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Estimation of Electrical Field Failures on Tantalum Capacitors in Automotive Applications Using Weibull Distribution: A Case Study

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ABSTRACT
Automobile manufacturers and their supply chain should release new products in shorter times and take quick corrective actions if a quality issue comes up. It is especially critical when the quality problem appears in the field because of the safety implications linked to automotive applications. Recently, the number of electronic components in automotive applications has grown exponentially, which includes tantalum capacitors. Therefore, failure analysis of electronic components has become a relevant stage for defining appropriate corrective actions. This paper presents information from an automotive application reporting ignited field failures on tantalum capacitors and the statistical analysis of this information using the Weibull distribution. Weibull distribution, historically, has been used to evaluate reliability tests of tantalum capacitors; in this paper, its use is to field applications expanded. The Weibull distribution parameters are calculated based on the failure data to estimate, under some considerations, the number of future field failures for this application. The linearization of the Weibull cumulative distribution function (cdf) is the base of the estimation, which allows us to make predictions using the linear equation obtained after the regression. The decreasing failure rate shown by the results is consistent with the self-healing mechanism inherent in tantalum capacitors.
***Keywords* –** Failures, Reliability, Self-healing process, Tantalum capacitors, Weibull distribution

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I. INTRODUCTION

Like many other industries, the automotive sector competes in a demanding market. Automobile manufacturers and their supply chain should release new products in shorter times and take quick actions if a quality issue is reported along the manufacturing stages up to the final users. It is especially critical when a quality problem appears in the field; in this case, the Engineers along the supply chain focus their efforts to look at the evidence, at the data that help them perform a risk assessment. The risk assessment's accuracy is relevant for taking the appropriate actions, in this case, such as proceed or not with a recall.

Recently, the number of electronic components in automotive applications has grown exponentially [1-4], especially in the market of electric and hybrid electric vehicles, which expects to grow even more in the following years [5-9]; tantalum capacitors are among those components with significant growth in the automotive industry. This new reality makes it relevant to have appropriate failure analysis tools for these electronic components when quality issues come out. Weibull distribution, historically, has been used to evaluate reliability tests of tantalum capacitors such as the Surge Step Stress Test (SSST) [10-11], tests involving the application of temperature and voltage as accelerations factors [12-13], among others. Not only the tantalum capacitors industry but others too employ the Weibull distribution as their preferred statistical tool to evaluate reliability tests, such as the ceramic capacitors industry [14-16]. There are references about its application using field data from automotive applications [17-18]. However, there are no quotations from automotive failures with tantalum capacitors as the root cause; it is in this area that this paper gives novelty. This article provides a statistical analysis method based on the Weibull distribution to estimate the number of field failures and its tendency on tantalum capacitors reported with high leakage current in an automotive application. Due to the limitations for getting the distance traveled for all automobiles regarded in this analysis, some considerations are to interpret the results taken. The failure rate also is calculated to have an idea about the failures' tendency: to establish if it is decreasing or not.

II. TANTALUM CAPACITOR MANUFACTURING

The tantalum pellets, which acts as the anode plate, is a mix of tantalum powder and binder presses using high pressure; a subsequent sintering step applies a high temperature that bonds the tantalum particles and removes the binder previously applied. Once finished, the tantalum pellet goes to an electrochemical process that converts the tantalum (Ta) into tantalum pentoxide (Ta_2O_5), a more resistive and stable material acting as the dielectric inside the capacitor [19-20]. Nowadays, mainly two semiconductor materials are used to make the cathode plate: Manganese Dioxide (MnO_2) or Conductive Polymer. If MnO_2 is used to make the cathode, the capacitors are known as MnO_2 tantalum capacitors; otherwise, as Polymer tantalum capacitors. Applied layers of graphite and silver in subsequent process steps complete the cathode plate.

Finally, the capacitor is connected to a lead frame to form the terminals and molded into an epoxy resin case. For many years, MnO_2 tantalum capacitors were the preferred choice for automotive applications. However, the Polymer tantalum capacitors' performance has improved meaningfully in the last five years, particularly under humidity conditions. Thus, they are capable to approve the requirements of the Automotive Electronics Council (AEC) Q-200 Document for passive components now [21], so their market share in automotive applications has grown.

III. FAILURE MODES IN TANTALUM CAPACITORS

Mainly two paths are carried out simultaneously in the analysis of field failures for tantalum capacitors. The manufacturing records of suspect material are analyzed as part of the first path, looking for any trend or potential issue during the production stages. The failure analysis (FA) of the returned components is part of the second path. It also includes the testing of not used capacitors from the suspect lots and the analysis of information about the final application, such as the voltage applied, the temperature conditions, time to failure, kilometers (Km), which are among the information to be analyzed. Two types of issues are the main affecting the performance of tantalum capacitors: electrical and physical, with electrical failures accounting for the most. The electrical issues in tantalum capacitors are evident through any of their main electrical parameters: the equivalent series resistance (ESR), the capacitance (CAP), the dissipation factor (DF), or the leakage current (LKG). An electrical problem exists if any of these parameters are out of specification [22-24].

In circuits with low resistance in series with the capacitor, a typical electrical field failure is the ignited part. It occurs when an unlimited current passes through a MnO2 tantalum capacitor burning it. Fortunately, due to the cathode material used, Polymer tantalum capacitors do not show this failure mode [25]; this characteristic is one reason why they are gaining market over MnO2 products.

Often, the physical failures are related to a couple of characteristics; the first one is related to the epoxy resin condition that encapsulates the capacitor; the second one is the physical condition of the two terminals used to mount the capacitors on printed circuit boards (PCB's). Examples of physical issues are broken epoxy, bent terminals, missing terminal, among others. Depending on the failure mode, different methods and tools are available to perform the FA [26-28]. However, because of the extensive damage incited on ignited capacitors, the FA of those parts is still limited; therefore, the statistical analysis of the available information from the field becomes even more relevant. This paper presents the information from an automotive application with ignited field failures on MnO2 capacitors; the failed parts data (km) are analyzed to get conclusions on the failure rate and its tendency.

IV. SELF-HEALING PROCESS IN MnO_2 TANTALUM CAPACITORS

The dielectric's performance, which is associated with the LKG and ignited failures in tantalum capacitors, is affected, among other factors, by the manufacturing processes, the testing and soldering stations at the customer side, and the application conditions in the field [14, 29-30]. Consequently, several high leakage current sites appear on the dielectric along with these steps. Even though the leakage current sites on the dielectric, the self-healing mechanism is activated in those sites when a limited current (not a surge one) flows through them: because of the generated heat by a limited current, the MnO2 around the leakage site changes to Mn2O3; a material with more resistivity which covers the leakage site and limits the current [31]. The self-healing mechanism makes possible the construction and use of tantalum capacitors. This mechanism makes possible a decreasing failure rate on MnO2 tantalum capacitors too. Despite the self-healing mechanism, there are limitations under surge current conditions; a high current will flow through the capacitor in such conditions starting an ignition process that may burn the part. FA of tantalum capacitors with catastrophic failures has improved, yet non-definitive conclusions still are obtained. The manufacturing records and field application conditions are valuable information to find the root cause in such cases. In the case of automotive applications, the information related to the field failures is as important as the FA of the returned parts; as part of the risk assessment, data such as the time to fail, km, or application conditions must be statistically analyzed. The Weibull distribution is one of the statistical tools that can be used in this phase of the problem.

V. METHODOLOGY

The Weibull distribution is a probability distribution widely used in reliability and life tests [32-33], in engineering, energy, and environmental studies, among others [14]. The three-parameter Weibull probability density function (pdf) is given by eq. (1).

$$f(x) = \frac{\beta}{\eta}\left(\frac{x-\gamma}{\eta}\right)^{\beta-1} e^{-\left(\frac{x-\gamma}{\eta}\right)^{\beta}} \quad (1)$$

where, β is the shape parameter or slope, η is the scale parameter or characteristic life, γ is the location parameter, and x is the variable, usually time. Because of the Weibull distribution's flexibility, other probability distributions can be modeled, such as the exponential distribution, lognormal, normal, among others. The shape parameter β determines what distribution is modeled; for instance, if β=1, it represents an exponential distribution. The location parameter γ defines a time with no failures: from the time cero to the time γ, there are not failure possibilities. If the first failure is possible to occur since the beginning of the test, γ is equal to zero; in that case, the Weibull pdf is a two-parameter equation. The two-parameter Weibull pdf is denoted as eq. (2).

$$f(x) = \frac{\beta}{\eta}\left(\frac{x}{\eta}\right)^{\beta-1} e^{-\left(\frac{x}{\eta}\right)^{\beta}} \quad (2)$$

Because an automobile can fail since the first km, this case study uses the two-parameter Weibull pdf. Accumulated failures are obtained by integrating eq. (2) and can be calculated as follows

$$F(x) = \int_0^t f(x)dx = 1 - e^{-\left(\frac{x}{\eta}\right)^{\beta}} \quad (3)$$

where, $F(x)$ is the cumulative distribution function (cdf). Eq. (3) can be rearranged, taking two times the natural logarithm of both sides gives

$$ln\left[\ln\left(\frac{1}{1-F(x)}\right)\right] = \beta\ln(x) - \beta\ln(\eta) \quad (4)$$

Eq. (4) has the form of the straight-line equation.

$$y = mx + b \quad (5)$$

where, m is the slope of the straight-line, and b is the intersection of the straight-line with the Y-axis. Hence, the parts of (4) and (5) match as follow

$$ln\left[\ln\left(\frac{1}{1-F(x)}\right)\right] = y \quad (6)$$

$$\beta = m \quad (7)$$

$$\ln(x) = x \quad (8)$$

$$-\beta\ln(\eta) = b \quad (9)$$

This process is known how the linearization of the Weibull distribution. Once the transformed Weibull equation is used to plot the data, the correlation with the straight-line equation allows the estimation of β and η. Besides, projections for other time values are possible, for instance, to estimate the number of additional defects in the future. In cases like the one covered in this paper, getting the information from each field failure, known as a warranty return, is a complex task for car manufacturers, so getting the data from the whole population of cars is practically impossible. Therefore, some assumptions need to be made. The first assumption is that the number of estimated failures will change once more information is from the field received; this is to happen considering that not all cars travel the same number of km within the same time. The second assumption is that the information received from the field failures is representative of the whole population of cars; this assumption allows us to know that the failure's tendency will not change once more data is received.

VI. RESULTS

Nineteen failures were reported with high leakage/ignited conditions at the moment of this analysis, from a total number of 250,000 MnO_2 tantalum capacitors already in the field. The information on each failed part (km) was available for investigation. The data received from the automotive manufacturer are listed in Table 1.

Table 1. Distance traveled by each automobile before failing.

Failure as received	Km	Failure as received	Km
1	135	11	1845
2	40	12	23
3	10	13	245
4	1255	14	866
5	8	15	42
6	12	16	9
7	1683	17	4012
8	956	18	154
9	12895	19	443
10	361	---	---

Once sorting the failures by distance and considering the km as the independent variable, the *x* and *y* values are calculated using (6) and (8). Eq. (10) is known as Bernard's approximation and can be used to calculate the accumulated failures F(x) [34].

$$p_i = \frac{i-0.3}{n+0.4} \quad (10)$$

where, *i* is the failure order, and *n* is the sample size, for this case study 250,000 capacitors. The values obtained from (6), (8), and (10) are shown in Table 2 and used to build the Weibull plot.

Table 2. Values of *x* and *y* used for the Weibull plot.

Order	Km	x=ln Km	F(x) = pi	y=ln(ln(1/(1-F(x))))
1	8	2.079	2.800E-06	-12.786
2	9	2.197	6.800E-06	-11.899
3	10	2.303	1.080E-05	-11.436
4	12	2.485	1.480E-05	-11.121
5	23	3.135	1.880E-05	-10.882
6	40	3.689	2.280E-05	-10.689
7	42	3.738	2.680E-05	-10.527
8	135	4.905	3.080E-05	-10.388
9	154	5.037	3.480E-05	-10.266
10	245	5.501	3.880E-05	-10.157
11	361	5.889	4.280E-05	-10.059
12	443	6.094	4.680E-05	-9.970
13	866	6.764	5.080E-05	-9.888
14	956	6.863	5.480E-05	-9.812
15	1255	7.135	5.880E-05	-9.741
16	1683	7.428	6.280E-05	-9.676
17	1845	7.520	6.680E-05	-9.614
18	4012	8.297	7.080E-05	-9.556
19	12895	9.465	7.480E-05	-9.501

A Weibull plot and its linear regression equation are calculated, with the values of *x* and *y* from Table 2; see Fig. 1.

The linear regression equation can be transformed, with (6) and (8), into eq. (11).

$$ln\left[\ln\left(\frac{1}{1-F(x)}\right)\right] = 0.3511 lnKm - 12.277 \quad (11)$$

Eq. (11) allows the estimation of accumulated failures for any value of Km. For instance, to estimate the number of accumulated failures at 30,000 km proceeds as follows:

$$ln\left[\ln\left(\frac{1}{1-F(x)}\right)\right] = 0.3511\ln(30{,}000) - 12.277 \quad (12)$$

Solving the right side of the equation

$$ln\left[\ln\left(\frac{1}{1-F(x)}\right)\right] = -8.657 \quad (13)$$

Eliminating one of the natural logarithms

$$ln\left(\frac{1}{1-F(x)}\right) = e^{-8.657} = 1.7390x10^{-4} \quad (14)$$

After eliminating the second natural logarithm and solving for F(t)

$$F(x) = 1.738x10^{-4} \quad (15)$$

So, the number of failures at 30,000 km is

$$Failures\ at\ 30{,}000\ Km = (1.738x10^{-4})(250{,}000) = 44$$

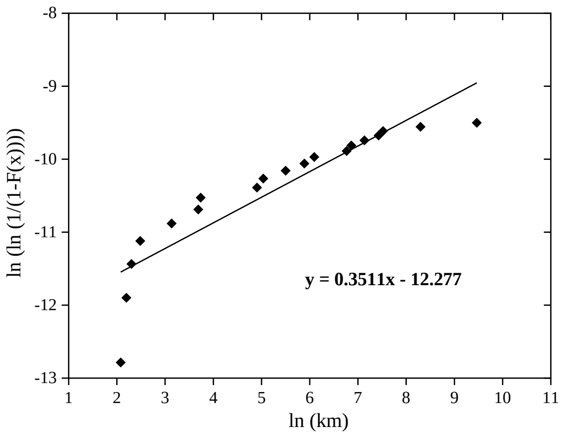

Figure 1. Weibull plot and linear regression for the values of *x* and *y*.

If the same calculations are repeated for 60,000 km and 90,000 km, 56 and 64 failures are obtained, respectively. It is clear from these results that, in this case, the failure rate decreases as far as the Km increase; this behavior is expected on this type of capacitor due to the self-healing mechanism previously explained.

The decreasing tendency is easier observed when the failure rate is plotted for different values of x, as shown in Fig. 2. The failure rate is calculated using eq. (16).

$$\lambda(x) = \frac{f(x)}{1-F(x)} = \frac{\beta}{\eta}\left(\frac{x}{\eta}\right)^{\beta-1} \quad (16)$$

The value of η needed for eq. (16) is obtained from eq. (9).

Since the number of failures is small versus the total number of capacitors in the field, the value of **η** becomes large, so that the difference among the calculated failure rates is hard to notice in a linear chart. Both axes are log scaled and *y* unit transformed into %/1000 km to fix this problem; these actions help see the tendency easier, see Fig. 2.

In reliability studies, the failure rate can show three tendencies: increasing, decreasing, or constant [35]. In the Weibull distribution, the value of the shape parameter β indicates the failure rate tendency: β <1 means a decreasing failure rate, β >1 means an increasing failure rate, and β =1 means a constant failure rate [36]. Based on the value of β, from (7) and (11), the decreasing failure rate is also evident for this case study. Here, β is equal to 0.3511 so that the decreasing failure rate is confirmed.

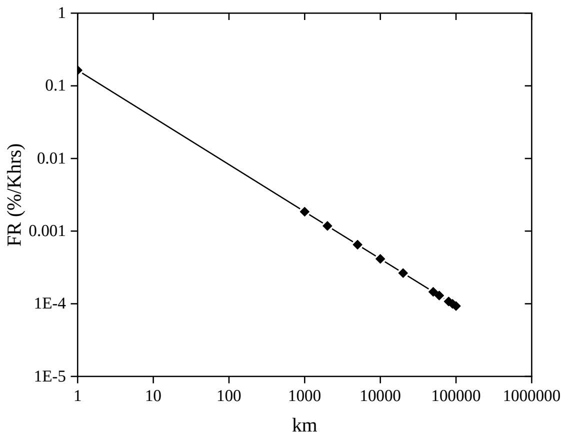

Figure 2. Failure rate at different Km.

VII. CONCLUSION

The Weibull distribution was used, in this paper, to estimate the number of field failures on tantalum capacitors in an automotive application. The linearization of the Weibull cdf was the base of the estimation, which allowed us to make predictions using the linear equation obtained after the regression. A decreasing failure rate is expected in tantalum capacitors due to their self-healing mechanism; in this case study, the calculated value of β was less than one, confirming the decreasing failure rate. Based on the assumptions previously established, the number of failures will change once more data is available from the field, not so in the failure's tendency.

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