

Random vibration testing of advanced wet tantalum capacitors

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Abstract

Advanced wet tantalum capacitors allow for improved performance of power supply systems along with substantial reduction of size and weight of the systems that is especially beneficial for space electronics. Due to launch-related stresses, acceptance testing of all space systems includes random vibration test (RVT). However, many types of advanced wet tantalum capacitors cannot pass consistently RVT at conditions specified in MIL-PRF-39006, which impedes their use in space projects. This requires a closer look at the existing requirements, modes and mechanisms of failures, specifics of test conditions, and acceptance criteria. In this work, different lots of advanced wet tantalum capacitors from four manufacturers have been tested at step stress random vibration conditions while their currents were monitored before, during, and after the testing. It has been shown that the robustness of the parts and their reliability are mostly due to effective self-healing processes and limited current spiking or minor scintillations caused by RVT do not increase the risk of failures during operation. A simple model for scintillations events has been used to simulate current spiking during RVT and optimize test conditions. The significance of scintillations and possible effects of gas generation have been discussed and test acceptance criteria for limited current spiking have been suggested.

Introduction

Advanced wet tantalum capacitors, e.g. TWA-series from AVX, HC-series from Evans, or ST-series from Vishay and relevant DLA LAM drawings (e.g., 93026, 10004), have lower equivalent series resistance and greater capacitance values compared to similar case size capacitors manufactured to MIL-PRF-39006 requirements. This allows for better filtering in power supply systems and a substantial reduction of size and weight of the modules used in space electronics. Due to delivery/shipping transportation, and mostly to launch-related stresses, acceptance testing of all space modules includes random vibration test (RVT). This testing provides a better simulation of actual environments compared to sinusoidal vibration, and is currently the predominant method for vibration testing of space systems [1]. The level of mechanical stresses during RVT depends on the launch vehicle used, is specified in the mission assurance requirements, and categorized in the relevant military specifications. A typical range of vibration stresses during launch is from 4.5 to 12.9 g rms [2]. For example, Shuttle experiences relatively large, up to 12 g rms levels of vibration during the launch and return periods.

Qualification testing of space units is carried out in 3 axes for a few minutes in each direction. The purpose of the test is to verify that the systems can survive the lift-off environments and also to provide a workmanship assessment. According to General Environmental Verification Specification (GEVS) [3], an overall qualification level for testing of space units is accepted at 14.1 g rms. Assuming a typical margin between the unit-level and element-level testing of ~3 dB, it is reasonable to require that the space-qualified capacitors should sustain 19.64 g rms (test condition II-E per MIL-STD-202, TM214). Although in many applications the systems are not operating during the launch, the unit-level testing is often carried out on working modules. Note that RVT cannot be replaced by a similar level sinusoidal vibration test because it activates a wide range of frequencies thus increasing the possibility of resonances in the system, and the peak values of the acceleration exceed substantially (typically 3 times) the overall specified rms value.

Anode slugs in wet tantalum capacitors have some freedom to move inside the case. Hitting the slug against the spacer might cause damage to the thin tantalum pentoxide dielectric resulting in failures. In some cases, evidences of the slug abrasion are observed on the failed capacitors at areas across the spacer. The probability of damage

increases substantially in the presence of particles generated by the cathode materials attached to the case of the part. These particles, when jammed inside the porous slug or between the slug and the spacer create significant local stresses sufficient to fracture the dielectric.

The sensitivity of wet tantalum capacitors to RVT was recognized during first attempts to employ these parts in space systems. Holladay [4], in his review of the history of the development of all-tantalum CLR79 capacitors for space applications, indicates that results of vibration testing were considered as one of the most important indicators of the successful design. If the fit between the slug and the Teflon spacers is not tight enough, a scrubbing action would occur, and this can disrupt the oxide dielectric and cause high direct current leakage (DCL) or shorts.

Difott [5], based on his studies of capacitors that failed RVT suggested that failures were due to movement/friction of the slug against Teflon spacer that damaged the dielectric. Failures during vibration manifested as current spiking that was measured by voltage drop across 10 kohm resistors connected to each capacitor in series. The electrical short (voltage spike) is momentary, because under continued bias the leakage current causes regrowth of the dielectric in the damaged area. The regrown dielectric is not as thick as the original because the original dielectric was formed at a higher voltage than the working voltage of the capacitor. Therefore, it is assumed that the regrown dielectric represents a weak spot in the slug.

Similar capacitors from different vendors had different probabilities of failure and parts with a tight contact between the slug and the Teflon spacer behaved much better [5]. Different results obtained for different lots of capacitors might be partially due to the duration of storage after manufacturing. It was suggested that cold flow of Teflon might result in formation of gaps between the slug and spacer with time. In this case, passing the test on freshly made parts does not guarantee that they will remain reliable after years of shelf life. Although so far there is no direct evidence that this mechanism (cold flow) will cause vibration related failures, it is still possible and might be more important for advanced capacitors that are more susceptible to failures under RVT.

Military wet tantalum capacitors are mechanically robust, qualified at high levels of vibration (up to 53.8 rms g for CLR79, CLR81, CLR90, and CLR91 "H" designated units), and have been successfully used in space applications for many years. However, most advanced wet tantalum capacitors, in particular capacitors that are manufactured per DLA LAM DWG#93026 or #10004, are specified for 20 g of sinusoidal high-frequency vibration testing only, and often fail at relatively low levels of RVT (e.g. at 10 g rms [6]), which impedes their use in space projects. The failures are manifested as current or voltage spiking during the testing, increased leakage currents after testing, and sometimes as an explosion of a capacitor spraying electrolyte onto surrounding areas.

Advanced wet tantalum capacitors feature a special design of the cathode layers that are formed on the internal surface of the tantalum case. These layers might be made of different materials (e.g. palladium, ruthenium oxide, or carbon/niobium oxide) that replace traditionally used cathodes made of sintered tantalum powder. This replacement allows for a substantial reduction in the thickness of the cathode layer, using the additional volume to increase the size of the anode slug. Considering that these parts are using tantalum powders of a smaller size, a substantial increase in capacitance and decrease of the equivalent series resistance (ESR), from 1.5 to more than 6 times, have been achieved without increasing the size of the parts. However, increased mass of the anode slug raises the pressure between the slug and Teflon spacer during mechanical testing. Some cathode materials are fragile and can easily generate particles caused by scrubbing during insertion of the slug, deformation during the case crimping or mechanical testing. Oxide layers formed on tantalum particles with a smaller size have greater built-in mechanical stresses [7], and for this reason are more fragile and more susceptible to fracturing under RVT.

Manufacturers are trying to improve performance of newly designed advanced wet tantalum capacitors under vibration testing. For example, T16 series from Vishay and the relevant DLA MAL DWG #13017 are qualified at 27.78 rms g (condition II-G per MIL_STD-202) [8]. To assure a better performance of the parts under RVT various measures can be used: (i) a tighter control over the size of the case, spacer and the slug to reduce its movement; (ii) formation of cathode layers that do not generate particles; (iii) using a capped top Teflon bushing and crimping of cathode side of the case to allow a better anode clamping; (iiii) application of felt liners that cover anode slugs to ease their insertion into the case and reduce the probability of particles getting on the surface or inside the slug. However, tighter size control makes assembly processes more difficult, crimping has a risk of generating more particles from the deformed cathode, and the use of felt liners might increase rubbing at the spacer area. Considering the variety of processes, materials, and designs involved in formation of the cathode layers, approaches to assure mechanical robustness of the parts might be different by different manufacturers.

Another problem in development of mechanically robust wet tantalum capacitors is related to inconsistency of the test techniques used by different manufacturers and test labs. The existing requirements in MIL-PRF-39006 are not specific, so different test monitoring techniques and failure criteria are used by different test labs (see next section). In the absence of identical test conditions and acceptance conditions, test results might be ambiguous and the efforts of manufacturers in developing new designs are difficult to assess.

Multiple testing of DWG#93026 capacitors that failed RVT that were carried out by GSFC test lab and other high-reliability Original Equipment Manufacturers (OEM), showed that the failed capacitors can recover in subsequent tests and operate reliably for a long period of time. This is commonly explained by the efficient self-healing (oxide re-growth) of wet tantalum capacitors and considered as a justification for using the lot that failed RVT. However, the self-healing promotes gas (mostly H₂) generation that increases resistance of cathodes [9], causes embrittlement of the case, and increases internal gas pressures sufficiently to cause rupture of the case [6]. The difference between the internal and external pressure increases in space, thus increasing the risk of case rupture and failure. For this reason, effects of H₂ generation should be considered in selecting acceptance criteria for RVT.

In this work, the existing requirements and practice of RVT have been analyzed. Leakage currents of different types of wet tantalum capacitors have been monitored before, during, and after random vibration testing. A procedure and acceptance criteria for RVT have been suggested for different risk level space projects based on analysis of experimental data and modeling.

Existing requirements and practice

According to MIL-PRF-39006, RVT is carried out at the specified value of power spectral density and overall g rms (53.8 g rms for the most robust, “H” designated parts) for 1.5 hours in each of the three mutually perpendicular directions. Electrical measurements are to be made during the last 30 minutes of testing to determine intermittent open-circuiting or short-circuiting in the capacitors. The measurements should be carried out using equipment allowing detection of any interruption of duration $\Delta t_{\text{meas}} = 0.5$ ms or greater. Post test requirements include DCL measurements that should not exceed 125% of the specified value.

Defects in the dielectric introduced during vibration testing could be revealed by increased leakage currents. However, considering that it is not clear what is the margin between the specified limit and actual DCL values (there is no specific procedure to select limits for DCL in wet tantalum capacitors), the requirement to increase this limit by 25% after RVT is not justified. Experience shows that measured leakage currents in the parts might be orders of magnitude below the limit. For this reason, to evaluate the results of vibration testing, a delta analysis should be made and the 25% requirement should be applied to the difference between leakage currents measured before and after the testing.

Intermittent shorts or open circuits during RVT appear as spiking during the current/voltage monitoring. However, the measurement technique and failure criteria are not specified and MIL-PRF-39006 just requires no “intermittent open-circuiting or short-circuiting”. This allows different manufacturers and test labs to carry out and assess results of monitoring differently.

Wet tantalum capacitors have a relatively large value of capacitance, and low impedance at frequencies above $f = 2/\Delta t_{\text{meas}} = 4$ kHz, which allows detecting intermittent open circuit conditions by monitoring AC current through the part during RVT at a 0.5 msec rate. For this case, a failure criterion can be defined as a reduction of AC current below a certain level, $I_{AC_crit} = k \times I_{AC_norm}$, where I_{AC_norm} is the current for a good part and $k = 1/3$ is a failure criterion constant. The value of k is not critical because a substantial, orders of magnitude, reduction of current is expected.

Intermittent short circuits can be revealed by monitoring DC currents or voltage drops across the capacitor. However, due to the self-healing process and relatively large internal resistance of capacitors during breakdown (see next section), the amplitude of current spiking and voltage drops might be relatively small. For this reason, selection of the failure criteria for the short circuit conditions is not obvious.

In the absence of specific failure criteria, different test labs are using different acceptance requirements for the RVT that range from disregarding current spiking as evidence of short circuiting to setting a certain voltage drop limits as a rejection condition. For example, National Technical Systems (NTS) measures a voltage drop across 6 capacitors connected in parallel using an oscilloscope. The bank of capacitors is biased with a rated voltage through a resistor

that is 10 times greater than ESR of the part. A failure is determined when the voltage across the capacitors drops to 5% of VR.

A special equipment, Capacitor Fault Monitor model CFM12-350, was designed for RVT per MIL-PRF-39006 by Mertronics to detect intermittent opens or shorts in capacitors during vibration and mechanical shock testing. The equipment provides up to 350V bias voltage through 20 kOhm resistors and has 12 channels with the input comparators that are sampled at 40 kHz. The momentary shorts are monitored by sensing voltages and failures are detected when a drop of 10% between the voltage across the capacitor and the set voltage occurs during 0.5 msec or more. To detect open conditions, a 40 kHz sine wave is used and the failure is detected when the impedance drops to the value corresponding to $\sim 0.2 \mu\text{F}$.

Although the above examples of RVT are in compliance with MIL-PRF-39006 requirements, several drawbacks of the existing practices should be noted: (i) different set-ups have different sensitivity to short-circuiting, (ii) different failure criteria are applied, and (iii) a single scintillation event is sufficient to cause lot failure. To better understand the significance of scintillations, their possible effects on reliability, and set RVT criteria, a reliable and consistent technique to observe scintillations is necessary.

Simulation of current spiking during RVT

Current spiking during vibration testing is due to damage, most likely cracks in the dielectric similar to what is shown in Fig. 1a. The current flowing in the damaged area results in oxide growth similar to the process that formed the oxide initially. As the self-healing of the dielectric progresses, the current sharply decreases. The process can be described as a scintillation breakdown.

To simulate the scintillation process, let us assume that a capacitor C is connected to a power supply V_0 through an external resistor R . During the scintillation breakdown the capacitor will be short circuited for a duration Δt (typically below 1 msec) through an internal resistor r as shown in Fig. 1b.

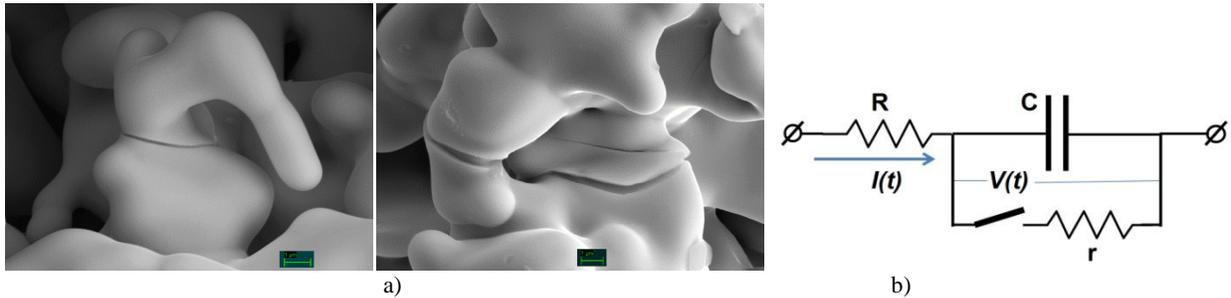


Figure 1. (a) Examples of cracks in tantalum pentoxide dielectric formed on the anode slugs. (b) An equivalent circuit simulating scintillation events.

Currents and voltages in the circuit can be described as follows:

$$I(t) = i(t) + C \frac{dV}{dt}, \quad V(t) = i(t) \times r, \quad V(t) = V_0 - R \times I(t), \quad (1)$$

where $i(t)$ is the short circuit current in the capacitor.

Solutions to these equations describe transients in the system during scintillations:

$$I(t) = \frac{V_0}{r + R} \times \left[1 - \exp\left(-\frac{t}{\tau'}\right) \right], \quad V(t) = V_0 \times \left[1 - \frac{R}{r + R} \times \left[1 - \exp\left(-\frac{t}{\tau'}\right) \right] \right], \quad (2)$$

at $0 < t < \Delta t$ (during scintillation), and

$$I(t) = \frac{V_0 - V(\Delta t)}{R} \times \exp\left[-(t - \Delta t) / \tau\right], \quad V(t) = V(\Delta t) + [V_0 - V(\Delta t)] \times \left[1 - \exp\left(-\frac{(t - \Delta t)}{\tau}\right) \right], \quad (3)$$

at $t > \Delta t$ (after scintillation).

The characteristic times in the equations above: $\tau' = \tau/(1+R/r)$ and $\tau = R \times C$, correspond to the rising and decreasing phases of the current transient during scintillation, and $V(\Delta t)$ corresponds to the voltage across the capacitor by the time the short ends.

The amplitude of the current spike is determined by the external limiting resistor, R , and internal resistor, r . The latter, depends on the specific resistance of the electrolyte, ρ , and the size of the crack, L , and can be estimated as $r = \rho/L$. Considering that the resistance of electrolyte is $\sim 1 \text{ Ohm} \cdot \text{cm}$ and the sizes of cracks can vary from $1 \mu\text{m}$ to $100 \mu\text{m}$, the values of r are in the range from 100 Ohm to 10 kOhm .

For a case of a $100 \mu\text{F}$ capacitor tested with a limiting resistor of $R = 10 \text{ kOhm}$ calculated variations of currents and voltages during scintillation events are shown in Fig.2. The duration of the short circuit period was assumed 1 msec and 10 msec , and the internal resistance varied from 100 Ohm to 10 kOhm .

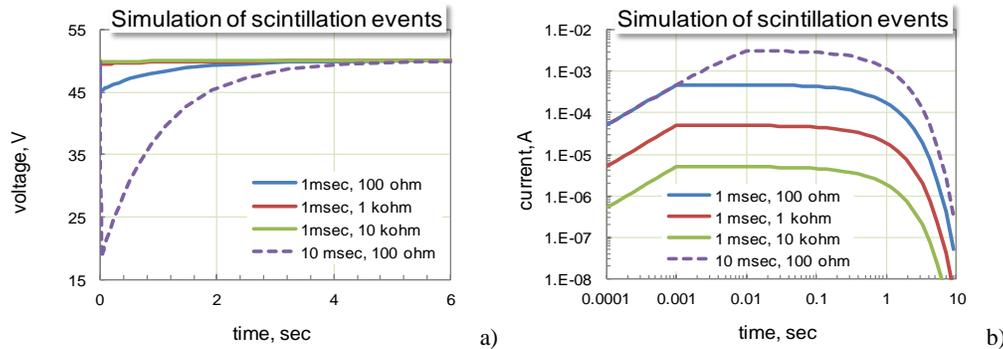


Figure 2. Voltage across the capacitor (a) and measured current (b) during scintillation events calculated per Eq.(2) and Eq.(3) for a $100 \mu\text{F}$ 50V capacitor connected to a power supply through a 10 kOhm resistor. The legends indicate duration of the short circuit, Δt , and the value of internal resistor, r .

Several conclusions can be made based on analysis of these results:

1. At $R = 10 \text{ kOhm}$, the voltage across the capacitor can drop substantially, to $\sim 10\% \text{ VR}$, at rather significant scintillations events when $\Delta t > 10 \text{ msec}$ and the damage is large enough to reduce r below 100 Ohm . This condition is close to a permanent short circuit, rather than to scintillation. Note, that the voltage drop decreases with the external resistor R and at low values, $\sim 100 \text{ ohm}$ or less, might be negligibly small.
2. The rate of current and voltage recovery is controlled by the value of $R \times C$ and occurs relatively slowly. For this reason there is no need for the sampling rate of 0.5 msec .
3. Considering that leakage currents in wet tantalum capacitors are typically in the range from 0.1 to $1 \mu\text{A}$, and the amplitude of current spiking is limited by the sum of internal and external resistors, detection of the scintillations can be carried out by monitoring currents through 10 kohm resistors at a 100 msec rate.

Limiting resistors do not affect possible degradation processes during scintillations. Due to large values of capacitors, the stored energy is sufficient to cause permanent damage to the part even when the external current in circuit is limited. For example, the size of tantalum that can be heated up to a melting point ($T_m = 3017^\circ\text{C}$) by the energy stored in a capacitor C charged to a voltage V at adiabatic conditions can be calculated as:

$$a = \sqrt[3]{\frac{C \times V^2}{0.66 \times \pi \times \rho \times c \times \Delta T}}, \quad (4)$$

where a is the radius of the tantalum sphere, $\rho = 16700 \text{ kg/m}$ is the density of tantalum, $c = 140 \text{ J/K} \cdot \text{kg}$ is the specific heat capacity, and $\Delta T \approx 3000 \text{ K}$ is the difference between room temperature and T_m . At $C = 100 \mu\text{F}$ and $V = 50 \text{ V}$, $a \approx 160 \mu\text{m}$ (6.4 mil), which is substantially greater than the size of a grain in tantalum anode slugs.

Experiment

Random vibration testing was carried out according to MIL-STD-202, TM 214, condition II, for 15 min sequentially at 10.76 g rms (Cond. II-C), 19.64 g rms (Cond. II-E), 34.02 g rms (Cond. II-H), and 53.79 g rms (Cond. II-K). Prior to the initiation of vibration, the parts were electrified at the rated voltage for 5 min . Leakage currents were monitored by measuring voltage drops across 10 kOhm resistors connected to each capacitor in series using a data acquisition system at 100 msec sampling rate. Four to six samples from each lot were used for the testing. Part

types used in this study are shown in Table 1. The first and the second numbers in the parts' index correspond to capacitance in microfarads and rated voltage in volts, the letter indicates the manufacturer, except for letter M that indicates MIL-PRF-39006 capacitors.

Table 1. Wet tantalum capacitors used in this study.

Group	Part, C_V_Mfr	C, uF	VR, V	case	DCL at 25C, uA	DCL at 85C, uA
1	100_15_M	100	15	T1	2	9
2	220_30_M	220	30	T2	3	16
3	560_25_A	560	25	T2	2	10
4	1800_25_A	1800	25	T4	4	25
5	470_75_A	470	75	T4	5	50
6	470_50_A	470	50	T3	3	25
7	150_100_A	150	100	T3	3	25
8	33_75_A	33	75	T1	1	5
9	110_75_A	110	75	T2	2	10
10	330_75_A	330	75	T3	3	30
11	470_75_A	470	75	T4	5	50
12	1500_50_D	1500	50	T4	15	110
13	470_75_D	470	75	T4	5	50
14	1200_75_D	1200	75	T4	25	250
15	560_25_B	560	25	T2	2	10
16	68_50_C	68	50	T1	1	5
17	220_50_C	220	50	T2	2	10
18	470_50_C	470	50	T3	3	25
19	680_50_C	680	50	T4	5	40
20	68_50_B	68	50	T1	1	5
21	220_50_B	220	50	T2	2	10
22	470_50_B	470	50	T3	3	25
23	680_50_B	680	50	T4	5	40
24	250_75_L2_C	250	75	L2	5	30

An example of test results for a 470 μ F 50 V capacitor tested at conditions II-E is shown in Fig. 3. In this example, the spikes had amplitudes from 2 to 20 μ A. The rise time was below 0.1 sec and the exponential decay had a characteristic time of 4.7 sec ($= 470 \mu\text{F} \times 10 \text{ k}\Omega$) that corresponds to the model described above. Note, that although Fig. 3 clearly indicates intermittent shorts, the voltage drops across the capacitor calculated per Eq.(3) are below 1 mV and most likely would be disregarded by some of the currently used techniques.

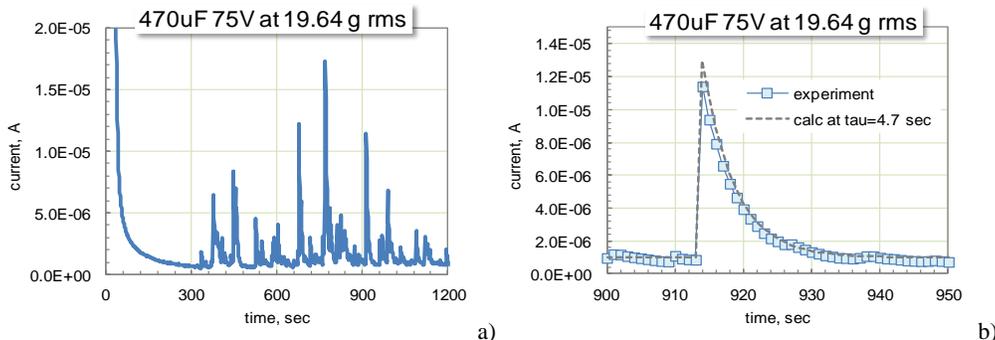


Figure 3. Typical results of random vibration testing showing current spiking (a) and approximation of the spike with an exponent calculated per Eq.(3) (b). Note that in this and the following figures vibration starts after 300 sec of electrification.

Results of step stress RVT

Examples of RVT results for different part types are shown in Fig. 4 and 5. On the charts below, scintillation events are indicated by sharp current spikes; however, by expanding the time scale an exponential decay similar to the one shown in Fig. 3b can be observed. The characteristic times in most cases corresponded to $C \times R$ values. Test results in Fig. 4a illustrate a case when no scintillations were observed at 34.02 g rms in five tested capacitors. Four out of five of these capacitors clearly failed the testing at the next level, 53.44 g rms (see Fig. 4b). Current spikes during this testing reached 0.45 mA, but the corresponded voltage drop across the capacitor was below 4.5 V. Obviously, these spikes would be disregarded and the lot would be accepted if a 10% voltage drop criteria is used.

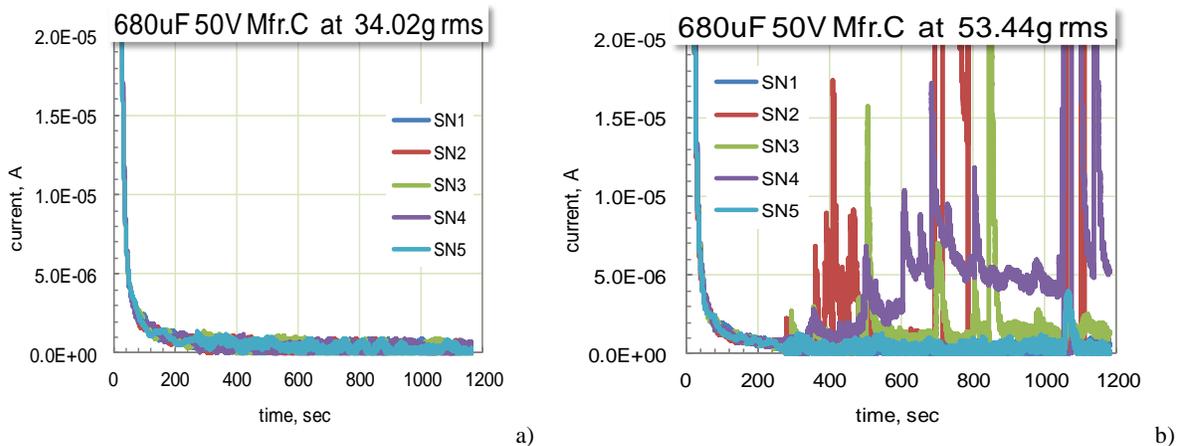


Figure 4. Variations of leakage currents with time for five 680 μ F 50 V capacitors during RVT at 34.02 g rms (a) and 53.44 g rms (b).

Testing of 470 μ F 50 V capacitors from Mfr.A showed some minor spiking at 10.76 g rms in 2 out of 4 parts (Fig. 5a) that increased notably at 19.64 g rms (Fig. 5b). However, the worst case spike amplitude was $\sim 7 \mu$ A, and the corresponding voltage drop ~ 70 mV only. Again, the presence of spiking is formally rejectable per MIL-PRF-39006, but the level of spiking, at least at 10.76 g rms, seems rather benign.

Note that tantalum capacitors employ an amorphous oxide layer that does not exhibit any piezoelectric response. For this reason, the observed spiking is not related to the piezo-effect as it might happen with ceramic capacitors.

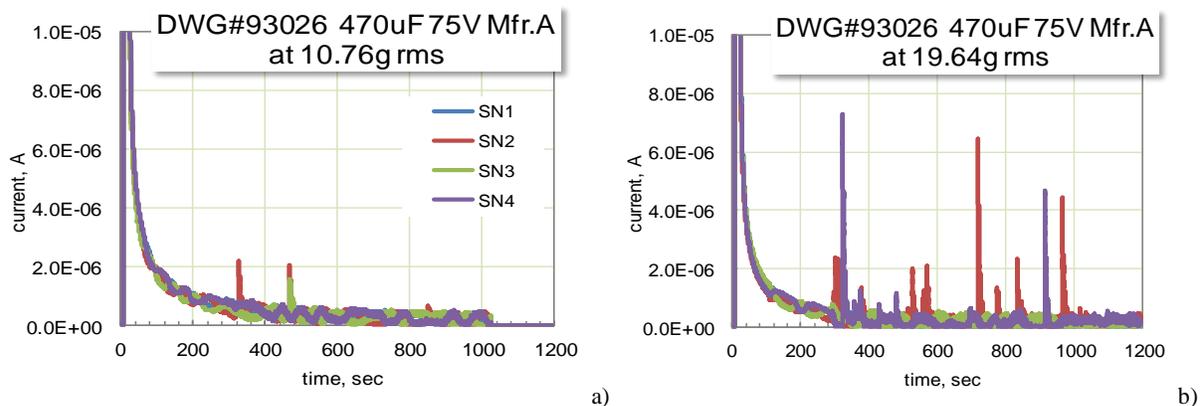


Figure 5. Results of RVT for four 470 μ F 50V capacitors at 10.76 g rms (a) and 19.64 g rms (b).

The technique used allows for an unambiguous detection of capacitors manifesting short-circuiting (scintillations) and discriminating them from the parts that do not have intermittent breakdowns as it is required per MIL-PRF-39006. Using this technique, the results of step stress random vibration testing of all parts shown in Table 1 were analyzed and the proportion of failures for different case size capacitors was plotted against the overall acceleration in Fig. 6.

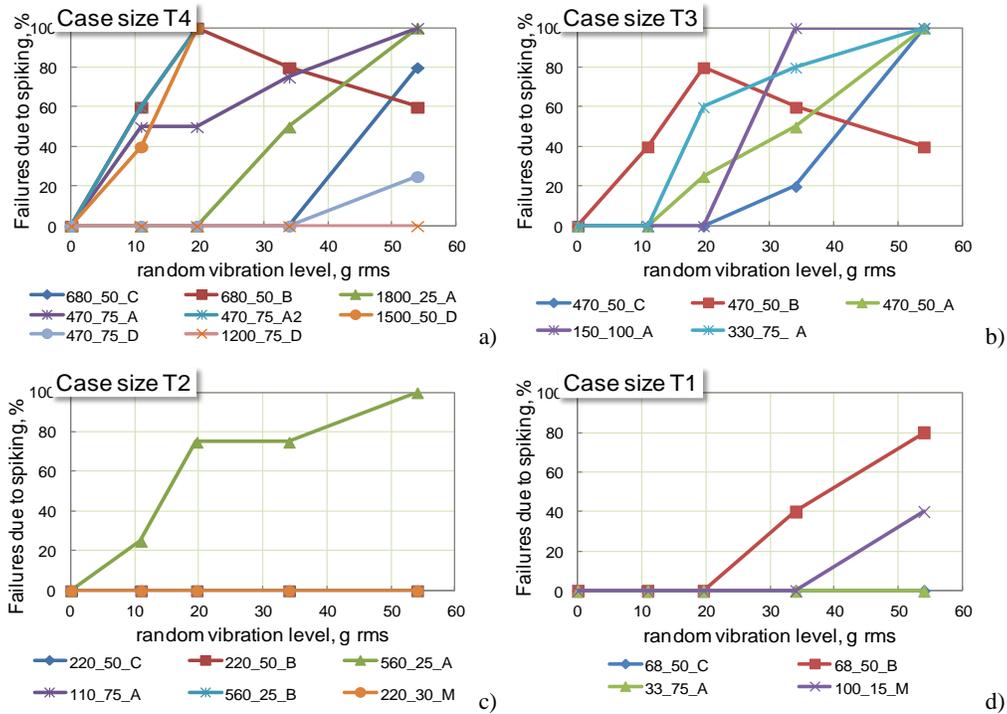


Figure 6. Proportion of failed capacitors detected by current spiking vs. stress level during 15 min step stress random vibration testing for different lots of parts in cases T4 (a), T3 (b), T2 (c), and T1 (d).

Analysis of the test results can be summarize as follows:

1. Generally, the proportion of failures increases with the level of stress. However, in two out of 23 lots some parts recovered at greater levels of stress. This is due to the self-healing process that was effective enough to restore the damaged area of the oxide during the testing.
2. The probability of failures increases with the size of capacitors. Four out of 8 tested lots in T4 cases had failures already after 10.76 g rms testing, whereas no failures were observed in four lots of capacitors in T1 case size even at 19.64 g rms.
3. Assuming that qualification for space applications requires testing at 19.64 g rms, only 4 out of 8 of T4 size, 2 out of 5 of T3 size, 5 out of 6 T2 size, and all 4 out of 4 T1 case size part types would be acceptable. Note that the testing was carried out in one direction only (perpendicular to the cylinder axis), so the results of full scale RVT might be even worse.

Post - RVT leakage currents

Results of monitored RVT and relaxations of leakage currents measured before and after RVT for two part types, 560 μ F 25 V and 470 μ F 75 V capacitors are shown in Fig. 7. In both cases substantial spiking was observed during vibration. However, leakage currents for the first part type were the same and followed identical relaxation before and after testing, whereas 470 μ F capacitors had increased leakage currents, behaved erratically and exhibited multiple current spikes. Monitoring of leakage currents in 470 μ F 75 V capacitors for 80 hours showed a trend of decreasing currents with time; indicating continuation of the oxide growth in damaged areas. The acceptable level of currents (5 μ A) was reached after a few hours under bias; however, spiking was still observed even after 10 hours of testing. Obviously, the level of damage was much less, and self-healing was much more effective, for 560 μ F 25 V capacitors. The following highly accelerated life testing (HALT) using these capacitors showed no anomalies.

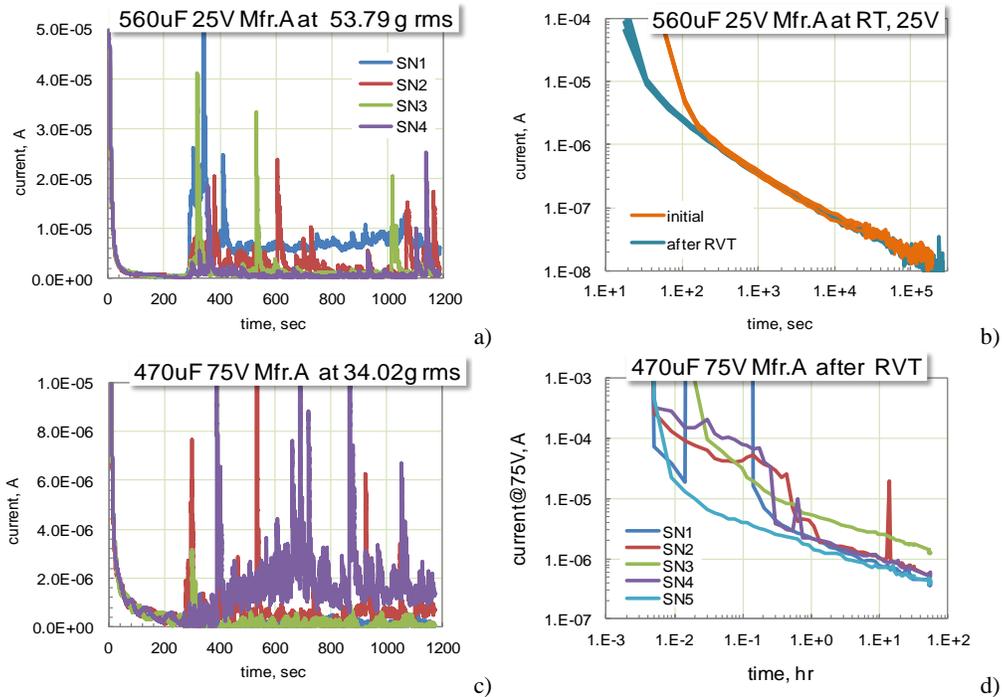


Figure 7. Monitored RVT (a, c) and relaxation of leakage currents with time at rated voltages before and after RVT (b, d) for 650 μ F 25 V (a, b) and 470 μ F 75 V (c, d).

In hi-rel applications wet tantalum capacitors are used at derated voltages, typically less than 60% of VR. To assess the recovery process at voltages below the rated, leakage currents in 470 μ F, 50 V and 680 μ F, 50 V from Mfr. B and C were monitored after RVT for 10 hours consequently at 20 V, 35 V, and 50 V. Results of these tests are shown in Fig. 8. Note that capacitors from both manufacturers exhibited significant spiking during the final step of RVT. Prior to RVT, similar value capacitors from both manufacturers had similar leakage currents. However, the post-RVT measurements revealed excessive leakage currents in capacitors from Mfr. C only.

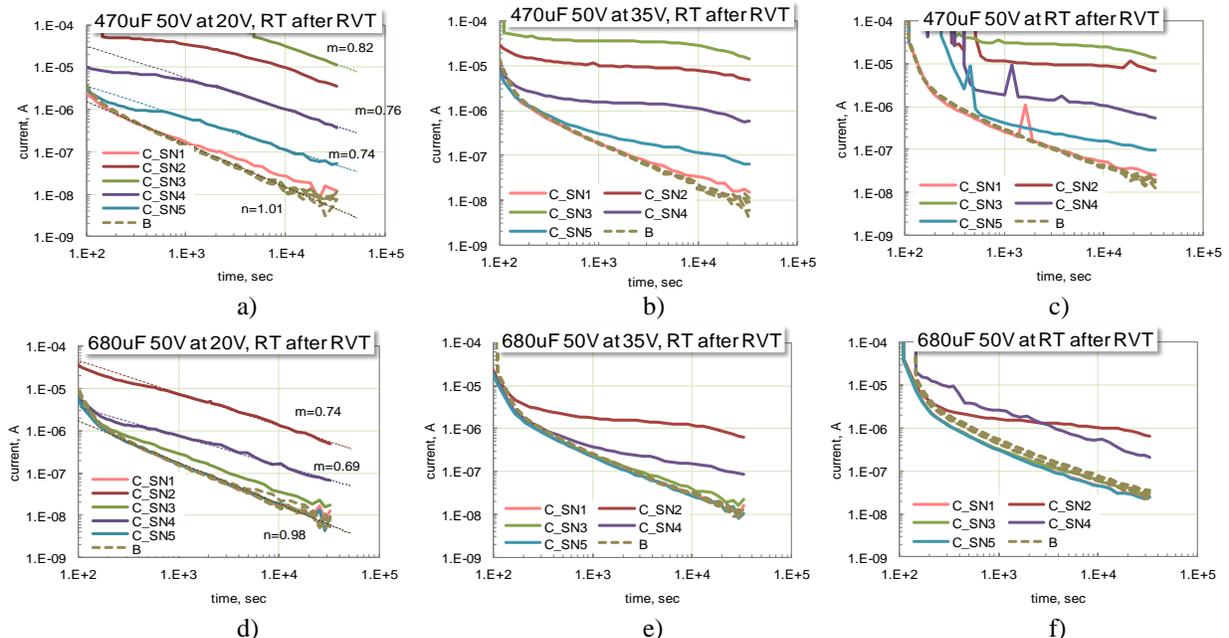


Figure 8. Relaxation of leakage currents with time of electrification at 20 V (a, d), 35 V (b, e), and 50 V (c, f) for 470 μ F 50 V (a, b, c) and 680 μ F 50 V (d, e, f) after RVT. Note that contrary to parts from Mfr.C, all capacitors from Mfr.B had currents similar to those observed prior to the testing.

The results show that currents in damaged capacitors decrease with time under bias roughly according to a power law, $I = A \times t^m$, where the constant m is in the range from 0.7 to 0.8, which is below the constant ($n \sim 1$) that describes absorption currents. The initial levels of currents in damaged capacitors vary by almost four orders of magnitude, but their recovery follows a power law with similar constant that apparently depends on the degree of damage.

Although currents decrease with time even at 40% of the rated voltage, 10 hours electrification at room temperature is not sufficient for full recovery. Ten hours were not sufficient even at 70% and 100% of the rated voltage and the currents remained one to three orders of magnitude greater than for virgin capacitors. Note that at 50 V the currents did not decrease smoothly, but exhibited spiking that are likely due to scintillation breakdowns in thin, freshly grown oxides at damaged areas.

To examine self-healing processes further, currents in the parts were monitored for 100 hours at room temperature, and then at 85°C and 125°C (see Fig. 9). The rate of recovery at room temperature (Fig. 9a, d) diminishes with time, and the exponent m decreases to ~ 0.3 . After 100 hour testing at room temperature, the currents still 1 to 2 orders of magnitude greater than initially.

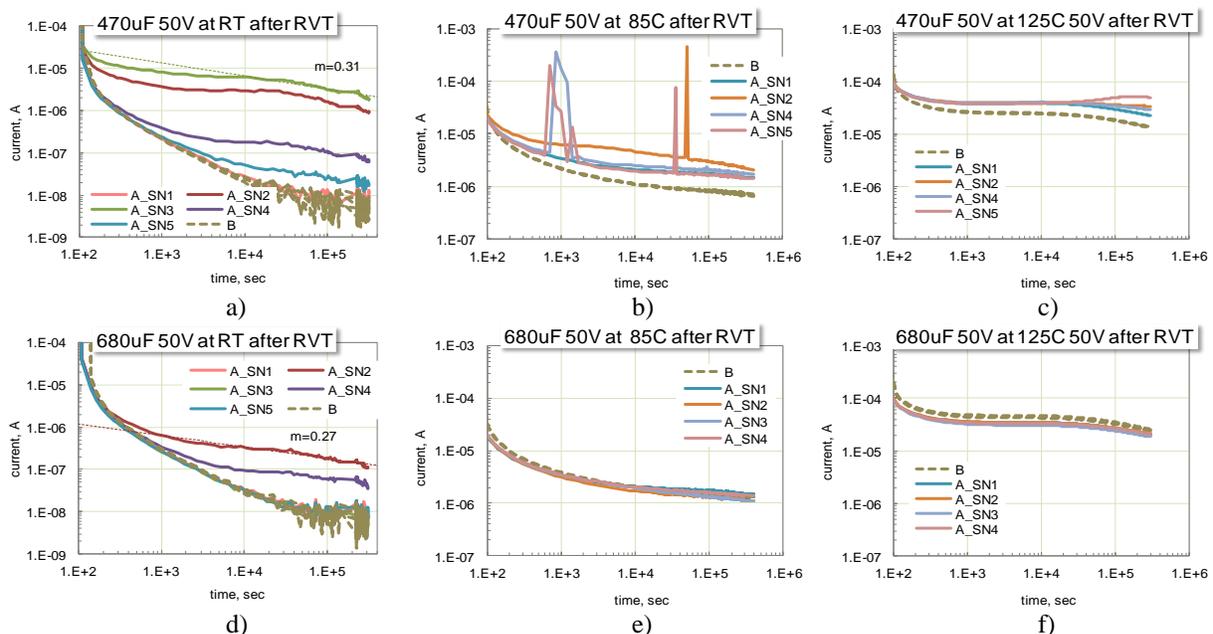


Figure 9. Leakage currents in the same parts as in Fig.8 during 100 hour testing at 50 V at room temperature (a, d), 85°C (b, e), and 125°C (c, f).

At 85°C, the difference between currents in damaged and normal capacitors was less than an order of magnitude for 470 µF capacitors (Fig. 9b) and practically identical for 680 µF capacitors (Fig. 9e). However, spiking of currents in 470 µF capacitors (Fig. 9b) indicates that scintillations still continue and in spite of self-healing. This means that capacitors damaged during vibration can pose a reliability risk. A more complete recovery occurs after 100 hour HALT at 50 V and 125°C (Fig. 9c and 9f). However, high intrinsic currents in the parts that are 3 to 4 orders of magnitude greater at 125°C than at room temperature might mask the presence of excessive currents related to the presence of defects. For this reason, to assure that the recovery process is complete, leakage currents should be measured at room temperature after a sufficiently long period of electrification to reduce absorption currents in the capacitors. Based on our experience, 1000 seconds is a reasonable compromise between the need to reduce substantially absorption currents and get test results fast enough.

Variations of currents measured after 1000 sec through the post-RVT testing for capacitors rated to 50 V are shown in Fig. 10. The results confirm that even severely damaged capacitors can restore their initial characteristics after 100 hours testing at rated voltage and 125°C. Capacitors with a lesser level of damage can be recovered at normal operating conditions.

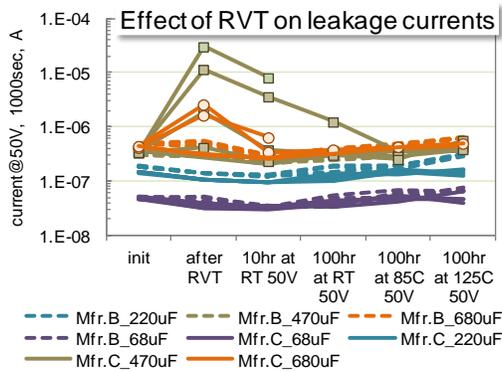


Figure 10. Leakage currents in capacitors rated at 50V measured before and after RVT. Marks indicate capacitors that had a substantial increase in DCL after vibration testing.

Discussion

Internal examinations of capacitors which failed RVT often reveal particles generated from cathode layers similar to those shown in Fig. 11. This is in agreement with the existing failure model, where particles that either jammed between the Teflon spacer and the slug or wedged between tantalum granules inside the slug are likely the major reason of RVT failures. These particles could be generated either by scrubbing during the anode slug insertion into the case, by the case deformation during crimping, or by mechanical and thermo-mechanical stresses during testing. Development of a more resistant cathode materials and optimization of the assembly process to reduce the possibility of shifting the slug inside the case might improve performance of the capacitors under mechanical stresses.

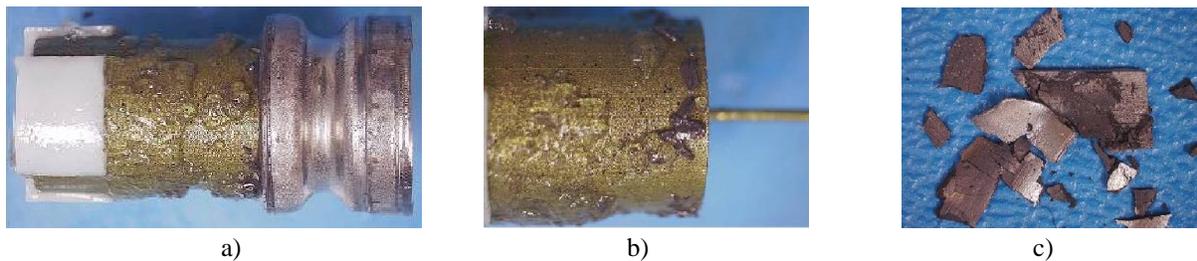


Figure 11. AN example of particles from the cathode material that were observed on the surface of slug in 330 μF 75 V capacitors from Mfr.A (a, b). Figure (c) shows fragments of the cathode layer. Although it is possible that some of the particles are artifacts related to cutting the case, similar particles can be generated during slug insertion or by the case crimping.

The particle-related mechanism of intermittent breakdowns during RVT implies that the failures are defect-related, and hence can be considered as infant mortality failures. In this case, RVT might be used as a screen to weed out potentially defective parts. From the other hand, mechanical stresses that are periodically applied to the slug during vibration might eventually cause fatigue-related or wear-out failures. In the latter case, using RVT as a screening process would consume the resource of the part and reduce its useful life. To assess the effectiveness of RVT as a screening procedure one needs to be sure that there is a substantial margin between the time to wear-out and duration of the screening.

In the attempt to assess the time to wear-out, 15 minutes cycles of RVT at high levels of vibration were repeated up to 3 hours of accumulated stress time. Results of these tests for three part types are shown in Fig. 12a. As seen previously, the number of failures varied with the stress duration inconsistently due to rapid self-healing. Nevertheless, no increase of the failure rate was observed, which indicates the possibility of using 15 min RVT as a screening procedure without a danger of causing wear-out failures within the next few hours of testing.

Results of multiple 15-minute tests for five samples of 470 μF 50 V from Mfr.B are shown in Fig. 12b where post-testing leakage currents are plotted against the duration of the stress at 64 g rms. In this case, it appears that the proportion of failures increases with the duration of test; hence, removing parts at the initial step of the test would not eliminate additional failures later on. Note that failures based on post-RVT DCL measurements correspond to a

greater level of damage to the part compared to the in-situ failures detected by spiking. In this case, different statistics might be necessary for the minor in-situ and more severe post testing failures.

Obviously, more data and analysis are necessary to make a decision for using RVT as a screening technique and selecting optimal test conditions. Currently, considering the variety of cathode materials and designs, and inconsistent history of behavior, RVT should be used as an acceptance test for each lot of wet tantalum capacitors intended for space applications.

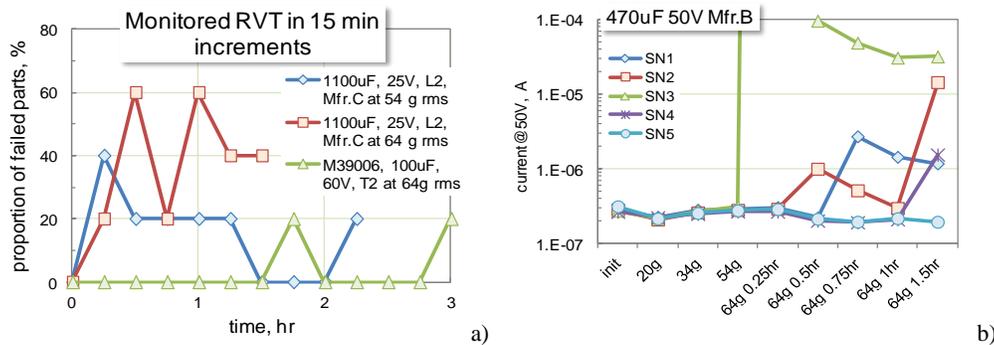


Figure 12. Variation of the proportion of failures with duration of random vibration testing for three types of capacitors (a) and variation of leakage currents through the testing of five samples of 470 μ F 50 V capacitors (b).

Due to the exceptional self-healing capability of wet tantalum capacitors, the parts exhibiting some limited amount of spiking during RVT can recover during the testing and operate reliably during applications. However, for projects that are not accepting any risks related to even minor damage to the dielectric, or requiring reliable operation during vibration, no current spiking should be allowed. Even a single spike that can be determined as a sharp increase in the current above $3 \times \text{DCL}$ should be a reason for lot rejection.

For the systems that are normally not operating during vibration or can accept capacitors with some damage to the dielectric, limited current spiking during RVT can be acceptable. In this case a careful evaluation of post-RVT currents in comparison with the initial characteristics might be sufficient. However, to reveal even minor damage to the dielectric, leakage currents should be monitored during RVT. Also, even if a unit is not operating during the launch, the system-level vibration testing is still carried out on operating units. For this reason, RVT should be carried out by monitoring currents or voltages on capacitors under bias.

Test results described above indicate that in most cases mechanical damage to the dielectric self-heals rather fast and does not cause increased leakage currents after the testing. This is often considered as a sufficient justification for using capacitors failing RVT in hi-rel applications. However, the self-healing goes along with electrolysis of the electrolyte and gas (mostly H_2) generation. The latter might increase internal pressure and cause embrittlement of the tantalum thus posing a risk of the case rupture and explosion in the system. This risk is greater for space systems operating in vacuum where internal pressure is not compensated by the atmospheric pressure.

To estimate what level of current spiking can be accepted before a substantial increase of gas pressure occurs, let us assume that the critical level of the pressure increase is $\Delta P = 0.1 \text{ atm}$ ($\sim 10 \text{ kPa}$). Calculations show that tantalum cases can sustain rather high internal pressures, more than a dozen of atmospheres. However, cold flow in the crimping areas and possible embrittlement due to hydrogen sorption might reduce the strength of the case substantially. Although the suggested criterion is rather conservative, it seems reasonable to eliminate possible risks of failures during operation in vacuum.

A part of the generated hydrogen, n_g moles, that increases pressure in the case will be accumulated in the gas volume V_g and another part, n_{el} , will be dissolved in the electrolyte having volume V_{el} . Some amount of hydrogen will be also dissolved in tantalum resulting in its embrittlement, but for conservative estimations it can be neglected.

The amount of H_2 that causes additional pressure ΔP can be calculated based on the gas law:

$$n_g = \frac{\Delta P \times V_g}{R \times T} \quad , \quad (5)$$

where $R = 8.3 \text{ J/K}_{\text{mol}}$, is the gas constant, and $T = 295\text{K}$ is the room temperature ($R \times T = 2.24 \times 10^4 \text{ mol/cc}_{\text{atm}}$).

The amount of hydrogen dissolved in the electrolyte can be estimated using the Henry's law, according to which the solubility of a gas in a solvent is directly proportional to the partial pressure of that gas above the solvent:

$$n_{el} = k_H \times V_{el} \times \Delta P \quad , \quad (6)$$

where k_H is a constant that for H₂/water system is 7.8×10^7 mol/cc_atm.

Assuming that the gas volume is a portion φ of the available free volume of the capacitor, V_f , the total amount of hydrogen can be calculated as follows:

$$n = n_g + n_{el} = \Delta P \times V_f \times \left[\frac{\varphi}{RT} + k_H \times (1 - \varphi) \right] \quad (7)$$

Hydrogen is generated in the process of reduction of H⁺ ions in the electrolyte and the relevant charge associated with the excessive current can be calculated using the Faraday's law:

$$Q_{cr} = \int_0^{t_{RVT}} i(t) \times dt = z \times F \times n_{cr} \quad , \quad (8)$$

where n_{cr} is the amount of hydrogen that causes pressure increase to $\Delta P = 0.1$ atm, $z = 2$ is the valence number, and $F = 96485$ C/mol is the Faraday's constant.

Case sizes (the length of the cylinder, L and its radius, R) as well as the calculated free volume, V_f , for different types of wet tantalum capacitors are shown in Table 2. The free volume available for gas accumulation was estimated as a half of the volume of case below the Teflon bush because a part of it is occupied by a porous anode slug (~50% pores), Teflon isolator, and gasket. Considering that the largest part of the free volume is occupied by electrolyte, for conservative estimations of the critical charge, we assume $\varphi = 0.05$. Values of the critical charge calculated per Eq. (5) to Eq.(8) are displayed in the last row of Table 2. Note that the values of Q_{cr} are close to the maximum transfer charge for reverse bias conditions according to DLA LAM drawings #93026 and #10004. Although the origin of this requirement for reverse bias is not known, it is possible that it is based on similar calculations.

Table 2. Critical charge for different case size wet tantalum capacitors.

Case size:	T1	T2	T3	T4	L2
L, mm	11.5	16.3	19.5	27	25.6
R, mm	2.4	3.6	4.8	4.8	3.6
Case volume, cm ³	0.21	0.66	1.41	1.95	1.04
V _f , cm ³	0.075	0.23	0.45	0.65	0.34
Critical charge, C	4.3E-03	1.3E-02	2.6E-02	3.7E-02	1.9E-02

For cases where current spiking was detected during RVT, values of the transferred charge, Q_t , were calculated by numerical integration of the $I-t$ curves. Results of these calculations as well as the results of RVT presented as a ratio of parts exhibiting spikes to the total number of tested capacitors (column "spikes") are shown in Table 3. For cases when several parts had spiking, the results of Q_t calculation are given for the worst case. The last column shows failures determined by excessive leakage current after RVT.

Out of 96 tests, 38 (40%) had failures due to the presence of current spikes. However, only in 6 cases (16%) out of 38, the spiking was extensive enough to fail the critical charge criterion. All lots that fail Q_{cr} eventually failed the excessive leakage current criterion, whereas all other lots had post-RVT leakage currents close to the initial values. A good correlation between results of the test using both methods confirms the correctness of the selected criteria.

Capacitors from the same manufacturer but with different lot date codes, e.g. 470_75_T4 1 and 2, had different probabilities of failure. Behavior of similar capacitors from different manufacturers was also different. The results indicate that the probability of failures during RVT is lot-related.

In the case of 680_50_T4_B capacitors, the transferred charge was close to the critical level. This indicates that there might be cases when a lot fails Q_{cr} criterion, but passes based on post-RVT leakage current measurements. These parts have greater risks of failures during the mission and should be rejected.

Table 3. Results of random vibration testing showing proportion of failures due to current spikes, critical transfer charge, and post testing measurements of leakage currents. Failures are indicated by red colors.

Part Number	10.8 g rms		19.6 g rms		34 g rms		54 g rms		Post RVT leakage
	spikes	Q _t , C	spikes	Q _t , C	spikes	Q _t , C	spikes	Q _t , C	
68_50_T1_C	0/5		0/5		0/5		0/5		0/5
220_50_T2_C	0/5		0/5		0/5		0/5		0/5
470_50_T3_C	0/5		0/5		1/5	3.4E-5	5/5	4.6E-1	4/5
680_50_T4_C	0/5		0/5		0/5		4/5	4E-2	2/5
68_50_T1_B	0/5		0/5		2/5	3.8E-3	4/5	8.6E-3	0/5
220_50_T2_B	0/5		0/5		0/5		0/5		0/5
470_50_T3_B	2/5	6.1E-5	4/5	1.2E-4	3/5	1.4E-2	2/5	8.9E-3	0/5
680_50_T4_B	3/5	7E-5	5/5	3.3E-4	4/5	1.4E-2	3/5	3.2E-2	0/5
250_75_L2_C	0/5		0/5		0/5		0/5		0/5
33_75_T1_A	0/5		0/5		0/5		0/5		0/5
110_75_T2_A	0/5		0/5		0/5		0/5		0/5
330_75_T3_A	0/5		3/5	1.6E-4	4/5	6.3e-4	5/5	7.7e-3	
470_75_T4_A 1	2/5	5E-4	3/5	4.1E-2	5/5	0.12			4/5
1500_50_T4_D	0/5		2/5	4.5E-2	5/5	0.1			3/5
470_75_T4_D	0/4		0/4		0/4		1/4	3.4E-4	
1200_75_T4_D	0/3		0/3		0/3		0/3		0/3
560_25_T2_B	0/5		0/5		0/5		0/5		0/5
100_15_T1_M	0/5		0/5		0/5		2/5	5E-4	0/4
220_30_T2_M	0/5		0/5		0/5		0/5		0/4
560_25_T2_A	1/4	1E-5	3/4	4.2E-4	3/4	5E-4	4/4	1.1E-3	0/4
1800_25_T4_A	0/4		0/4		2/4	1.3E-3	4/4	3.7E-3	0/4
470_75_T4_A 2	2/4	2E-5	2/4	5.3E-5	3/4	1.8E-4	4/4	1.4E-4	0/4
470_50_T3_A	0/4		1/4	1.1E-4	2/4	4.5E-4	4/4	2.7E-3	0/4
150_100_T3_A	0/4		0/4		4/4	9.3E-2	4/4	8.9E-2	2/4

Recommendations

1. Considering that space projects can use parts of different quality, the test flow in Fig.13 is recommended for quality levels L1, L2, and L3, per NASA/NEPAG risk matrix classification [10].
2. Due to diversity of materials used and designs of advanced wet tantalum capacitors, their poor history and inconsistent behavior under random vibration, RVT should be used as a lot acceptance test for each batch of capacitors intended for space applications.
3. Test conditions, in particular, the sample size (typically 6) and the level of stress (selected at 3 dB above the unit-level requirements; typically 19.6 g rms) should be in accordance with MIL-PRF-39006 with the following exceptions:
 - a. Stress duration 15 min in each direction;
 - b. Leakage currents at rated voltages should be monitored through 10 kohm resistors connected in series with each capacitor at a sampling rate of 0.1 sec. Vibration should be started after 5 min of electrification.
 - c. The presence of current spikes that exceed 3 times the level of currents measured at 5 min before vibration should be considered as an intermittent breakdown indicating a failure due to shorting.

4. Failures due to excessive gas generation shall be determined by comparing total charge transferred during vibration testing (from 300 sec to 1200 sec) with critical values that depend on the case size (see Table 2).
5. Leakage currents after the testing shall be monitored for 1000 sec at room temperature (5 sec sampling rate) for L2 and L3 projects, and also for 100 hours at 85°C (10 min sampling) for L2 projects. Increase of DCL above 25% of the initial levels (5 min measurements) and any evidence of current spiking shall be considered a post-testing leakage current failure.
6. Due to the cold flow of compressed Teflon gaskets and spacers, the slugs might become loose with time thus increasing the risk of capacitors' failures under vibration. For this reason, retesting is necessary if parts with lot date codes older than 5 years are to be used.

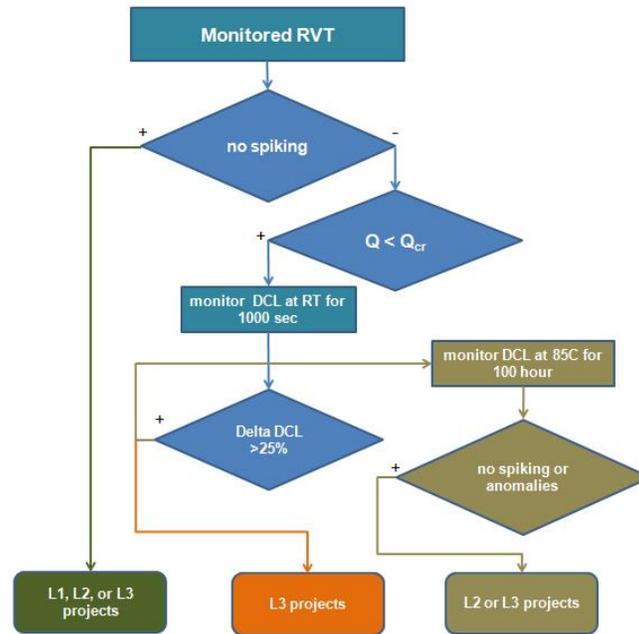


Figure 13. Test flow and acceptance requirements for random vibration testing for different risk level projects.

Summary

The existing requirements for RVT do not have failure criteria for intermittent short-circuiting, which allows for ambiguous interpretation of the test results. In the absence of specific test conditions and requirements, passing the test does not guarantee that the capacitors were not damaged.

Damage to the dielectric that occurs during RVT can affect reliability of the parts in two ways: (i) by increasing leakage currents and the probability of scintillation breakdowns and (ii) by raising the risk of mechanical rupture of the case due to embrittlement of tantalum caused by hydrogen generation and increased internal pressure.

Capacitors exhibiting some minor current spiking during the testing might self-heal to a degree that does not increase substantially the risk of failures. This can be assured by monitoring leakage currents after the testing and comparing leakages before and after RVT. To guarantee mechanical robustness of the capacitors, the gas generation, as measured through the transfer charge during current spiking should be below a certain critical level.

Modeling of the scintillation breakdowns and experiments show that intermittent shorting during RVT can be reliably detected by monitoring leakage currents through 10 kOhm resistors connected in series with capacitors at a sampling rate of 100 msec.

The probability of intermittent shorting during RVT is greater for capacitors in larger case sizes. The robustness of capacitors with similar values and sizes is both manufacturer and lot related.

Attempts to evaluate the possibility of using RVT as a screening process have been made, but the results were not conclusive.

RVT is recommended for lot acceptance of capacitors intended for space applications. Test requirements and failure criteria for different risk category projects have been suggested (see Fig 13).

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