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Analysis of Weibull Grading Test for Solid Tantalum Capacitors

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Abstract

Weibull grading test is a powerful technique that allows selection and reliability rating of solid tantalum capacitors for military and space applications. However, inaccuracies in the existing method and non-adequate acceleration factors can result in significant, up to three orders of magnitude, errors in the calculated failure rate of capacitors. This paper analyzes deficiencies of the existing technique and recommends more accurate method of calculations. A physical model presenting failures of tantalum capacitors as time-dependent-dielectric-breakdown is used to determine voltage and temperature acceleration factors and select adequate Weibull grading test conditions. This model is verified by highly accelerated life testing (HALT) at different temperature and voltage conditions for three types of capacitors. It is shown that parameters of the model and acceleration factors can be calculated using a general log-linear relationship for the characteristic life with two stress levels.

I. Introduction.

As manufactured, electronic components might have a certain proportion of defective parts that would cause failures early during operation, so-called infant mortality (IM) failures. One of the major methods of removing these marginal devices is 100% screening of the lot by applying stresses at or above the maximum operating conditions. The specific of the Weibull grading test (WGT) as a screen is that it not only removes IM failures as a regular burn-in (BI) screen, but does it in a controllable way that allows determining the failure rate (FR) of the lot. The original idea of this test that goes back to 1960th was to permits each customer to pay for only as much grading as he needs, without the risk of getting too little or overpaying for too much reliability [1].

The period of IM failures is characterized by a decreasing FR with time and distribution of these failures are typically described using a Weibull function with the shape factor, β, below one. It is generally assumed that for electronic components the IM period is followed by a so-called random failure or useful life period when FR levels off. The parts that passed BI assumed to have an exponential distribution of times to failure (or Weibull distribution with $\beta = 1$). Following this period, the failure rate might increase due to wear-out mechanisms of degradation with the relevant Weibull distributions having $\beta > 1$. In many cases this wear-out period is not achieved under normal operating conditions and reliability of parts is determined by random failures at the level that is verified during extended life testing (typically 10,000 hrs test) by accumulation the necessary amount of device-hours.

An approach that is used for reliability estimations of solid tantalum capacitors is different compared to other established reliability electronic components. It is commonly accepted that tantalum capacitors have no wear-out mechanisms, their FR is declining during long-term operation [1-3], and the distribution of times-to-failure can be adequately described by Weibull functions with $\beta < 1$. In this case, by determining parameters of Weibull distribution based on results of WGT it is possible to calculate variations of FR with time and stop the test when the required level is achieved. This gives a conservative estimation of FR because it will further decrease with time, and the reliability of parts during operation should be even better than the calculated value.

A combination of BI that is typically a screening procedure and of assessment of FR that is typically a sample-base qualification procedure results in a substantial cost saving and makes WGT one of the most important tests for solid tantalum capacitors. Although life testing is often used for FR verification, conditions of life test per MIL-PRF-55365 are not sufficient to confirm the reliability level for parts with FR below 1%/1000 hr [4]. For this reason manufacturers and users of solid tantalum capacitors are relying on the results of WGT for both, the assurance and verification of the necessary reliability level.

WGT is currently performed typically for 40 hrs at a rated temperature of 85 ^{o}C and acceleration of failures is achieved by applying voltages exceeding the rated voltage (VR) up to 1.52 times. Calculations of the test conditions (applied voltage) and reliability grading per MIL-PRF-55365 are based on two assumptions. First is that times to failure of tantalum capacitors can be described with a two-parameter unimodal Weibull distribution that allows for calculation of the failure rate during the testing conditions:

$$\lambda(t) = \frac{-\beta \times \ln(1 - F(t))}{t}, \tag{1a}$$

where β is the Weibull shape parameter, $\beta < 1$, F(t) is the proportion of parts failing by time t, and t is the time of testing.

Second condition is that the voltage acceleration factor is an exponential function of applied voltage, V, that can be written in a simple form:

$$AF = \exp(B \times u), \tag{1b}$$

where u is the voltage accelerating parameter, $u = V/VR-1$, and $B = 18.772$ is the voltage acceleration constant.

With these assumptions, the failure rate at operating conditions (85 °C and V = VR) is calculated as $\lambda(t)/AF$. Equation (1b) was obtained by Navy Crane in the late 1970s for hermetically sealed solid tantalum capacitors [5], and its applicability for contemporary chip tantalum capacitors is questionable [6-7].

It will be shown in this paper that errors in FR calculations increase substantially at high levels of voltage acceleration. This might require using another accelerating factor for WGT – temperature. However, literature data on the effect of temperature are limited and contradictory, so currently there is no methodology that would allow testing and calculations of FR at different temperature and voltage conditions.

The importance of WGT for reliability assurance of tantalum capacitors requires a thorough analysis of deficiencies of the used methodology and possible errors in determining failure rate. Some problems related to technical implementation of this test, in particular to detection of failures as blown 1A or 2A fuses, have been discussed before [4]. In this paper we consider possible variations of the calculated FR, estimate errors caused by uncertainty in acceleration factors, and suggest a method for determining WGT conditions at different temperature and voltages based on physics of failure approach. Experimental data will be used to demonstrate the technique of determining AF based on the time dependent dielectric breakdown model (TDDB) and application of general log-linear relationship for characteristic life.

II. Errors of failure rate estimations

Neglecting early failures.

According to MIL-PRF-55365 failures that occur during WGT before 0.25 hr are defined as infant mortality failures and are not used for calculations. However, the slope of distributions during WGT is always assumed to be below 1, which corresponds to a decreasing FR, and all observed failures should be considered as IM failures. Note also, that at V = 1.5VR AF = 20000 and 0.25 hr of WGT corresponds to ~7 months of operation at rated conditions.

A virtual lot of capacitors with a set post-WGT failure rate, $\lambda(t_{WGT})$, was generated using a Monte-Carlo method and Weibull-7 software available from ReliaSoft to simulate results of Weibull grade testing. For a given shape factor, β, that is considered the same for accelerated and normal conditions, and accelerating factor, AF, calculated per Eq.(1b) at a given accelerating voltage $V = (u+1)\times VR$ the failure rate at test conditions $\lambda(t_{WGT}) = AF \times FR$ For this case the characteristic life at WGT conditions can be calculated as:

$$\eta_{WGT} = \left[\frac{\beta \times t_{WGT}^{\beta - 1}}{\lambda(t_{WGT})} \right]^{1/\beta} , \tag{2}$$

where t_{WGT} is the duration of testing.

The effect of neglecting early failures was evaluated for a case when β = 0.1, FR = 0.01%/1000 hr = 1e-7 1/hr, and *u* = 0.4. The calculations yield AF = 1824 and η_{WGT} = 9.36E12 hr. Figure 1 shows the simulated distribution of times to failure for 300 capacitors tested at 85 °C and V = 1.4 VR. This virtual lot has 23 samples failing before 40 hrs (WGT failures) out of which 17 samples failed before 0.25 hr, one sample failed between 0.25 hr and 2 hr and five more samples failed between 2 hr and 40 hr. The chart shows also distributions calculated for all 23 samples that "failed" during WGT and for 6 samples that are selected per MIL-PRF-55365 requirements as failures between 0.25 hr and 40 hr. The distribution calculated for 23 samples had β= 0.12 and η_{WGT} = 3E10 hr that is close to the parameters calculated for the whole lot. However, calculations per MIL-spec requirements resulted in the characteristic life that is eight orders of magnitude less than the expected value and β exceeding the expected value by a factor of seven.

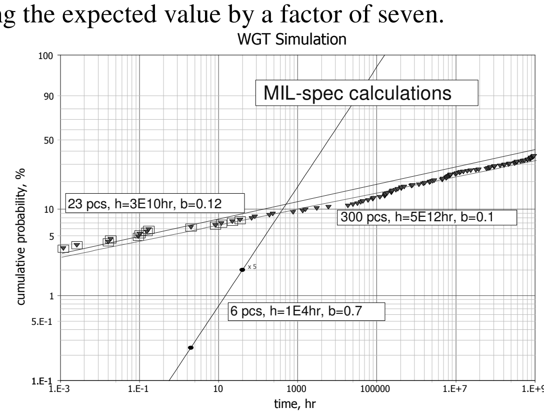
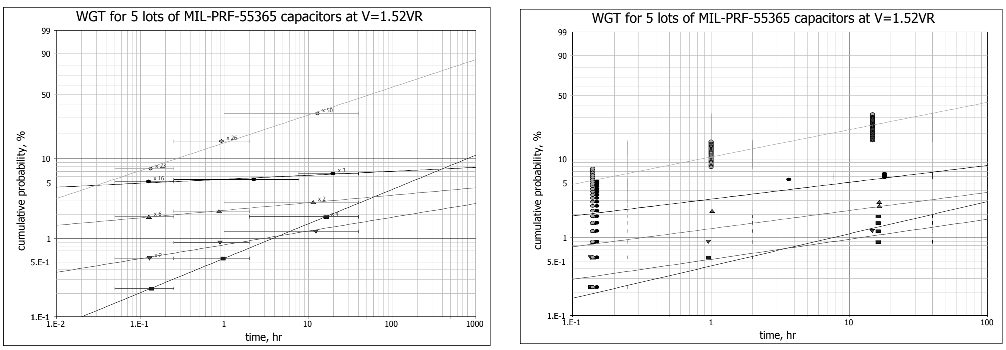


Figure 1. Monte-Carlo simulation of distributions of times to failure during WGT at β = 0.1, FR = 1e-7 1/hr, and *u* = 0.4 for 300 samples (triangular marks), for 23 samples selected at t < 40 hrs (large square marks), and for 6 samples selected per MIL-PRF-55365 (black circles).

Uncertainty in the time to failure and method of approximation.

Neglecting early failures might be one of the sources of errors during analysis of WGT results. Another source is related to the assumption that all failures in the interval from 0.25 hr to 2 hr occurred at t1 = 2 hr, and all failures in the interval 2 hr to 40 hr occurred at t2 = 40 hr. A regression analysis (RA) or maximum likelihood estimation (MLE) for the interval data take into account the uncertainty of time to failure and provide more accurate estimations of the parameters of Weibull distributions.

Results of WGT for 5 lots of MIL-PRF-55365 capacitors were analyzed using RA and MLE with Weibull-7 ReliaSoft software and also by following MIL-spec recommendations. Figure 2 displays results of WGT that have been obtained using regression analysis (a) and MLE (b) for three time intervals: before 0.25 hr, between 0.25 hr and 2 hr, and between 2 hr and 40 hr. The regression analysis apparently allows for calculation of probability lines that follow experimental data more closely, but MLE method accounts for censored data more accurately then regression analysis and is more suitable when interval data are used for calculations. Obviously, the more time intervals are available and/or the more accurately the times to failure are estimated, the more accurate results of analysis are.



a) b)

Figure 2. Results of WGT for 5 types of MIL-PRF-55365 capacitors analyzed using regression analysis (a) and maximum likelihood estimation (b).

Analysis show that different calculation techniques might result in variations of FR up to an order of magnitude. Considering that MLE provides most accurate estimations of parameters of Weibull distributions, calculations per MIL-PRF-55365 might result in FR that is less by several times than the real values.

Statistical variations in the number of failures for high reliability parts.

Possible statistical variations in the number of failures during WGT of high reliability parts might result in significant variations of Weibull distributions and calculated FR due to a relatively small total number of failures.

Using Monte-Carlo simulation described above four virtual lots of capacitors with 300 pcs each having the same FR of 0.01%/1000 hr but different values of β have been generated. Relevant distributions of times to failure are shown in Figure 3. The results indicate that as β is increasing, the probability of observing failures during WGT decreases substantially and at λ_{WGT} = 1.8E-4 1/hr and β = 1 only one out of 300 samples fails during the testing.

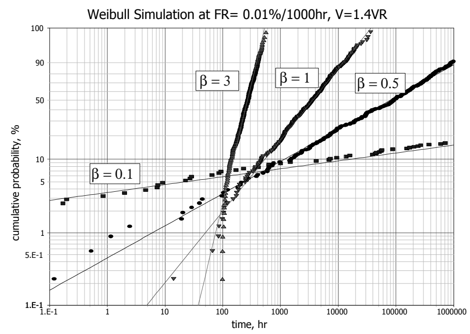


Figure 3. Monte-Carlo simulation of times to failure during testing at 85 °C and V= 1.4VR for lots having the same FR = 0.01%/1000 hr but different values of β.

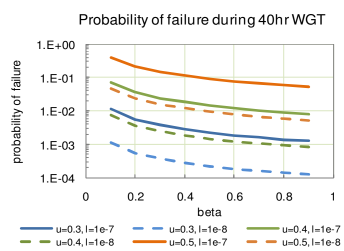


Figure 4. Probability of failure during WGT for lots having FR = 0.01%/1000 hr and 0.001%/1000 hr at V/VR=1.3, 1.4, and 1.5.

For high quality lots a small number of failures is expected even at a relatively small values of the slope β. The probability of failure during WGT can be calculated using Weibull function:

$$F(t) = 1 - \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right], \quad (3)$$

where $t = t_{WGT}$, and η is the characteristic life for the Weibull grade test conditions, η_{WGT}.

To have at least a few failures during testing of 300 samples, the probability of failure should be above ~1%. Assuming t_{WGT} = 40 hr and calculating η_{WGT} for FR = 0.01%/1000 hr and FR = 0.001%/1000 hr per Eq.(2) at different β, the values of $F(t_{WGT})$ were calculated for test conditions at u = 0.3, 0.4, and 0.5. Results of these calculations are shown in Figure 4 and indicate that at FR = 0.001%/1000 hr and u = 0.4 the probability of failures during WGT is below 1% for all cases when $\beta > 0.1$. At highly accelerated test conditions when u = 0.5 this probability is below 1% at relatively large $\beta > 0.5$.

For cases when only a few failures are observed, random variations in the number of failed samples during 0.25 hr to 2 hr or in 2 hr to 40 hr periods might result in significant variations of distributions. Analysis showed that at a small number of failures an error in determining FR can be as high as an order of magnitude.

III. Physical model of WGT failures.

Thermochemical model of time dependent dielectric breakdown.

In our previous work [7] it has been shown that failures of solid tantalum capacitors can be considered as time-dependent dielectric breakdown, TDDB, and time to failure, TF, can be described using the thermochemical model developed for oxide films by McPherson and co-workers [8-9]. According to this model, electrical breakdown occurs when the local electrical field weakens polar molecular bonds to the level at which thermal energy is sufficient to cause the breakage. This model predicts that the time to failure is an exponential function of electric field, E, in the oxide:

$$TF = t_o \times \exp\left(-\gamma E + \frac{\Delta H}{kT}\right), \tag{4}$$

where ΔH is the activation energy required for displacement of ions from their normal bonding environment, γ is the field acceleration parameter, and t_o is a time constant. For Ta_2O_5 dielectric ΔH is in the range from 1.7 eV to 2 eV and γ = 13.6 cm/MV [8]. However, the presence of large concentration of electron traps and movable oxygen vacancies in anodic Ta2O5 dielectric can change local polarization, so the effective activation energy, ΔH, is likely in the range from 1 eV to 2 eV [7, 10].

According to this equation the breakdown field, E_{BR}, is determined as a field at which breakdown occurs instantly (TF ~ t_o) at the following condition:

$$\gamma \times E_{BR} = \frac{\Delta H}{kT} \tag{5}$$

Substitution of (5) in (4) allows for expression of TF as a function of applied and breakdown voltages:

$$TF = t_o \times \exp\left[\frac{\Delta H}{kT} \times \left(1 - \frac{V}{V_{BR}}\right)\right], \tag{6}$$

A similar model for tantalum capacitors with manganese cathodes has been suggested by Y. Freeman and as described by E. Reed and co-workers in [11] was attributed to degradation in

Ta2O5 caused by oxygen-ion migration mechanism. It has been shown [11] that for low-voltage tantalum capacitors with polymer cathodes acceleration factors are better described by empirical Prokopowicz-Vaskas model.

Assuming that VBR is proportional to the rated voltage, $VBR = n \times VR$, where n is a constant, TF in Eq.(6) can be expresses via a ratio of applied and rated voltages. With this assumption acceleration factor for time to failure in general case, when both temperature and voltage of testing are varying, can be written in the following form:

$$ATF = \frac{TF(T_1, V_1)}{TF(T_2, V_2)} = \exp\left\{\frac{\Delta H}{k}\left[\left(\frac{1}{T_1} - \frac{1}{T_2}\right) - \frac{1}{nVR}\left(\frac{V_1}{T_1} - \frac{V_2}{T_2}\right)\right]\right\},$$

(7)

Note that the acceleration factor for failures is just a reverse of time to failure acceleration, *AF = 1/ATF*.

When voltage is constant, and acceleration is achieved by increasing temperature only, the above equation can be simplified and converted into Arrhenius-like form:

$$ATF_T = \frac{TF(T_1)}{TF(T_2)} = \exp\left[-\frac{E_{eff}}{k}\left(\frac{1}{T_2} - \frac{1}{T_1}\right)\right],$$

(8)

where $E_{eff} = \Delta H \times \left(1 - \frac{V}{nV_R}\right)$ is the effective activation energy that depends on applied voltage.

The effective activation energy is decreasing with applied voltage and the range of possible E_{eff} values at ΔH in the range from 1 eV to 2 eV and V/VR in the range from 1.1 to 1.5 varies from 0.4 eV to 1.4 eV.

In the case when temperature of the test is constant the voltage acceleration factor can be expressed similar to Eq.(1):

$$ATF_V = \frac{TF(V_R)}{TF(V)} = \exp\left[\frac{\Delta H}{nkT} \times \left(\frac{V}{V_R} - 1\right)\right] = \exp(-Bu),$$

(9)

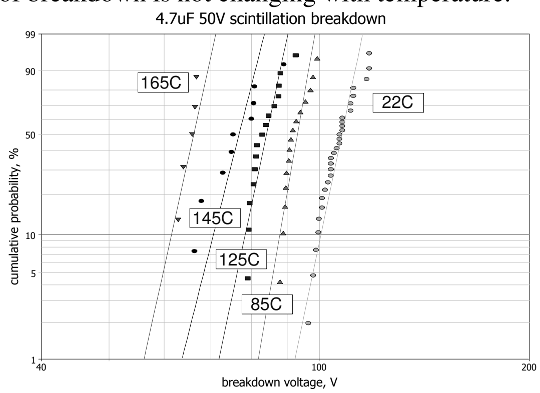
where $B = \frac{\Delta H}{nkT}$

(9a)

Based on this theory the voltage acceleration constant B is decreasing with temperature and considering possible variations of ΔH and n is likely in the range from 10 to 28.

Temperature dependence of breakdown voltages.

Distributions of VBR measured at different temperatures for parts rated for 50V and 63V are shown in Figure 5. An increase in temperature results in decreasing of breakdown voltages as predicted by the theory. The slopes of distributions remain practically the same indicating that the mechanism of breakdown is not changing with temperature.



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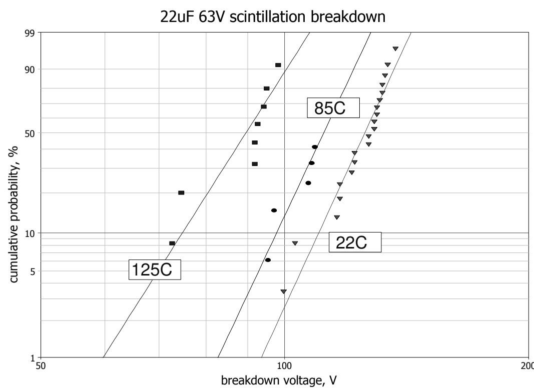


b)

Figure 5. Distributions of VBR at different temperatures for 4.7uF 50V (a) and 22uF 63V (b) solid chip tantalum capacitors.

Based on Eq.(5) the breakdown voltage is reversely proportional to absolute temperature and the slope of VBR(1/T) line can be used to estimate the value of activation energy, ΔH:

$$V_{BR} = \frac{\Delta H \times d}{\gamma \times kT}, \quad (10)$$

Variations of average breakdown voltages with temperature in the range from 22 ^{o}C to 165 ^{o}C for three part types are plotted against 1/T in Figure 6. In this coordinates the experimental data can be approximated with straight lines as predicted by Eq.(10).

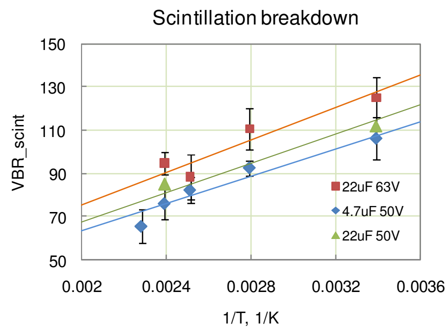


Figure 6. Temperature dependencies of breakdown voltages for 22uF 63V, 22uF 50V, and 4.7uF 50V capacitors. Error bars correspond to standard deviations.

Assuming γ = 13.6 cm/MV and thickness of Ta2O5 layer proportional to the rated voltage, d = a*VR, where a = 7 nm/V, the values of ΔH were calculated based on the slopes of VBR(1/T) lines for these three parts as well as several other parts tested earlier [12]. Results of these calculations are shown in Table 1 and indicate a range of ΔH variations from 1 eV to 2 eV which corresponds to the expectations.

Table 1. Activation energies calculated based on temperature dependence of VBR.

Part	slope, V*K	d, nm	ΔH, eV
22uF 63V	38699	441	0.99
4.7uF 50V	31665	350	1.03
22uF 50V	33864	350	1.10
3.3uF 10V	8926	70	1.45
10uF 25V	21331	175	1.38
15uF 10V	9557	70	1.55
100uF 16V	11320	112	1.15
220uF 6V	7321	42	1.98
6.8uF 35V	30314	245	1.40

HALT at different test conditions for three part types.

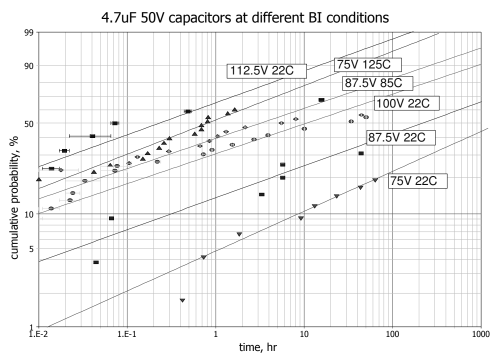
Highly accelerated life testing, HALT, was carried out for three part types in the range of temperatures from room to 130 ^{o}C and voltages varying from 1.25VR to 2.25VR according to the test matrix presented in Table 2. Test results were monitored using a data acquisition system that checked periodically condition of 125 mA fuses connected in series with each capacitor. This allowed detection of time to failure with an accuracy of better than 5%.

Table 2. HALT test matrix.

Part	Voltage, V	Temperature, °C	Time, hr	QTY

4.7uF 50V	75	125	100	34
	87.5	85	80	33
	75	22	150	40
	87.5	22	48	38
	100	22	72	51
	112.5	22	24	11
22uF 50V	80	125	50	13
	60	130	100	4
	87.5	22	100	17
	100	22	64	17
22uF 63V	80	125	50	20
	95	85	48	40
	100	22	200	18
	110	22	75	21

Results of HALT are plotted in Weibull coordinates in Figure 7. The slopes of distributions at different levels of stress were similar suggesting that acceleration most likely did not cause changes in the mechanism of failure.



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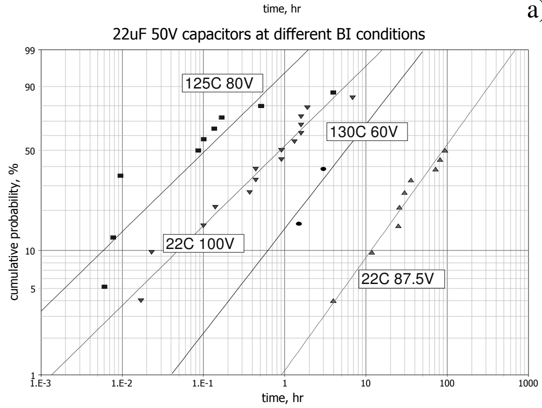

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Figure 7. Results of highly accelerated life testing for 4.7uF 50V (a) and 22uF 50V (b) capacitors at different accelerating factors (voltage and temperature).

Estimation of parameters of the model.

In accordance with the TDDB model, the characteristic time of Weibull distribution can be expressed as a function of voltage and temperature:

$$\eta = \eta_o \times \exp\left[\frac{\Delta H}{kT} \times \left(1 - \frac{V}{nV_R}\right)\right], \quad (11)$$

where η_o is a time constant.
By setting:

$$\alpha_0 = \ln(\eta_0); \quad \alpha_1 = \frac{\Delta H}{k}; \quad X_1 = \frac{1}{T}; \quad \alpha_2 = -\frac{\Delta H}{k \times n \times V_R}; \quad X_2 = \frac{V}{T}, \quad (12)$$

The characteristic life can be presented as a general log-linear relationship:

$$\eta = \exp(\alpha_0 + \alpha_1 X_1 + \alpha_2 X_2) \quad (13)$$

This allows using ALTA-7 software available from ReliaSoft to calculate parameters of the model by approximating experimental results using the maximum likelihood estimations method.

Table 3 displays parameters of log-linear approximation and parameters of the model calculated based on Eq.(12). The table includes also the total number of failed samples, F, total number of suspended samples, S, shape factor of Weibull distributions, β, and voltage acceleration constant B that was calculated at 85 ^oC per Eq.(9a).

Table 3. Parameters of log-linear and HALT models

data source	F	S	β	α_0	α_1	α_2	t_0, hr	ΔH, eV	n	B_85C
4.7uF 50V	90	117	0.24	-15.06	12761.6	-68.61	2.9E-07	1.1	3.7	9.6
22uF 50V	40	41	0.40	-28.13	21026.1	-124.49	6.1E-13	1.8	3.4	17.4
22uF 63V	59	43	0.24	-28.45	25072.2	-145.03	4.4E-13	2.1	3.5	20.6

Activation energy ΔH was in the range between 1.1 eV and 2.1 eV which is close to the range of data obtained based on temperature dependence of VR and literature data. The ratio between the breakdown and rated voltages, n, was between 3.4 and 3.7 which is somewhat larger than was expected based on measurements of distributions of VBR, from ~2 to ~2.3.

Variations in acceleration constant B were from 9.6 to 20.6 which is in accordance to our estimations made earlier.

These data demonstrate the applicability of the TDDB model to describe acceleration factors of Weibull grading tests, and the log-linear relationship for estimating parameters of the model. Using this approach an estimation of the voltage acceleration factor can be obtained by testing parts at two stress levels only and both, voltage and temperature acceleration factors can be calculated based on testing at three temperature/voltage levels of stress. The larger the number of stress levels and quantity of tested parts the more accurate estimations can be made.

IV. Estimation of WGT conditions at different temperatures and voltages.

Weibull grading tests at two conditions are equivalent when the product of test duration and acceleration factor remains the same:

$$AF(T_1,V_1)\times t_1 = AF(T_2,V_2)\times t_2 \ , \qquad (14a)$$

or the ratio of the acceleration factors is inversely proportional to the durations of tests:

$$AF_R = \frac{AF(T_2,V_2)}{AF(T_1,V_1)} = \frac{t_1}{t_2} \ , \qquad (14b)$$

where T1, V1, t1 and T2, V2, t2 are temperatures, voltages, and durations for two WGT conditions.

Weibull grading tests for high-reliability tantalum capacitors are typically carried out at T1 = 85 ^{o}C, t_1 = 40 hr, and voltages varying from V1 = 1.3VR to 1.52VR. Let us assume that parameters of the failure model have been determined similar to what was done above, so the value of AF can be calculated at any combination of temperatures and voltages. Let us assume also that two out of three variables determining test conditions (T, V, and t_{WGT}) are set. For example, we need to find the necessary test voltages that would be equivalent to condition 1 for two cases: first, T_2 = 145 ^{o}C and t_2 = 40 hrs and second T_2 = 105 ^{o}C and t_2 = 160 hrs.

In the first case when duration of testing at conditions 2 and 1 is the same, the necessary voltage accelerating conditions can be determined at the intercept of the line AF = 1 and the curves AF(u2) for a given temperature T2. Results of calculations showed that increasing temperature from 85 ^{o}C to 145 ^{o}C allows for reduction of test voltage from 1.3VR to 0.9VR for 4.7 uF 50 V capacitors and to 0.95VR for 22 uF 50 V capacitors. When the test duration is increased to 160 hr, the necessary acceleration factor can be decreased in t1/t2 = 4 times. For this case the required test voltage is V2 = 1.02VR for 4.7 uF 50 V capacitors and 1.1VR for 22 uF 50 V parts.

Similar calculations have been repeated for u1 = 0.4 and u1 = 0.5 conditions. Based on these calculations to assure conditions equivalent to T1 = 85 ^{o}C and V1 = 1.5VR at T2 = 145 ^{o}C, the necessary voltage for 4.7 uF 50 V capacitors should be V2= 1.13VR and V2 = 1.18VR for 22 uF 50 V capacitors. For the case when T2 = 105 ^{o}C and t2 = 160 hr the required voltages are V2 = 1.22VR and V2 = 1.32VR for 4.7 uF and 22 uF parts respectively.

V. Discussion.

Historical data on AF used for WGT.

Navy Crane report from 1982 describes results of testing at 85 ^{o}C of more than 29,000 hermetically sealed solid tantalum capacitors manufactured per MIL-C-39003/1 by five manufacturers. The purpose of the testing was to determine acceleration factors for different types of tantalum capacitors and decide how they can be combined for different values, voltages, case sizes, and manufacturers.

It was found that for the majority of the part types the Weibull shape factor β was less than one and testing of good units at rated conditions for 5000 hr after accelerated test conditions at voltages up to 2.5VR showed no failures. The electrical end point data indicated that some units healed themselves even after blowing one ampere fuses during accelerated testing. This is in agreement with our observations and confirms that failures of tantalum capacitors can be considered as time dependent scintillation breakdown.

No significant variations in AF between manufacturers, rated voltages and sizes of the capacitors were observed. Experimental data were averaged together resulting in exponential voltage dependence of AF in the form that is currently used in MIL-PRF-39003 and MIL-PRF-55365: AF = 7.03412025E-9×exp(18.77249321×V/VR). Note that the preexponential coefficient is just a normalization constant that assures AF = 1 at V = VR, so this equation can be written in a simple form, AF = exp(Bu), where u = V/VR-1, and B=18.772. In this form AF is determined by the acceleration constant B only.

Variations of the observed acceleration factors with applied voltage that were accumulated during that study are displayed in Figure 8. The legend shows values of acceleration constant B calculated for cases with minimal and maximum AF. The chart has also data reported by KEMET back in 1972 for their high-reliability Weibull graded hermetic capacitors [13] and recent data presented in 2006 by Paulson [14] who carried out extensive testing of 10 uF 16 V capacitors at voltages from 1.6VR to 3VR. Paulsen approximated his data with a power function that resulted in exponent of 18.5. The line in Figure 8 is an approximation of Paulsen's test results obtained at 85 ^{o}C with the exponential function per Eq.(1b) that resulted in B = 8.

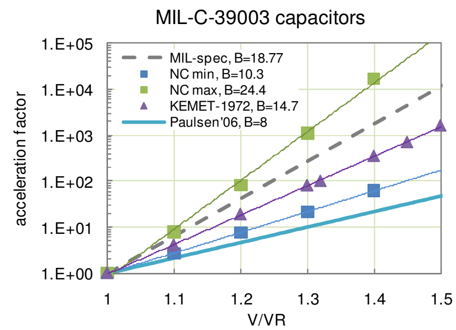

Figure 8. Experimental data for acceleration factors from Navy Crane report, 1982, for various hermetic solid tantalum capacitors. Square marks show minimal and maximal data, triangle marks represent data reported by KEMET in 1972, blue line is a results of calculations based on Paulsen results (2006), and dashed line corresponds to the currently used acceleration factors.

Experimental data obtained in late 1970th confirmed exponential dependence of acceleration factors on voltage and showed that different lots of tantalum capacitors might have significant variations of the constant B, from 10.3 to 24.4. At high stress factors, u ~ 0.5, the variations of AF can reach up to three orders of magnitude, which is in agreement with our estimations made based on TDDB model.

Note that KEMET-72 data are identical to those presented by Didinger in 1964 [1]. The Navy Crane equation that was first accepted for MIL-C-39003 specification in 1982 remains also unchanged over almost 30 years and is used for AF calculations of contemporary solid chip tantalum capacitors. This is likely due to the difficulties, or even impossibility to describe different part types using the same set of acceleration factors, so any attempts to come up with a "combined" AF that is applicable to all lots of capacitors would face the same difficulties. Most likely adequate values of AF can be obtained for a specific group of parts only.

According to MIL-PRF-55365 life testing can be carried out for 2000 hrs either by testing of 102 parts (with one sample allowed to fail) at V = VR and T = 85 ^{o}C or by testing 24 samples (without failures) at V = 2/3VR and T = 125 ^{o}C. Assuming that these test conditions verify the same failure rate and that the acceleration factor of testing can be determined as a product of voltage AF_V and temperature AF_T, the effective activation energy of should be ~2.1 eV. This is a relatively large value that casts some doubts on the equivalence of the life test conditions.

Reliability AF reported by manufacturers.

Most manufacturers of tantalum capacitors suggest acceleration factors that can be used to calculate reliability of their product at different application conditions including temperature, voltage, and series resistance of the circuit. In general, electronic components might have different acceleration factors for infant mortality failures during BI and random failures during application conditions. However, for tantalum capacitors IM period is considered extending through the whole useful life of the parts, and it is reasonable to expect that the same AF can be applied to WGT at V > VR and application conditions at V < VR.

Figure 9 shows voltage dependence of AF below the rated voltage for tantalum capacitors manufactured by six different vendors in comparison with the MIL-spec data. Note that Vishay believes that if their capacitors are manufactured per military requirements, reliability of the product should follow the rules established by the relevant military specifications and refer their customers to MIL-HDBK-217F for calculations of acceleration factors.

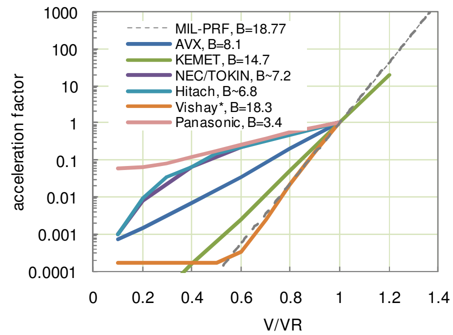

Figure 9. Variations of acceleration factors with voltage for solid tantalum capacitors manufactured by different vendors. Legend indicates calculated values of the acceleration constant, B.

At similar conditions different vendors suggest AF varying more than three orders of magnitude, and the effective values of B are in the range from 3.4 to 18.3. Both MIL documents, MIL-PRF-55365 and MIL-HDBK-217, apparently use the same acceleration constant B = 18.7 at V > VR and at 0.5VR < V < VR. The spread of AF factors suggested by different manufacturers is increasing as voltage decreases below VR and the range of effective values of the acceleration constant B is close to those found experimentally for WGT and for our estimations based on TDDB model.

The observed difference in AF might be due to some technological variations that are specific to different vendors or to different methodology of defining rated voltages. However, different lots of capacitors from the same vendor have different AF [14], and lot-to-lot variations would result in a similar spread of AF as shown in Figure 8. In this case results of Figure 9 might reflect a limited (due to a high cost of reliability testing) experience that each vendor has with reliability of their product.

Assuming the AF(T) function follows the Arrhenius law, the effective activation energies were estimated based on charts suggested by different vendors to calculate the effect of temperature on reliability of their capacitors. Results of these calculations are summarized in Table 4 and indicate the range of E_a from 0.16 eV to 1.17 eV. This is far below the value calculated above based on life test conditions in MIL-PRF-55365, but close to the range of possible variations predicted by the TDDB model.

Table 4. Activation energies calculated based on data suggested by different vendors and MIL specifications.

AVX	KEMET	MIL-PRF-55365	HITACHI	NEC/ TOKIN	Vishay/ MIL-HDBK	Panasonic
0.63	1.17	2.1	0.62	0.66	0.15	0.16

VI. Conclusion

1. Monte-Carlo simulations and analysis of results of HALT and Weibull grading tests showed that the estimated failure rate might vary significantly depending on the method of calculation and acceleration factor used. Reliance on MIL-PRF-55365 method for reliability rating of solid tantalum capacitors might be misleading.
2. Errors related to the method of calculation, including neglecting initial failures, approximation technique, and possible statistical variations in the number of failed samples, sum up to approximately an order of magnitude. Possible deviations of the accelerating factor from values calculated per MIL-PRF-55365 specification are the major source of errors in failure grading. These errors increase with voltage exponentially and can cause variations in the calculated failure rate up to three orders of magnitude.
3. A thermochemical model for time-dependent dielectric breakdown has been used to determine temperature and voltage acceleration factors of WGT. The model predicts an exponential dependence of AF on voltage, similar to the currently used equation, but with the voltage acceleration constant B depending on temperature and physical characteristics of the dielectric. Temperature dependence of AF can be presented in the Arrhenius-like form with the effective activation energy depending on applied voltage.
4. A method for calculation of acceleration factors based on approximation of test results with a general log-linear relationship at two stress factors has been demonstrated.
5. Analysis of literature data showed a wide spread of voltage and temperature accelerating factors suggested by different manufacturers of tantalum capacitors to estimate reliability of their product. The reported voltage acceleration factors vary up to four orders of magnitude, and the effective activation energies are in the range from 0.16 eV to 2 eV, which is in agreement with predictions of the TDDB model.

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VIII. References.

[1] G. H. Didinger, "Tantalum capacitor accelerated life testing," *Evaluation Engineering,* vol. Sept/Oct, 1964.

[2] J.D.Prymak*, et al.*, "Derating review of Ta-MnO2 vs. Ta-polymer vs.Al-polymer vs. NbO-MnO2," presented at the CARTS Europe, Nice, Fr, 2004.

[3] T.Zednicek and J.Gill, "Voltage derating rules for solid tantalum and niobium capacitors," presented at the CARTS Europe, Stuttgart, Germany, 2003.

[4] A. Teverovsky, "Screening and Qualification Testing of Chip Tantalum Capacitors for Space Applications," in *CARTS USA*, New Orleans, LA, 2010.

[5] J. N. Burkhart, "Use of accelerated testing techniques in military specification MIL-C--39003," in *CARTS*, Phoenix, AZ, 1983, pp. 111-117.

[6] J. L. Paulsen*, et al.*, "Reliability of Tantalum Polymer Capacitors," in *CARTS 2004: 24th Annual Capacitor and Resistor Technology Symposium*, 2004, pp. 114-121.

[7] A. Teverovsky, "Scintillation Breakdowns and Reliability of Solid Tantalum Capacitors," *IEEE Transactions on device and materials reliability,* vol. 9, pp. 318-324, 2009.

[8] L. McPherson*, et al.*, "Proposed universal relationship between dielectric breakdown and dielectric constant," in *Digest. International Electron Devices Meeting, IEDM '02*, 2002, pp. 633 - 636.

[9] J. W. McPherson*, et al.*, "Trends in the Ultimate Breakdown Strength of High Dielectric-Constant Materials," *IEEE transactions on electron devices,* vol. 50, pp. 1771-1778, August 2003 2003.

[10] A. Teverovsky, " Degradation of Leakage Currents in Solid Tantalum Capacitors under Steady-State Bias Conditions " in *60th Electronic Components and Technology Conference*, Las Vegas, NV, 2010.

[11] E. K. Reed*, et al.*, "Reliability of Low-Voltage Tantalum Polymer Capacitors," in *CARTS USA 2005*, Palm Springs, CA, 2005, pp. 189-198.

[12] A. Teverovsky, "Scintillation and Surge Current Breakdown Voltages in Solid Tantalum Capacitors," *IEEE Transactions on Dielectrics and Electrical Insulation,* vol. 16, pp. 1134-1142, 2009.

[13] KEMET, *GR500, General specification for graded reliability fixed tantalum, solid electrolyte, high-reliability capacitors*, 1972.

[14] J. L. Paulsen, "Reliability Characterization of Tantalum Capacitors with MnO2 Counter-Electrode," in *CARTS Europe: 24th Annual Capacitor and Resistor Technology Symposium*, Bad Homburg, Germany, 2006.