# EFFECTS OF MULTIPLE STRESSES ON POWER CABLES AND ENERGY STORAGE DEVICES-A COMPARATIVE STUDY

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***Abstract* – Multiple stress life tests are becoming increasingly useful in today's industry in order to develop efficient tools to predict performances of electrical systems. In Electrical Engineering domain, the life of a systems or product is developed as a function of single or multiple stresses. The actual mathematical models applied for life analyses are Statistics (Proportional Hazards) based models and Empirical-Statistics models (Arrhenius, Weibull). In this paper was used a life-stress model: Arrhenius-Weibull. In this sense, it was developed a multiple stress analysis in order to identify the effects of multiple stresses on power cables and supercapacitors life distributions. Both analysed electrical systems can be implemented together in different power supply systems from land transportation. The analysis was developed using ALTA software package from ReliaSoft Corporation and the multiple stresses considered where: temperature, humidity, vibrations and on/off cycling operation, only for supercapacitors. The analysis results consist of a proposed comparative model regarding mixed stresses that may occur on power cables/ supercapacitors and how these effects could influence future performances of a supply power system/ energy recovery system.**

**All the obtained data after ALTA application are related to life distributions and plots modeling. The determined plots refers to: PDF plots, Life vs. Stress, Weibull plots, Acceleration factor vs. Stress, Failure rate vs. Time, Standard Deviation vs. Stress.**

***Keywords***: *multiple stresses, power cables, supercapacitors, Weibull distribution, life distributions, accelerated tests, Arrhenius-Weibull model.*

## 1. INTRODUCTION

European Union directive 2005/ 32/ EC establishes the ecodesign criteria that electrical equipments must meet: the environmental impact of manufacturing materials and the behavior in exploitation. Basically, it was highlighted the need to develop electrical systems with respect to lifecycle and energy efficiency [1]. For the electrical systems, there is a need of a procedural framework development to manage all the operating performance and aging degradation mechanisms under multiple stresse-asset management [2].

For electrical equipment, the role of a multiple stresse analysis is to create effective tools to obtain lifetime prognoses and also to improve the operation performances and the quality/reliability indices [3-6]. The novelty of the study is the development of a multiple life stress analysis for electrical equipments that are used on power supply systems from land transportation. In this sense, it was developed a comparative study on the effect of multiple stresses on power cables and energy storage devices. The electrified rail systems are grid users of the main grid and the connection is made through power cables. Figure 1 describes the supply principle of an AC railway system [13].

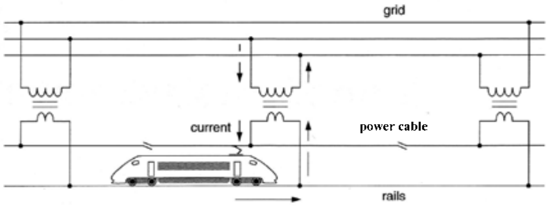


Figure 1: Supply model of a railway system.

The AC voltage from the grid is transformed to a lower voltage level and connected to power cables and rails. By cyclically connecting the transformers between phases, it is overcome the effect of asymmetrical load [13]. About storage devices implementation in land transportation, a single supercapacitor cell is not sufficient to achieve the required performances, due to low voltage that it develops. For this reason, several cells are putted in series (10 packs Maxwell), to accomplish technical requirements of the application. In this paper was analyzed a pack of supercapacitors type BPAK0058E015B1 (258.59 K, 150 V).

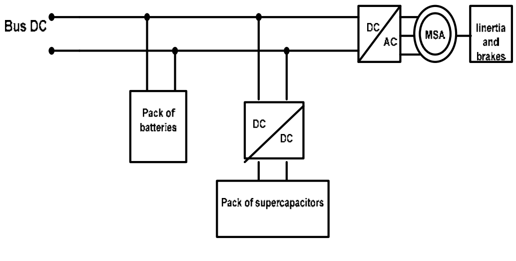


Figure 2: Electric hybrid vehicle power supply system.

The electric power of inverter is given by the supercapacitors and batteries. The pack of supercapacitors represent the power source that ensures optimal functionality of the traction motor (MSA) in punctual operations–accelerations, breakings.

Aging mechanisms are complex and occur under synergetic electrical, thermal, mechanical and environmental stresses, variable for different equipment. Thus, in the literature [6, 8-12], the main aging factors and aging mechanisms developed in power cables (C) and supercapacitors (SC) are underlined (Table 1).

| Aging Factors | Aging Mechanisms | C | SC |
|---|---|---|---|
| **Thermal** | | | |
| High temperature<br>Temperature cycling | Chemical reaction | ✓ | |
| | Thermal expansion | ✓ | |
| | Diffusion | ✓ | |
| | Insulation melting | ✓ | |
| | Anneal locked-in mechanical stresses | ✓ | |
| Low temperature | Cracking | ✓ | |
| | Thermal contractions | ✓ | |
| | Internal resistance increasing; | | ✓ |
| | Total capacitance decreasing | | ✓ |
| | Variation of ionic conductivity of the electrolyte | | ✓ |
| | Double layer thickness variation | | ✓ |
| **Electrical** | | | |
| Voltage,<br>AC, DC impulse | Partial discharges | ✓ | |
| | Electrical trees | ✓ | |
| | Water trees | ✓ | |
| | Charge injections | ✓ | |
| | Dielectric losses and capacitance | ✓ | |
| Overvoltages | Distorsion, namely outside leakage of the material | | ✓ |
| Overcurrents | Overloading | ✓ | ✓ |
| | Overheating | ✓ | ✓ |
| | Burning | ✓ | ✓ |
| **Mechanical** | | | |
| Cyclic bending | Yielding of material<br>Cracking<br>Breaking | | |
| Vibrations | | ✓ | |
| Fatigue | | ✓ | ✓ |
| Tensile | | ✓ | ✓ |
| Compressive | | | |
| Shear stresses | | | |
| **Environmental** | | | |
| Water | Electrical tracking | ✓ | |
| Humidity | Water treeing | ✓ | |
| Contamination | Corrosion | ✓ | ✓ |
| Liquids | Dielectric losses and capacitance | ✓ | ✓ |
| Radiations | Chemical reaction rate increase | ✓ | ✓ |

Table 1: Factors and aging mechanisms for power cables (P) and supercapacitors (SC).

The main aging factors that can affect performances of power cables used in land transportations applications are: mechanical (vibrations), thermal (variable temperature depending on cable load) and environmental (mostly high humidity).

Comparatively, the energy storage devices are affected by thermal and mechanical aging factors.

In the comparative study on the effects of multiple stresses that may appear at power cables and supercapacitors embedded on a power supply system for land transportation, the following stresses are considered:

- for cables: vibrations, temperature, humidity;
- for supercapacitors: vibrations, temperature, on/ off cycle operation (on/ off cycle operation applied stress was considered according with the operation principle of supercapacitor).

The paper describes a theoretical procedure to determine the Weibull parameters and reliability measures, considering as input values, data obtained from exploitation.

The Accelerated Life Testing Data Analysis (ALTA) package software, developed by ReliaSoft Corporation, was applied [11].

## 2. THEORETICAL APPROACH

If the two-parameter Weibull life distribution is selected, the following relations are used [15]:

- the cumulative density function (cdf) of Weibull distribution is:

$$F(t,\eta,\beta) = 1 - \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right] \tag{1}$$

- the probability density function (pdf) of Weibull distribution is:

$$f(t,\eta,\beta) = \frac{\beta}{\eta}\cdot\left(\frac{t}{\eta}\right)^{\beta-1}\cdot\exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right] \tag{2}$$

where $\beta$ is the shape parameter, and $\eta$ is the scale parameter (characteristic life), and t is the time until the failure ($t \geq 0$).A change in the scale parameter, $\eta$, has the same effect on the distribution as a change of the abscisa scale. The experimental plot must be a straight line in a coordinate system:

$$x = \log t;\quad y = \log\left(\ln\frac{1}{1-F}\right) \tag{3}$$

The reliable life of an entity, for a specified reliability and for the mission starting at age zero, can be determined using (4).

$$R(t) = \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right] \tag{4}$$

Considering the the Arrhenius model as the model for life-stress description the next relationship was applied:

$$L(S) = C \cdot \exp\left(\frac{B}{S}\right) \tag{5}$$

where, $S$ is the stress level, $C$ and $B$ are the model parameters.
The Arrhenius plot, with the coordinates ($1/S$; $\ln L$) is obtained from relation (4):

$$\ln L(S) = \ln C + \frac{B}{S} \tag{6}$$

The $C$ parameter is obtained from Arrhenius plot analysis, as the first term from (5) is the intercept of the Arrhenius line. Another important metric to be determined is the Arrhenius acceleration factor, defined as the life ratio corresponding to a duty cycle rating stress level ($S_n$) and to a superior stress level ($S_a$):

$$AF = \frac{L_{Sn}}{L_{Sa}} \tag{7}$$

Combining the relations (5) and (6), it results:

$$AF = \exp\left(\frac{B}{S_n} - \frac{B}{S_a}\right) \tag{8}$$

The Arrhenius-Weibull model of the failures is obtained by considering the characteristic life $\eta$ as the characteristic life $L(S)$:

$$\eta = L(S) \tag{9}$$

The failure rate under a stress level $S$ will be:

$$\lambda(t,S,\beta) = \frac{f(t,S,\beta)}{F(t,S,\beta)} \tag{10}$$

With the proposed Arrhenius-Weibull model, using (1), (2) and (8), the relationship for failure rate, becomes:

$$\lambda(t,S,\beta) = \frac{\beta}{C \cdot \exp\left(\frac{B}{S}\right)} \cdot \left(\frac{t}{C \cdot \exp\left(\frac{B}{S}\right)}\right)^{\beta-1} \tag{11}$$

The standard deviation of the failure time is another reliability measure, determined with the relation:

$$\sigma_R = C \cdot \exp\left(\frac{B}{S}\right) \cdot \sqrt{\Gamma\left(\frac{2}{\beta}+1\right) - \left(\Gamma\left(\frac{1}{\beta}+1\right)\right)^2} \tag{12}$$

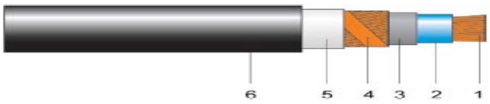
where $\Gamma(2/\beta+1), \Gamma 1/(1/\beta+1)$ are Gama functions. This measure provides information about the spread of the data at each stress level. In order to obtain the reliability metrics, the following procedure [14, 16] was applied:

i) Select a life distribution, more appropriate for the current study. It was used the Weibull distribution as the underlying life distribution;
ii) Select a model that describes a characteristic point or a life characteristic of the distribution from one stress level to another;
iii) Parameter estimation-this step involves fitting a model to the data and solving for the parameters that describes that model-Maximum likelihood estimation method (MLE) was applied. For both analyzed entities, the considered input data were chosen as follows:
   - For the cable, were used the recorded data from exploitation (times to failure and numbers of incidents) [20] ;
   - For the supercapacitors, the values for times to failure were chosen according with [9, 18] ;

Derive reliability information-once the parameters of the underlying life distribution and life-stress relationship have been estimated, a variety of reliability information about the product can be derived, such as: failure rate, mean life, standard deviation.
The present approach has allowed to directly compare power cables and supercapacitors, and to distinguish between alternative possibilities for their functions.

## 3. RELATED WORK

For the proposed analysis, the following entities have been chosen: (a) a power cable (Figure 3), designed for railway applications; (b) a supercapacitor pack (Figure 4), with 10 packs in series, designed for energy storage application.



1-Copper stranded conductor; 2-XLPE insulation; 3-Semiconducting layer to avoid water propagation; 4-Stell strips screen ; 5-Strips layer to avoid water; 6-MDPE outer sheath; Cable type: C2XS(F)2Y; $U_0/U$=1.8/3/3.6 kV; Conductor admissible temperature:+363 K.

Figure 3: Power cable structure.

C=23 F; ESR=42 MΩ; $I_C$=0,10 mA; $R_{th}$=2,20 C/W; Operating temperature range: -40$^0$C to +65$^0$C; Rated Voltage: 15 V (DC); supercapacitor type: BPAK0058 E015 B1

Figure 4: Supercapacitor specifications.

In the current study, the considered stresses have been: temperature ($T$), humidity ($H$), vibration ($V$), on/ off cycle operation (0 / 1) (only for supercapacitors).

The values for the applied stresses have been set according with technical guide specifications for power cables and supercapacitors [17, 18].

The objectives of this analysis have been established: to find the stress with the greatest impact on life distribution for power cable and supercapacitor; to establish the life distribution relationships under multiple stresses; to identify the upper limit of a stress that could affect the performances of each analyzed entity

The hypotheses for both entities were:

- the Arrhenius relationship is admitted as life stress model, and the underlying life distribution is the Weibull distribution. Basically, the Arrhenius model was considered for temperature, vibrations and for humidity, and for on/off operation stress there is no transformation;
- the considered normal duty cycle rating stress levels are: for temperature-$T_n$=348 K, for humidity-$H_n$=0.45 RH, for vibrations-$V_n$=10 Hz.

The stress profiles proposed to be applied both on power cable (Table 2) and supercapacitor (Table 3), were chosen according with [15, 16].

| Stress | Description |
|---|---|
| A | Temperature varies between (323:10:353)<br>Humidity and vibrations were kept at normal duty cycle rating stress levels-$H_n$=0.45 RH and $V_n$=10 Hz |
| B | Humidity varies between (0.3:0.1:0.6)<br>Temperature and vibrations were kept at normal duty cycle rating stress levels-$T_n$=348 K and $V_n$=10 Hz |
| C | Vibrations varies between (5:5:20)<br>Temperature and humidity were kept at normal duty cycle rating stress levels-$T_n$=348 K and $H_n$=0.45 RH |

Table 2: Power cable stress profiles.

For the supercapacitor, each stress profile has on time cycles (A, C) and off time cycles (B).

| Stress | Description |
|---|---|
| A | Temperature varies between (323:10:353)<br>Vibrations were kept at normal duty cycle rating stress level-$V_n$=10 Hz |
| B | Vibrations varies between (5:5:20)<br>Temperature was kept at normal duty cycle rating stress level-$T_n$=348 K |

Table 3: Supercapacitors stress profiles.

The stress profiles were chosen according so that won't induce failure modes that would never occur under normal duty cycle rating stress levels.

## 4. RESULTS AND DISCUSSIONS

The ALTA modeling results are summarized in Table 4 and Table 5, in which the Weibull distribution parameters for cable and for supercapacitor are shown. Because were considered 3/ 2 types of stresses, it were computed 4/ 3 shape parameters, that would help to define the shape for every stress distribution function.

| Stress | A | B | C | Duty cycle rating |
|---|---|---|---|---|
| $\eta$ [$h$] | -195,0841 | 0,4094 | 34,7979 | 263,6904 |
| $\beta$ | 3.4559 | | | |

Table 4: The determined Weibull parameters for power cable.

| Stress | A | B | Duty cycle rating |
|---|---|---|---|
| $\eta$ [$h$] | -16,33 | 0,9344 | 7096,8430 |
| $\beta$ | 3,9554 | | |

Table 5: The determined Weibull parameters for supercapacitor.

One can observe that failure rates both for the power cable and supercapacitor are increasing with time, since the value of $\beta$ is higher than 1.

In Figure 5/ Figure 6 are shown the probability density functions (*pdf*) both for the power cable (C) and the supercapacitor (SC), according with the Arrhenius-Weibull model and Table 4/ Table 5.

Regarding the probability plots-Weibull plots, they are shown in Figure 7/ Figure 8. Each probability plot is associated with a corresponding stress level. In ALTA multiple lines were plotted on a probability plot, each corresponding to a different stress level [16]. In this study, were modeled 2 probability plots, both for C and SC. Each plot, has 4 different lines, because every stress profile, was proposed considering 4 different values for the measure that varies. For example, stress A, has 4 different temperature values, as: 323 K, 333 K, 343 K, 353 K.

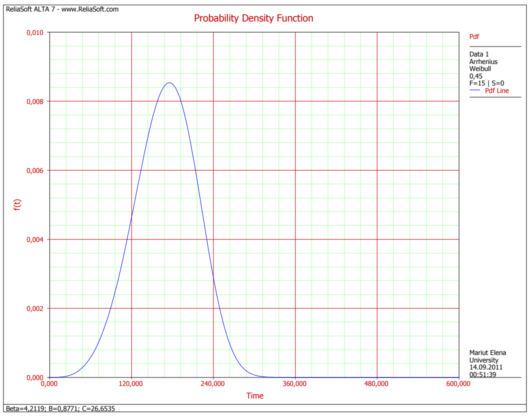


Figure 5: Probability density function for C.

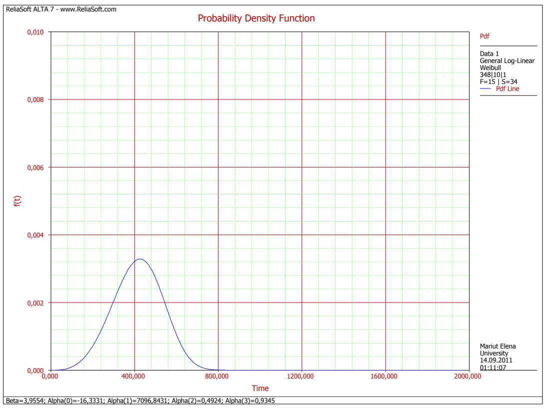


Figure 6: Probability density function for SC.

For the power cable, the scale parameter is increased, while $\beta$ is kept at the same value and this is the reason why the distribution gets stretched out to the right and its height decreases, while maintaining its shape. For the SC Weibull plot, $\eta$ is decreased while $\beta$ is kept the same, so the distribution gets pushed in towards the left and its height increases.

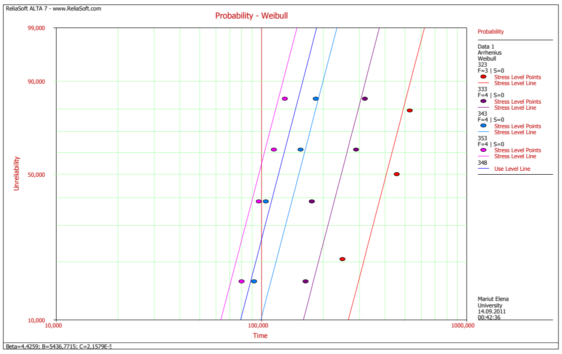


Figure 7: Arrhenius-Weibull probability plot for C.

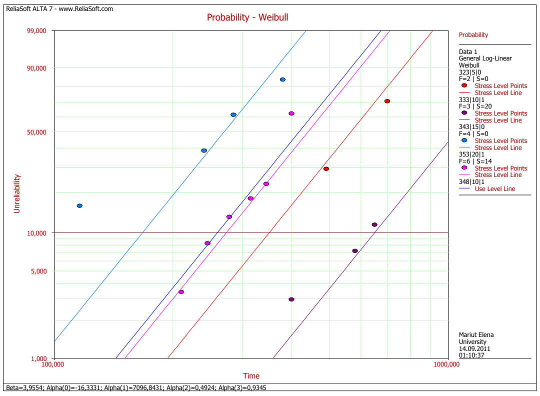


Figure 8: Arrhenius-Weibull probability plot for SC.

The Weibull plots were used to examine the choice of an underlying life distribution and the assumption of a common slope (shape parameter) at all stress levels. The linearity of the data and the fact that the data for each stress level appears parallel reinforce the assumption made. In order to assess the effect of each stress on a equipment's failure, were plotted Life vs. Stress curves for cable (Figure 9 a-c) and supercapacitor (Figure 10 a-b). Since the life for each studied entity is a function of applied stresses, than different Life vs. Stress plots are available.

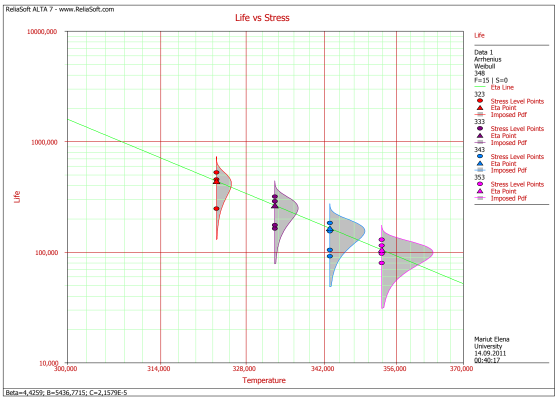


Figure 9-a: The Life vs. Stress (Stress A).

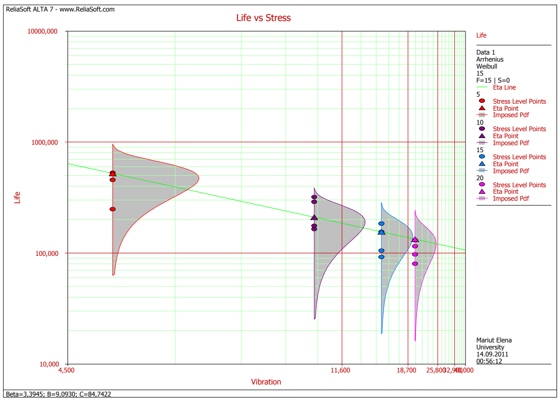


Figure 9-b: The Life vs. Stress (Stress B).

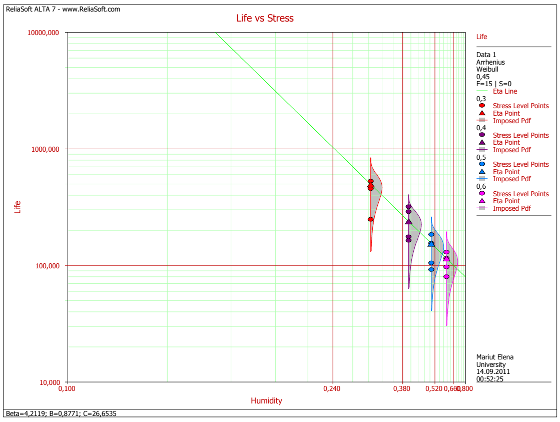


Figure 9-c: The Life vs. Stress (Stress C).

Life vs. stress plots are the most important plots in multiple stress analysis. The shaded areas are the imposed *pdfs* at each stress level. The imposed *pdfs*, helps to determine the range of the life at each stress level. To better understand the life plots (Arrhenius plots), it is necessary to consider the eta line, being the life line of the product.

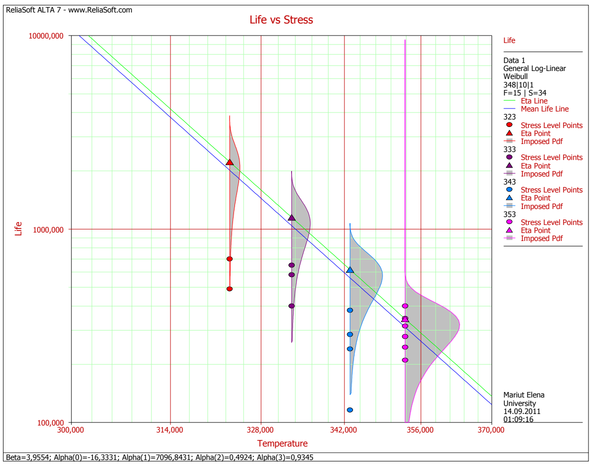


Figure 10-a: The Life vs. Stress (Stress A).

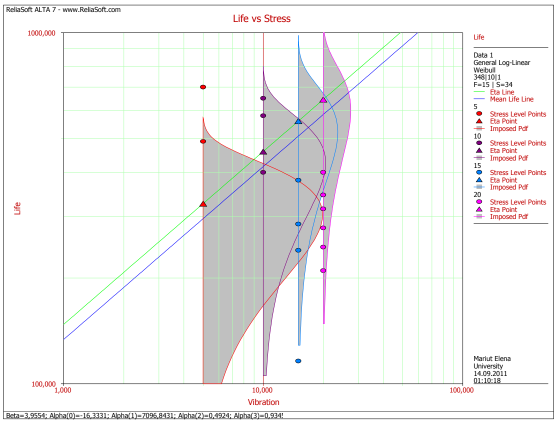


Figure 10-b: The Life vs. Stress (Stress B).

In Table 6/ Table 7, are presented the values for life distributions both for power cable (C) and supercapacitor (S), considering all the applied stresses.

| ***T* [K]** | **323** | **333** | **343** | **348** | **353** |
|---|---|---|---|---|---|
| $L_T$ [h] | 450 | 275 | 175 | 150 | 100 |
| ***H* [RH]** | **0.3** | **0.4** | **0.45** | **0.5** | **0,6** |
| $L_H$ [h] | 500 | 250 | 185 | 165 | 125 |
| ***V* [Hz]** | **5** | **10** | **15** | **20** | |
| $L_V$ [h] | 550 | 220 | 185 | 150 | |

Table 6: Mean life distributions for C.

| ***T* [K]** | **323** | **333** | **343** | **348** | **353** |
|---|---|---|---|---|---|
| $L_T$ [h] | 2200 | 1200 | 600 | 450 | 350 |
| ***V* [Hz]** | **5** | **10** | **15** | **20** | |
| $L_V$ [h] | 650 | 575 | 460 | 320 | |

Table 7: Mean life distributions for SC.

All applied stresse profiles, have a significant impact on life distribution for the power cable. Basically, the power cable is very sensitive at those stresses therefore, the thermal, mechanical and environmental aging factors contribute to the accelerated degradation process of the cable, in time. The supercapacitor is strongly affected by vibrations, it has a small life distribution, when it is subjected to different vibrations levels. According to life vs. stress plots, it can be observed that the supercapacitor has a greater life distribution, because it has an on/ off operating cycle.

In order to assess the effect of the degradation process on a future power supply system, with a C and SC embedded, it was plotted the Failure Rate (FR) vs. Time curve, both for power cable and supercapacitor.

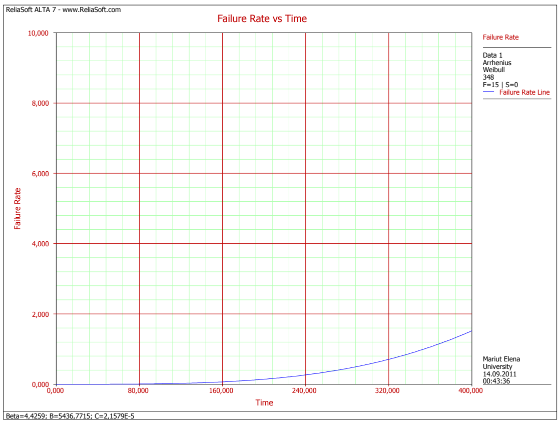


Figure 11: The FR vs. Time for cable.

Figure 11 and 12, shows the expected number of failures per unit time at a particular stress level, in this case first stress profile-A.

Both, Figure 11 and Figure 12, were obtained considering the Arrhenius-Weibull model, described by (10).

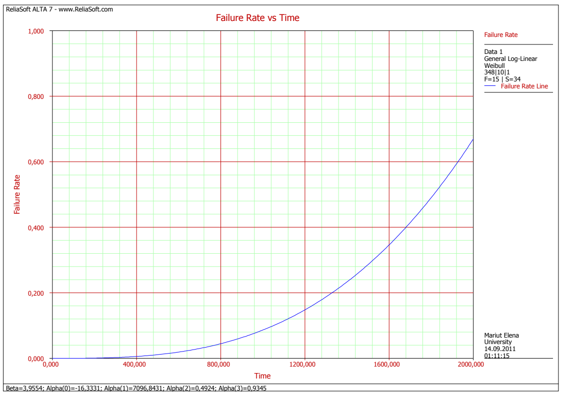


Figure 12: The FR vs. Time for supercapacitor.

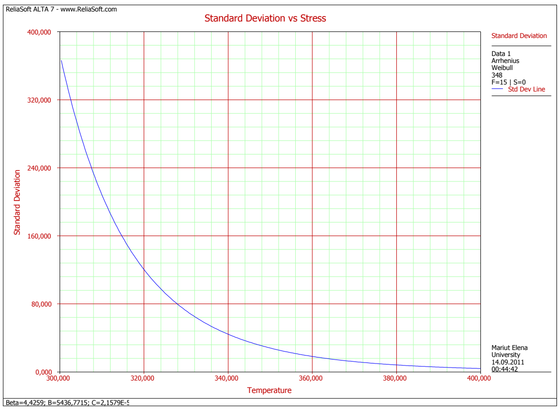


Figure 13: Standard Deviation vs. T for C.

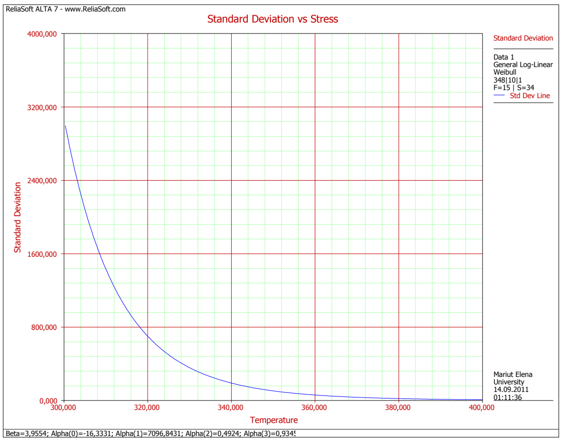


Figure 14: Standard Deviation vs. T for SC.

For the power cable the failure rate had an exponential distribution and for the supercapacitor the failure rate had a liniar distribution. For the power cable, the failure rate will increase quite quickly and for the supercapacitor, the failure rate increase is very slowly.

Another determined plot both for power cable and supercapacitor is the Standard deviation vs. Stress plot. Standard Deviation vs. T is a useful tool in multiple stress analysis and it provides information about the spread of the data at each stress level.

For both, the power cable and the supercapacitor, the standard deviation plot has an exponential decrease.

## 5. CONCLUSIONS

The development of a quantitative multiple stress life analysis both on a power cable and a supercapacitor pack was done. In this sense, were modeled: the pdf and Arrhenius-Weibull probability plots, the Life vs. Stress plots (for different stress profiles), Failure rate vs. Time plots and Standard Deviation vs. Stress plots. It was shown that both cable and supercapacitor were affected significantly by multiple proposed stresses, near multiple stress analysis. Also, according with Life vs. Stress plots, the supercapacitor will have a higher lifetime estimation than the power cable. Also, it was observed that the stress with the greatest impact on life distribution for the supercapacitors are mechanical-vibrations. All the applied stress profiles affect the life distribution for the power cable. The degradation process is more relevant for cable than for supercapacitor. Related to Failure rate plots, for the power cable, the failure rate will increase quite quickly and for the supercapacitor, the failure rate increase is very slowly. This is because the supercapacitor does not work all the time, it has an on/ off operating cycle. The standard deviation plot provides information about the spread of the data at each stress level.

Based on current study, asset management actions can be established in order to increase the performances in operation for a future power supply system for land transportation. For a future work, the current obtained results will be applied in order to develop an analysis regarding electrical efficiency of a power supply system for land transportation. The system will have a power cable and a supercapacitor embedded.

The paper describes o procedure to determine the Weibull parameters and reliability measures, considering data obtained from exploitation.

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