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TANTALUM CAPACITOR TESTS IN TEC-EPC LAB

TESTS ON INDIVIDUAL CAPACITORS

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1 INTRODUCTION

Due to their limited dimensions and weight compared to other capacitor types of equivalent performance, Solid Tantalum capacitors are widely used by many manufacturers in power supplies and in other applications where considerable surge and RMS currents are applied.

The previous ESA standard about de-rating rules for EEE components (RD #1, dated 1992) forbad the use of Tantalum Capacitors in power supply filters, and the reason of the prohibition was the (past) low reliability of such components in low impedance applications, where high surge and/or RMS currents were expected.

Component design and manufacturing updates along the years improved the quality of the tantalum capacitors, such that the original indications of circuit impedance from manufacturers have been reduced from several Ohm/Volt to fractions of Ohm/Volt. Lately the requirements of minimum circuit impedance for the use such of capacitors was even removed, provided that the relevant voltage, current and temperature ratings are respected.

For space applications, where long-term reliability is an utmost need, the concept of components application de-rating is applied to increase their reliability.
The documents AD #1 and #2 are currently applicable to all ESA projects, and give specific rules to be complied in the use of solid tantalum capacitors.

Despite the application of the de-rating rules set up by RD #1, in the recent past there have been cases of unexplained failures in space equipments, and gave some concern and brought ESA to issue a specific alert on tantalum capacitors applications (AD #3)
The exact cause of the failures has not been confirmed, however an investigation into possible causes has been performed at ESTEC resulting in the corrective/preventative actions defined in the relevant Alert.
The list of actions in AD #3 is not exhaustive however and is subject to addition pending further investigation.

2 SCOPE AND OBJECTIVES

2.1 Scope

The scope of this document is to summarize all the information and test results coming out from the tantalum capacitor tests campaign for single uses performed by TEC-EPC in the TEC-EP laboratory.

2.2 Objectives

The overall objectives of this test campaign were:

- To clarify the limits of utilization, in particular regarding the maximum allowable RMS current.

- To check capacitors robustness with respect to their rated limits.

- To check if the present ECSS de-rating rules do define a safe envelope of application.

To accomplish the above objectives, the following types of stress were performed:

- Surge Current Tests
- Over voltage tests
- Over current tests

3 APPLICABLE DOCUMENTS

The following documents are considered as applicable:

AD #1 ECSS-Q-60-11A, EEE Components, De-rating and end-of-life parameter drifts, 7-Sep-2004

AD #2 TEC-Q/04-6649/QCT, EEE COMPONENT DERATING (ESA TAILORING OF ECSS-Q-60-11A), issue 1 rev 0, 14-Sep-2004

AD #3 EA-2004-MEP-06-A, ESA Alert on Use of Tantalum Capacitors on power supply filters, 29-Oct-2004

4 REFERENCE DOCUMENTS

The following documents are given as a reference:

RD #1 ESA PSS-01-301 Issue 2
RD #2 "An Exploration of Leakage Current" AVX Technical Information
RD #3 "Tantalum and Niobium Oxide Capacitors Equivalent Circuit Model Applicability to Simulation Software" J. Pelcak, 17th European Passive Components Conference, October 2003, Stuttgart, Germany.

5 LIST OF ACRONYMS

CB	Capacitor Bank
EEE	Electrical, Electronic & Electro-Mechanical
TC	Tantalum Capacitors
SCT	Surge Current Tested
STD	Standard
PCB	Printed Circuit Board
ESR	Equivalent Series Resistor
ESL	Equivalent Series Inductor
X	Capacitance
IR	Infrared
SP	Soldering Process
PT	Period of Test
WC	Worst Case

6 LIMIT OF UTILISATION: DETERMINATION OF THE RMS CURRENT FROM THE POWER DISSIPATION FOR TAJ D 22UF 35V.

In practical design cases, the designer needs to choose the capacitors to be used in the circuit according to the required electrical performances.
For low impedance, high RMS current applications, the designer needs the information of the capacitor rated voltage, rated RMS current, and impedance characteristics.
In the datasheet, or in the space procurement specification, the rated/de-rated RMS Current is not specified for the TC. The limitation is usually specified in terms of maximum rated allowable power dissipation per package. The following paragraph explains how to derive the maximum RMS current from the maximum power dissipation.
The guidelines of AVX for one single capacitor are the following:
The current waveform applied to the capacitor shall be decomposed in Fourier series. AVX provides the typical ESR values in function of frequency, and it is then possible to calculate the typical RMS power dissipation at each harmonic. Root-square sum of the individual harmonic contributions gives the typical RMS power dissipation for one capacitor. The next paragraph presents this method by using different ESR values (typical, maximum, or measured) of tantalum capacitors TAJ D 22uF 35V.

6.1 Method of the manufacturer with the typical ESR

Assuming to apply a square current waveform (130KHz) with duty cycle=0.5, the RMS current at 25°C has to be lower than 1.12 A RMS to respect the rated power dissipation for that package (150mW) by using the typical ESR values in function of frequency at 25°C provided by AVX for a tantalum capacitor TAJ D 22uF 35V.

I amplitude [A]	Fs [Hz]	Harmonics []	F [Hz]	Amplitude of the Harmonic [A]	I [RMSA]	I*I	Typical ESR [Ohms]	P [W]	Total P [W]
1.12	130000	1	130000	1.428887107	1.010375763	1.020859183	0.1264	1.29E-01	1.50E-01
		3	390000	0.476295702	0.336791921	0.113428798	0.09769	1.11E-02	
		5	650000	0.285777421	0.202075153	0.040834367	0.09279	3.79E-03	
		7	910000	0.20412673	0.144339395	0.020833861	0.09013	1.88E-03	
		9	1170000	0.158765234	0.112263974	0.0126032	0.0882	1.11E-03	
		11	1430000	0.129898828	0.091852342	0.008436853	0.08674	7.32E-04	
		13	1690000	0.109914393	0.077721213	0.006040587	0.08563	5.17E-04	
		15	1950000	0.09525914	0.067358384	0.004537152	0.08479	3.85E-04	
		17	2210000	0.084052183	0.059433868	0.003532385	0.08415	2.97E-04	
PI		19	2470000	0.075204585	0.053177672	0.002827865	0.08366	2.37E-04	
3.14159265		21	2730000	0.068042243	0.048113132	0.002314873	0.08328	1.93E-04	
		23	2990000	0.062125526	0.043929381	0.001929791	0.08299	1.60E-04	
		25	3250000	0.057155484	0.040415031	0.001633375	0.08276	1.35E-04	
		27	3510000	0.052921745	0.037421325	0.001400356	0.08259	1.16E-04	
		29	3770000	0.049271969	0.034840544	0.001213863	0.08245	1.00E-04	
		31	4030000	0.046093132	0.032592767	0.001062288	0.08235	8.75E-05	
		33	4290000	0.043299609	0.030617447	0.000937428	0.08227	7.71E-05	
		35	4550000	0.040825346	0.028867879	0.000833354	0.08222	6.85E-05	
				sqrt of sumsq		1.115911994			

But… the approach identified by AVX is NOT the worst case one, since the **TYPICAL** ESR=f(F) is used, and the power dissipated by the capacitor may be HIGHER than calculated !!!

6.2 Maximum RMS current obtained using the maximum ESR given by the manufacturer

The maximum ESR (specified in the datasheet) can be used to determine the power dissipation with the same Fourier approach. The Rated Pd (150mW) is achieved for a the square wave current (130KHz) with 50% duty cycle equal to 0.41 A RMS with a considered ESR of 0.9Ω provided by AVX for a tantalum capacitor TAJ D 22uF 35V.

I amplitude [A]	Fs [Hz]	Harmonics []	F [Hz]	Amplitude of the Harmonic [A]	I [RMSA]	I*I	Typical ESR [Ohms]	P [W]	Total P [W]
0.41	130000	1	130000	0.522748106	0.36963873	0.136632791	0.9	1.23E-01	1.50E-01
		3	390000	0.174249369	0.12321291	0.015181421	0.9	1.37E-02	
		5	650000	0.104549621	0.073927746	0.005465312	0.9	4.92E-03	
		7	910000	0.074678301	0.052805533	0.002788424	0.9	2.51E-03	
		9	1170000	0.058083123	0.04107097	0.001686825	0.9	1.52E-03	
		11	1430000	0.047522555	0.033603521	0.001129197	0.9	1.02E-03	
		13	1690000	0.040211393	0.028433748	0.000808478	0.9	7.28E-04	
		15	1950000	0.034849874	0.024642582	0.000607257	0.9	5.47E-04	
		17	2210000	0.030749889	0.021743455	0.000472778	0.9	4.26E-04	
PI		19	2470000	0.027513058	0.01945467	0.000378484	0.9	3.41E-04	
3.14159265		21	2730000	0.024892767	0.017601844	0.000309825	0.9	2.79E-04	
		23	2990000	0.022728179	0.016071249	0.000258285	0.9	2.32E-04	
		25	3250000	0.020909924	0.014785549	0.000218612	0.9	1.97E-04	
		27	3510000	0.019361041	0.013690323	0.000187425	0.9	1.69E-04	
		29	3770000	0.018025797	0.012746163	0.000162465	0.9	1.46E-04	
		31	4030000	0.016862842	0.01192383	0.000142178	0.9	1.28E-04	
		33	4290000	0.015840852	0.011201174	0.000125466	0.9	1.13E-04	
		35	4550000	0.01493566	0.010561107	0.000111537	0.9	1.00E-04	
				sqrt of sumsq		0.408248404			

6.3 Maximum RMS current obtained by measurements of the capacitor impedance

With the frequency analyser the impedance of the single capacitor is measured at 25°C. By using the real part of the measured impedance and assuming to apply a square current waveform (130KHz) with duty cycle=0.5, the RMS current at 25°C has to be lower than 0.93 A RMS to respect the rated power dissipation for that package (150mW).

I amplitude [A]	Fs [Hz]	Harmonics []	F [Hz]	Amplitude of the Harmonic [A]	I [RMSA]	I*I	Typical ESR [Ohms]	P [W]	Total P [W]
0.93	130000	1	130000	1.18781194	0.839909878	0.705448603	0.183	1.29E-01	1.50E-01
		3	390000	0.395937313	0.279969959	0.078383178	0.142	1.11E-02	
		5	650000	0.237562388	0.167981976	0.028217944	0.131	3.70E-03	
		7	910000	0.16968742	0.119987125	0.01439691	0.126	1.81E-03	
		9	1170000	0.131979104	0.09332332	0.008709242	0.124	1.08E-03	
		11	1430000	0.107982904	0.076355443	0.005830154	0.124	7.23E-04	
		13	1690000	0.091370149	0.064608452	0.004174252	0.124	5.18E-04	
		15	1950000	0.079187463	0.055993992	0.003135327	0.124	3.89E-04	
		17	2210000	0.069871291	0.049406463	0.002440999	0.124	3.03E-04	
PI		19	2470000	0.062516418	0.044205783	0.001954151	0.125	2.44E-04	
3.14159265		21	2730000	0.056562473	0.039995708	0.001599657	0.126	2.02E-04	
		23	2990000	0.051643997	0.036517821	0.001333551	0.127	1.69E-04	
		25	3250000	0.047512478	0.033596395	0.001128718	0.128	1.44E-04	
		27	3510000	0.043993035	0.031107773	0.000967694	0.129	1.25E-04	
		29	3770000	0.040959032	0.02896241	0.000838821	0.129	1.08E-04	
		31	4030000	0.038316514	0.027093867	0.000734078	0.13	9.54E-05	
		33	4290000	0.035994301	0.025451814	0.000647795	0.131	8.49E-05	
		35	4550000	0.033937484	0.023997425	0.000575876	0.133	7.66E-05	
				sqrt of sumsq		0.927640528			

6.4 *Summary*

To have an idea of the maximum allowable current for different tantalum capacitor types, the same three approaches were applied for single use of TAJ 10uF, TPS 10uF and 22uF 35V. The FIG.1 summarizes this study. The details of the calculations for the TAJ 10uF and the TPS are available in annexes 1, 2 and 3.

	RMS Current* per types of tantalum capacitors			
Type / ESR	TAJ		TPS	
	10uF, 35V, K, RHJ, case D	22uF, 35V, M, RNJ, case D	10uF, 35V, K, R0300, case D	22uF, 35V, M, R0200, case D
Typical from AVX @25degC	1A RMS	1.12A RMS	0.9 A RMS	1.19 A RMS
Max at 100Khz	0.39A RMS	0.41 A RMS	0.71 A RMS	0.87 A RMS
Measured at @25degC	0.74A RMS	0.93 A RMS	0.93 A RMS	0.91 A RMS

• Assuming to apply a **square current waveform** with duty cycle=0.5 at 130KHz
• Power Dissipation of 150mW (cases D)

Fig.1: RMS current of TAJ and TPS capacitors to respect the rated power dissipation

For the same value of capacitance and rated voltage, the TPS capacitors give better performances than the TAJ ones: the TPS allow higher RMS current due to the lower ESR and the reduced ESR spread characteristics (Fig.2).

	TAJ		TPS	
	10uF	**22uF**	**10uF**	**22uF**
Maximum Esr at 100kHz	1Ω	0.9Ω	0.3Ω	0.2Ω

Fig.2: maximum ESR at 100kHz given in the manufacturer datasheet.

To follow a safe engineering approach, in absence of the envelope ESR(f) the user shall make use of the ESR maximum value given in the datasheet. Note that this may lead to a poor utilization of the devices….

6.5 Remark concerning the measured impedances

The measured impedances (part 8 of this document presents the method and the set-up used to measure the impedance) of the capacitor 22uF, 35V, TAJ, case D, appear rather different with respect to the typical ones given in the datasheet. Fig.3 shows the measured impedances of 10 capacitors (22uF) and the typical one given by the manufacturer. In consequence, the RMS current value calculated with the measured ESR=f(F) is rather different from the calculation with the typical ESR=f(F) given by the manufacturer. It is important to note that the manufacturer explained that their typical impedances are only given for information.

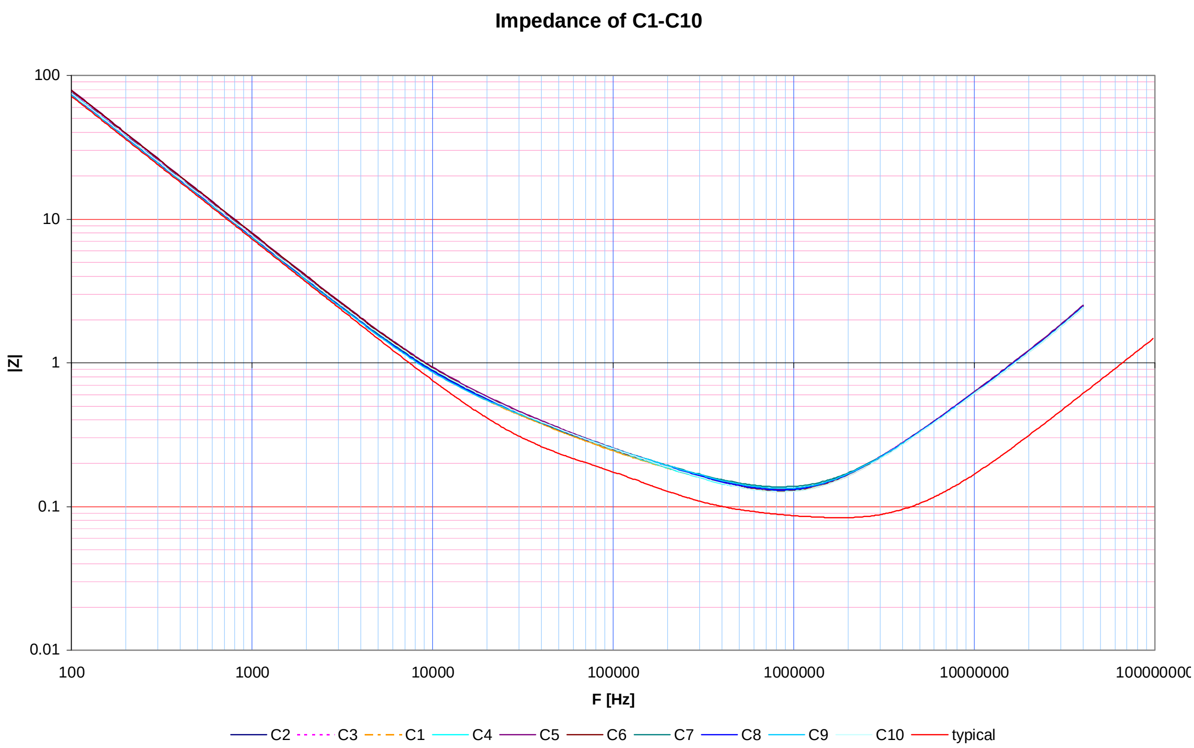


Fig.3: Impedances of TAJD, 22uF, 35V measured in the TEC-EP laboratory and the typical one given by the manufacturer

7 TESTS PERFORMED

In the following paragraphs the tests performed during the single capacitors test campaign will be reported test case by test case.
The capacitors tested were the TAJ, 22uF, 35V, cases D (ref.: TAJD226M035RNJ-AVX). These capacitors were commercial samples, never surge current tested by AVX.

7.1 Surge Current Tests

This part presents the different conditions applied to the single capacitors for the surge current tests. Three types of surge current tests were performed.

- **Surge Current Test 1:** This test is very close to the one specified in #RD1. 10 surge current peaks (55A) were injected into the capacitor.

- **Surge Current Test 2:** The characteristics of this test were the same than the previous one, except that the current pulses were repeated: 3600 surge current peaks (55A)

- **Surge Current Test 3:** The surge current peaks were repeated with higher amplitude than in the two previous tests: 3600 surge current peaks (110A).

7.1.1 GENERAL CONDITIONS

The general conditions for all the surge current tests were the following:

- Each capacitor was tested individually.
- Each capacitor was charged/discharged at its rated voltage (35V for the tested capacitors).
- The tests were performed at room temperature and pressure.
- Before and after the SCT, the leakage current and the impedance of the capacitor under test were measured and compared.
- The capacitor was fixed by a clip on the breadboard (it was not soldered).

7.1.2 CONDITIONS OF THE SURGE CURRENT TEST 1

The conditions of the nominal surge current test were the following:

- Each capacitor was 5 times charged/discharged at the rated voltage.
- The 10 peaks of current (5 charges, 5 discharges) were always higher than the rated voltage divided by the sum of the typical ESR plus 0.5Ω. The typical ESR given by the manufacturer for the TAJ, D, 22uF, 35V is 138.7mΩ at 100kHz. In other words, the peaks of current were higher than 55A.
- The rising and falling time of the charge/discharge between 10% and 90% of the rated voltage was always lower than 20us.

7.1.3 CONDITIONS OF THE SURGE CURRENT TEST 2

The conditions of the nominal surge current test were the following:

- Each capacitor was charged/discharged at the rated voltage (35V) at the frequency of 1Hz. Every second the capacitor was charged and discharged, and the total time of the test was 30 minutes. At the end of the test, the capacitor was charged about 1800 times and discharged 1800 times.
- The peak of current was always higher than the rated voltage divided by the sum of the typical ESR plus 0.5Ω. The typical ESR given by the manufacturer for the TAJ, D, 22uF, 35V is 138.7mΩ at 100kHz. In other words, the peak of current was higher than 55A.
- The rising and falling time of the charge/discharge between 10% and 90% of the rated voltage was always lower than 20us.

7.1.4 CONDITIONS OF THE SURGE CURRENT TEST 3

To see the effects of higher surge current, the capacitors were tested individually like in the SCT test 2, but with surge current peak higher than 110A. The conditions of the SCT test 3 were the following:

- Each capacitor was charged/discharged at the rated voltage (for the capacitors tested, it is 35V) at the frequency of 1Hz. Every second the capacitor was charged and discharged, and the total time of the test was 30 minutes. At the end of the test, the capacitor was charged about 1800 times and discharged 1800 times.
- The peak of current was always higher than the twice the rated voltage divided by the sum of the typical ESR plus 0.5Ω. The typical ESR given by the manufacturer for the TAJ, D, 22uF, 35V is 138.7mΩ at 100kHz. In other words, the peak of current was higher than 110A.
- The rising and falling time of the charge/discharge between 10% and 90% of the rated voltage was always lower than 20us.

7.1.5 SET-UPS OF THE SURGE CURRENT TESTS

7.1.5.1 Surge Current Test 1

The set-up for the Surge Current Test 1 is shown in fig. 4.
A capacitor bank was placed close to the set-up to supplement the power supply to provide current surges.
2 MFETs (M1 and M2) were used to charge/discharge the capacitor. A mechanical switch for this test commanded them manually. The resistor R1 was adjusted to obtain the required current peak (>55A).

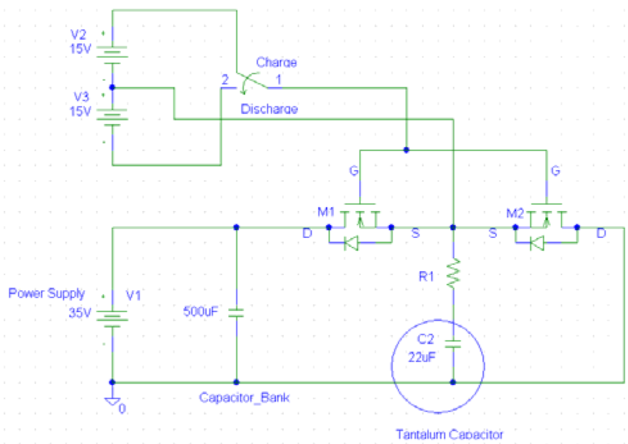


Fig. 4: Set-up of the Surge Current Test 1

7.1.5.2 Surge Current Tests 2 and 3

The set-up for the Surge Current Tests 2 and 3 is shown in fig. 5.

The power stage of the set-up remains the same than for the previous test. A low frequency generator, via a driver, commanded the 2 MFETs used for charge and discharge.

The resistor R2 was adjusted to obtain the peak of current required (>55A for the surge current Test 2, and >110A for the Surge Current Test 3).

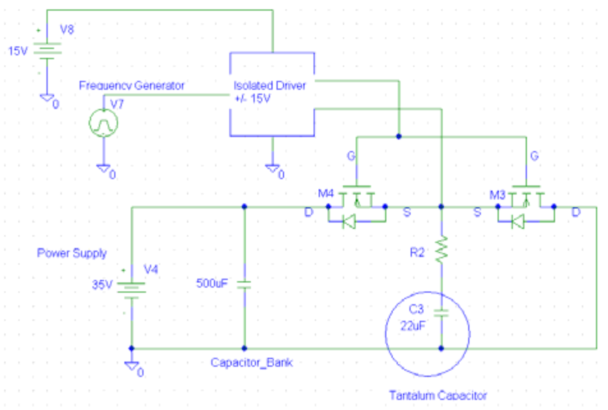


Fig. 5: Set-up of the Surge Current Tests 2 and 3

The measurement of the current and the voltage were realized with a scope Tektronix TDS3034B and with current probes Tektronix TCP202.
The pulse generator used for the periodic tests was a Hewlett Plackard 811A (20MHz).

7.2 Voltage Tests and Current Tests

7.2.1 GENERAL CONDITIONS

The general conditions for all the voltage and current tests were the following:

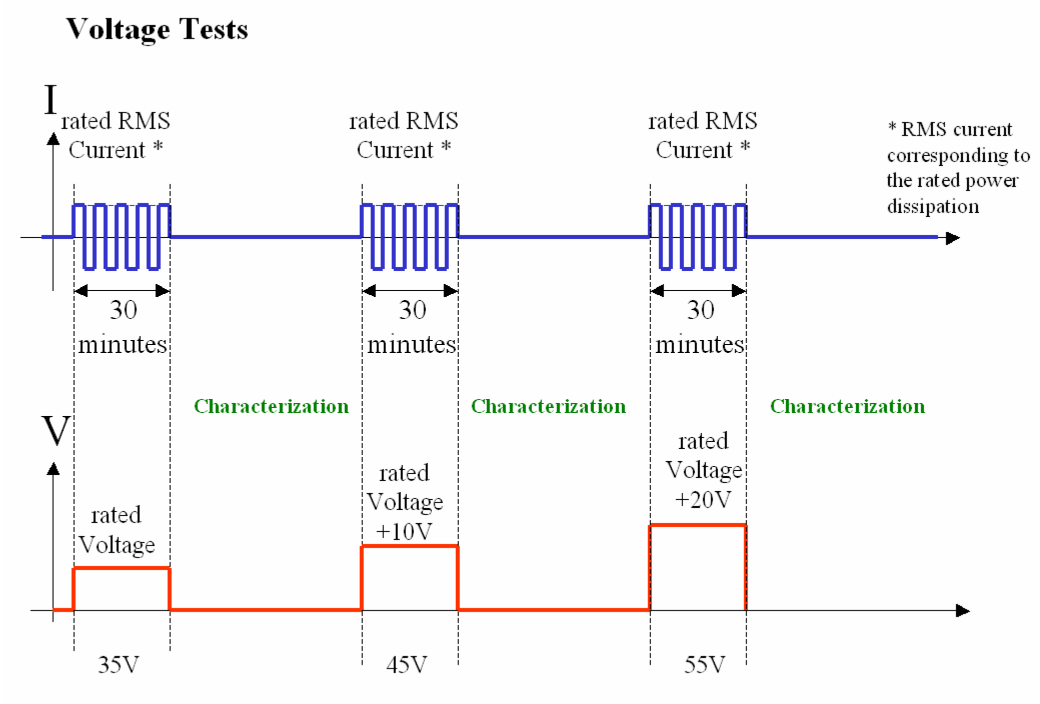
- Each capacitor was tested individually.
- The tests were performed at room temperature and pressure.
- The capacitor was fixed by a clip on the breadboard (it was not soldered).
- The current injected in the capacitor was almost square wave current (duty cycle 50%, frequency 130KHz).

7.2.2 VOLTAGE TESTS CONDITIONS

The voltage tests conditions were the following:

- The capacitor was tested at different level of voltage during periods of 30 minutes. The tests started at the rated voltage (35V).
- At the end of each testing period, after minimum 12 hours of rest time, the capacitor signature was taken (leakage current and impedance). The voltage was then increased (10V step) for the next period of test.
- The test stopped at four times the rated voltage or when the capacitor failed.
- The capacitor was stressed at the rated power dissipation (150mW). To reach this power dissipation the current injected in the capacitor was almost square wave current (duty cycle 50%, frequency 130KHz) with an RMS value of 1Arms, as it is explained in the background paragraph.

Fig. 6 summarizes the overall voltage test applied to the capacitor.



Fi.6: Voltage Test Conditions

7.2.3 CURRENT TESTS CONDITIONS

The current tests conditions were the following:

- The capacitor was tested individually at different level of current at the rated voltage (35V) during periods of 30 minutes. The tests started at the current (1Arms) corresponding to the rated power dissipation (150W), as it is explained in the background paragraph.
- At the end of each testing period, after minimum 12 hours of rest time, the capacitor signature was taken (leakage current and impedance). The RMS current was then increased (1A rms step) for the next period of test.
- The test stopped at 4 times the current corresponding to the rated power dissipation or when it failed.

Fig. 7 summarizes the overall current test applied to the capacitor.

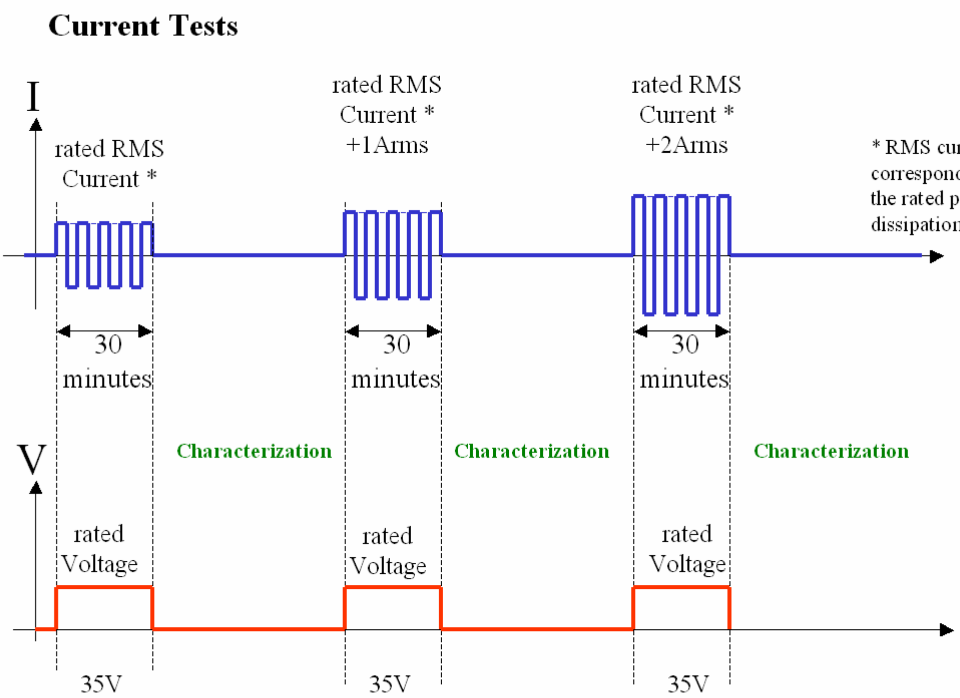


Fig. 7: Current Test Conditions

7.2.4 SET-UPS OF THE VOLTAGE AND CURRENT TESTS

The topology of the converters used to stress electrically the capacitor is a step-down converter (single inductor buck topology). Fig. 8 illustrates the topology with the theoretical waveforms of current at different points of the circuit.

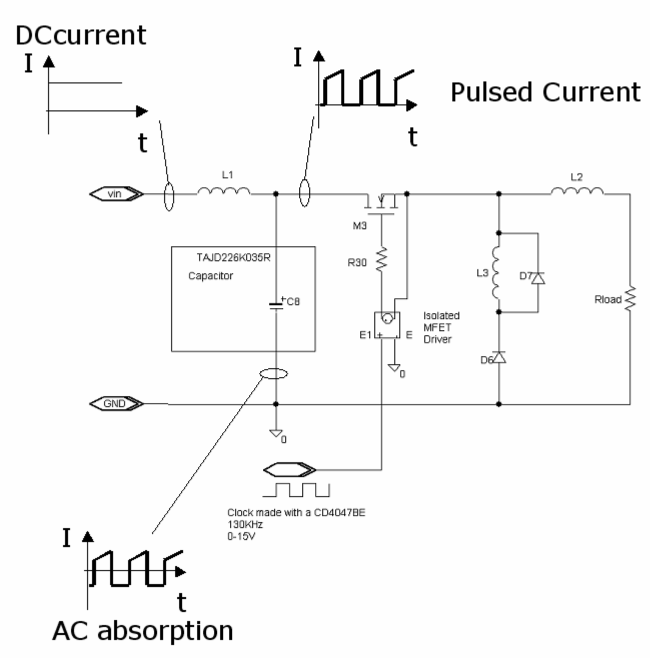


Fig. 8: Buck converter to stress electrically the capacitor (Voltage and Current Tests)

The current injected in the capacitor bank is almost square wave. The slopes when the current is positive were due to the presence of the inductors. The capacitor and the inductor L1 form an input filter, which allows the power supply to deliver a constant current. The capacitor absorbs the AC part of the MFET M3 current.

Fig. 9 illustrates the typical waveform of current injected in the capacitor.

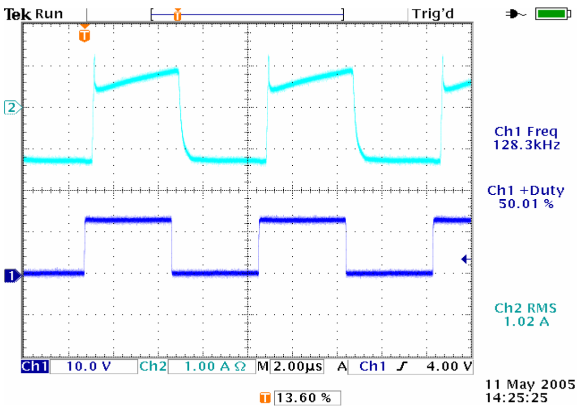


Fig. 9: Example of current injected in the capacitor

The measurement of the current and the voltage were realized with a scope Tektronix TDS3034B and with current probes Tektronix TCP202. The multimeter used to measure capacitor voltage was a Fluke 45 Dual Display.

8 ELECTRICAL SIGNATURES MEASUREMENTS

8.1 Impedances

The impedances were measured with an Impedance Gain-Phase analyser HP4194A from 100Hz to 40MHz at ambient temperature and pressure (Fig. 10). The perturbation injected in the capacitors was 0.5V RMS with a DC bias of 2.2 volts.

Fig. 10: Frequency Analyser

Before and after each characterization, the test set up was validated by the characterization of a “stable” PM90SR 10uF,10mΩ ESR at ambient temperature). This simple test allows checking the stability of the frequency analyser and the quality of the measurements. Fig. 11 shows how the equipment gives a good appreciation of this stable capacitor.

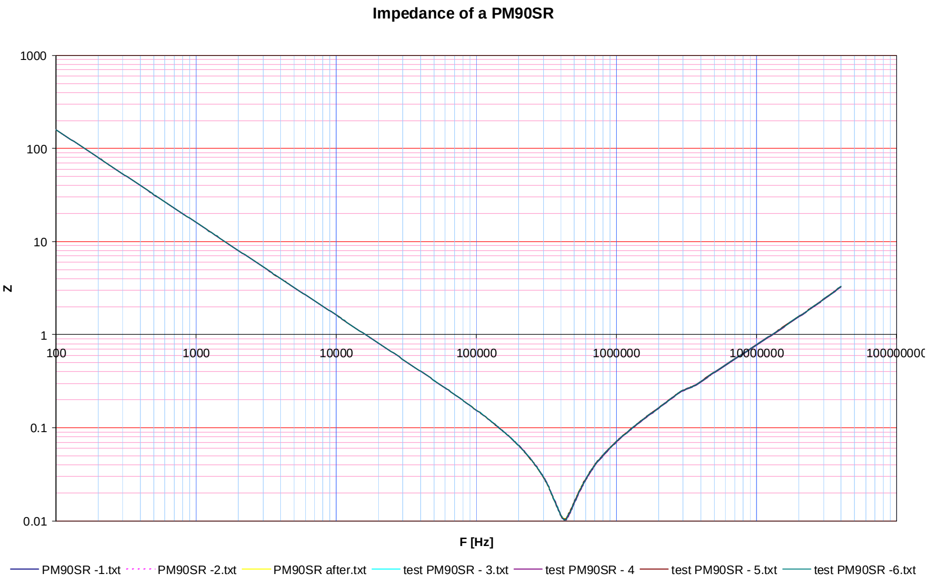


Fig 11: Verification of the measurements with a stable capacitor PM90SR

The PM90 SR measured impedances before/after any test were always very close each other. The equivalent circuit RLC in series of the PM90SR was also identified.

`Example of RLC equivalent circuit of a PM90SR 10uF given by the frequency analyser:`
`R=10.0964mΩ, L=13.7734nH, C=9.99071uF.`

For the single characterization a clip connector was used to avoid any issue due to hand soldering. Fig. 12a and b present the set-up used to identify the signatures of the capacitors.

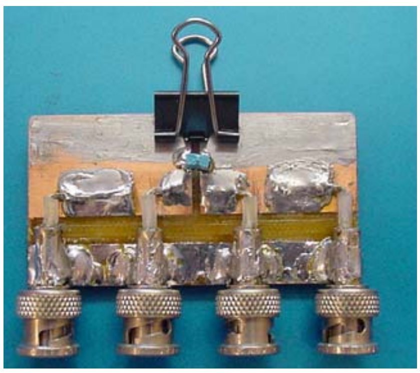


Fig 12a and 12b: Frequency Analyser and its clip connector

8.2 Leakage current

The leakage current depends on three factors: time, temperature and voltage applied to the capacitors. For more detail concerning the leakage current of tantalum capacitors, please refer to RD#2.

The measurements of the leakage current were realised after 4 minutes and 30 seconds after DC voltage application, at ambient temperature and with a dc voltage of 35V (+/-2%). A resistor was placed in series with the capacitor to limit the charging current and to read the leakage current via the voltage drop of this resistor. A steady source of power, such as a regulated power supply was used. The leakage current of the single TC was measured with the same principle of clip connector used for impedance characterisation. A resistor of 100kΩ was placed in series with the TC to obtain a good reading of the leakage current.

Fig 13 presents the schematic of the circuit used to measure the leakage current.

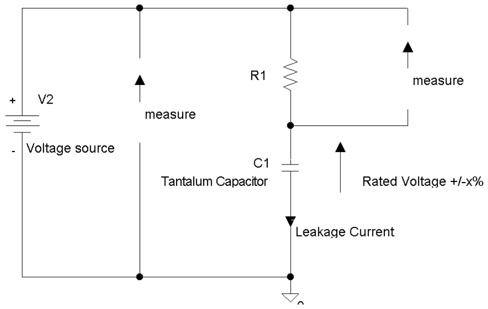


Fig 13: Circuit for the leakage measurement

The voltage source used to supply the capacitor consisted in 2 power supplies in series (Delta Elektronika ES-030-5 (30V-5A)). During the measurement, a Philips multimeter PM2525 with thermocouple were used to measure the ambient temperature. Two multimeters were used to measure the voltage of the power supply (Philips PM2525) and the leakage current via the voltage drop of the series resistor (Fluke 45 Dual Display Multimeter).

9 RESULTS AND ANALYSIS OF THE TESTS

9.1 Surge Current Tests

9.1.1 SURGE CURRENT TEST 1

21 capacitors TAJD, 22uF, 35V were tested with the nominal surge current test. The 5 current peaks were recorded and are available in the annex 4.

For the capacitor T1, the two first surge current peaks are presented in Fig. 14:

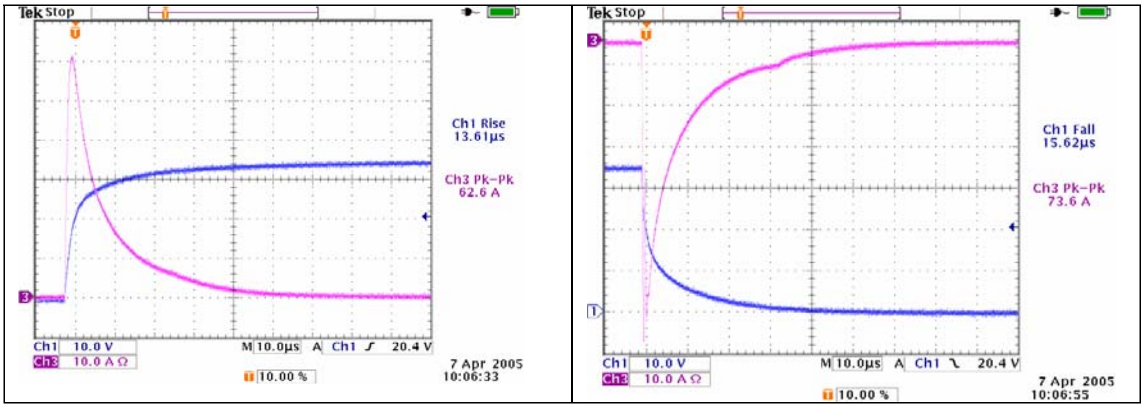


Fig. 14: Two first surge current peaks of T1

During the test, one capacitor (T6) failed at the second charge. The capacitor failed in short-circuit, and the power supply was switched off to avoid burn out.

9.1.1.1 Influences on the capacitors leakage current:

The leakage current of the capacitors was measured before and after the test. The following table summarizes the measurements:

Capacitor	LC before SCT [A]	LC after SCT (2 days) [A]	Ratio
T1	6.01E-08	6.01E-08	1.00
T2	6.31E-08	6.41E-08	0.98
T3	9.62E-08	9.32E-08	1.03
T4	7.01E-08	7.21E-08	0.97
T5	6.81E-08	6.51E-08	1.05
T7	7.51E-08	7.61E-08	0.99
T9	6.71E-08	6.51E-08	1.03
T10	1.46E-07	1.40E-07	1.04
T11	7.51E-08	7.31E-08	1.03
T12	7.31E-08	7.21E-08	1.01
T13	7.11E-08	7.01E-08	1.01
T14	7.21E-08	7.01E-08	1.03
T15	9.72E-08	9.02E-08	1.08
T16	7.41E-08	7.01E-08	1.06
T17	7.86E-08	7.51E-08	1.05
T18	6.91E-08	6.51E-08	1.06
T19	6.61E-08	6.71E-08	0.99
T20	2.18E-07	2.00E-07	1.09
T21	8.01E-08	7.81E-08	1.03
T22	1.90E-07	1.75E-07	1.09

The surge current test did not have appreciable impacts on the leakage current of the 20 tested capacitors.

9.1.1.2 Influences on the capacitors impedances

The impedances measurements of the tested capacitors, before and after the SCT are available in annex 5.

The SCT did not have a visible impact on the tested capacitors impedances. The few visible differences are due to the slight differences in the position of the capacitor on the bench and also to the clip set-up.

9.1.2 SURGE CURRENT TESTS 1 AND 2

Five capacitors were tested (T23-T27). Other 5 capacitors were not stressed, but used for reference measurements, to validate the leakage and impedances measurements (T1-T5).

9.1.2.1 Influences on the capacitor leakage current

The following table summarizes the leakage current measurements:

Leakage Current

		before SCT	after SCT (2 days)	after the tests of T23-T27 SCT nominal 30 minutes	after the tests of T23-T27 SCT high level 30 minutes
ref	T1	6.01E-08	6.01E-08	5.41E-08	5.81E-08
ref	T2	6.31E-08	6.41E-08	6.51E-08	6.51E-08
ref	T3	9.62E-08	9.32E-08	9.12E-08	9.52E-08
ref	T4	7.01E-08	7.21E-08	6.81E-08	7.01E-08
ref	T5	6.81E-08	6.51E-08	6.51E-08	6.81E-08
tested	T23	6.71E-08		6.21E-08	6.11E-08
tested	T24	9.52E-08		8.41E-08	8.62E-08
tested	T25	7.01E-08		6.31E-08	6.41E-08
tested	T26	1.01E-07		9.02E-08	9.02E-08
tested	T27	7.01E-08		6.31E-08	6.51E-08

The repeated surge current tests 1 and 2 did not have appreciable impacts on the leakage current of the 5 tested capacitors.

9.1.2.2 Influences on the capacitor impedances

The impedances measurements of the tested capacitors, before and after the SCT, are available in annexes 5 and 6.

The SCT did not have appreciable impacts on the impedances of the capacitors under test. The few visible differences are due to slight differences in the position of the capacitor on the bench and also to the clip set-up.

9.2 Voltage Stress Tests

Seven capacitors were tested (T7-T9-T10-T11-T12-T13-T14) during this test.
Other five capacitors were not stressed, but used for reference measurements, to validate the leakage and impedances measurements (T1-T5).

The capacitors were tested at 35V, 45V, 55V, 65V, 75V, 80V, and 85V.

T7: no failure at 85V
T9: failure at 75V (after 1 min)
T10: failure at 75V (after 1 min)
T11: no failure at 85V
T12: failure at 80V (after 1 min)
T13: failure at 85V (after 27 min)
T14: failure at 85V (after 25 min)

9.2.1 INFLUENCES ON THE CAPACITOR LEAKAGE CURRENT

The leakage current of the capacitors was measured before and after each test step. Fig. 15 summarizes the measurements.

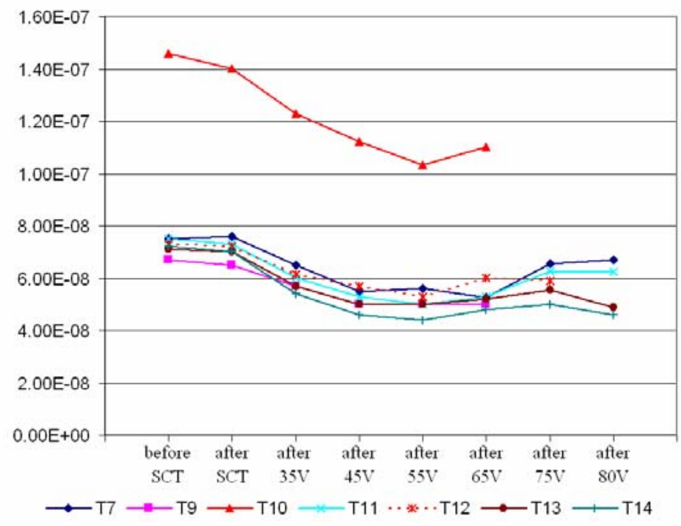


Fig. 15: Leakage Current Measurement during the over-voltage Test

The voltage stress tests did not have any appreciable impact on the leakage current of the 7 tested capacitors until the end of the test. The leakage current of the 5 capacitors used for references (T1-T5) was constant.

9.2.2 INFLUENCES ON THE CAPACITOR IMPEDANCES

The impedances measurements of the tested capacitors, before and at the different level of over-voltage stress are available in annex 7.

The voltage stress tests did not have any appreciable impact on the tested capacitors impedances. The few visible differences are due to slight differences in the position of the capacitor on the bench and also to the clip set-up.

9.3 Current Stress Tests

Seven capacitors were tested (T15-T21).5 capacitors were not stressed, but used for reference measurements, to validate the leakage and impedances measurements (T1-T5).

The capacitors were tested at 1Arms, 2Arms, 3Arms and 4 Arms.

No capacitors failed during the test.

9.3.1 INFLUENCES ON THE CAPACITOR LEAKAGE CURRENT

The leakage current of the capacitors was measured before and after each test step.Fig.15 summarizes the measurements:

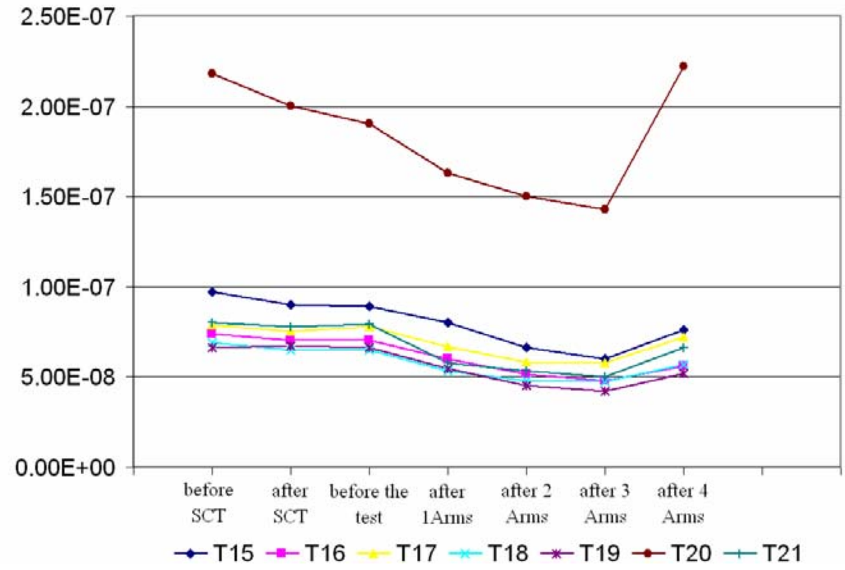


Fig. 15: Leakage Current Measurement during the over-current Test

The leakage current did not change, with exception of one capacitor, for which the leakage current increased appreciably at 4 Arms.
The leakage current of the 5 capacitors used for references (T1-T5) was constant.

A similar test was performed on another type of capacitor (TAJ, 10u, 35V, case D) and in that case the leakage current increased appreciably just before failing on the next current step (the failure occurred at more than 4 times the current corresponding to the rated power dissipation).

9.3.2 INFLUENCES ON THE CAPACITOR IMPEDANCES

The impedances measurements of the tested capacitors, before and at the different level of over-current stress are available in annex 8.

The current stress tests did not have appreciable impacts on the impedances of the capacitors under test. The few visible differences are due to slight differences in the position of the capacitor on the bench and also to the clip set-up.

10 CONCLUSIONS

10.1 Concerning the tests results

Concerning the initial characteristics of the capacitors, the measured impedances of the capacitor 22uF, 35V, TAJ, case D, appear rather different with respect to the typical ones given in the datasheet.

The **surge current test** appears to be an important screening to be performed for hi-reliability space applications.
Concerning the **over-voltage** stress tests, the performances of the capacitors did not get worse until the failure occurred. The voltage failures occurred at >75V, ie **more than twice the rated voltage**.

During the **over-current** stress tests, the performances of the capacitors did **not degrade when a current up to 4 times** the current corresponding to the rated power dissipation was applied.

Concerning the capacitor failures experienced so far the following remarks can be made:

- When a capacitor failed, it failed in **short-circuit** (a few hundreds of mΩ).
- The sound emitted by the capacitor due to a voltage failure was different than the one due to a current failure.
- In case of voltage failures, a crack was visible on the capacitor: it appeared as a dielectric failure.
- In case of a current failure, the destruction was sometimes explosive and could damage the PCB on which the capacitor was mounted.

10.2 In general

The presented tests were performed on only a few capacitors, and for this reason **any generalization** of the results of this study should be **taken with great care**.

The **soldering process** was not part of this study but may have an impact on the performances of the tantalum capacitors and on the explanation of the failures occurred in ESA programs.

TPS capacitors, which have a lower maximum ESR, seem likely to be used in the future for space application. For the same volume and weight, they can indeed absorb higher rms currents than the TAJ capacitors.

11 ANNEX 1: DETERMINATION OF THE MAXIMUM RMS CURRENT IN A TAJ (K RHJ) 10UF 35V CASE D

Single configuration

Method of the manufacturer with the typical ESR

Assuming to apply a square current waveform with duty cycle=0.5, the RMS current at 25°C has to be lower than 1 A RMS to respect the rated power dissipation for that package (150mW) by using the typical ESR values in function of frequency at 25°C provided by AVX.

I amplitude [A]	Fs [Hz]	Harmonics []	F [Hz]	Amplitude of the Harmonic [A]	I [RMSA]	I*I	Typical ESR [Ohms]	P [W]
1.00	130000	1	130000	1.270441417	0.898337741	0.807010697	0.1621	1.31E-01
		3	390000	0.423480472	0.299445914	0.089667855	0.1194	1.07E-02
		5	650000	0.254088283	0.179667548	0.032280428	0.1043	3.37E-03
		7	910000	0.181491631	0.128333963	0.016469606	0.09801	1.61E-03
		9	1170000	0.141160157	0.099815305	0.009963095	0.0945	9.42E-04
		11	1430000	0.115494674	0.081667067	0.00666951	0.09209	6.14E-04
		13	1690000	0.097726263	0.069102903	0.004775211	0.09025	4.31E-04
		15	1950000	0.084696094	0.059889183	0.003586714	0.08876	3.18E-04
		17	2210000	0.074731848	0.052843397	0.002792425	0.08753	2.44E-04
PI		19	2470000	0.066865338	0.047280934	0.002235487	0.0865	1.93E-04
3.14159265		21	2730000	0.06049721	0.042777988	0.001829956	0.08564	1.57E-04
		23	2990000	0.055236583	0.039058163	0.00152554	0.08492	1.30E-04
		25	3250000	0.050817657	0.03593351	0.001291217	0.08431	1.09E-04
		27	3510000	0.047053386	0.033271768	0.001107011	0.0838	9.28E-05
		29	3770000	0.043808325	0.030977163	0.000959585	0.08337	8.00E-05
		31	4030000	0.040981981	0.028978637	0.000839761	0.083	6.97E-05
		33	4290000	0.038498225	0.027222356	0.000741057	0.0827	6.13E-05
		35	4550000	0.036298326	0.025666793	0.000658784	0.08244	5.43E-05
				sqrt of sumsq		0.992171325		

Maximum RMS current via the maximum ESR given by the manufacturer

The maximum of the real part of the impedance (ESR max is specified in the datasheet) can be used to determine the power dissipation. Rated Pd (150mW) is achieved for a the square wave current with 50% duty cycle equal to 0.39 A RMS with a considered series resistor of 1Ω.

I amplitude [A]	Fs [Hz]	Harmonics []	F [Hz]	Amplitude of the Harmonic [A]	I [RMSA]	I*I	Typical ESR [Ohms]	P [W]	Total P [W]
0.39	130000	1	130000	0.495921512	0.350669464	0.122969073	1	1.23E-01	1.50E-01
		3	390000	0.165307171	0.116889821	0.01366323	1	1.37E-02	
		5	650000	0.099184302	0.070133893	0.004918763	1	4.92E-03	
		7	910000	0.07084593	0.050095638	0.002509573	1	2.51E-03	
		9	1170000	0.05510239	0.038963274	0.001518137	1	1.52E-03	
		11	1430000	0.045083774	0.031879042	0.001016273	1	1.02E-03	
		13	1690000	0.038147809	0.026974574	0.000727628	1	7.28E-04	
		15	1950000	0.033061434	0.023377964	0.000546529	1	5.47E-04	
		17	2210000	0.029171854	0.020627616	0.000425499	1	4.25E-04	
PI		19	2470000	0.026101132	0.018456288	0.000340635	1	3.41E-04	
3.14159265		21	2730000	0.02361531	0.016698546	0.000278841	1	2.79E-04	
		23	2990000	0.021561805	0.015246498	0.000232456	1	2.32E-04	
		25	3250000	0.01983686	0.014026779	0.000196751	1	1.97E-04	
		27	3510000	0.018367463	0.012987758	0.000168682	1	1.69E-04	
		29	3770000	0.017100742	0.01209205	0.000146218	1	1.46E-04	
		31	4030000	0.015997468	0.011311918	0.000127959	1	1.28E-04	
		33	4290000	0.015027925	0.010626347	0.000112919	1	1.13E-04	
		35	4550000	0.014169186	0.010019128	0.000100383	1	1.00E-04	
				sqrt of sumsq		0.387297751			

Maximum RMS current after the measure of the single impedance

With the frequency analyser the impedance of the single capacitor is measured at 25°C. Assuming to apply a square current waveform with duty cycle=0.5, the current waveform applied to the capacitor is decomposed in Fourier series. It is then possible to calculate the RMS power dissipation at each harmonic with the measured impedance. Root-square sum of the individual harmonic contributions gives the RMS power dissipation for one capacitor after characterization. The RMS current at 25°C has to be lower than 0.74 A RMS to respect the rated power dissipation for that package (150mW) by using the measured impedance at 25°C.

I amplitude [A]	Fs [Hz]	Harmonics []	F [Hz]	Amplitude of the Harmonic [A]	I [RMSA]	I*I	Typical ESR [Ohms]	P [W]	Total P [W]
0.74	130000	1	130000	0.937840163	0.663153139	0.439772086	0.294	1.29E-01	1.50E-01
		3	390000	0.312613388	0.221051046	0.048863565	0.229	1.12E-02	
		5	650000	0.187568033	0.132630628	0.017590883	0.21	3.69E-03	
		7	910000	0.133977166	0.094736163	0.008974941	0.2	1.79E-03	
		9	1170000	0.104204463	0.073683682	0.005429285	0.194	1.05E-03	
		11	1430000	0.085258197	0.060286649	0.00363448	0.191	6.94E-04	
		13	1690000	0.072141551	0.05101178	0.002602202	0.189	4.92E-04	
		15	1950000	0.062522678	0.044210209	0.001954543	0.187	3.65E-04	
		17	2210000	0.055167068	0.039009008	0.001521703	0.187	2.85E-04	
PI		19	2470000	0.049360009	0.034902797	0.001218205	0.186	2.27E-04	
3.14159265		21	2730000	0.044659055	0.031578721	0.000997216	0.186	1.85E-04	
		23	2990000	0.040775659	0.028832745	0.000831327	0.186	1.55E-04	
		25	3250000	0.037513607	0.026526126	0.000703635	0.186	1.31E-04	
		27	3510000	0.034734821	0.024561227	0.000603254	0.187	1.13E-04	
		29	3770000	0.032339316	0.02286735	0.000522916	0.187	9.78E-05	
		31	4030000	0.030252908	0.021392037	0.000457619	0.188	8.60E-05	
		33	4290000	0.028419399	0.02009555	0.000403831	0.188	7.59E-05	
		35	4550000	0.026795433	0.018947233	0.000358998	0.189	6.79E-05	
				sqrt of sumsq		0.732421114			

12 ANNEX 2: DETERMINATION OF THE MAXIMUM RMS CURRENT IN A TPS (M R0200) 22UF 35V CASE D

Single configuration

Method of the manufacturer with the typical ESR

Assuming to apply a **square current waveform** with duty cycle=0.5, the RMS current at 25°C has to be lower than **1.19 A RMS** to respect the rated power dissipation for that package (150mW) by using the **typical** ESR values in function of frequency at 25°C provided by AVX.

I amplitude [A]	Fs [Hz]	Harmonics []	F [Hz]	Amplitude of the Harmonic [A]	I [RMSA]	I*I	Typical ESR [Ohms]	P [W]	Total P [W]
1.20	130000	1	130000	1.528410709	1.080749577	1.168019648	0.1112	1.30E-01	1.50E-01
		3	390000	0.509470236	0.360249859	0.129779961	0.08236	1.07E-02	
		5	650000	0.305682142	0.216149915	0.046720786	0.0775	3.62E-03	
		7	910000	0.218344387	0.154392797	0.023837136	0.07521	1.79E-03	
		9	1170000	0.169823412	0.120083286	0.014419996	0.0736	1.06E-03	
		11	1430000	0.138946428	0.098249962	0.009653055	0.07235	6.98E-04	
		13	1690000	0.117570055	0.083134583	0.006911359	0.07136	4.93E-04	
		15	1950000	0.101894047	0.072049972	0.005191198	0.07057	3.66E-04	
		17	2210000	0.089906512	0.063573505	0.00404159	0.06994	2.83E-04	
PI		19	2470000	0.080442669	0.056881557	0.003235511	0.06944	2.25E-04	
3.14159265		21	2730000	0.072781462	0.051464266	0.002648571	0.06905	1.83E-04	
		23	2990000	0.06645264	0.046989112	0.002207977	0.06874	1.52E-04	
		25	3250000	0.061136428	0.043229983	0.001868831	0.06849	1.28E-04	
		27	3510000	0.056607804	0.040027762	0.001602222	0.06829	1.09E-04	
		29	3770000	0.052703818	0.037267227	0.001388846	0.06814	9.46E-05	
		31	4030000	0.049303571	0.03486289	0.001215421	0.06802	8.27E-05	
		33	4290000	0.046315476	0.032749987	0.001072562	0.06792	7.28E-05	
		35	4550000	0.043668877	0.030878559	0.000953485	0.06785	6.47E-05	
				sqrt of sumsq		1.193636525			

Maximum RMS current via the maximum ESR given by the manufacturer

The maximum of the real part of the impedance (ESR max is specified in the datasheet) can be used to determine the power dissipation. Rated Pd (150mW) is achieved for a the square wave current with 50% duty cycle equal to 0.87 A RMS with a considered series resistor of 0.2Ω.

I amplitude [A]	Fs [Hz]	Harmonics []	F [Hz]	Amplitude of the Harmonic [A]	I [RMSA]	I*I	Typical ESR [Ohms]	P [W]	Total P [W]
0.87	130000	1	130000	1.108914266	0.784120797	0.614845425	0.2	1.23E-01	1.50E-01
		3	390000	0.369638089	0.261373599	0.068316158	0.2	1.37E-02	
		5	650000	0.221782853	0.156824159	0.024593817	0.2	4.92E-03	
		7	910000	0.158416324	0.112017257	0.012547866	0.2	2.51E-03	
		9	1170000	0.123212696	0.087124533	0.007590684	0.2	1.52E-03	
		11	1430000	0.100810388	0.071283709	0.005081367	0.2	1.02E-03	
		13	1690000	0.085301097	0.060316984	0.003638139	0.2	7.28E-04	
		15	1950000	0.073927618	0.05227472	0.002732646	0.2	5.47E-04	
		17	2210000	0.065230251	0.046124753	0.002127493	0.2	4.25E-04	
PI		19	2470000	0.058363909	0.041269516	0.001703173	0.2	3.41E-04	
3.14159265		21	2730000	0.052805441	0.037339086	0.001394207	0.2	2.79E-04	
		23	2990000	0.048213664	0.034092209	0.001162279	0.2	2.32E-04	
		25	3250000	0.044356571	0.031364832	0.000983753	0.2	1.97E-04	
		27	3510000	0.041070899	0.029041511	0.000843409	0.2	1.69E-04	
		29	3770000	0.038238423	0.027038648	0.000731088	0.2	1.46E-04	
		31	4030000	0.035771428	0.025294219	0.000639798	0.2	1.28E-04	
		33	4290000	0.033603463	0.023761236	0.000564596	0.2	1.13E-04	
		35	4550000	0.031683265	0.022403451	0.000501915	0.2	1.00E-04	
				sqrt of sumsq		0.866024141			

Maximum RMS current after the measure of the single impedance

With the frequency analyser the impedance of the single capacitor is measured at 25°C. Assuming to apply a square current waveform with duty cycle=0.5, the current waveform applied to the capacitor is decomposed in Fourier series. It is then possible to calculate the typical RMS power dissipation at each harmonic with the measured impedance. Root-square sum of the individual harmonic contributions gives the RMS power dissipation for one capacitor after characterization. The RMS current at 25°C has to be lower than 0.91 A RMS to respect the rated power dissipation for that package (150mW) by using the measured impedance at 25°C.

I amplitude [A]	Fs [Hz]	Harmonics []	F [Hz]	Amplitude of the Harmonic [A]	I [RMSA]	I*I	Typical ESR [Ohms]	P [W]	Total P [W]
0.91	130000	1	130000	1.162028231	0.821678042	0.675154805	0.191	1.29E-01	1.50E-01
		3	390000	0.387342744	0.273892681	0.075017201	0.149	1.12E-02	
		5	650000	0.232405646	0.164335608	0.027006192	0.138	3.73E-03	
		7	910000	0.166004033	0.117382577	0.013778669	0.134	1.85E-03	
		9	1170000	0.129114248	0.09129756	0.008335245	0.132	1.10E-03	
		11	1430000	0.10563893	0.074698004	0.005579792	0.131	7.31E-04	
		13	1690000	0.089386787	0.063206003	0.003994999	0.13	5.19E-04	
		15	1950000	0.077468549	0.054778536	0.003000688	0.13	3.90E-04	
		17	2210000	0.068354602	0.048334002	0.002336176	0.13	3.04E-04	
PI		19	2470000	0.061159381	0.043246213	0.001870235	0.132	2.47E-04	
3.14159265		21	2730000	0.055334678	0.039127526	0.001530963	0.132	2.02E-04	
		23	2990000	0.050522967	0.035725132	0.001276285	0.1325	1.69E-04	
		25	3250000	0.046481129	0.032867122	0.001080248	0.1335	1.44E-04	
		27	3510000	0.043038083	0.03043252	0.000926138	0.134	1.24E-04	
		29	3770000	0.040069939	0.028333726	0.0008028	0.1345	1.08E-04	
		31	4030000	0.037484782	0.026505743	0.000702554	0.1355	9.52E-05	
		33	4290000	0.035212977	0.024899335	0.000619977	0.137	8.49E-05	
		35	4550000	0.033200807	0.023476515	0.000551147	0.1375	7.58E-05	
				sqrt of sumsq		0.907504332			

13 ANNEX 3: DETERMINATION OF THE MAXIMUM RMS CURRENT IN A TPS (K R0300) 10UF 35V CASE D

Single configuration

Method of the manufacturer with the typical ESR

Assuming to apply a square current waveform with duty cycle=0.5, the RMS current at 25°C has to be lower than 0.9 A RMS to respect the rated power dissipation for that package (150mW).

I amplitude [A]	Fs [Hz]	Harmonics []	F [Hz]	Amplitude of the Harmonic [A]	I [RMSA]	I*I	Typical ESR [Ohms]	P [W]	Total P [W]
0.91	130000	1	130000	1.155573694	0.817113995	0.667675282	0.1153	7.70E-02	1.50E-01
		3	390000	0.385191231	0.272371332	0.074186142	0.9154	6.79E-02	
		5	650000	0.231114739	0.163422799	0.026707011	0.07784	2.08E-03	
		7	910000	0.165081956	0.116730571	0.013626026	0.07133	9.72E-04	
		9	1170000	0.128397077	0.090790444	0.008242905	0.06783	5.59E-04	
		11	1430000	0.105052154	0.07428309	0.005517978	0.06565	3.62E-04	
		13	1690000	0.088890284	0.062854923	0.003950741	0.06411	2.53E-04	
		15	1950000	0.077038246	0.054474266	0.002967446	0.06293	1.87E-04	
		17	2210000	0.067974923	0.048065529	0.002310295	0.06197	1.43E-04	
PI		19	2470000	0.060819668	0.043006	0.001849516	0.06117	1.13E-04	
3.14159265		21	2730000	0.055027319	0.03891019	0.001514003	0.06047	9.16E-05	
		23	2990000	0.050242335	0.035526695	0.001262146	0.05987	7.56E-05	
		25	3250000	0.046222948	0.03268456	0.00106828	0.05935	6.34E-05	
		27	3510000	0.042799026	0.030263481	0.000915878	0.05889	5.39E-05	
		29	3770000	0.039847369	0.028176345	0.000793906	0.05849	4.64E-05	
		31	4030000	0.037276571	0.026358516	0.000694771	0.05814	4.04E-05	
		33	4290000	0.035017385	0.02476103	0.000613109	0.05783	3.55E-05	
		35	4550000	0.033016391	0.023346114	0.000545041	0.05756	3.14E-05	
				sqrt of sumsq		0.90246356			

Maximum RMS current via the maximum ESR given by the manufacturer

Maximum ESR from the datasheet: ESRmax=0.3Ω (at 100Khz) Rated Pd (150mW) is achieved for a square wave current equal to 0.71 A RMS.

I amplitude [A]	Fs [Hz]	Harmonics []	F [Hz]	Amplitude of the Harmonic [A]	I [RMSA]	I*I	Typical ESR [Ohms]	P [W]	Total P [W]
0.71	130000	1	130000	0.905423601	0.640231168	0.409895949	0.3	1.23E-01	1.50E-01
		3	390000	0.301807867	0.213410389	0.045543994	0.3	1.37E-02	
		5	650000	0.18108472	0.128046234	0.016395838	0.3	4.92E-03	
		7	910000	0.129346229	0.091461595	0.008365223	0.3	2.51E-03	
		9	1170000	0.100602622	0.071136796	0.005060444	0.3	1.52E-03	
		11	1430000	0.082311236	0.058202833	0.00338757	0.3	1.02E-03	
		13	1690000	0.069647969	0.049248551	0.00242542	0.3	7.28E-04	
		15	1950000	0.060361573	0.042682078	0.00182176	0.3	5.47E-04	
		17	2210000	0.053260212	0.037660657	0.001418325	0.3	4.25E-04	
PI		19	2470000	0.047653874	0.033696377	0.001135446	0.3	3.41E-04	
3.14159265		21	2730000	0.04311541	0.030487198	0.000929469	0.3	2.79E-04	
		23	2990000	0.039366244	0.027836138	0.000774851	0.3	2.32E-04	
		25	3250000	0.036216944	0.025609247	0.000655834	0.3	1.97E-04	
		27	3510000	0.033534207	0.023712265	0.000562272	0.3	1.69E-04	
		29	3770000	0.031221503	0.022076937	0.000487391	0.3	1.46E-04	
		31	4030000	0.029207213	0.020652618	0.000426531	0.3	1.28E-04	
		33	4290000	0.027437079	0.019400944	0.000376397	0.3	1.13E-04	
		35	4550000	0.025869246	0.018292319	0.000334609	0.3	1.00E-04	
				sqrt of sumsq		0.707104887			

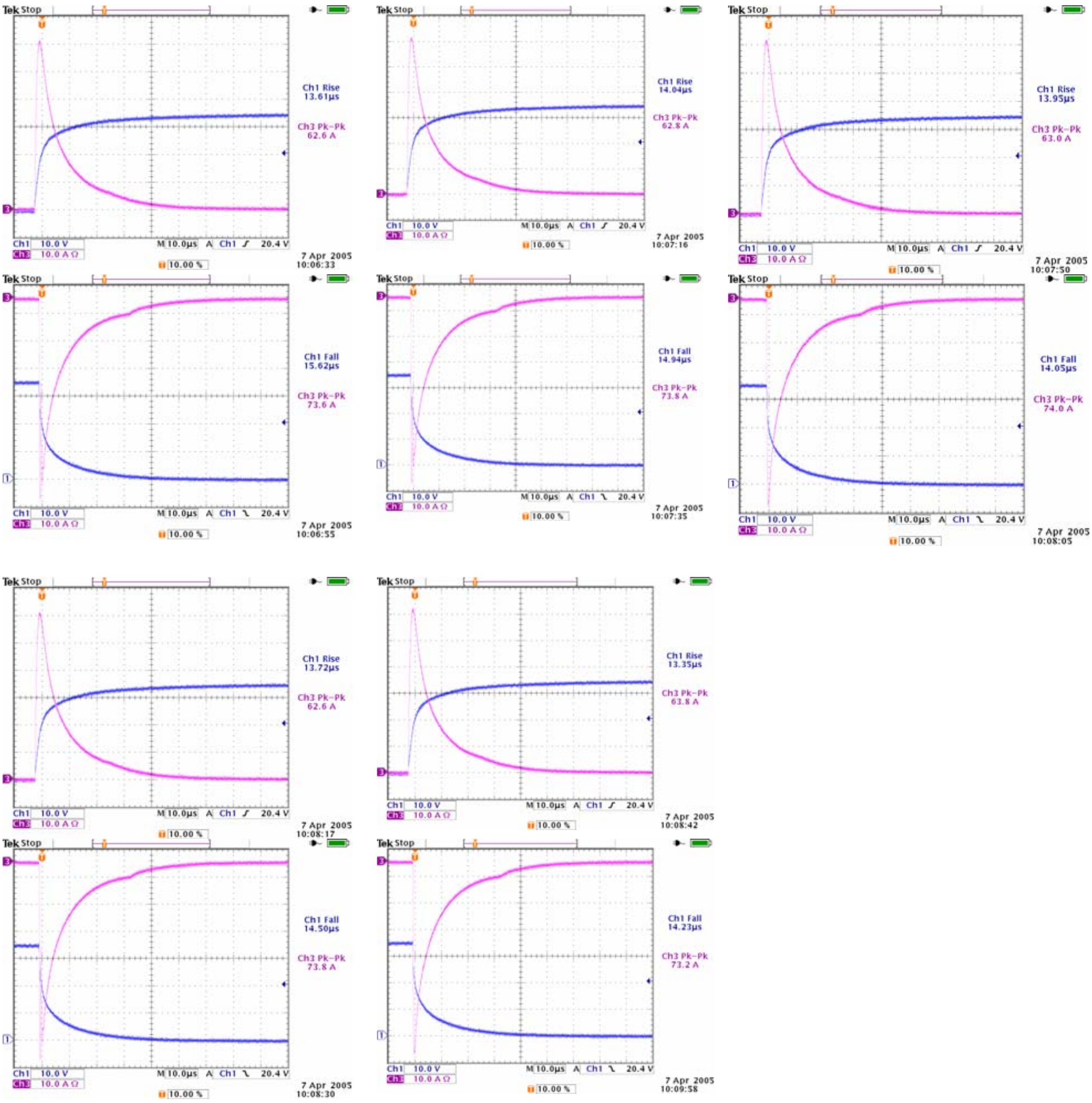
Maximum RMS current after the measure of the single impedance

With the frequency analyser the impedance of the single capacitor is measured at 25°C. Assuming to apply a square current waveform with duty cycle=0.5, the current waveform applied to the capacitor is decomposed in Fourier series. It is then possible to calculate the typical RMS power dissipation at each harmonic with the measured impedance. Root-square sum of the individual harmonic contributions gives the RMS power dissipation for one capacitor after characterization. The RMS current at 25°C has to be lower than 0.93 A RMS to respect the rated power dissipation for that package(150mW) by using the measured impedance at 25°C.

I amplitude [A]	Fs [Hz]	Harmonics []	F [Hz]	Amplitude of the Harmonic [A]	I [RMSA]	I*I	Typical ESR [Ohms]	P [W]	Total P [W]
0.93	130000	1	130000	1.18781194	0.839909878	0.705448603	0.101	7.13E-02	8.24E-02
		3	390000	0.395937313	0.279969959	0.078383178	0.08	6.27E-03	
		5	650000	0.237562388	0.167981976	0.028217944	0.07	1.98E-03	
		7	910000	0.16968742	0.119987125	0.01439691	0.065	9.36E-04	
		9	1170000	0.131979104	0.09332332	0.008709242	0.0615	5.36E-04	
		11	1430000	0.107982904	0.076355443	0.005830154	0.0595	3.47E-04	
		13	1690000	0.091370149	0.064608452	0.004174252	0.0579	2.42E-04	
		15	1950000	0.079187463	0.055993992	0.003135327	0.057	1.79E-04	
		17	2210000	0.069871291	0.049406463	0.002440999	0.056	1.37E-04	
PI		19	2470000	0.062516418	0.044205783	0.001954151	0.0553	1.08E-04	
3.14159265		21	2730000	0.056562473	0.039995708	0.001599657	0.055	8.80E-05	
		23	2990000	0.051643997	0.036517821	0.001333551	0.0546	7.28E-05	
		25	3250000	0.047512478	0.033596395	0.001128718	0.0545	6.15E-05	
		27	3510000	0.043993035	0.031107773	0.000967694	0.0542	5.24E-05	
		29	3770000	0.040959032	0.02896241	0.000838821	0.0541	4.54E-05	
		31	4030000	0.038316514	0.027093867	0.000734078	0.054	3.96E-05	
		33	4290000	0.035994301	0.025451814	0.000647795	0.054	3.50E-05	
		35	4550000	0.033937484	0.023997425	0.000575876	0.054	3.11E-05	
				sqrt of sumsq		0.927640528			

14 ANNEX 4: SURGE CURRENT TEST 1, RESULTS

SCT of T1

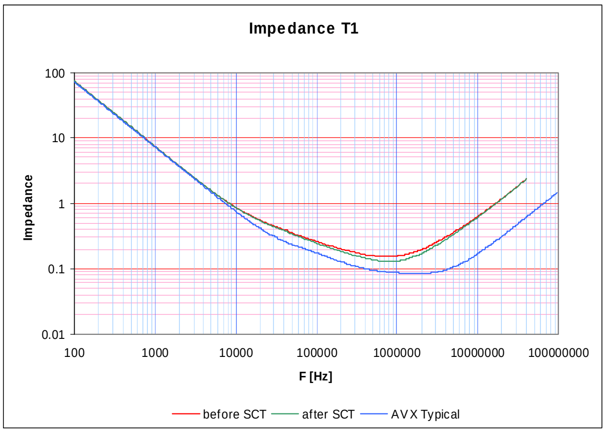


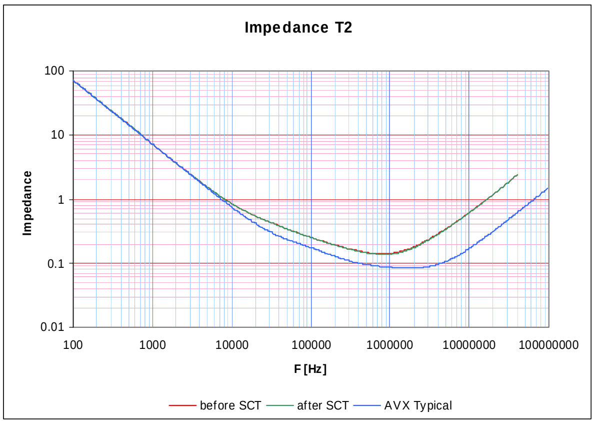
SCT of T1-T22

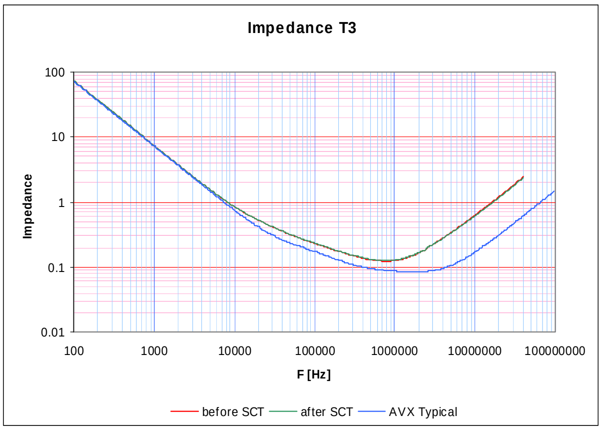
Capacitor	Charge/Discharge	Charge Peak Amplitude [A]	rise time [us]	Discharge Peak Amplitude [A]	fall time [us]
T1	1	62.6	13.61	73.6	15.62
	2	62.8	14.04	73.8	14.94
	3	63	13.95	74	14.05
	4	62.6	13.72	73.8	14.5
	5	63.8	13.35	73.2	14.23
T2	1	61.4	12.94	72.6	13.83
	2	63.6	12.91	75.6	14.87
	3	49.8	14.89	73.6	15.33
	4	61.2	14	74.2	14.49
	5	61.6	12.67	75	14.4
T3	1	63	12.67	75.6	14.3
	2	64.2	12.1	75.2	14.09
	3	64.8	13.42	75.2	15.43
	4	62.4	13.12	76.6	14.61
	5	62.6	13.51	75.4	15.03
T4	1	63.8	13.1	72.6	14.17
	2	62.2	13.34	71.2	14.48
	3	64	12.45	75	14.26
	4	64.2	13.26	74.8	13.9
	5	64.4	13.14	74.8	13.84
T5	1	64.6	13.48	75	14.82
	2	62.2	12.37	75.4	14.79
	3	64.4	12.05	77.2	13
	4	62.2	12.96	75.4	14.92
	5	65.4	12.91	70.2	14.48
T6	1	62	13.57	75.2	14.97
	2	**FAILURE !**			
	3				
	4				
	5				
T7	1	60.8	13.08	71.2	14.51
	2	61.2	12.68	70.2	13.87
	3	62	13.06	65	14.65
	4	62.6	12.46	73.6	14.11
	5	62.2	12.6	74.8	14.68
T8	1	64.6	13.72	74.8	14.12
	2	62.6	14.08	74.8	14.84
	3	64.2	13.68	74.8	15.17
	4	64.6	13.91	74.6	14.61
	5	62.8	13.72	67.4	15
T9	1	63.8	13.49	75.6	14.65
	2	54.4	14.96	74.2	15.04
	3	62	14.05	69.8	15.64
	4	63.8	12.79	74.6	14.71
	5	61.6	13.81	52.8	15.79
T10	1	61.2	13.83	73.4	14.25
	2	63.6	13.89	62.8	15.77
	3	64	13.03	67.8	14.72
	4	63.6	13.26	63.4	14.98
	5	63.8	13.53	75.2	13.91

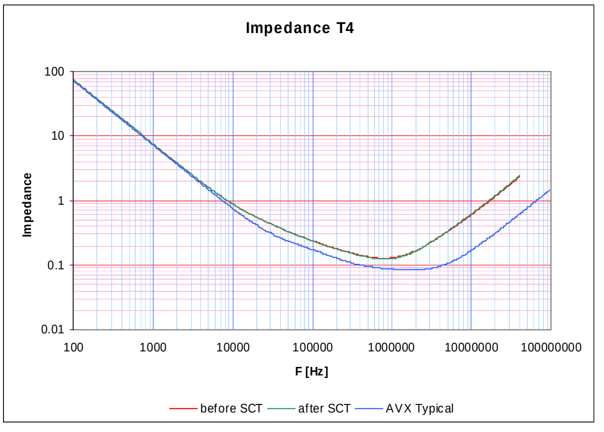
Capacitor	Charge/Discharge	Charge Peak Amplitude [A]	rise time [us]	Discharge Peak Amplitude [A]	fall time [us]
T11	1	56.4	18.99	74.2	14.26
	2	62.8	14.36	65.4	17.45
	3	64.4	13.32	75	13.86
	4	64.8	13.73	74.2	14.26
	5	64	13.48	74.8	15.09
T12	1	61.2	11.22	72.2	14.08
	2	62.6	12.1	73.6	14.44
	3	62.4	11.74	72.4	13.41
	4	62.6	12.58	72.6	13.7
	5	63	13.2	74	13.61
T13	1	63.4	12.97	74.8	14.46
	2	64.6	12.99	70	15.45
	3	63	13.3	75.2	14.23
	4	61.8	11.96	74.4	14.36
	5	64.4	12.67	74.6	14.08
T14	1	63.4	12.87	73.8	15.35
	2	63.2	13.82	67.8	14.93
	3	64	14.37	75	14.42
	4	61.4	14.23	73.6	15.19
	5	64	13.17	74	15.52
T15	1	60.8	13.08	73.6	14.76
	2	63.4	12.35	73.6	13.81
	3	61	14.34	73.6	14.17
	4	63	12.79	73.8	14.17
	5	55	14.51	74	13.64
T16	1	60.4	12.79	73.4	14.08
	2	63.4	12.67	74.4	14.1
	3	63.6	13.27	57	18.45
	4	62.4	13.61	73.8	14.92
	5	63	13.21	55.4	19.41
T17	1	63.8	13.73	73.4	15.08
	2	61.4	15.43	73.2	15.4
	3	61	12.55	74.4	15.86
	4	61.8	14.09	74	13.96
	5	60.8	13.98	72	14.56
T18	1	60.4	12.48	69.2	14.71
	2	63.8	11.59	73.6	13.68
	3	63.4	12.06	73.2	13.66
	4	63	12.24	73.8	13.26
	5	63.4	13.13	74.8	13.98
T19	1	64.2	12.88	75	13.7
	2	64.8	12.97	75.2	14.15
	3	62	12.81	74.8	13.64
	4	64.6	12.86	74.8	14.02
	5	63.8	12.77	62	17.78
T20	1	64.8	14.16	74.2	15.87
	2	64	12.71	73.6	15.24
	3	61.6	14.2	75.2	14.68
	4	64.2	14.19	73.8	14.46
	5	64.2	14.58	75.6	14.58
T21	1	61	13.42	66	16.23
	2	61	12.49	73.2	14.77
	3	61.6	12.52	74.6	13.86
	4	64	12.87	72.4	14.74
	5	61.6	13.06	72.6	15.03
T22	1	62.2	13.52	74	14.48
	2	63.6	14.24	73.8	14.21
	3	63.6	14.43	73	15.67
	4	63.4	13.41	74.6	15.14
	5	60.8	14.03	73.4	14.12

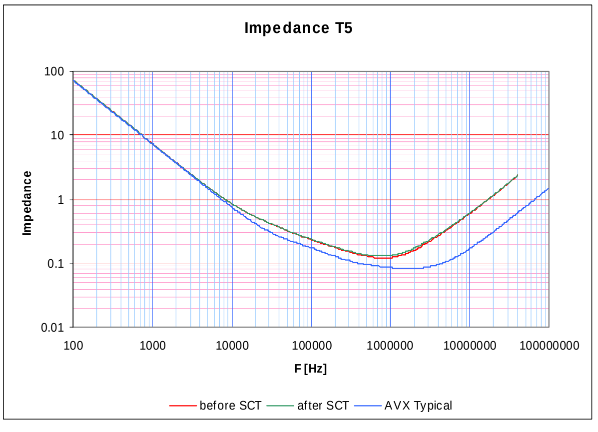
15 ANNEX 5: IMPEDANCES DURING THE SURGE CURRENT TEST 1

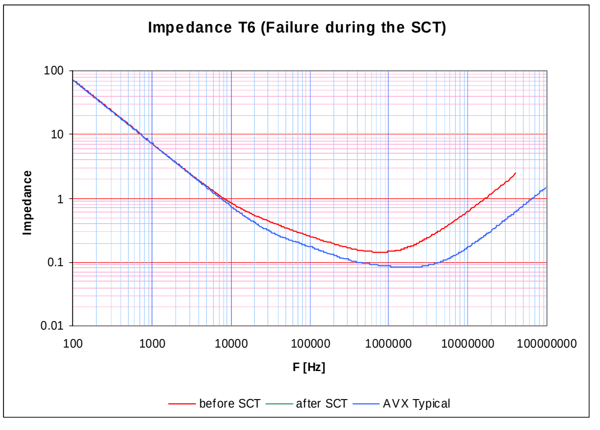




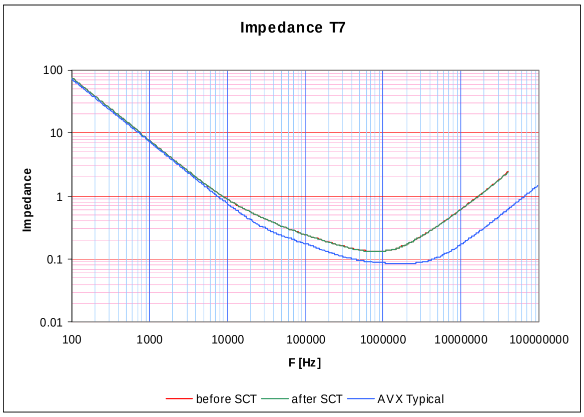


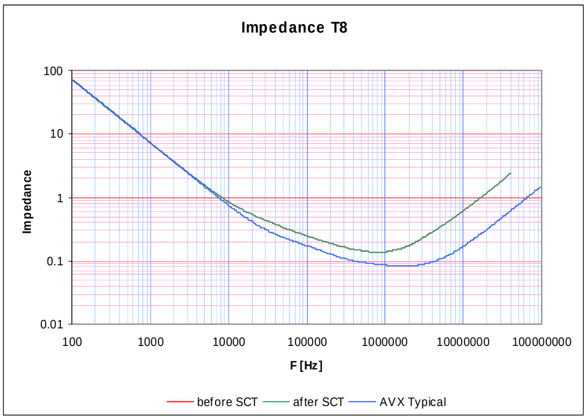


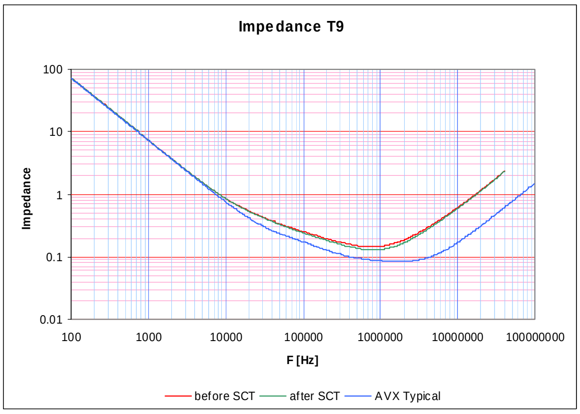


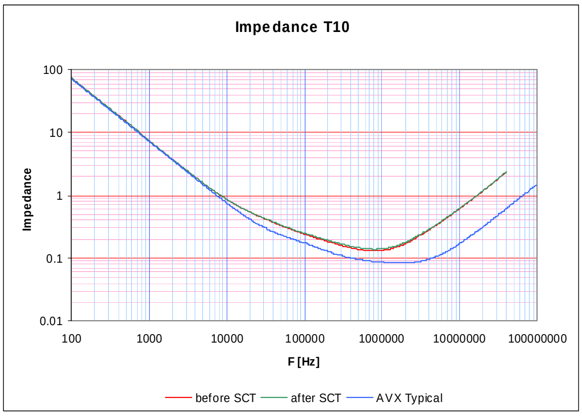


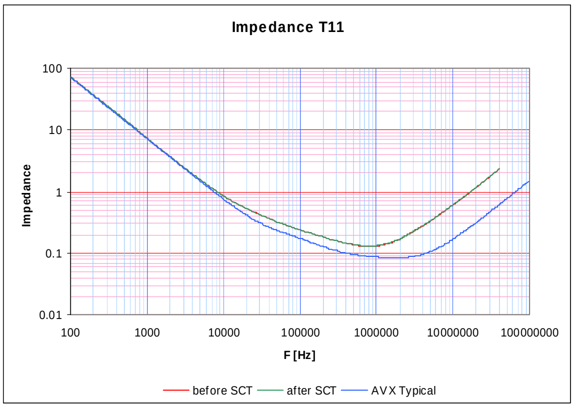
Impedances before and after the Surge Current Test 1

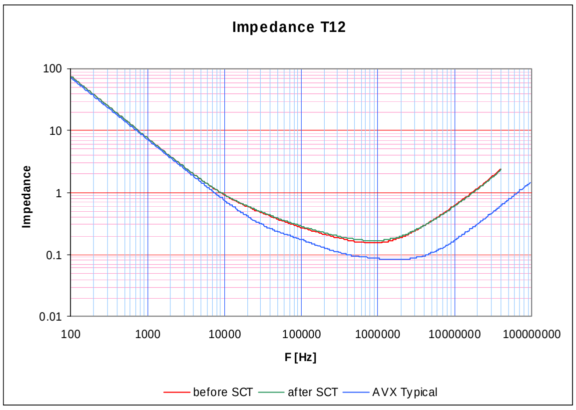




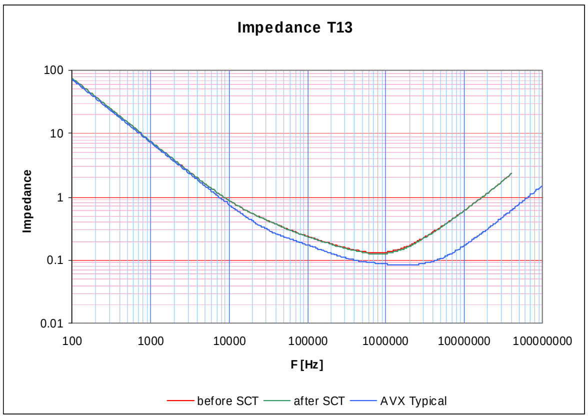


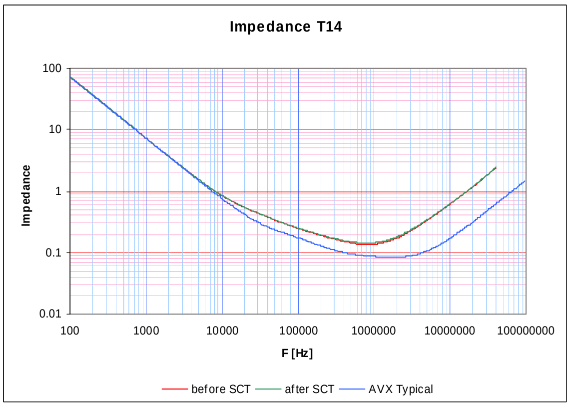


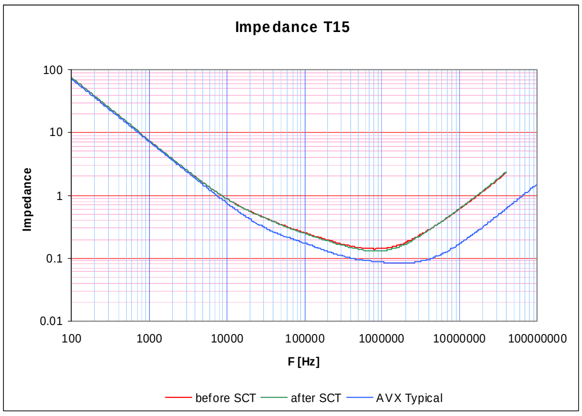


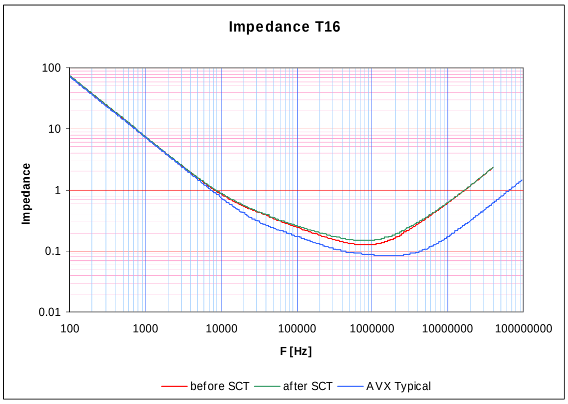


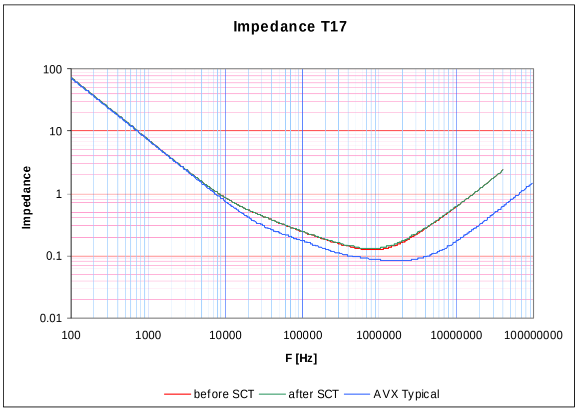
Impedances before and after the Surge Current Test 1

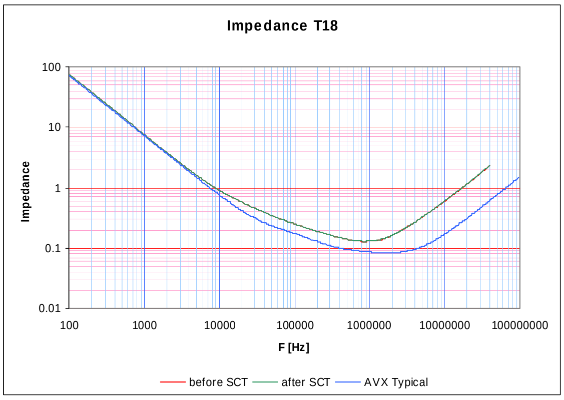




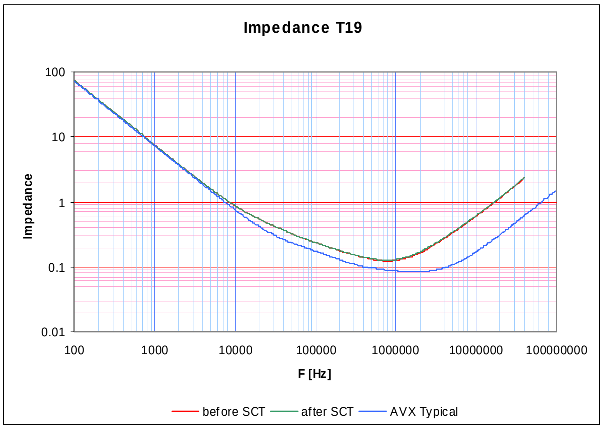


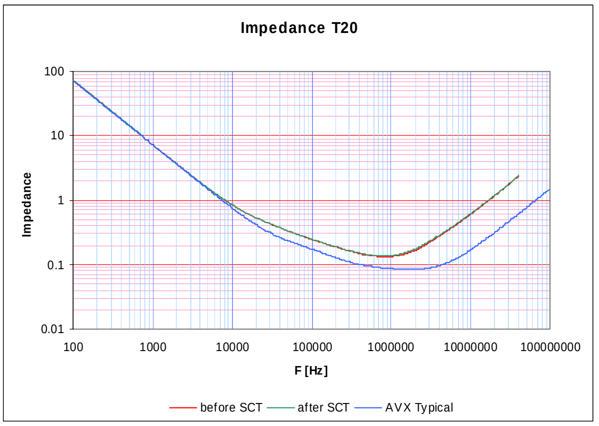


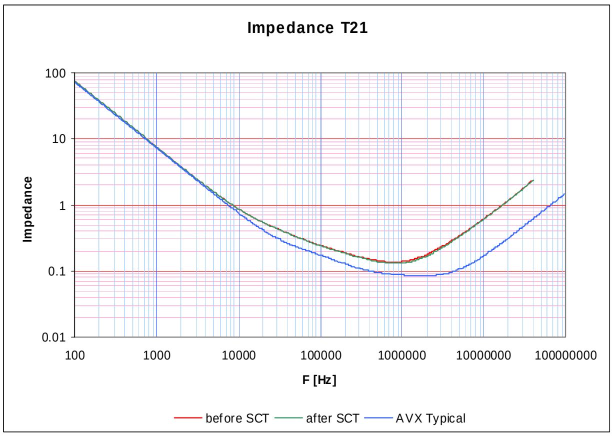


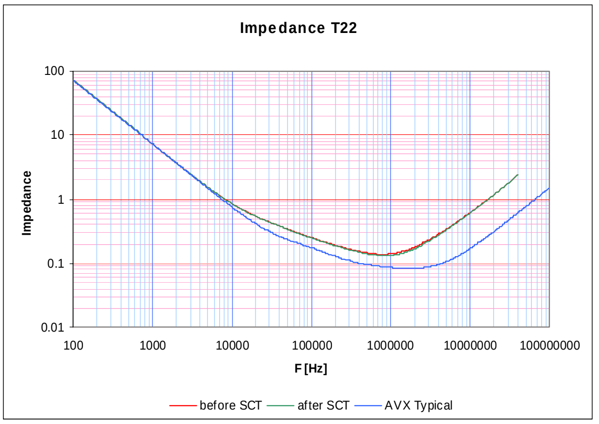


Impedances before and after the Surge Current Test 1

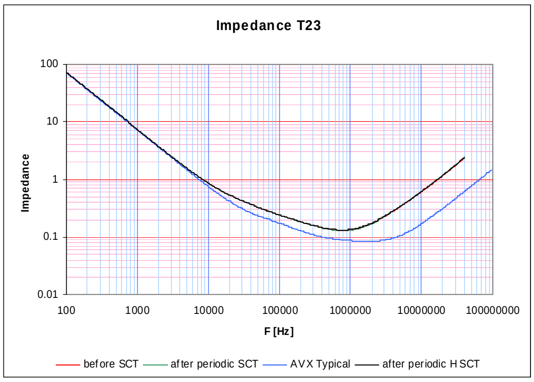


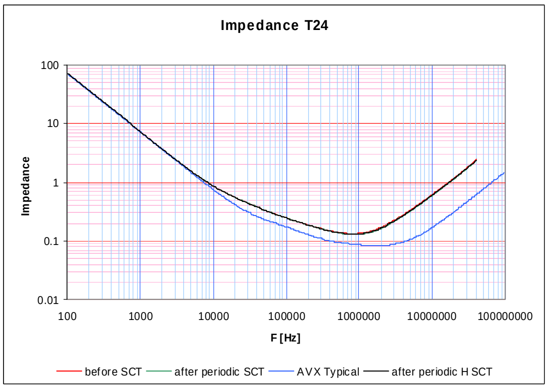


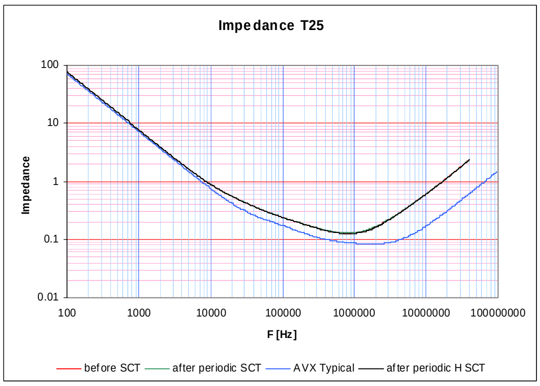


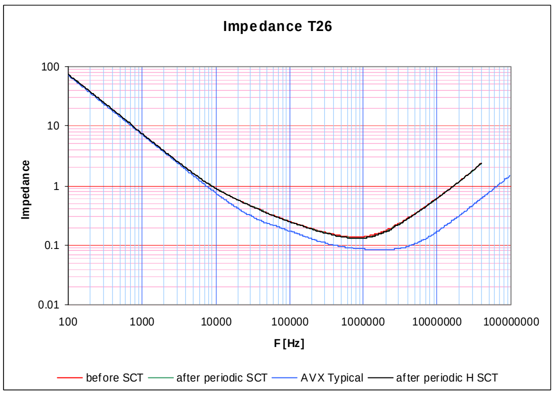


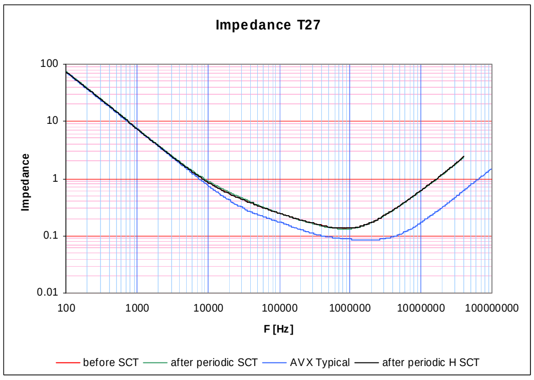
16 ANNEX 6: IMPEDANCES DURING THE SURGE CURRENT TESTS 2 & 3



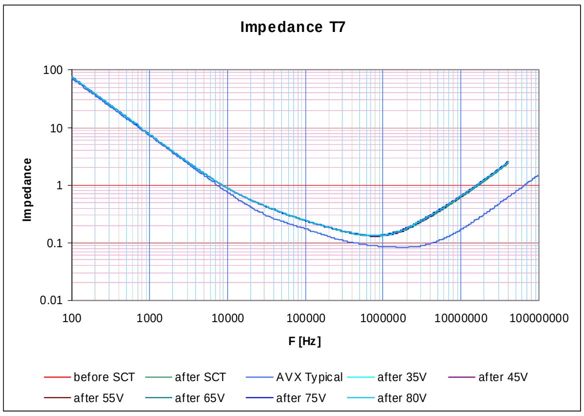


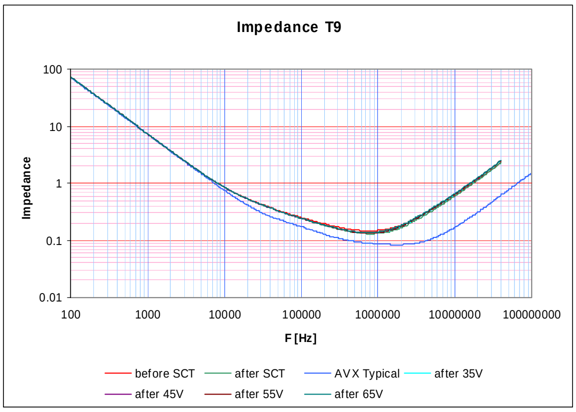


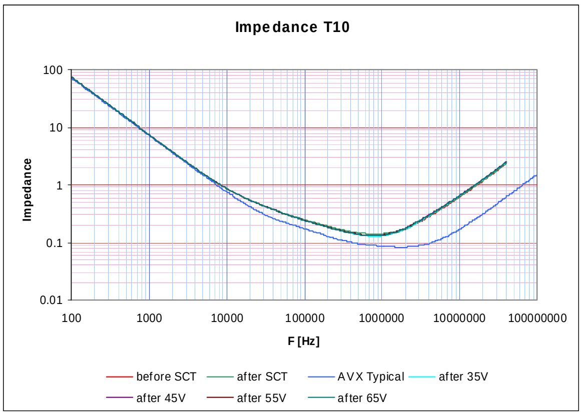


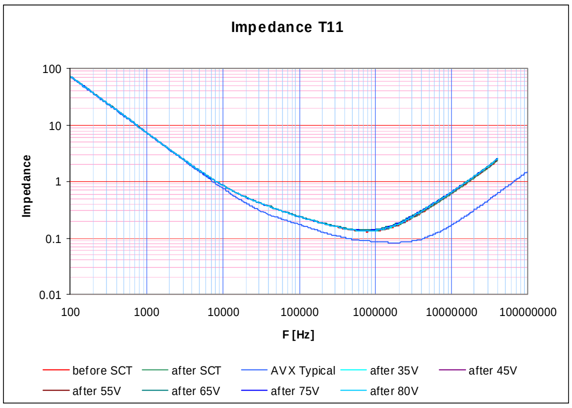


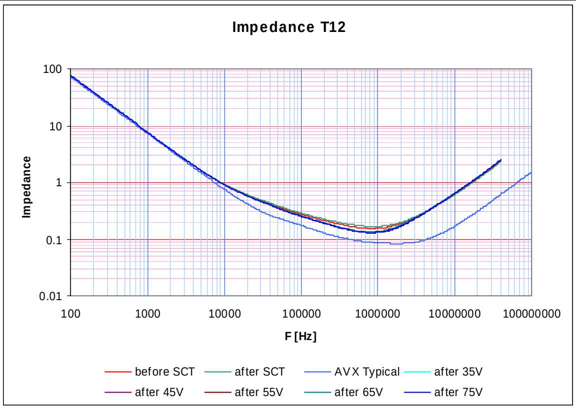
17 ANNEX 7: IMPEDANCES DURING THE VOLTAGE TESTS

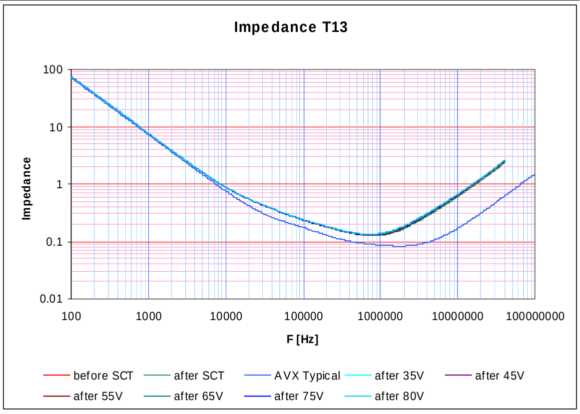


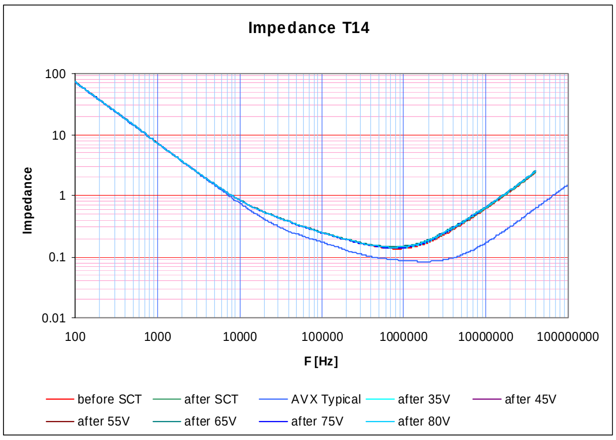




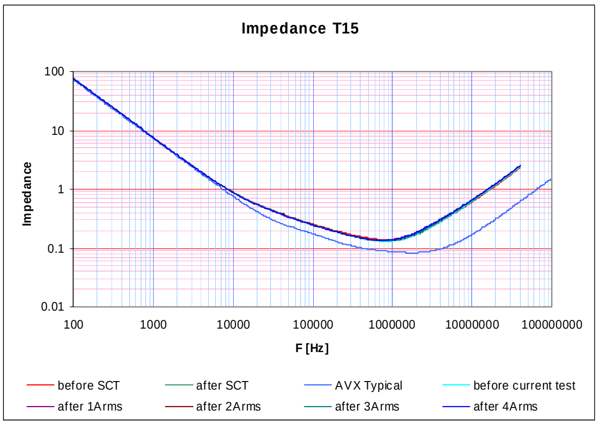


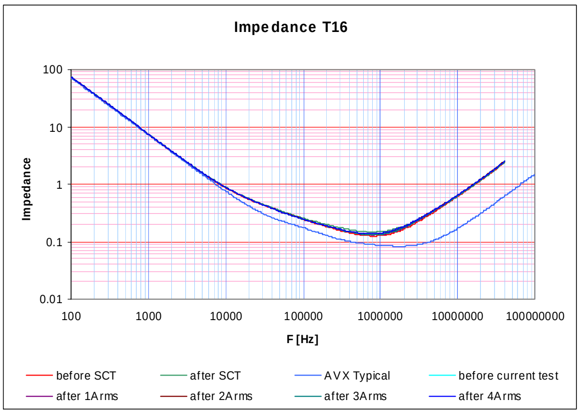


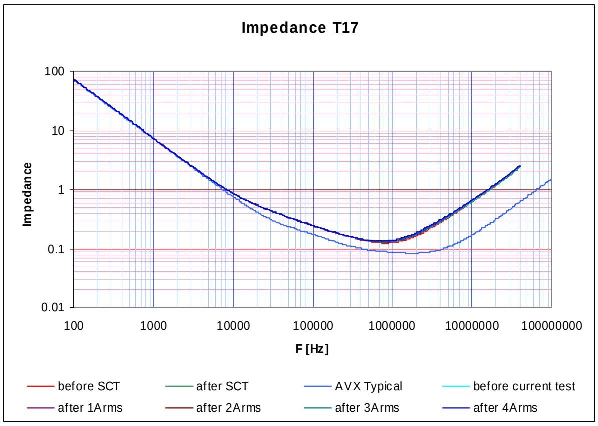


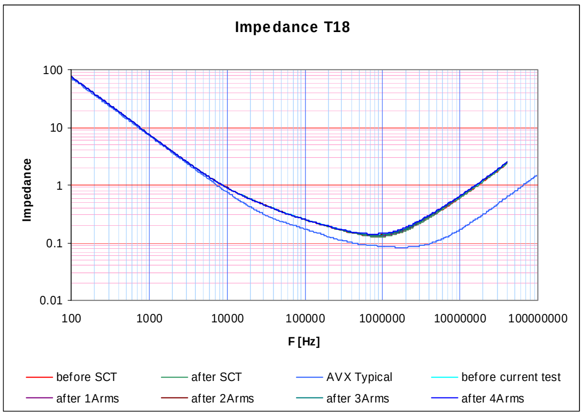

Impedance T14
100
10
1
0.1
0.01
Impedance
100
1000
10000
100000
1000000
10000000
100000000
F [Hz]
before SCT
after SCT
AVX Typical
after 35V
after 45V
after 55V
after 65V
after 75V
after 80V

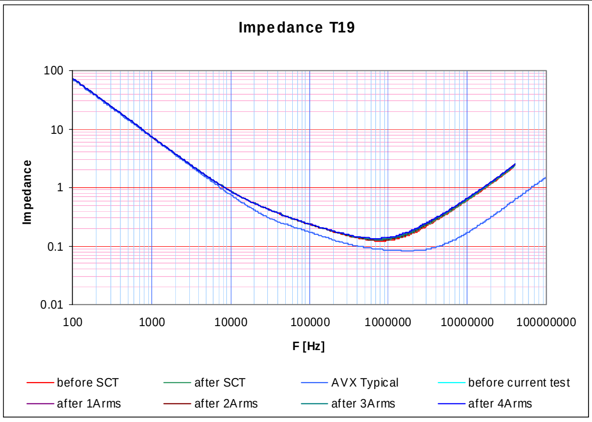
18 ANNEX 8: IMPEDANCES DURING THE CURRENT TESTS

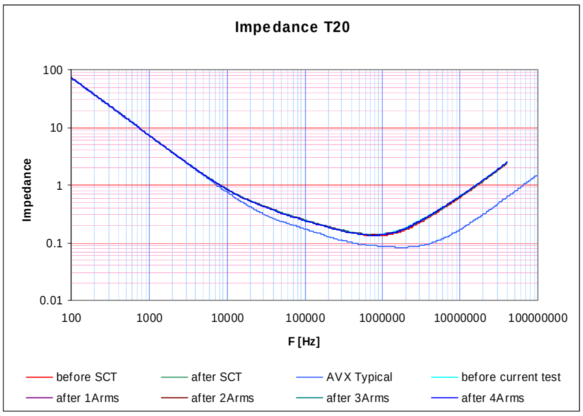


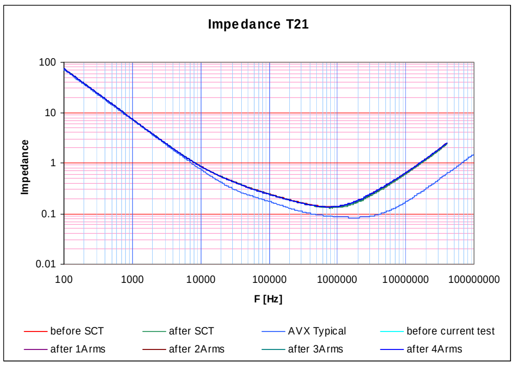











Impedance T21
100
10
1
0.1
0.01
Impedance
100
1000
10000
100000
1000000
10000000
100000000
F [Hz]
before SCT
after SCT
AVX Typical
before current test
after 1Arms
after 2Arms
after 3Arms
after 4Arms