Derating Tantalum Capacitors

Depends on the Cathode System

Collaborated by Jon Rhan & Jerard Jose, presented by Jerard Jose for CMSE in 2023, Los Angeles, CA

Overview

- Vishay will compare the various derating schemes for tantalum capacitors with different cathode systems: MnO_2, wets, and polymer. Other factors to be considered include the applied voltage, temperature, application, and reliability level, all of which will impact derating for the design
- Cathode types: MnO_2, polymer, wet
    - Failure (what is a failure?) – FRL / FIT / MTBF, failure rate in PPM
        - Current derating standards / recommendations / etc.
        - FIT vs temperature (% rated voltage)
    - Testing
    - Reliability
    - Applications: deratings for commercial vs military vs space
- Conclusion / summary

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Reliability Characteristics and Failure Modes

A question arises: If we manufacture a capacitor with a predefined rated voltage (meaning: definite dielectric thickness) and then test it for DCL and apply a surge current stress – why using the capacitor at a derated voltage needed?

- For your working conditions, the voltage on the capacitor is the sum of DC bias, AC ripple voltage, and any possible transient peaks, etc. This sum should not exceed the rated voltage for solids.
- In some applications (especially input filters in low impedance circuits), the current pulses may reach very high values, even more than those applied during our surge current tests.
- Besides that, voltage derating (along with temperature derating where necessary, and adding series impedance) further improves capacitor reliability (meaning a decreased failure rate (FR)).

Reliability Characteristics & Failure Modes

- Basic definitions:
  - FR is characterized by the number of failed parts during a certain period. Usually, it's expressed in N per 1000 unit/hours
  - For example, if 200 capacitors worked in field applications for 500 hours, the unit/hour amount is 200 x 500 = 100 000. If during this period there were three failed parts, the FR (in N) will be: 3*100/100 000 = 0.003 %
  - Mean time to failure (MTTF) is the inverse value to FR: MTTF = 1/FR (FR to be expressed as a number, not a percent). So, for the above example: MTTF = 100/0.003 = 33 333 (hours)

Solid Tantalum Capacitors

- Military acceptance of tantalums in the late 1950s led to the establishment of standard life testing procedures:
  - Rated voltage for 1000 hours at +85 °C with current limiting resistors in series. This is a “steady state” test procedure and is still the industry standard
  - “M” level exponential failure rates for the above test conditions were 1 % per 1000 hours
  - Standard military and commercial products were designed to meet this failure rate requirement
  - Low impedance circuitry (minimal current limiting resistance) requires better than M failure rates
  - Voltage derating greatly enhances reliability
- As field FR data became available (primarily through military studies), actual reliability calculations became possible:
  - MIL-STD-217 was developed for capacitors
  - Derating of applied voltage from full rated voltage down to 50 **% -** 66 % dropped field FRs to approximately 5 FIT -15 FIT from hundreds of thousands of FIT

Exponential Failure Rates

We also use life test results to calculate the "**base FR**" for a certain type / series of capacitors. "**True FR**" depends on the application (see MIL HDBK 217F).

Accumulated data helps us predict the reliability (life, MTBF) of the capacitors. This is done periodically on selected lots (not a 100 % test) and helps "establish" the reliability of a product line.

This is called the **exponential model** (60 % confidence level) and is calculated as below:

Definition of base FR:

- F_r = (N of failures +1)/1000 hours expressed in % per thousand hours.

Exponential failure rate levels:

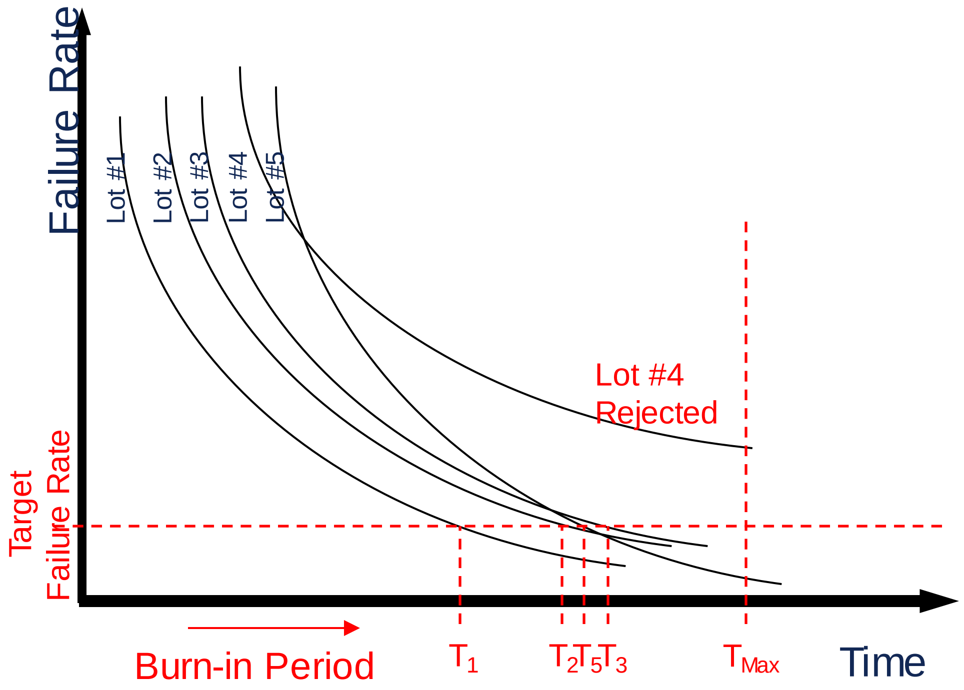
- **M= 1 % per thousand hours**
- P = 0.1 %
- R= 0.01 %
- S: 0.001 %

Weibull Voltage Grading & Failure Rates

- Weibull FR grading
  - B: 0.1 % per 1000 hours
  - C: 0.01 %
  - D: 0.001 %
- Conditions:
  - Voltage: 1.3 ~ 1.5 x RV
  - +8 5°C
  - 40 hours (or longer if needed)
- Benefits:
  - Screens out infant mortality failures
  - Screening continues until a specific reliability level is achieved
  - Eliminates lot to lot variability in reliability performance
  - Screens out lots that exhibit uncharacteristic behavior

CHARACTERISTIC DISTRIBUTION OF FAILURE RATE VS. TIME FOR TANTALUM CAPACITORS

(WEIBULL DISTRIBUTION)



Reliability Characteristics & Failure Modes

- Solid electrolyte tantalum capacitors of all styles (conformal, molded, or hermetically sealed) are very reliable and for all practical purposes have an unlimited lifespan when used within the voltage / temperature ratings and circuit impedance guidelines assigned by the manufacturer
- The properties of tantalum pentoxide dielectric (Ta_2O_5) are such that there is no dielectric wear-out under derated application conditions, and usually failures are found in the very beginning at the first “switch on” (early life FR or infant mortality). The FR then decreases over time (see Figure 1)

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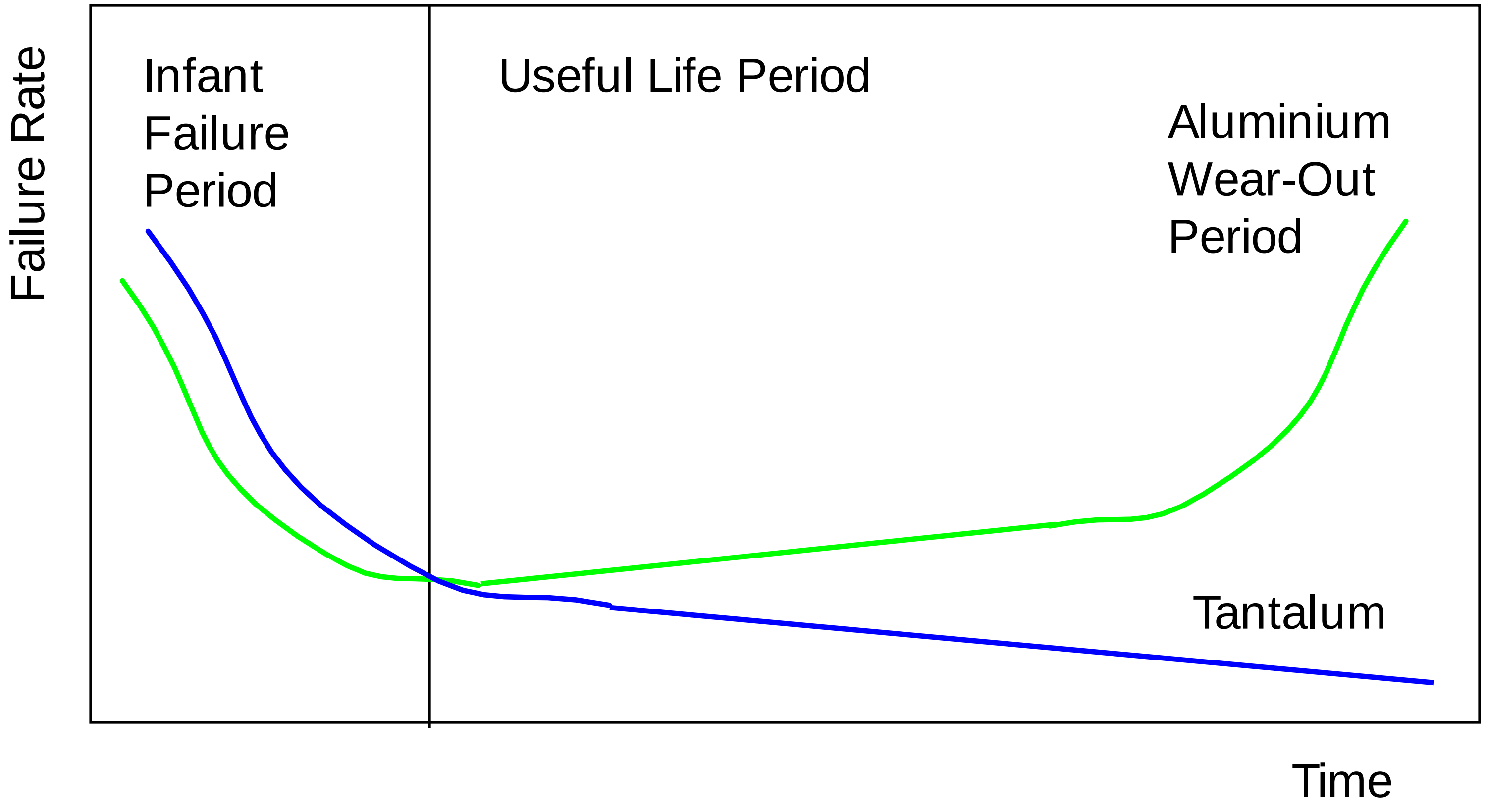
Reliability Characteristics & Failure Modes

- Figure 1: FR during lifetime
- Typical curve (“bathtub”), like for AL capacitors
- Decreasing FR, like for tantalum capacitors



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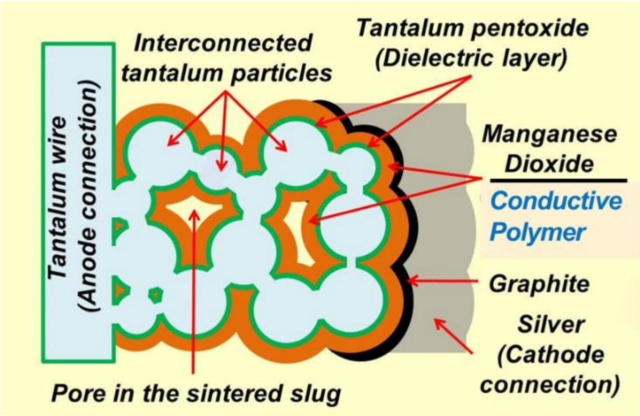
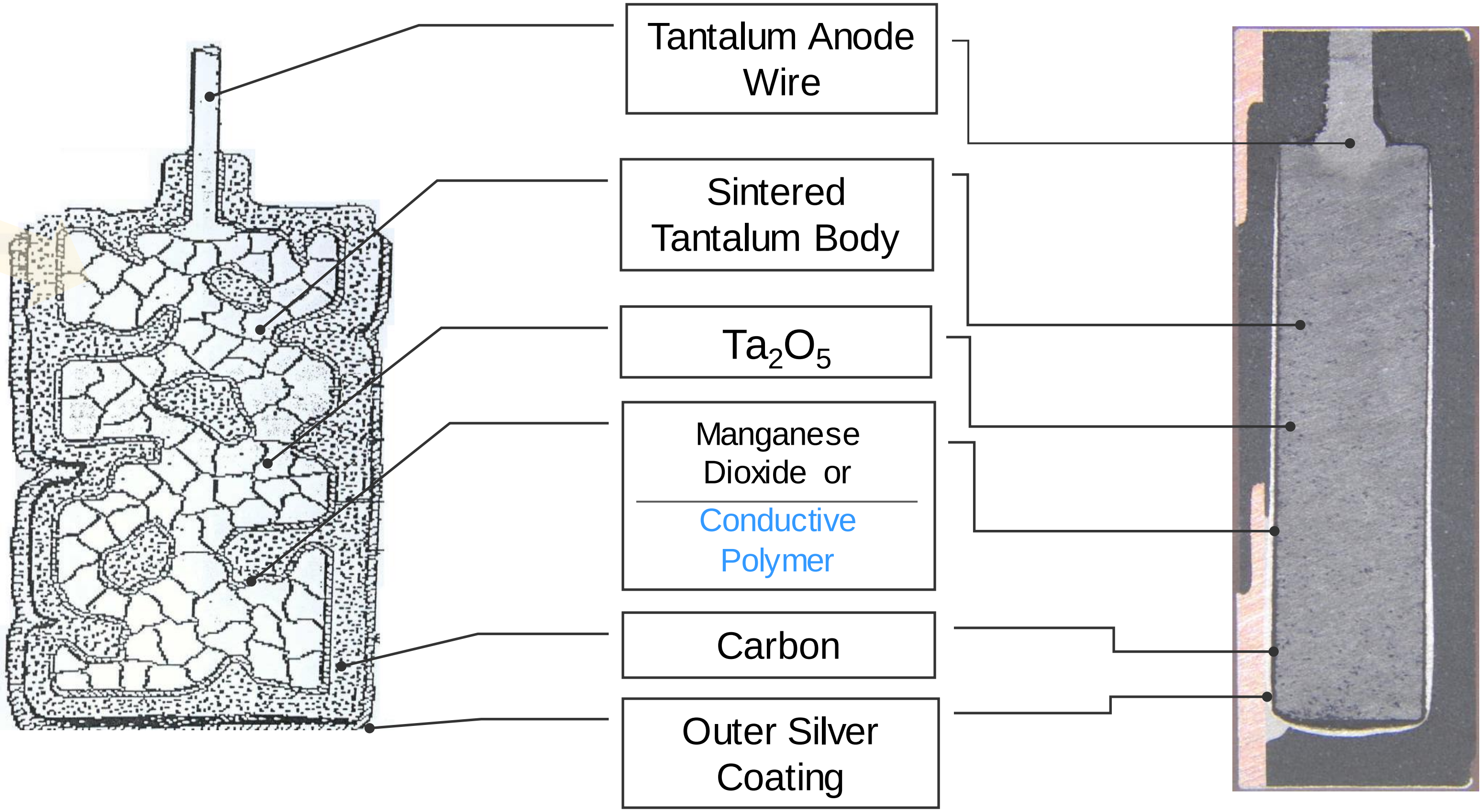
Basic Solid Tantalum Capacitor Element





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MnO2 Solid Tantalum Capacitors

- Vishay - along with other manufacturers of tantalum capacitors - recommends derating the DC voltage in order to increase the long term reliability of the capacitors. Similar recommendations are provided by the EIA-809 “Solid Tantalum Capacitor Application Guide” and relevant NASA and military specifications. Usually, the recommendation is that the application (working) voltage be between 0.5 V and 0.6 V of the rated voltage. For rated voltages ≥ 35 V, Vishay recommends an even higher derating ratio, with a minimum of 50 % derating. The following table shows a practical approach to derating for several popular voltage rails (working voltages).

RECOMMENDED VOLTAGE DERATING GUIDELINES (below 85 °C)	
VOLTAGE RAIL	**CAPACITOR VOLTAGE RATING (V)**
≤ 3.3	6.3
5	10
10	20
12	25
15	35
24	50 or series configuration
28	63 or series configuration
≥ 32	75 or series configuration

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Voltage Acceleration Models: MnO_2

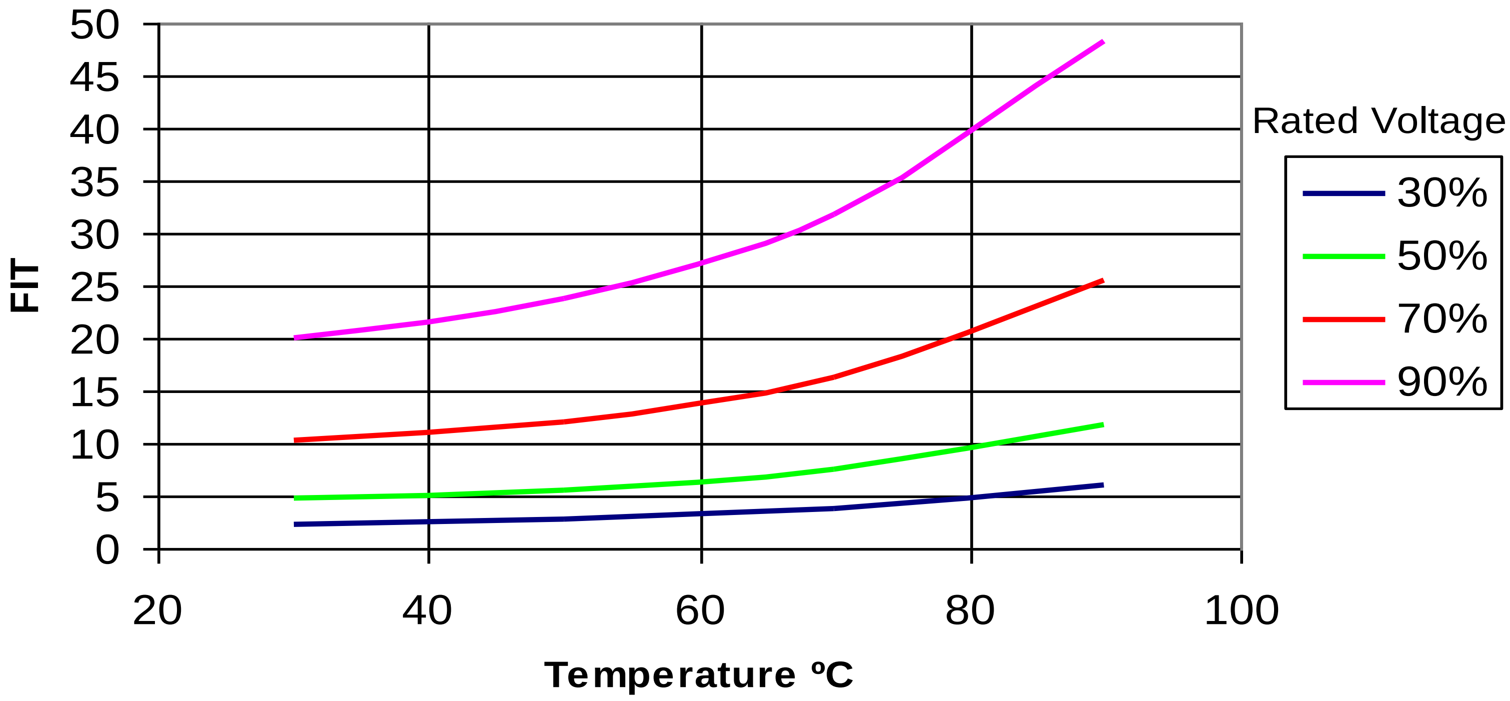
- The FR [λp] for MnO_2 capacitors is defined in MIL-HDBK-217F Notice 2:

  $\lambda_p = \lambda_b \pi_T \pi_C \pi_V \pi_{SR} \pi_Q \pi_E \; x \; 1000$, where λb represents the basic failure rate [BFR]

- The formula reflects the effect of voltage, temperature, and multiple environmental factors. The latter factors are difficult to define precisely
- The voltage acceleration factor (VAF) π_V has a strong effect on FR, especially when derating factor S is above 0.6 [60 %].

$$\textbf{VAF}\ [\pi_V] = \{S/0.6\}^{17} + 1, \text{ where [Derating] } S = \frac{Application\ Voltage}{Rated\ Voltage}$$

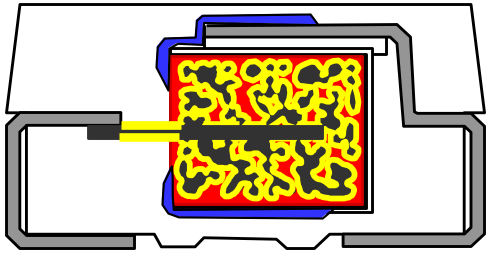
MnO2 Solid Tantalum Failure Rate



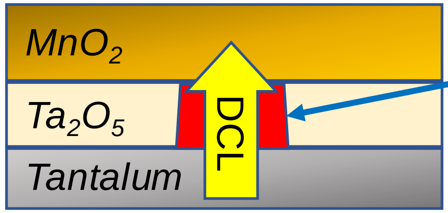
100uF low Z circuit, .6 base FIT = parts/billion hours

Tantalum Capacitors Healing Mechanism: MnO2 vs. Polymer

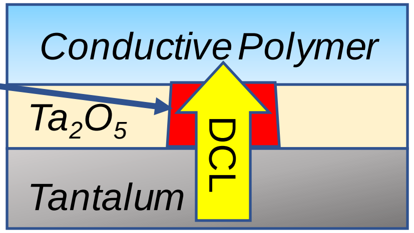
MnO_2 Capacitors



Polymer Capacitors

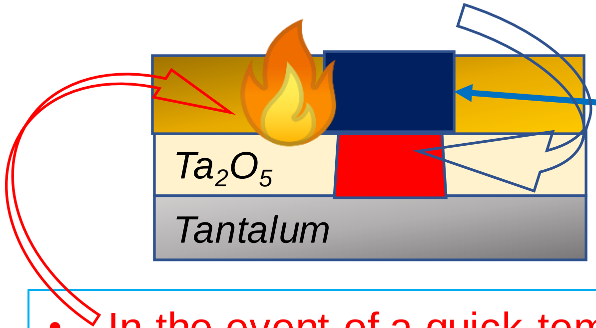


Defect in dielectric causes elevated DCL, resulting in a local temperature increase

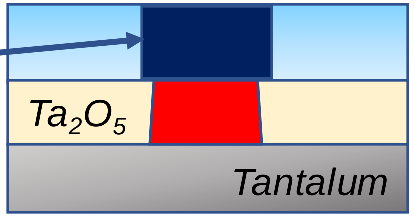


- Temperature increase to ~500 °C
- *Under heat* MnO_2 *--->*Mn_2O_3 *+ O*
- Highly resistive Mn_2O_3 electrically isolates the failure spot

- Temperature increase to ~300°C.
- Conductive polymer resistance increases under heat.
- Failure spot electrically isolated.



Insulator



- In the event of a quick temperature rise, ignition may occur

- If no oxygen is available in the system, *the ignition may not occur!*

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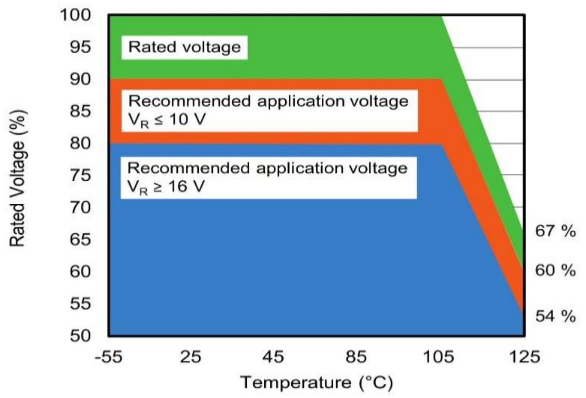
Polymer Background

- The question about a difference in recommended derating for tantalum polymer capacitors compared to conventional tantalum MnO_2 capacitors is frequently asked
- Tantalum polymer capacitors represent an advanced version of conventional tantalum MnO_2 capacitors
- They use conductive organic polymer material as a counter electrode rather than traditional MnO_2 cathode material



- In addition to significantly lower ESR, a conductive polymer cathode features more robust performance under voltage stress. This allows for more generous derating recommendations. While 50 % to 60 % derating is recommended for MnO_2 capacitors, the following is applicable for polymer capacitors:
- - 90 % for products rated up to 10 Vr
- - 80 % for products 16 Vr and higher

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Voltage Acceleration Models: Polymer

The FR of **polymer** capacitors is defined in *MIL- PRF – 32700 "CAPACITOR, FIXED, ELECTROLYTIC (CONDUCTIVE POLYMER TANTALUM)…" as:*

$$\boldsymbol{FR} = \frac{F \times 10^5}{(N)(Ttest)(Av)(Ar)}$$, *where*

FR = failure rate level in percent per ,000 hours at DC rated voltage and +85 °C

F = number of failures

N = number of capacitors tested

T_{test} = test duration in hours

A_V = ***VAF***

A_T = temperature acceleration factor (*TAF)*

- Voltage acceleration is defined by the power law model:

$$\boldsymbol{VAF} = (V_R/V)^{VRE}$$

V= Application voltage, V_R= Rated voltage

VRE= Voltage ratio exponent, experimentally determined as described in Appendix B of the MIL- PRF – 32700 specification

- The value of *VRE* ranges from 14 to 19 as defined in § B.4 of the same specification

Polymer Tantalum Capacitors

- It is recommended that capacitors with voltage ratings up to 10 V be derated by 10 % (90 % of rated voltage) and capacitors with voltage ratings greater than 10 V be derated by 20 % (80 % of rated voltage). Users should contact the manufacturer for more information

MIL-PRF-32700

TABLE I. Voltage.

Symbol	Voltage (V_{dc})	
	Rated (+85°C)	Derated (+125°C)
A	2.5	1.7
B	3	2.0
C	4	2.7
D	6.3	4.2
F	10	6.7
H	16	10.7
J	20	13.3
K	25	16.7
L	30	20.0
M	35	23.3
N	50	33.3
P	63	42.0

Derating Recommendations: MnO_2 vs. Polymer Capacitors

- It is common to calculate the ***FR*** during useful life of components based on the life test results as:

$$\boldsymbol{FR} = \frac{\chi^2(\alpha,(2m+2))}{2} \times \frac{1}{AF} \times \frac{1}{Nt}$$

where χ^2 is the chi-square function, α is the confidence level, m is the number of failures, N is the number of tested samples, t is the duration of the test, and *AF= VAF*TAF* is the acceleration factor that depends on test voltage and temperature

Parameter	Basic Failure Rate	MnO_2 capacitors	Polymer capacitors
Reference document		*MIL-HDBK-217F Notice 2*	*MIL- PRF – 32700*
Voltage acceleration model	N/A	$\boldsymbol{VAF}\ [\boldsymbol{\pi_V}] = \{S/0.6\}^{17}+1,\ S=\frac{V}{Vr}$	$VAF=(V_R/V)^{VRE}$
Voltage Ratio exponent [VRE]	-	-	16
Derating [V/V_R]	1	0.5	0.8
Voltage acceleration factor [VAF]	1.0	23.2	35.5
Temperature acceleration factor [TAF]	1.0		
Number of units tested (N), pcs	100		
Test hour per unit (t), hours	1000		
Number of failures (m), pcs	0		
Chi-Aquare @ confidence level (α)	4.6		
Confidence level (α)	0.9		
Failure Rate FR, % 1000 hours	2.3%	0.1%	0.1%
MTTF, years	4.96	115	176

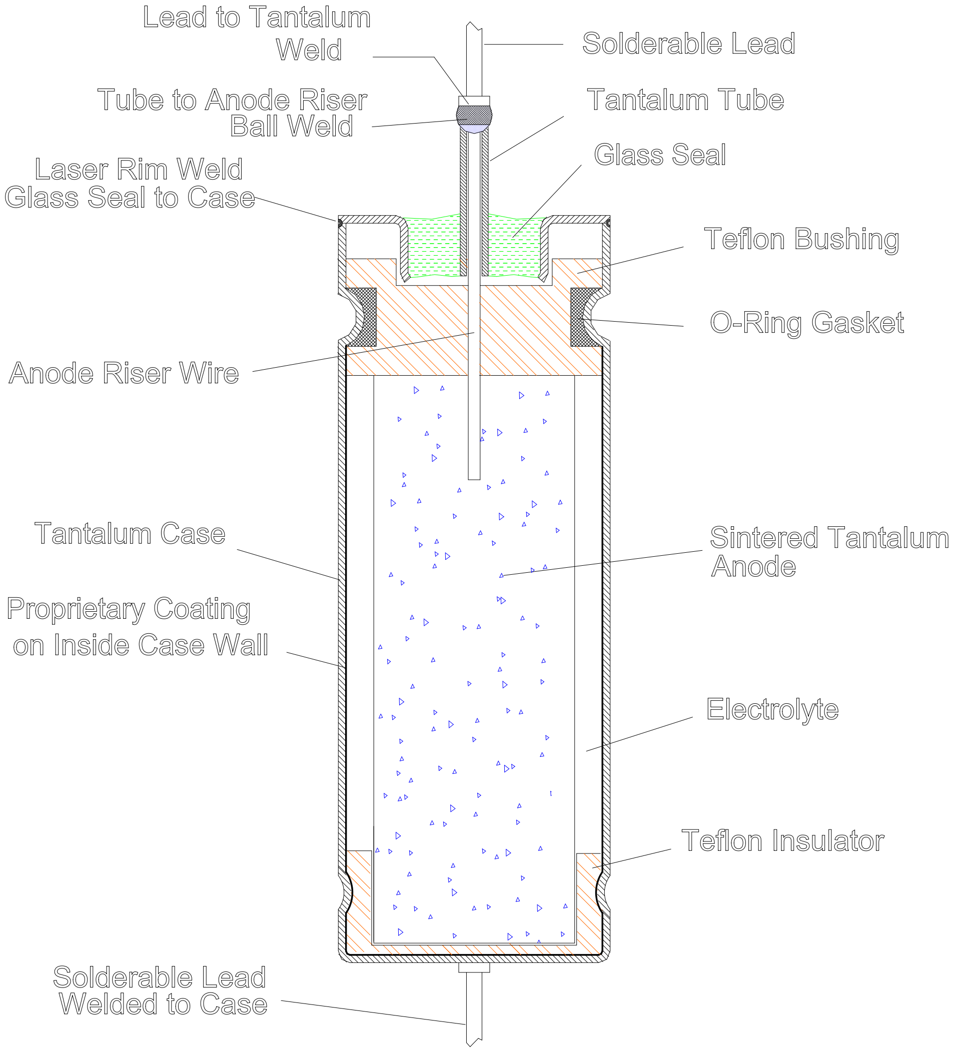
Example: A life test of 100 samples for 1000 h at the specified temperature and rated voltage predicts an FR of 2.3 %/1000 h, even if no failures (m = 0) occurred. This would not be acceptable in the majority of applications.

Derating of 50 % for MnO_2 capacitors and 80 % for polymer capacitors brings the predicted FR to approximately the same level of 0.1 % and increases MTTF from five years to over 100 years!

Tantalum Capacitors Derating Recommendations: MnO_2 vs. Polymer

- Derating is required in order to provide reliable operation of the capacitor under given application conditions. It is also instrumental in prevention of post board mounting and first power-on failures
- While the failure mode of tantalum capacitors is dielectric breakdown under temperature / voltage stress, not each dielectric breakdown event leads to a failure, due to the ability of the capacitors to self-heal
- FR should NOT be confused with turn-on / surge events. FIT assumes the part is energized and stable. Transient events, at any time, can cause a weakness to fail
- Decreasing FR is a result, in part, of self-healing mechanisms. These mechanisms operate under steady-state conditions and have limited effect in surge events

Wet Tantalums



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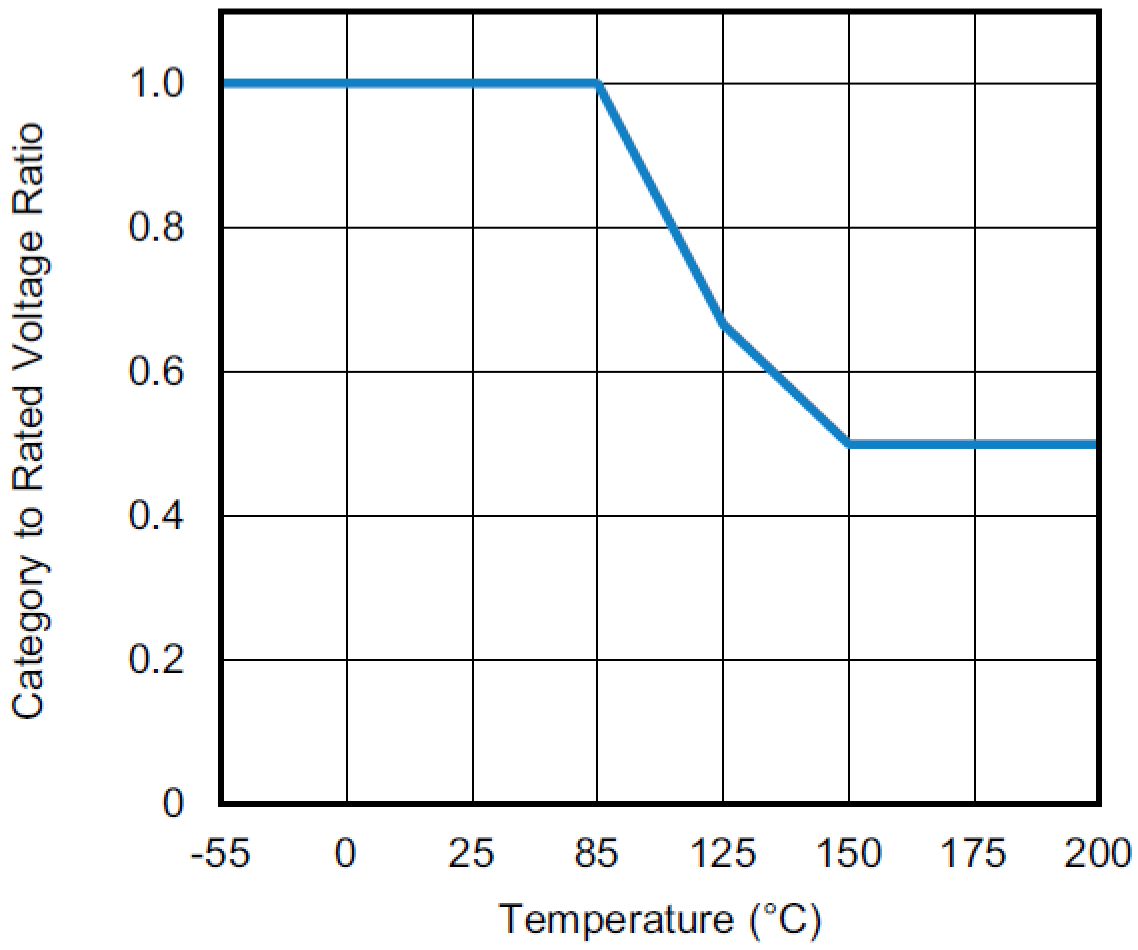
Wet Tantalum Capacitors Derating



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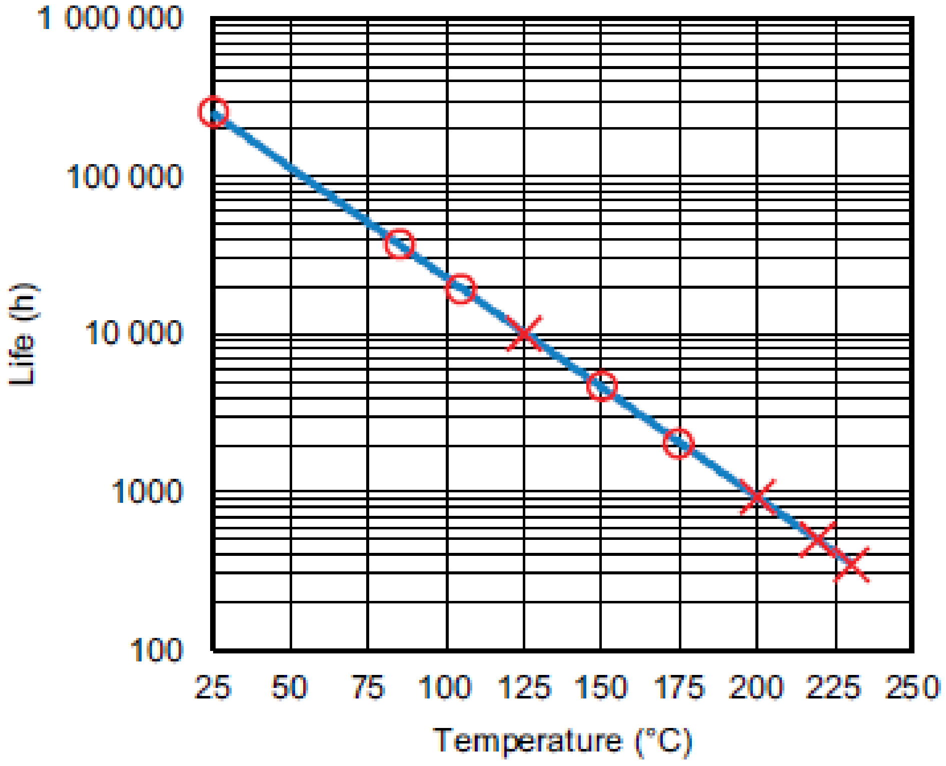
Life Versus Temperature for Wet Tantalum Capacitors

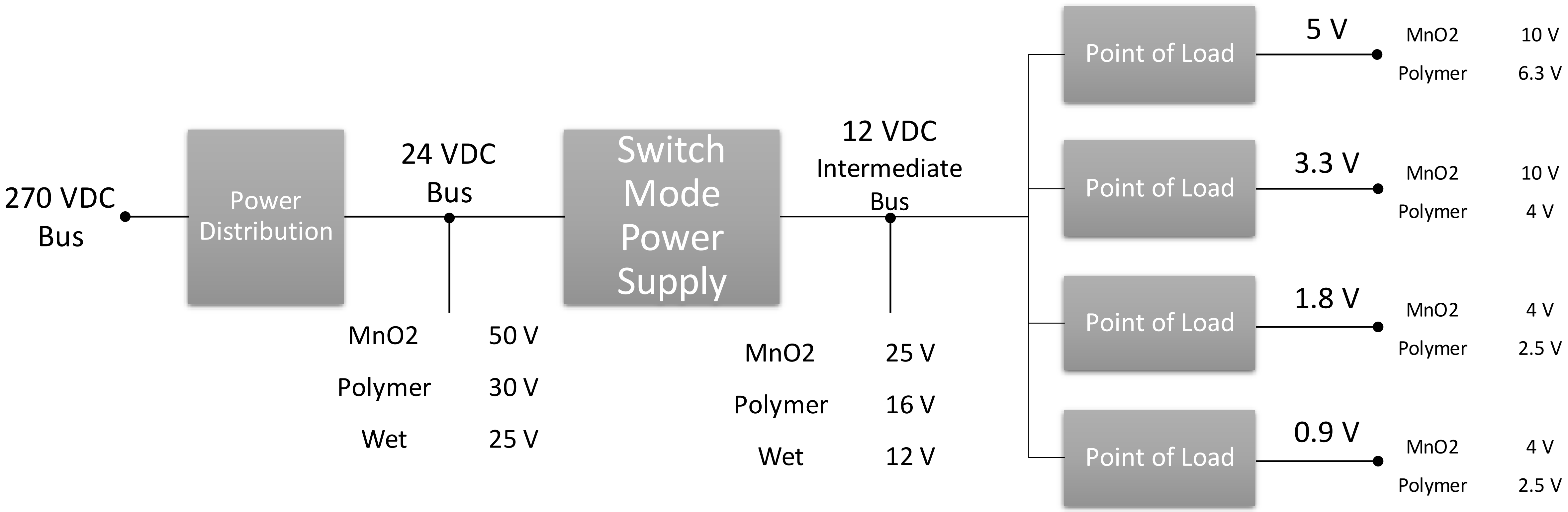
- The data points "X" are fixed from ongoing reliability test data at +125 ºC and above at the appropriate voltage derating
- We also have extensive data for 10 000 hours at +85 ºC at rated voltage. The "circled" data points are estimated from the fitted curve
- As a reminder, any application above +85 ºC should be at a derated voltage appropriate for the temperature



Wet Tantalum Capacitor
Life vs. Temperature (Fitted Curve)

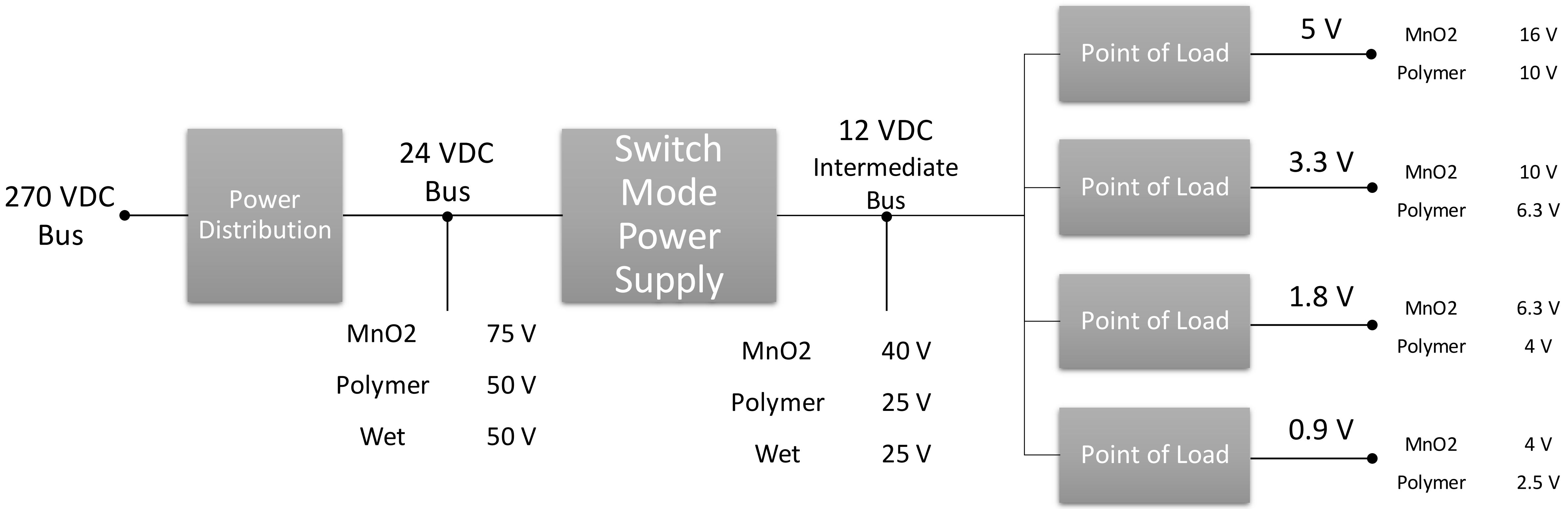
Example: MIL-STD-704 Power Distribution & Filtering

Maximum Temperature 85 °C



Example: MIL-STD-704 Power Distribution & Filtering

Maximum Temperature 125 °C



Space Flight Derating

Table 4 CAPACITOR DERATING REQUIREMENTS

Voltage derating is accomplished by multiplying the maximum operating voltage by the appropriate derating factor appearing in the chart below.

Type	Military Style	Voltage Derating Factor 1/	Maximum Ambient Temperature
Ceramic	CCR, CKS, CKR, CDR **2/**	0.60	110 °C
Glass	CYR	0.50	110 °C
Plastic Film	CRH, CHS	0.60	85 °C
Tantalum, Foil	CLR25, CLR27, CLR35, CLR3	0.5	70 °C
Tantalum, Wet Slug	CLR79, CLR81	0.60 0.40 **3/**	70 °C 110 °C
Tantalum, Solid (Note 4)	CSR, CSS, CWR	0.50 0.30 **4/**	70 °C 110 °C

Notes:

1/ The derating factor applies to the sum of peak AC ripple and DC polarizing voltage.
2/ For low-voltage applications (<10 Vdc), parts shall be rated at least 100 Vdc for styles CCR, CKR, CDR.
3/ Derate voltage linearly from 70 °C to 110 °C.
4/ The effective series resistance shall be at least 0.1 ohms per volt or 1 ohm, whichever is greater, for Grade 2 applications, and at least 0.3 ohms per volt or 1 ohm whichever is greater, for Grade 1 applications.

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Summary

- Choosing between solids and wet style tantalums is generally guided by either capacitance, low leakage current, or both. Wets offer a combination of high capacitance at high voltage, but at a size and cost tradeoff. Size, low cost, and ESR are solids' strengths
- Derating rules should be appropriately applied based on the cathode system, not because it's tantalum
- The voltage on the capacitor is the sum of the DC bias, AC ripple voltage, and any transient peaks and should NEVER exceed the rated voltage for solids. Wets handle these surges
- Generally:
  - MnO_2 derate to 50 % Vr for 85 ℃
  - Polymer derate to 80 % Vr for 105 ℃
  - Wet derate to 80 % -90 % Vr for 85 ℃

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THANK YOU

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