithmetic which gives 40 °C as in the numerical example #1.

The statistical average of Af is:
$\widehat{A_f} = 1174.9$
(23)

The probabilistic Arrhenius model on Tu parameter permit to reduce the test time by nearby a factor 2 (ratio (23)/(14)).

This formulation is slightly (1.06 %) more conservative [LAM 13].

c) Statistic on Tb (bench temperature) parameter

Based on the same scientific approach developed in the paragraph 2.2.b, it is possible to appreciate the bench temperature variability. This variability can be the picture of the control sensor uncertainty in the climatic chamber (usually less than 2 K).

$$A_f = \exp\left[\beta'\left(\frac{1}{T_b}-\frac{1}{T_u}\right)\right] \qquad with\ \beta' = -\frac{E_a}{k}$$
$$\alpha' = \exp\left(\frac{-\beta'}{T_u}\right) \quad \text{then } \widehat{A_f} = \alpha' \exp\left[\frac{\beta'}{\overline{T_b}}\right]$$
(24)

Tb is a random variable defined by a uniform distribution, with iso probability in the area $\left[T_a^{'}\ ;T_b^{'}\right]$ where $T_a^{'} < T_b^{'}$

$$\bar{\gamma}^{'} = \frac{1}{\Delta T^{'}.\beta^{'}}\left[T_{a'}^2.\exp\left(\frac{\beta^{'}}{T_{a'}}\right)\left\{1+\frac{2.T_{a'}}{\beta^{'}}\right\} - T_{b'}^2.\exp\left(\frac{\beta^{'}}{T_{b'}}\right)\left\{1+\frac{2.T_{b'}}{\beta^{'}}\right\}\right]$$
(25)

$\overline{T_b}'$ can be deduced as $\overline{T_b}' = \frac{\beta'}{\ln(\overline{\gamma'})}$
(26)

Numerical example #3 :

Road public usage : Tu = 40°C (313.15 K)
Ea = 0.85 eV

Bench Temperature: Tb = 120 °C (393.15 K) with a small variation of 0.1 K (with a Pt100 sensor to control the climatic chamber for instance).

The statistical average of Af is:
$\widehat{A_f} = 601.8$
(27)

The uncertainty of the bench temperature (climatic chamber) reduces the acceleration factor (ratio (27)/(14)) about 1 %.

d) Combination of the 3 probabilistic models

The Arrhenius model defined by the acceleration factor Af (4)

$$A_f = \exp\left[-\frac{E_a}{k}\left(\frac{1}{T_b}-\frac{1}{T_u}\right)\right]$$

uses 3 different parameters Ea, Tb, Tu which can be evaluated by a probabilistic model (13) (24) (18) respectively. These statistical variables are independent of one another. Consequently, the acceleration factor is the sum of all variability. In other words:

$$\widehat{A_f} = \sum_{i=1}^{k} \overline{A_{fi}} - kA_f \ (24)$$

or

$$\widehat{A_f} = \overline{A_f(T_u)} + \overline{A_f(T_b)} + \overline{A_f(E_a)} - 3.A_f$$

(28)

with

A_f : defined by a constant Arrhenius model (4)

$\overline{A_f(T_u)}$: defined with a variability of usage temperature (18)

$\overline{A_f(T_b)}$: defined with a variability of bench temperature (24)

$\overline{A_f(T_{Ea})}$: defined with a variability of Ea (13)

Considering the numerical examples #1, #2 and #3 :

$$\widehat{A_f} = 298$$

That means, if the road public usage is 15.000 hours (cumulative usage time for 15 years), the constant Arrhenius model defines an equivalent test time of 25 hours. The new Arrhenius probabilistic models assesses an equivalent test time of 50 hours.

The graph 11 describes the influence of all statistical dispersions of the 3 parameters.

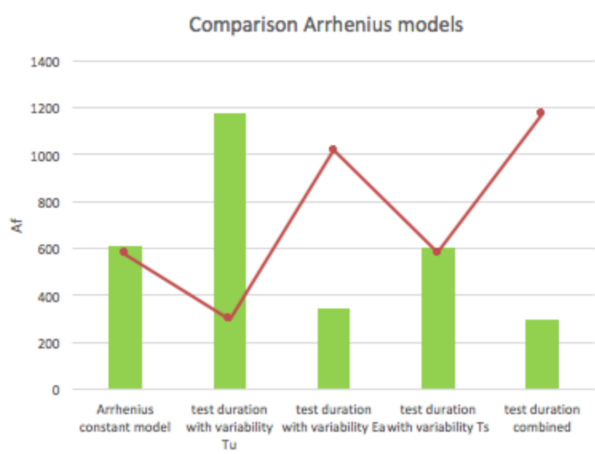

Figure 11 Comparison of Arrhenius models

II. EXPERIMENTAL CASE

II.1 Assumptions

According to a German carmaker, the specimen is exposed to undego the temperature distribution exposed in the table 1 below.

Temperature (°C)	Pe
-40°C	6
23°C	20
40°C	6
75°C	8
85°C	1

Table 1: Distribution of Temperature

The max temperature which can be seen by the specimen is 85°C.

This mission profile is defined by one temperature associated with a percentile of the life time of the system supposed of 15 years, 300.000 Km and 8000 hours of working.

8000 hours on 15 years is equivalent of 533 hours of working per year. According the state of the art about driving pattern in Europe, this amount corresponds to 70 % of driver severity.

Table 1 gives some extract of the mission profile based on some points extracted from a statistical distribution. Indeed, the temperature distribution is not just 6 points but a continuous mathematical function as represented in figure (12-b). Based on this fact, it is more realistic to write the mission profile not by some points but with a "band" of temperature like the histogram (12-a) shows. In this example, the "band" is defined by the temperature plus or minus 5 K.

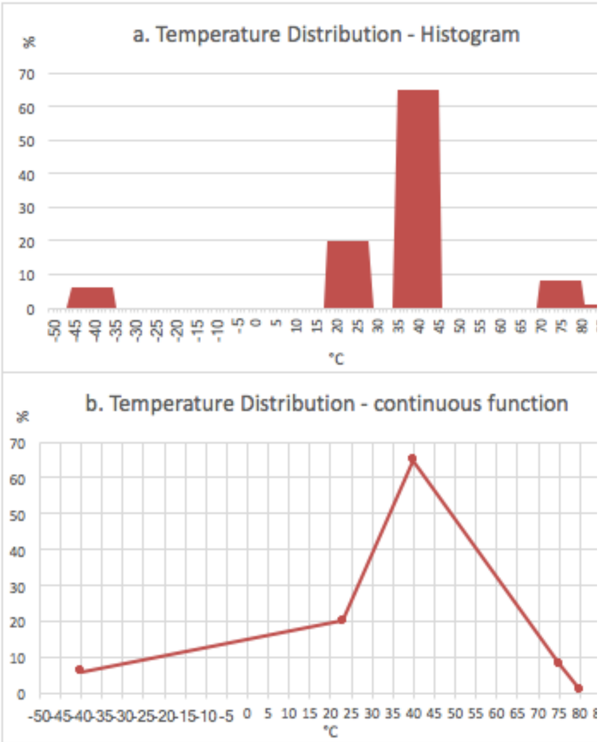

Figure 12 – Temperature Distribution

So in the Arrhenius model the parameter Usage Temperature Tu, can be defined by this table (2).

Temperature band (°C)	Percentile (%)
(-45;-35)°C	6%
(18;28)°C	20%
(35-45)°C	65%
(70;80)°C	8%
(75;85)°C	1%

Table 2 : Distribution of temperature by band

This mission profile assumes to cover a worldwide usage with the objective of 95 % of Reliability, Level of Confidence 80 % at 15 years and 300.000 Km. The warranty period is 3 years.

In this concrete case the product of interest it is an automotive sensor which is placed outside of the car. The product contains a sealing and it can be assessed a value for Ea of 0,64eV +/- 0,15 eV for a thermal-oxidation failure mechanism of sealing material in such an automotive system [KOM 17]. During product validation the sensor is exposed to different tests, like thermal life test. To enable an assessment of functionality and tightness, the product is continuously monitored during the tests and in defined intervals a tightness check is carried out by using a leakage test with 0.2 bar pressure overload.

Finally, the temperature of climate chamber is controlled with +/- 2 K at the max temperature of the tested system +85 °C.

Figure 13 shows several products placed inside a climate chamber.

Figure 13 Product placed in climate chamber

II.2 Results

According carmaker the duration for a thermal life test is defined as 1656 h at max. temperature.

According to the Constant Arrhenius Model, the acceleration factor is 11.5 and an equivalent test time of 697.4 hours to cover 15 years, 300.000 Km or 8000 hours of working is obtained.

Based on the Probabilistic Arrhenius Model, the acceleration factor is 8.8 or 908.1 hours to represent the total life time.

The figure 14 below exposes the impact of all parameters.

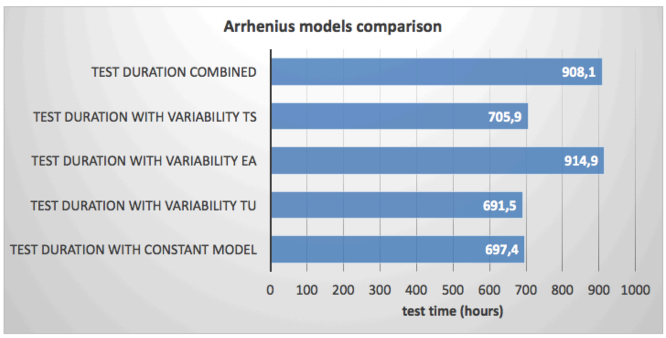

Figure 14: Arrhenius models comparison

II.3 Exploration

Following the figure 3.2, there is a significant gap between Constant Arrhenius Model, close to 700 hours of test, and Probabilistic Arrhenius Model, more than 900 hours.

What should be the risk if the Constant Arrhenius Model is applied?

Based on Binomial law (equation 1), the test can be fixed as following:

$$T = t \, . \left[\frac{Ln\,(\alpha)}{n.\,Ln(R_t)}\right]^{\frac{1}{\beta}}$$

(29)

t: Initial test time
n: Number of specimen tested
β: Shape parameter for a 2-parameter Weibull
C : Level of Confidence
α=1-C
R: Reliability target

In this example, it is imposed:

T : 908 h, n=6 α=20%, R=95%, β=2 (degradation phenomenon). In other words, it is supposed that the Probabilistic Arrhenius Model covers the Reliability Target of the customer and is equivalent damage of the total life time.

In this case, if 697 hours of test (Constant Arrhenius Model) are applied, only 91,67 % of Reliability (based on the equation 29) is achieved.

Apparently, even if the customer target is not achieved, it can be "negligible" to apply a Constant Arrhenius Model instead of Probabilistic Model.

What should be the cost impact on the Warranty period of 3 years?

To assess the financial risk, a Weibull distribution 2-parameters is used as:

$$F(t) = 1 - Exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right] \quad (30)$$

η: Scale parameter
F: Probability of failure
β: Shape parameter

With the Reliability Target (95 %), it is possible to calculate the scale parameter with a β=2 (degradation phenomenon) at t=15 years. And so, η=66 years is obtained.

Now, the probability of failure in the warranty period at 3 years is:

$$F\,(3\,years) = 1 - Exp\left[-\left(\frac{3}{66}\right)^2\right] = 0{,}21\,\%\,of\,failure$$

0,21 % of failure in 3 years is the expected warranty cost with a reliable design demonstrated with the Probabilistic Arrhenius Model.

With Constant Arrhenius Model, the Reliability demonstration is only 91.7 % at 15 years. As previously, the scale parameter is defined with η=51 years. In this case, the probability of failure in the warranty period can be assessed as following:

$$F\,(3\,years) = 1 - Exp\left[-\left(\frac{3}{51}\right)^2\right] = 0{,}35\,\%\,of\,failure$$

0,35 % of failure in 3 years is the expected warranty cost demonstrated with the Constant Arrhenius Model.

In other words, there would be almost twice (1,7 times) more warranty cost if the reliability demonstration is limited with the Constant Arrhenius Model for this specific failure mechanism. This clearly illustrate the importance to use the Arrhenius Probabilistic Model.

RESULTS AND DISCUSSIONS

In this Section authors are required to present the results by pointing out upon their own contributions to the field.

Table 1. RMS and crest factor for sine and square waves.

	sine wave	square wave
crest factor	1.414	1
RMS value	0.707	1

CONCLUSIONS AND OUTLOOK

The Arrhenius relationship has been widely used for decades. Some recent applications are in, for example, medical devices [JIA 03], lithium ion cells [BRO 01], petroleum-based ferrofluid [SEG 99], and motor insulation systems [ORA 00]. But note that the Arrhenius relationship is not universally applicable to all cases where temperature is an accelerating stress. Some examples are reported in [GIL 05] on a commercial chloroprene rubber cable jacketing material, and in [DIM 99] on ultrathin silicon dioxide film. Therefore this explained probabilistic model is developed to cover reliability tests based on Arrhenius for mechatronic products where many different materials are used with their characteristic activation energies related to aging processes and climate load. In a first experimental phase the usage of the model could be proved, further tests have to be carried out to underline this. It is important to check the adequacy of the model by using the test data.

QUOTATION

"Reliability is, after all, engineering in its most practical form." James R. Schlesinger (1929-2014), US Secretary of State for Defense.

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