NASA Electronic Parts and Packaging (NEPP) Program

NEPP Task:

Quality and Reliability of Advanced Wet and Solid Tantalum Capacitors

Guidelines for Selection, Screening and Qualification of Advanced Wet Tantalum Capacitors Used for Space Programs

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2012

Guidelines for selection, screening and qualification of advanced wet tantalum capacitors used for NASA space programs

I. Scope.

These guidelines are developed for use by NASA space projects and are applicable to extended range, high volumetric efficiency wet tantalum capacitors similar to those manufactured per commercial specifications (e.g. Vishay SuperTan capacitors, ST-, STA-, and STE-style, AVX TWA-style, Evans THQ-, HC-style), DSCC drawings (e.g. #93026, #10004, #04003, #04005), and per military specifications (e.g. MIL-PRF-39006/33, CLR93). These extended range capacitors employ new cathode layer materials and design that are different from the one used in M39006 types capacitors (sintered tantalum powder with anodic oxide layer).

Capacitors selected for space projects shall meet the requirements of MIL-PRF-39006 for "H" designated parts for all requirements that are not specified in Tables below. General comments for selection of wet tantalum capacitors per GSFC EEE-INST-002 should be used as applicable. In case of conflict between requirements this document shall prevails.

II. Background.

Wet tantalum capacitors are used typically in power supply lines, and their failure might have catastrophic consequences for the unit and space mission. Therefore all applications of wet tantalum capacitors should be considered as critical and they should be qualified for use in space systems after thorough screening and qualification for projects of all levels.

Extended range, high volumetric efficiency wet tantalum capacitors feature a special design of cathode layers that are formed on the internal surface of tantalum case (see Figure 1). These layers might be made of different materials (e.g palladium, ruthenium oxide, or niobium oxide) that replace traditionally used cathodes made of sintered tantalum powder. This replacement allows for a substantial reduction of the thickness of the cathode layer and for using of the additional volume to increase the size of the anode slug. Considering that these parts are using smaller size tantalum powders (so-called high-CV powder), 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. The range of rated voltages and capacitances for traditional wet tantalum capacitors (CLR79, 81, 90, and 91) and parts with high volumetric efficiency (DWG93026 and CLR93) for different case sizes is shown in Figure 2.

A substantial improvement in the performance of the parts (increased capacitance and decreased ESR) did not come free. In addition to a general concern that capacitors with larger value of

capacitance have typically a greater risk of failure (because capacitors with a larger surface area are more likely to have a defect in the dielectric) there are two new design-related issues: increased sensitivity to mechanical stresses (shock and vibration) and to reverse voltage conditions.

The first is due to the increased mass of the anode slug that raises pressure between the slug and Teflon insulator during mechanical testing, and to the presence of particles generated from the cathode layer. These floating in electrolyte particles can penetrate into pores of the slug and damage the dielectric when the slug is deforming as a result of stresses developed during mechanical vibration or shock.

The second issue, sensitivity to reverse bias, is due to changes in the cathode materials. In a traditional design of wet tantalum capacitors, a specially formed oxide layer on the surface of tantalum powder sintered to the case prevents high leakage currents in reverse polarity. In the absence of this oxide barrier, reverse currents became large and result in electrolysis of the electrolyte, which is typically a 30% to 40% by weight solution of sulfuric acid in water. At sufficiently large currents a fast generation of gases (mostly hydrogen) increases internal pressure in the case and might cause its fracture, explosion, leak of the electrolyte onto the board thus shorting and damaging other components in the system. Reverse bias might also result in a substantial increase of forward currents due to electroplating of the cathode materials on the surface of anode slug, prohibiting self-healing, and resulting eventually in failures due to increased internal gas pressure.

High reliability of wet tantalum capacitors, DSCC DWG93026 including, is due to a large degree to the self-healing process that results in oxide growing at the defective areas of the dielectric such as cracks, thin oxide areas, or microfissures. Experiments show that parts that failed after mechanical tests due to excessive leakage currents can recover with time of operation under bias. These excessive currents are typically due to mechanically-induced damage (e.g. cracking) to the tantalum pentoxide dielectric and recovery of these parts with time of operation under forward bias is a manifestation of the self-healing mechanism that results in a local electrochemical oxidation of tantalum at the damaged areas. The electrochemical oxidation results in the growth of the Ta2O5 dielectric similar to the process that forms dielectric initially during anodic oxidation of the tantalum pellet. This process goes along with the electrolysis of electrolyte and gas, mostly hydrogen, evolution. During the initial oxide growth the formed gases are dissolved in atmosphere, but when it happens in a hermetically sealed part, gas generation results in a buildup of the internal pressure. Hermetically sealed wet tantalum capacitors might sustain high pressures and some lots can pass life testing at high temperatures, up to 200 ^{o}C. However, diffusion of hydrogen into the case results in embrittlement of tantalum and increases the risk of its fracture. High internal gas pressure increases substantially the rate of electrolyte leaking to the glass seal area thus increasing leakage current on the surface of glass and the risk of corrosion of the weld between the tantalum tube and nickel lead. For these reasons, the capability of self-healing of wet tantalum capacitors should not be abused, and the risk of

damaging of tantalum pentoxide dielectric during mechanical stresses and the level of leakage currents under reverse bias should be limited by proper design, selection, and testing of the parts.

III. Failure Rate and Construction Analysis

Table I. Capacitor Requirements

Capacitor style and type	Reference specification	Failure Rate Level (FRL) required **1/**			Construction Analysis/DPA **2/, 3/**		
		Level 1	Level 2	Level 3	Level 1	Level 2	Level 3
CLR93	MIL-PRF-39006/33	R or S	P or R	M or P	3	1	N/A
SCD	e.g. DWG93026	N/A	N/A	N/A	3	1	N/A
Commercial **4/**	e.g. Vishay style ST, STA, STE	N/A	N/A	N/A	5	3	N/A

Notes:

1/ The failure rate (FR) is estimated by life testing at steady-state conditions that is obtained by accumulating the necessary amount of device-hours of operation at rated voltages and temperatures. Other tests e.g. ripple current life, thermal shock, mechanical vibration, reverse bias, etc. are qualification tests that do not determine reliability of the part quantitatively. Although FR is an important characteristic, it does not take into account multiple factors that might cause failures during system-level testing or application, and for these reasons capacitors with low FRL (e.g. parts rated to reliability level R or S) should not be confused with "space qualified" capacitors, and compliance with requirements in Tables II and III is imperative. Note also that FR for operating conditions can be substantially reduced by voltage and temperature derating; however, derating might not increase reliability under environmental stresses to the same degree as for steady-state operation.

2/ Construction analysis (CA) and destructive physical analysis (DPA) shall be performed per Appendix A.
CA/DPA sample size shall be per Table I or S-311-M-70 whichever is larger.

3/ Numbers indicate the quantity of samples required.

4/ Commercial parts are not recommended for Level 1 projects.

IV. Lot Acceptance Tests

Table II. Screening requirements (Group A testing)

Inspection/Test	Test Methods, Conditions, and Requirements **1/**	Part Type/Level		
		1	2	3
1. Visual and mechanical Examination	Marking, workmanship and design per applicable specification and in accordance with M39006 as applicable.	X	X	X
2. Thermal Shock	MIL-STD-202, Method 107, condition A (with step 3 at +125°C). 5 cycles -55C to +125C	X	X	X
3. Voltage Conditioning (Burn-In) **2/**	1.1*VR, 85C. Post–BI DCL should be within the specified limits and not exceed initial DCL values more than two times			
	160 hours	X		
	96 hours		X	
	48 hours			X
4. Electrical Measurements	At min, max, and room temperature as specified			
AC measurements: capacitance and dissipation factor **3/**	In accordance with MIL-PRF-39006 at 120 Hz	X	X	X
DC Leakage **4/**	In accordance with MIL-PRF-39006 but after 5 min of electrification	X	X	X
IR and DWV **5/**	MIL-STD-202, TM 302 and 301 if applicable	X		
5. Seal Test	MIL-STD-202, Method 112.			
Fine leak	Condition C	X	X	X
Gross Leak	Condition A or D	X	X	X
6. Percent Defective Allowable **6/**	5%	X		
	10%		X	
	20%			X

Notes:

1/ Test data shall be recorded for all parametric tests specified in this table.

2/ a) MIL-PRF-39006 requires voltage conditioning at rated voltage and for 48 hours only. This testing is carried out at working conditions (for both, temperature and voltage), does not create a sufficient stress to reveal defective parts and remove infant mortality failures in the extended range capacitors. Note that a similar burn-in test for solid tantalum capacitors (Weibull grading test) is carried out typically at voltages in the range from 1.3VR to 1.52 VR. Considering that wet tantalum capacitors operate at conditions close to breakdown, increasing voltage to more than 1.1VR might be risky. For this reason, stress voltage is increased to 1.1VR and duration of the test increased to 160 hours for level 1 parts and 96 hours for level 2 parts.

b) Post-BI measurements of DCL should be taken within 24 hours after the testing. Rising of DCL indicates degradation processes that might increase leakage currents with time of operation to the level when the rate of gas evolution will cause substantial build-up of the internal pressure and failures. For these reasons a possible increase of DCL is limited to the two times of the initial value.

3/ a) Some documents specify dissipation factors (DF), some equivalent series resistance (ESR), and some both characteristics. These parameters are not independent and one can be calculated if another is known:

$$ESR = \frac{DF}{2\pi fC}$$

b) The specified values of ESR are measured at 120 Hz and considering a substantial decrease of ESR with frequency (see Figure 3) are not related to the power dissipation caused by ripple currents that might have a much higher frequency.

c) ESR decreases with capacitance and these two parameters have a close correlation as shown in Figure 4. In applications with substantial ripple currents capacitors of larger values are preferable.

4/ a) Currents measured after voltage application are due to electron absorption in the dielectric and decrease with time, typically as a power function, $I \sim t^{-n}$, where $0.8 < n < 1.2$ (see Figure 5). In large-value wet tantalum capacitors this current decline might continue for hours before stabilization at a certain leakage level. M39006 requires measurements of DCL to be taken within 5 minutes of electrification. This allows manufacturers to complete DCL testing as soon as the reading is below the specified level (that is typically much greater than the actual level of leakage currents). However, for quality assurance purposes it is important to take measurements after the same electrification period, and to get data as close as possible to the real leakage currents. For this reason leakage currents should be measured after 5 min ±0.1 min of electrification.

b) Typically, leakage currents of wet tantalum capacitors are consistent and have very tight distributions, so any out-of-family parts can be revealed relatively easily, for example, a simple 3-sigma criteria can be used to identify and screen-out outliers.

5/ These tests evaluate the quality of the sleeves on the case of the parts only.

6/ Only DCL, seal test, and catastrophic failures of AC parameters (capacitance and dissipation factors) are considered. Failures related to parametric variations of capacitance and/or dissipation factor that do not exceed two times of the specified tolerance do not count for PDA calculations.

Table II.A. Requirements for group B testing

Inspection/Test	Test Methods, Conditions, and Requirements **1/**	Part Type/Level		
		1	2	3
Random vibration **1/**	Samples from each lot are tested as a part of lot conformance inspection. Method 214 of MIL-STD-202, test condition II-E (19.6 rms g), 1.5hr in two directions, last 30 min. – monitored. DCL, C, and DF to specification.	9(0) X	6(0) X	3(0) X

1/ According to NASA requirements all space units suppose to pass a random vibration test that simulates stresses during spacecraft launch. The level of vibration depends on the type of the launch vehicle, but typically Mission Assurance Requirements (MAR) acceptance conditions for space projects include random vibration testing at 14.1 rms g. To assure a certain margin to the box-level testing, it is reasonable to require that all wet tantalum capacitors should pass random vibration test at 19.6 rms g (test condition II E per MIL-STD-202). This level of stress is still far below the requirements for group "H" designated parts manufactured per MIL-PRF-39006 (overall acceleration 53.8 rms g). Note that during a random vibration test at 19.6 rms g spikes of acceleration can reach 50 g peak, so the high frequency test is not a replacement for the random vibration test.

V. Qualification

Table III. Qualification requirements.

Inspection/Test	Test Methods, Conditions, and Requirements **1/**	Part Type/Level		
		1	2	3
Group 1	For qualification testing use parts that passed			
Screening to Table II	screening tests.	X	X	X
Group 2	Shock and vibration HF in accordance with MIL-PRF-39006.	12(0)	6(0)	4(0)
Shock	Method 213 of MIL-STD-202, condition D- half sine (100 g's), DCL, DC, and DF to specification.	X	X	X
Vibration, High Frequency	Method 204 of MIL-STD-202, condition H (20 g's), 2 axes, 4 hours each axis, last 30min. – monitored. DCL, C, and DF to specification.	X	X	X
Thermal shock	Per MIL-PRF-39006, 300 cycles -55C to +125C.	X	X	
Group 3	In accordance with MIL-PRF-39006	5(0)	3(0)	3(0)
Solderability	MIL-STD-202, TM 208	X	X	
Terminal strength	MIL-STD-202, TM 211, test conditions A and C	X	X	X
Group 4	In accordance with MIL-PRF-39006	12(0)	6(0)	3(0)
Resistance to solvents	MIL-STD-202, TM 215	X	X	
Resistance to soldering heat **2/**	MIL-STD-202, TM 210	X	X	X
Moisture resistance	MIL-STD-202, TM 206	X	X	
Group 5 2/	In accordance with MIL-PRF-39006	12(0)	6(0)	3(0)
Stability at low and high temperatures	In accordance with MIL-PRF-39006. C, DF, and DCL at 25C, -55C, 85C, and 125C	X	X	X
Surge voltage	In accordance with MIL-PRF-39006. 1000 cycles of 1.15VR at 85C, 0.5 min charge, 5.5 min discharge through 1kOhm.	X	X	
Reverse voltage **3/**	In accordance with MIL-PRF-39006 at T= 85C except for reverse voltage is reduced from 3V to 1.5V and duration of testing as shown below:			
	Level 1: 96 hours followed by 96 hours at VR	X		
	Level 2: 48 hours followed by 48 hours at VR		X	
	Level 3: 24 hours followed by 24 hours at VR			X
Group 6	In accordance with MIL-PRF-39006	22(0)	22(0)	11(0)
AC ripple life **4/**	at T= 85C, VR, 63% of ripple current, 40 kHz. DCL, C, and DF to specification			
	Level 1: 2000 hours	X		
	Level 2: 1000 hours		X	X
Group 7	per JEDEC JESD22-A103 Condition B	5(0)	3(0)	N/A
High temperature storage life **5/**	1000 hrs at 150 C Visual examination; DCL, C, and DF to specification.	X	X	

Notes:

1/ Test data shall be recorded for all parametric tests specified in this table.

2/ No external visual or catastrophic electrical failures after resistance to soldering heat testing are allowed. In case of parametric failures the lot might be accepted based on additional tests suggested by FRB.

3/ Tantalum capacitors that have been used for space applications so far (MIL-PRF-39006 capacitors) are qualified by testing at 85 C and 3 V reverse bias for 125 hours and are proven to have a sufficient margin to accommodate possible reverse bias stresses that might happen during ground phase testing and integration period and during applications.
DSCC DWG93026 and MIL-PRF-39006/33 does not allow continuous operation at reverse bias and possible transient reverse voltage surges should have peak reverse voltage ≤ 1.5 V and the product of the peak current times the duration of the reverse transient should be less than 0.05 ampere-second. However, there is no clear description of the test to verify the suggested limit and most importantly, experiments show that some part types might fail at a transfer charge that is much lower than 0.05 C, whereas others can sustain much greater transfer charges.
Considering that reverse bias conditions might happen during testing and troubleshooting of the systems, or due to unforeseen circumstances during the mission, testing for reverse bias at 85 C and 1.5 V is a reasonable compromise for these type of parts.

4/ Ripple current life test shall be carried out at 85C and rated voltage with 63% of the rated AC ripple current at 40 kHz. These conditions envelope DC life testing and for this reason only ripple current life test is required.
This test is required for every lot of level 1 and level 2 parts. For level 3 parts results of testing of the same part type capacitors that are completed within a year of the procurement lot date code are acceptable.

5/ Failures of wet tantalum capacitors are often related to the internal gas pressure that is building up due to electrolysis of the electrolyte caused by excessive leakage currents in forward (e.g. due to damage in the dielectric as a result of mechanical stresses) or in reverse directions. In these cases, mechanical integrity of the part and its capability to sustain large internal pressures determine the probability of failure. For this reason it is important to assure that the part is robust enough, will not degrade with time under pressure, and the electrolyte will not leak above the bushing Teflon insulator to the glass seal area and cause corrosion of the lead weld. Although HTSL testing does not result in hydrogen generation and does not imitate closely degradation of the case strength related to hydrogen embrittlement caused by electrolysis of the electrolyte, it simulates long-term effect of high internal gas pressure. Passing this test gives additional assurance in quality and reliability of the extended range wet tantalum capacitors.

VI. Freshness policy

Due to the cold flow of compressed Teflon gaskets and loss of elasticity of the silicone rubber O-ring gaskets there is a risk of internal dehermetization of the parts that might cause a leak of electrolyte to the glass seal and cause corrosion of the weld with time of storage. Note that the seal test is not capable of revealing this type of degradation.

As a result of cold flow of the Teflon insulator, the anode slag can become loose. This might increase the risk of damaging of the tantalum pentoxide dielectric during mechanical stresses. For these reasons the use of parts with lot date codes older than 5 years is not recommended. If these parts are to be used, rescreening and requalification are required. Lot acceptance testing shall consist of steps 1, 4 (except for measurements of IR and DWV, that are related to the sleeve), and 5 of Table II (no catastrophic failures allowed) and random vibration per Table II.A. Requalification shall consist of groups 3, and 5 (stability at low and high temperatures only) of Table III (no catastrophic failures allowed).

VII. Derating

Table IV. Derating Requirements

Voltage Derating Factor **1/**	Maximum ambient temperature	Ripple current
0.6	70 °C	TBD **2/**
0.4 **3/**	110 °C	

Notes:

1/ The derating factor applies to the sum of peak AC ripple and DC polarizing voltage.

2/ Derating for ripple currents of parts for space applications should account for changes in the heat dissipation of the part in vacuum. The requirements will be determined in 2013.

3/ Derate voltage linearly from 70 °C to 110 °C.

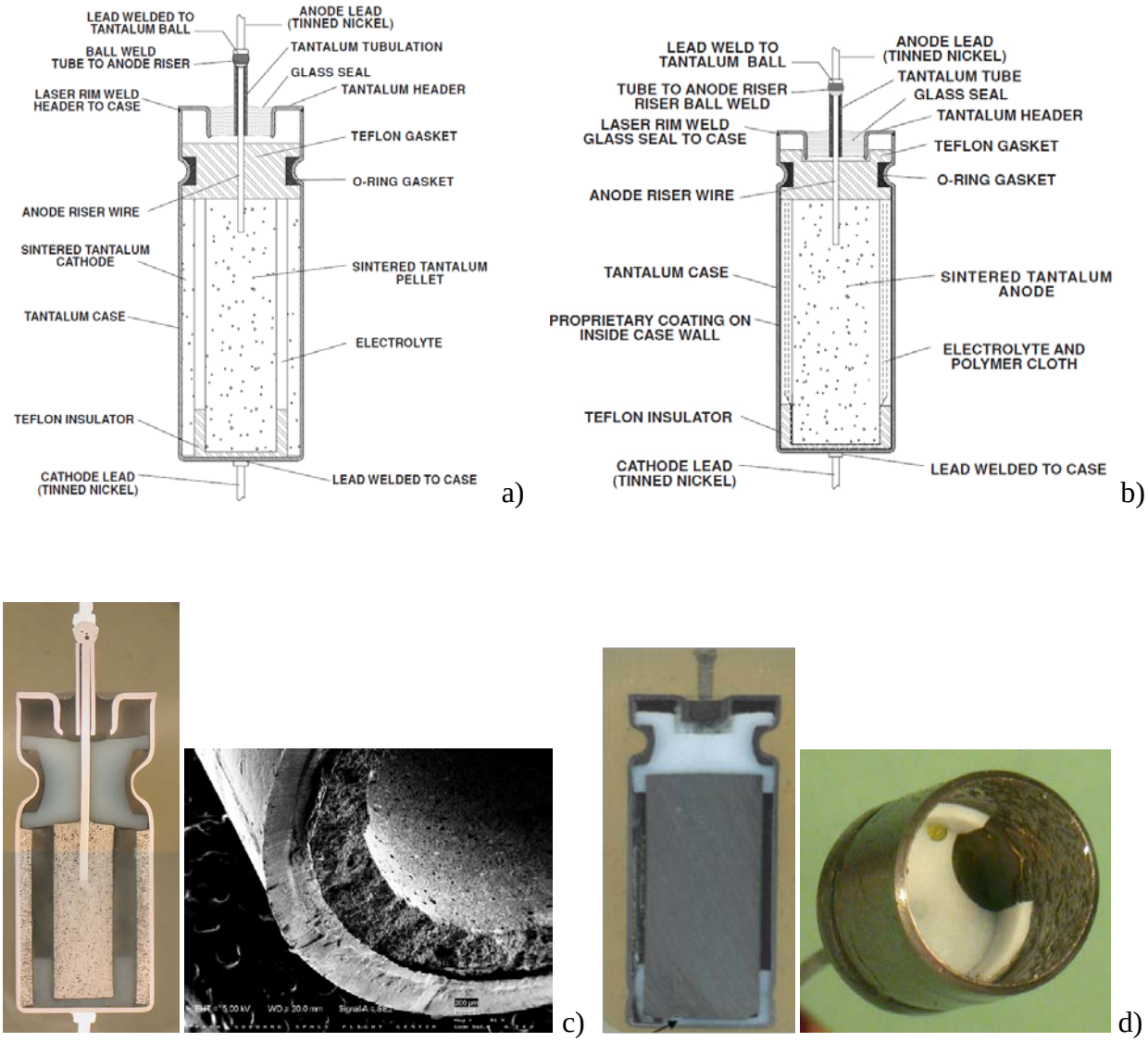


Figure 1. Drawings of a regular tantalum cathode MIL-PRF-39006 capacitor (a) and an extended range capacitor per DWG93026 (b) manufactured by Vishay. Figures c) and d) show cross-sectional and internal cathode areas views of a regular (c) and extended range (d) wet tantalum capacitors. Note the difference in the thickness of cathode layers in regular (a, c) and extended range (b, d) wet tantalum capacitors.

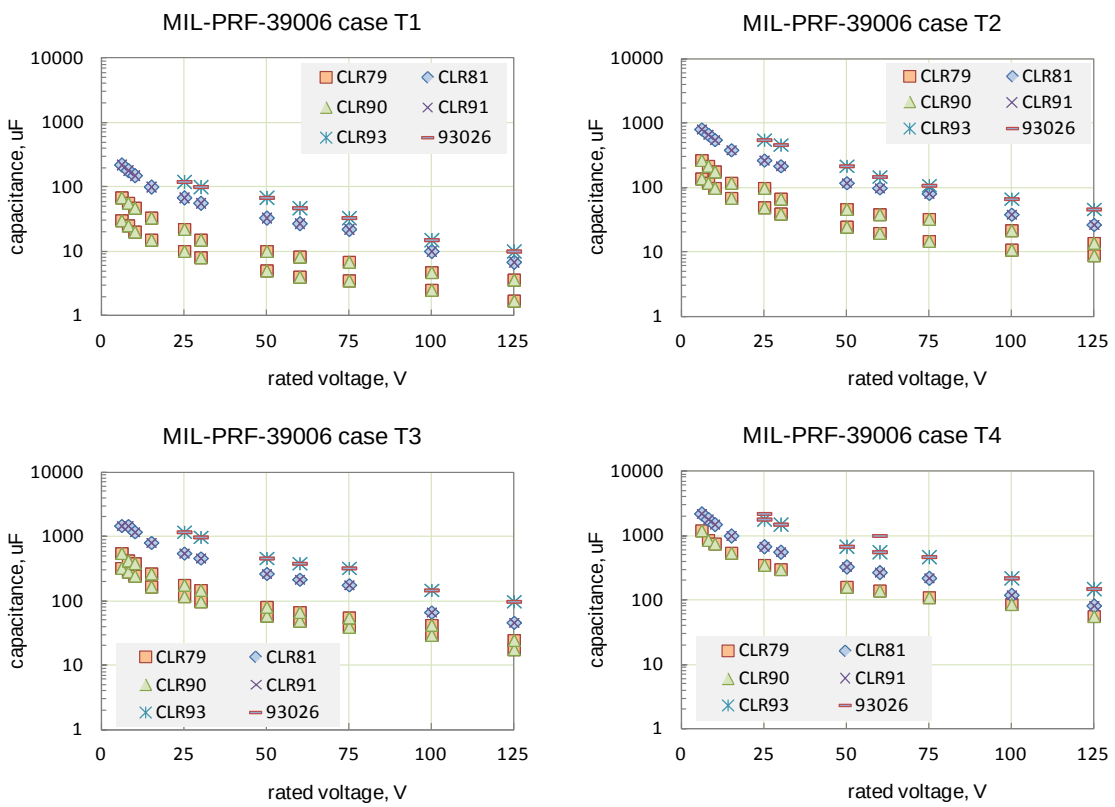
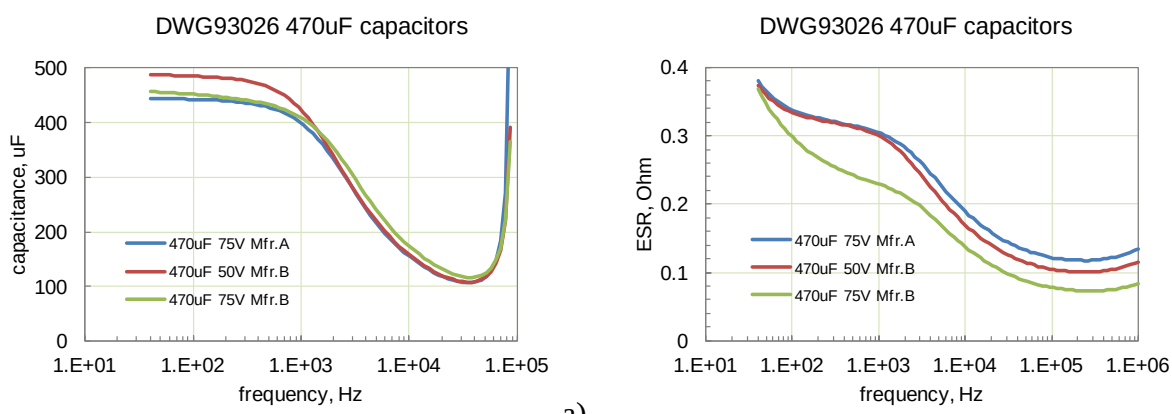


Figure 2. Comparison of the ranges of capacitance and rated voltages for different part types in case sizes T1, T2, T3, and T4.



a) b)

Figure 3. Example of frequency dependencies of capacitance (a) and equivalent series resistance, ESR, (b) for 470 uF 93026-style capacitors. Note that the roll-off of capacitance starts at ~ 1 kHz and the self-resonance frequency of the parts is ~ 100 kHz.

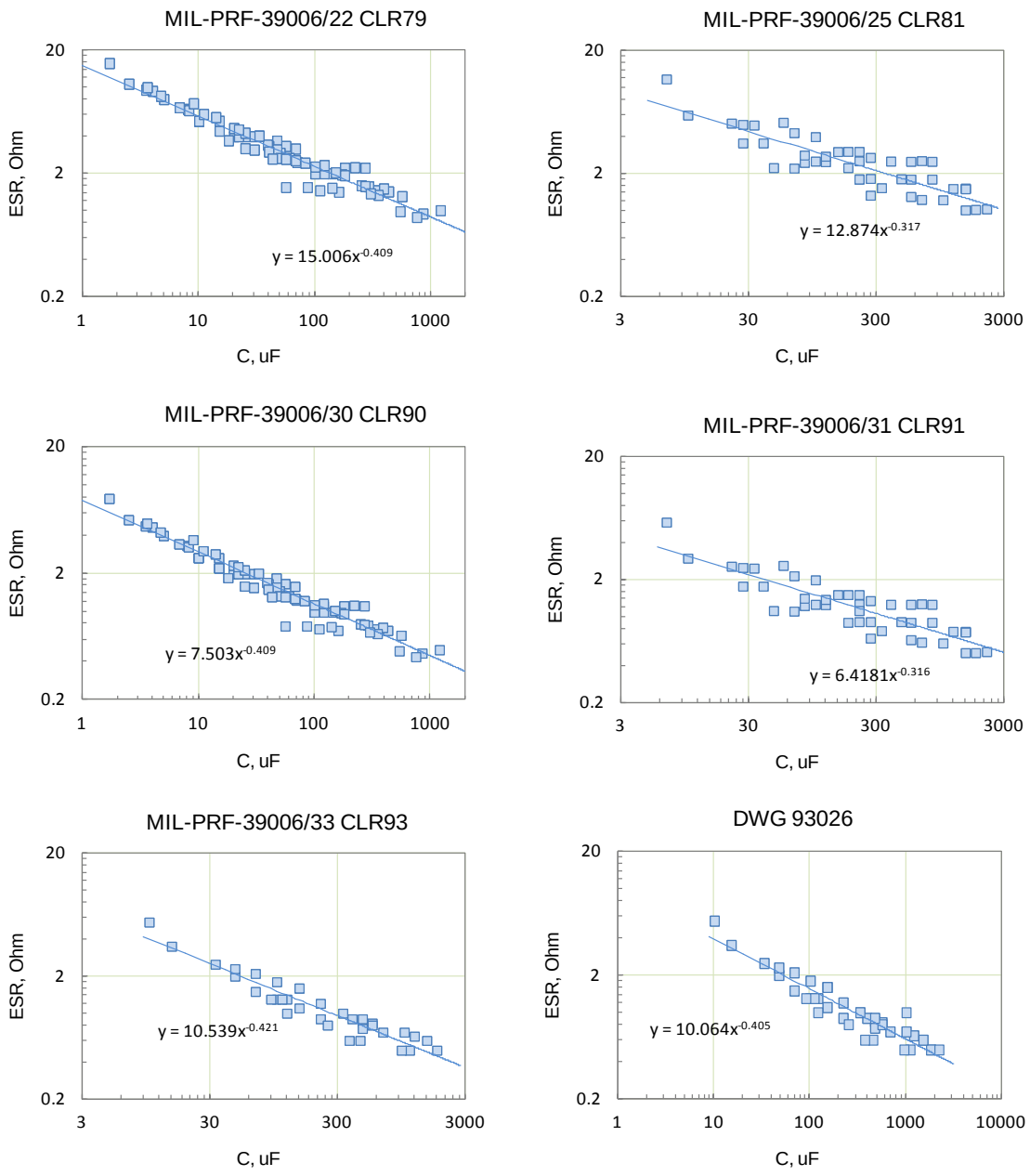
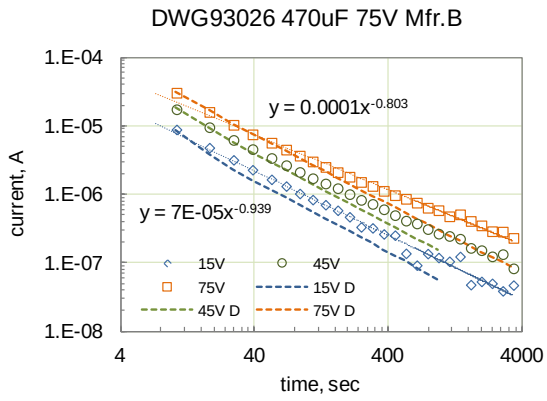
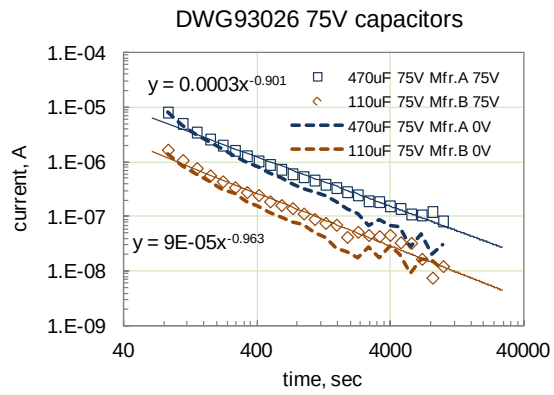


Figure 4. Correlation between the specified values of capacitance and equivalent series resistance (ESR) for different styles of wet tantalum capacitors.



a)



b)

Figure 5. Examples of variations of currents with time after voltage application for 75 V 93026-style capacitors. Figure a) shows current relaxation for a 470uF capacitor at different voltages and figure b) shows current variations for 110uF and 470uF capacitors. Note that depolarization currents (dashed lines) that were measured in short circuit capacitors right after polarization are close to the polarization currents. This means that DCL values for the extended range capacitors are normally due not to the presence of defects, but to the charge absorption processes (electron trapping in the dielectric).

Appendix A

Construction analysis/DPA for wet tantalum capacitors

Considering a high price of space-grade wet tantalum capacitors, to reduce the cost of the analysis and get more information related to quality and reliability of the parts, CA/DPA is recommended to carry out using vibration test or life test samples.

Test	Procedure
Prohibited materials	Verify that pure tin is not used as a lead finishing material using XRF analysis
External visual	Per MIL-PRF-1580, TM 10.8.
Crimp level [1A/]	Measure diameters of the case and groove area.
Radiography [2A/]	Side view only. Check for bulging, location and alignment of the slug.
Hermeticity	Per MIL-PRF-39006
Decapsulation	Per MIL-PRF-1580
Internal examination	Check for particles in the electrolyte, on the surface of cathode, anode, and on the cloth or felt liner if used. Check for proper locations of the Teflon and O-ring rubber gaskets
Cathode coating/material [3A/]	Composition of the cathode material should be evaluated using XRF or EDS. Condition and integrity of the cathode layer should be evaluated using high-power optical microscope or SEM.
Anode slug [4A/]	a) Low power optical examination: anode slug should be of uniform color and free of defects. b) SEM examination: examine areas along the edges of the anode slug (at X5,000 minimum) to reveal cracks, oxide crystals, and foreign materials.

Notes:

1A/. Diameters of the case and groove area as it is shown in Figure 1A should be measured to estimate the level of crimping C = d/D*100. Typically, for T2 cases the value of C is within the range from 69% to 72%.
Insufficient crimping might result in poor internal sealing. Over crimping might cause excessive cracking in the cold flow area of the case similar to those shown in Figure 2A. These cracks reduce the strength of the case and facilitate diffusion of hydrogen that might cause intergranular brittle fracture with time of operation under high internal gas pressure.

2A/. Radiography can reveal bulging of the case and improper location of the slug (see Figure 3A).

3A/. In cases when the specification for the part indicates material of the cathode layer, or this information is available from previous DPAs, check for any material or design changes in the lot.

4A/. Defects in anodically grown tantalum pentoxide dielectrics similar to those shown in Figures 4A and 5A are considered responsible for excessive leakage currents and failures of tantalum capacitors. These micrometer- and sub-micrometer size defects are always present in the dielectric and at relatively low concentration most likely are not a reliability concern. However, excessive concentration of these defects might result in excessive leakage currents that would cause gas generation, build-up of internal pressure, and failures of the parts.
Due to the field-induced crystallization, concentration of crystals is typically greater on parts after life testing. Large concentration of the crystals after voltage conditioning indicate a greater than normal level of degradation in the dielectric and require additional analysis and testing to assure long-term reliability of the part.
Experience shows that the probability of crystal growth and fracturing of the dielectric is greater along the edges of the slug. For this reason areas of the curved side of the slug close to the bases are recommended for inspection.
Note: dry the slug properly to remove electrolyte from the pores before SEM examinations.

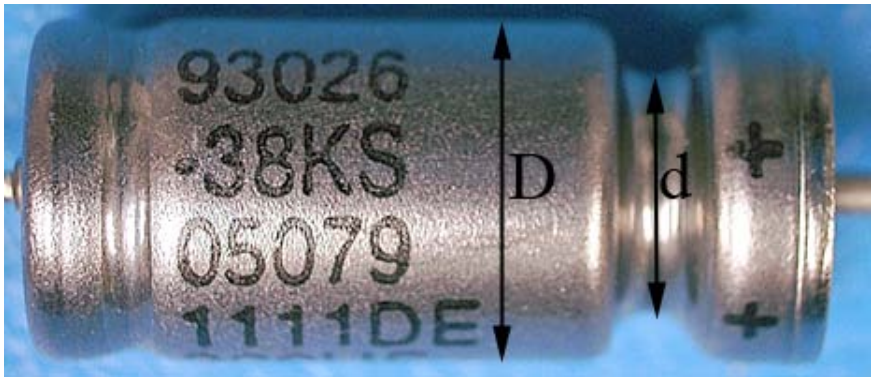


Figure 1A. Sizes of the case (D) and groove area (d) of the capacitor that allow for estimation of the crimping level.

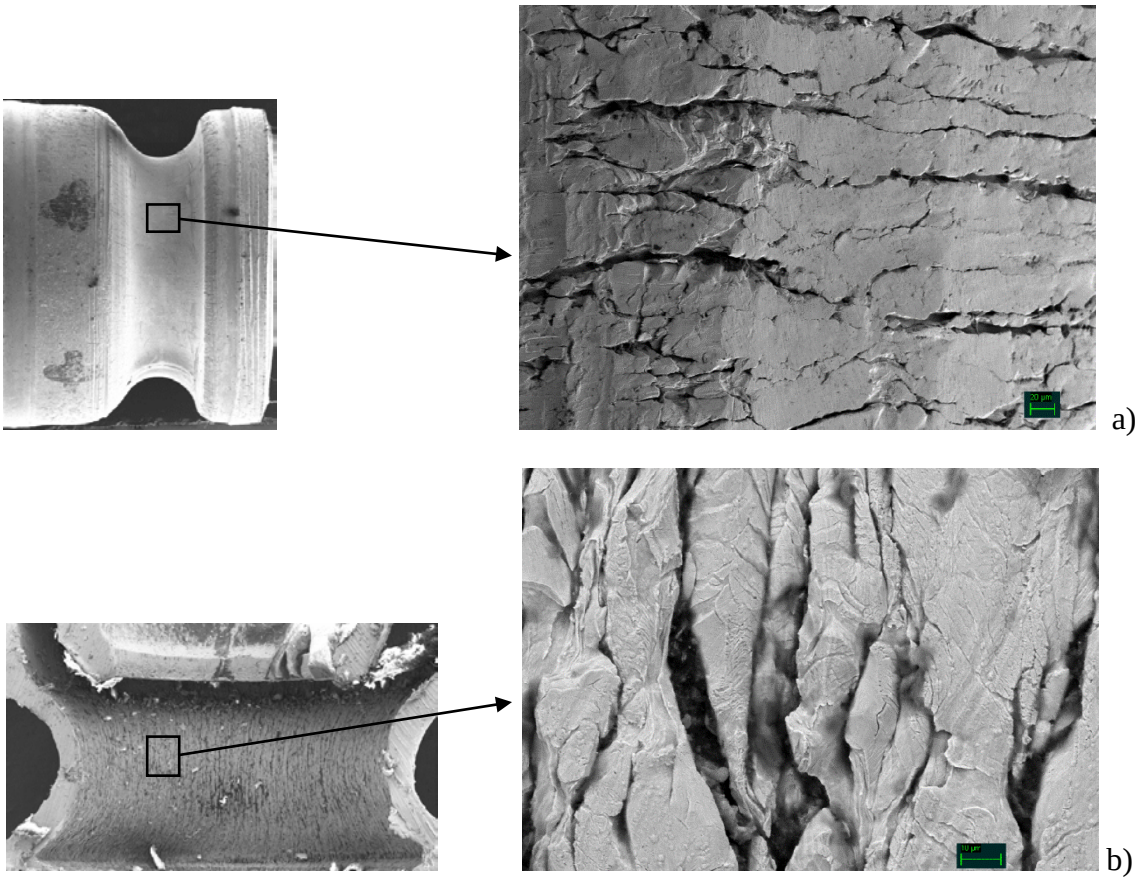


Figure 2A. External (a) and internal (b) surfaces of the crimped area showing cracking caused by cold work during formation of the groove.

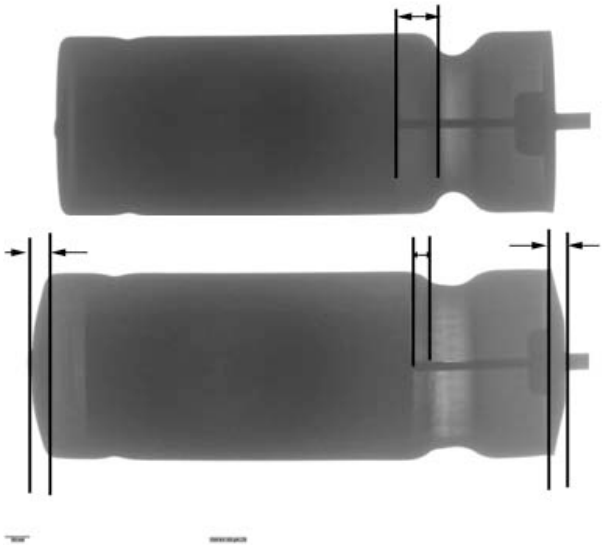


Figure 3A. Radiographic views of a normal (top picture) and bulged (bottom picture) capacitors. Note a shift to the right of the slug compared to a normal location.

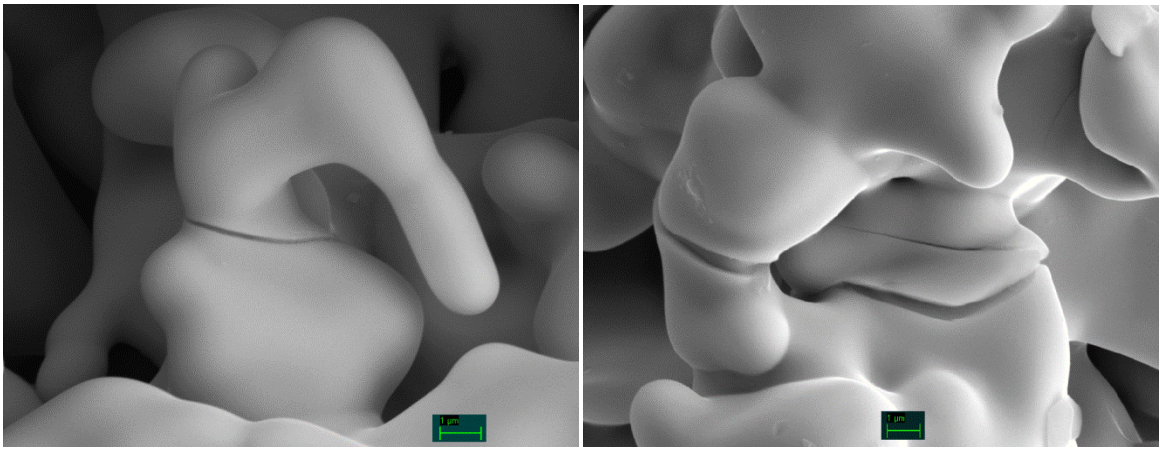
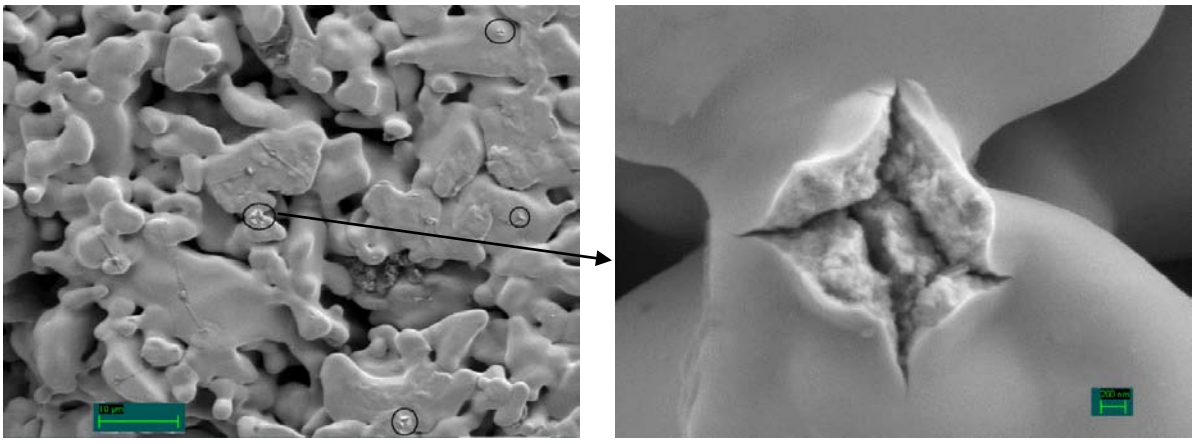
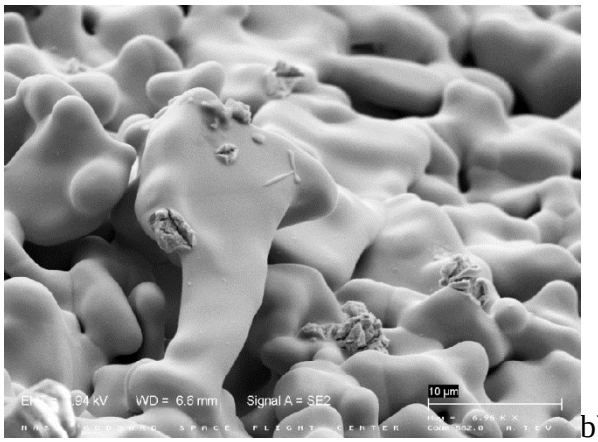


Figure 4A. Examples of cracks in tantalum pentoxide dielectric on the surface of anode slug.



a)



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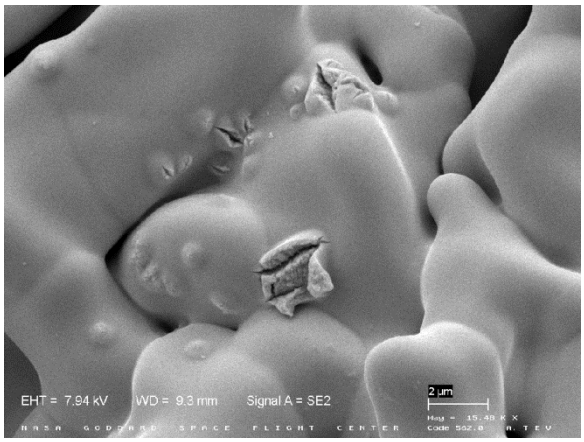

c)

Figure 5A. Tantalum oxide crystals growing through the anodic amorphous tantalum pentoxide layer and disrupting the integrity of the dielectric. Excessive concentration of the crystals indicates poor quality of the Ta/Ta2O5 system, a higher probability of degradation related to the presence of oxygen vacancies in the dielectric, and raises a reliability concern.