NEPP Task: “Reliability of Advanced Wet and Solid Tantalum Capacitors”
Subtask 2013:
“Ripple Current Testing and Derating for Wet Tantalum Capacitors”

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Deliverable to NASA Electronic Parts and Packaging (NEPP) Program to be published on nepp.nasa.gov.
# List of Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>IR</td>
<td>Infra red</td>
<td>CM</td>
<td>Current multipliers</td>
</tr>
<tr>
<td>DCL</td>
<td>Direct current leakage</td>
<td>VBR</td>
<td>Breakdown voltage</td>
</tr>
<tr>
<td>VR</td>
<td>Rated voltage</td>
<td>CCS</td>
<td>Constant current stress</td>
</tr>
<tr>
<td>ESR</td>
<td>Equivalent series resistance</td>
<td>PWB</td>
<td>Printed wiring board</td>
</tr>
<tr>
<td>DC</td>
<td>Direct current</td>
<td>PS</td>
<td>Power supply</td>
</tr>
<tr>
<td>AC</td>
<td>Alternative current</td>
<td>AF</td>
<td>Acceleration factor</td>
</tr>
<tr>
<td>LF</td>
<td>Low frequency</td>
<td>FR</td>
<td>Failure rate</td>
</tr>
<tr>
<td>HF</td>
<td>High frequency</td>
<td>PCT</td>
<td>Power cycling test</td>
</tr>
<tr>
<td>RT</td>
<td>Room temperature</td>
<td>VAC</td>
<td>Alternative current voltage</td>
</tr>
</tbody>
</table>
Outline

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- Experiment and IR Images
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- Discussion
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  - How Stressful the Ripple Current Testing is?
  - Thermal Resistance at Different Test Conditions.
  - Power cycling test.
  - Requirements for maximum ripple current, thermal resistance, and maximum dissipated power.
  - Derating.
- Conclusion and recommendations.

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Introduction

- The maximum ripple current for wet tantalum capacitors, $I_{rm}$, is one of the most difficult parameters to specify [1].
- Most studies related to ripple currents were carried out for commercial chip tantalum capacitors: $I_{rm}$ is specified at a temperature rise of 10 to 20 °C at room temperature (RT) [2-4].
- E. Reed [4-5] and J. Prymak [3, 6] analyzed requirements for $I_{rm}$ for chip Ta capacitors: (i) the manufacturers’ requirements are very conservative; (ii) ripple currents do not create new failure mechanisms, and the major effect is due to the temperature rise, $\Delta T$.
- There are no ripple current requirements for M55365 chip Ta capacitors that are supposed to operate at applications where the alternating current component is small compared to the direct current leakage (DCL).
- The major failure mechanism for aluminum electrolytic capacitors is electrolyte loss caused either by DC or ripple-current induced self-heating, resulting in gas evolution and its diffusion through the seal.

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Ripple-current-induced heating affects the failure rate of Al capacitors, for which detailed thermal models have been developed [7-12]. Analysis showed that the heat transfer by radiation and convection are comparable.

EEE-INST-002 requirements for temperature derating: 70 °C at 60% of rated voltage (VR) to 110 °C at 40% VR. A 70% derating of ripple currents is suggested for solid hermetic capacitors, and there is no derating requirement for ripple currents for wet capacitors [14].

Evans [13] recommends determination of \( I_{rm} \) based on charts presented for different case sizes. There is no specific data on the temperature rise from other manufacturers.

Self-heating caused by ripple current can be calculated using a simple equation:

\[
\Delta T = I_r^2 \times ESR(T, f) \times R_{th}(T, case\_size, envir.)
\]

This requires knowledge of temperature and frequency dependence of the equivalent series resistance, \( ESR(T, f) \), and thermal resistance, \( R_{th} \), that depends on temperature, case type, and environmental conditions (air circulation, vacuum, etc.).

A complex character of \( \Delta T \) dependence on a variety of external and internal parameters explains difficulties with \( I_{rm} \) specification.
Purpose

- Analyze the existing ripple current testing requirements per MIL-PRF-39006 and assess their sufficiency for space applications.
- Develop a thermal model for high-volumetric efficiency wet tantalum capacitors.
- Evaluate temperature distributions along the surface of cases (check for hot spots).
- Suggest the temperature rise testing technique.
- Evaluate thermal resistance of different types of high volumetric efficiency wet tantalum capacitors at three environmental conditions: in still air, in a temperature chamber with forced convection, and in vacuum.
- Evaluate thermal conditions at the ripple current life testing and suggest a more effective qualification test.
- Suggest testing and derating requirements for ripple currents.
References


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Existing Requirements
Existing Ripple Current Requirements

- No requirements for ripple current derating means that the rated conditions are acceptable.
- MIL-PRF-39006 specifications have tables with maximum ripple current, $I_{rm}$, at standard conditions: 40 kHz, 2/3VR, still air, $T_{amb} = 85^\circ C$.
  
  “The ripple current listed in table represents a rating calculated by using a maximum internal temperature rise ($\Delta T$) at $50^\circ C$ at 40 kHz at 85°C ambient temperature, with a maximum peak rated voltage of 66.67 percent of the 85°C peak voltage rating.”
- A table in MIL-PRF-39006 shows multiplying factors to account for different frequencies, voltages, and temperature conditions.
- It is assumed that maximum internal temperature should be less than $135^\circ C$.
- A method to determine $I_{rm}$ is not specified, and MIL-PRF-39006 does not require temperature rise measurements.
- The specified values of $I_{rm}$ are based on historic data that are adjusted for the frequency dependence of ESR for new capacitors; however, the method of the adjustment is not specified and different manufacturers might use different techniques.

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Ripple Current Life Testing

- MIL-PRF-39006 test conditions: 85 °C, DC voltage + I_{rm} at 40 kHz for 2000 hrs, 8 samples of each case size, 1 failure accepted (32/1)?
- To remain within the specification limits, either reduction of ripple current to 0.63 I_{rm} at VR or decrease of voltage to 2/3VR at I_{rm} are needed.
- Different manufacturers and test labs read the spec differently.
  Mfr.A: \( V = VR - VAC_{p-p} \).
  Mfr.V: \( V = VR + VAC_{p-p} < V_{surge} = 1.15VR \).
- Some test labs are testing at VR and I_{rm} disregarding VAC, others, at VR and 0.63×I_{rm}
- **EEE-INST-002**: “\( V_{test} = VR + I_{rm} \)” at 40 kHz for 1000 hr for L2, (22/1)?
- Slash sheet specifications require AC ripple life test at 2/3VR and I_{rm-}

- Confusion with the test requirements results in substantial variations in the level of stress during ripple current life testing.
- Alternative current (AC) ripple life test requirements should be stated explicitly.
- Why from 3% to 4% of life test samples are allowed to fail the test?
ESR is specified at 120 Hz, but $I_{rm}$ at 40 kHz; still they are closely correlated, why?

Correlation between $I_{rm}$ and ESR for cases sizes from T1 to T4 (case volume in cc)

- $I_{rm}$ decreases according to a power law: $I_{rm} = (ESR)^n$, $0.51 < n < 0.64$.
- Considering that $I_{rm}$ is not determined by testing, the correlation might be due to the methodology of $I_{rm}$ calculations.

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ESR is a complex function of $T$ and $f$.

- Power dissipation depends on the value of ESR($T, f$):
  \[ P = I^2_r \times ESR(T, f) \]

- ESR is decreasing with temperature at high frequencies (HF), but is rising at low frequencies (LF).
- There is a risk of thermal run-away at LF, typically below ~1 kHz.
- ESR($T$) at HF (> 1kHz) corresponds to the temperature dependence of resistance of sulfuric acid. ESR($f$) at LF is determined by the AC resistance of $\text{Ta}_2\text{O}_5$ layer, but at HF - by resistance of the electrolyte.
At RT and LF, ESR is controlled by characteristics of Ta$_2$O$_5$ dielectric; at HF – by electrolyte.

Different types of capacitors with the same value of capacitance might have different ESR.

Damaged capacitors have increased ESR at low frequencies.

For a given $I_r$, power dissipation at LF is substantially greater than at HF.

$P = I_r^2 \times ESR(T, f)$.

Damaged capacitors have increased ESR at low frequencies => importance of analysis of ESR distributions => use 3 sigma criteria.
Current Multipliers (CM) for Different Frequencies per MIL-PRF-39006

- CM values are given for 6 frequencies only.
- It is reasonable to assume that CM values are selected so that the dissipated power remains constant at any frequency:

\[ P(f) = I_{40k}^2 \times ESR_{40k} = CM_f^2 \times I_{40k}^2 \times ESR_f \quad \Rightarrow \quad ESR_f = \frac{ESR_{40k}}{CM_f^2} \]

- Based on M39006 Tables, the calculated values of ESR at frequencies other than 40 kHz can be approximated with a logarithmic function:

\[ ESR_f = A \times \ln(f) + B = ESR_{40k} + A \times \ln\left(\frac{f}{40}\right) \]

✓ CM values are consistent with the experimental ESR data in a relatively narrow frequency range only, from 10 to 100 kHz.
ESR values at different temperatures and frequencies can be calculated assuming that the maximum temperature, $\Delta T + T_0$, is limited to 135 °C.

At room temperature and 40 kHz, the maximum ripple current $I_{rm} = I_{40k, RT}$, is assumed to increase temperature by 50 °C: 

$$50 = I_{40k,RT}^2 \times ESR_{40k,RT} \times R_{th}$$

Temperature rise at ambient temperature $T_0$ and frequency $f$:

$$\Delta T(T_0, f) = (CM_{f,T} \times I_{40k,RT})^2 \times ESR_{f,T} \times R_{th}$$

At $T_0 = 105^\circ$C, maximum temperature rise: $\Delta T = 135 – 105 = 30^\circ$C, at $T_0 = 125^\circ$C, maximum temperature rise: $\Delta T = 135 – 125 = 10^\circ$C.

$$ESR_{f,T} = \frac{ESR_{40k,RT}}{CM_{f,T}^2} \times \frac{\Delta T}{50}$$

To limit temperature of the capacitor below 135 °C, ripple currents at higher temperatures should be reduced more substantially.
CM for Different Temperatures

- Poor agreement with experimental data of ESR at low frequencies.
- Substantial errors for all frequencies at temperatures below RT.
- Tabulated values of current multipliers at low temperatures are assumed to be the same as for 55 °C, which results in substantial errors.

**CM values specified at 2/3VR**

<table>
<thead>
<tr>
<th>T, deg.C</th>
<th>120Hz</th>
<th>1kHz</th>
<th>10kHz</th>
<th>40kHz</th>
<th>100kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>≤55</td>
<td>0.6</td>
<td>0.72</td>
<td>0.88</td>
<td>1</td>
<td>1.1</td>
</tr>
<tr>
<td>85</td>
<td>0.6</td>
<td>0.72</td>
<td>0.88</td>
<td>1</td>
<td>1.1</td>
</tr>
<tr>
<td>105</td>
<td>0.46</td>
<td>0.55</td>
<td>0.68</td>
<td>0.77</td>
<td>0.85</td>
</tr>
<tr>
<td>125</td>
<td>0.27</td>
<td>0.32</td>
<td>0.4</td>
<td>0.45</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Experimental and calculated (dashed lines) $ESR(T, f)$ values.

Values of ESR were calculated based on the tabulated values of CM and experimental values of $ESR_{40k, RT}$:

$$ESR_{f,T} = \frac{ESR_{40k, RT}}{CM^{2}_{f,T}} \times \frac{\Delta T}{50}$$

and $\Delta T$ decreasing at high T.

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Breakdown Voltages and Limits to Ripple Voltages

- Superposition of ripple and DC voltage creates a risk of breakdown.
- VBR for different types of wet Ta capacitors was measured using a constant current stress (CCS) testing technique.

- Breakdown is terminated by self-healing.
- Margin of VBR decreases at large VR.
- VBR for #93026 capacitors are somewhat lower than for MIL-PRF-39006.
- High-voltage capacitors have small margin (20% to 50% of VR) and operate close to the breakdown region.
- Exceeding VR is risky because of low margin => limit to the peak voltage:
  \[ VR > V_{DC} + ESR \times I_r \]
- The risk of breakdown is more likely for high-voltage devices at low frequencies and temperatures.
- Derating should depend on rated voltage.

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Thermal Model
Thermal Modeling

- Heat from the capacitor is released via convection, radiation, and conduction along the leads.
- \( R_{\text{conv}}, R_{\text{rad}}, \) and \( R_{\text{cond}} \) are thermal resistances of the relevant processes. \( R_{\text{int}} \) is the internal thermal resistance between the Ta slug (core) and surface of the case. 
- \( C \) is the heat capacitance.
- Temperatures of the board and contact pads are assumed to be equal to the environment temperature.

**Case-to-ambient thermal resistance:**

\[
R_{th} = (1/R_{\text{conv}} + 1/R_{\text{rad}} +1/R_{\text{cond}})^{-1}
\]
Internal Thermal Resistance

- **Material characteristics.**

\[ R_{th} = \Sigma R_{th_i} \]

<table>
<thead>
<tr>
<th>case</th>
<th>( L, \text{mm} )</th>
<th>( D, \text{mm} )</th>
<th>( H_{\text{electr.}, \text{mm}} ) ((k=0.45 \text{ W/m}_K))</th>
<th>( H_{\text{case}, \text{mm}} ) ((k=57.5 \text{ W/m}_K))</th>
<th>( H_{\text{sleeve}, \text{mm}} ) ((k=0.15 \text{ W/m}_K))</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>12</td>
<td>5.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>T2</td>
<td>17</td>
<td>7.5</td>
<td>0.25</td>
<td>0.25</td>
<td>0.1</td>
</tr>
<tr>
<td>T3</td>
<td>20</td>
<td>10</td>
<td>0.3</td>
<td>0.25</td>
<td>0.1</td>
</tr>
<tr>
<td>T4</td>
<td>27</td>
<td>10</td>
<td>0.35</td>
<td>0.25</td>
<td>0.1</td>
</tr>
</tbody>
</table>

- **Results of calculations.**

\[ R_{th} = \Sigma R_{th_i} \]

<table>
<thead>
<tr>
<th>case</th>
<th>( R_{th_{\text{electrol.}}} )</th>
<th>( R_{th_{\text{case}}} )</th>
<th>( R_{th_{\text{sleeve}}} )</th>
<th>( R_{th}, \text{K/W} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>2.27</td>
<td>0.02</td>
<td>6.80</td>
<td>9.09</td>
</tr>
<tr>
<td>T2</td>
<td>1.39</td>
<td>0.01</td>
<td>4.16</td>
<td>5.56</td>
</tr>
<tr>
<td>T3</td>
<td>1.06</td>
<td>0.01</td>
<td>3.18</td>
<td>4.25</td>
</tr>
<tr>
<td>T4</td>
<td>0.92</td>
<td>0.01</td>
<td>2.75</td>
<td>3.67</td>
</tr>
</tbody>
</table>

Thermal resistance of internal layers:

\[ R_{th_i} = \frac{H_i}{k_i \times \pi \times D \times L} \]

\( D \) and \( L \)- diameter and length of the case; \( H \) - thickness of the layer, \( k \)-thermal conduction.

- Considering that \( P_{\text{max}} \) for case T4 parts is typically below \(~1.5\) W and for T1 case parts it is below \(~0.5\) W, the difference between the core temperature and case temperature is below \(~6\) °C.
Conduction and Convection

- Heat flow through the wires.
  \[ R_{th}^{w.r.} = \frac{L_{w.r.}}{k_{Ni} \times \pi \times r^2} \]

At \( L_w \sim 10 \text{ mm} \), \( r = 0.03 \text{ mm} \), and \( k_{Ni} = 90.9 \text{ W/m}_K \), for two leads, \( R_{th}^{wl} = 195 \text{ K/W} \).

- Heat flow through convection:
  \[ R_{th}^{conv.} = \frac{1}{h_{conv} \times S} \]
  \[ h_{conv} = \frac{k}{L} \times C_1 \times \left( a \times L^3 \times \Delta T \right)^n \]

In a simplified form the heat transfer coefficient:
  \[ h_{conv} = 1.32 \times \left( \frac{\Delta T}{D} \right)^{0.25} \]

Thermal resistance calculated for convection in still air at \( \Delta T = 50 \text{ °C} \)

<table>
<thead>
<tr>
<th>calc at ( \Delta T=50 )</th>
<th>D, mm</th>
<th>L, mm</th>
<th>( h_c, \text{ W/m}^2\text{K} )</th>
<th>S, mm(^2)</th>
<th>( R_{th_conv} ), K/W</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>4.78</td>
<td>11.51</td>
<td>13.35</td>
<td>208.7</td>
<td>359</td>
</tr>
<tr>
<td>T2</td>
<td>7.14</td>
<td>16.26</td>
<td>12.08</td>
<td>444.8</td>
<td>186</td>
</tr>
<tr>
<td>T3</td>
<td>9.53</td>
<td>19.46</td>
<td>11.23</td>
<td>725.3</td>
<td>123</td>
</tr>
<tr>
<td>T4</td>
<td>9.53</td>
<td>26.97</td>
<td>11.23</td>
<td>950.1</td>
<td>94</td>
</tr>
<tr>
<td>THQA</td>
<td>15.2</td>
<td>7</td>
<td>12</td>
<td>650</td>
<td>128</td>
</tr>
</tbody>
</table>

- Heat transfer coefficient slightly increases for smaller size parts.
- \( R_{th} \) decreases for larger case sizes mostly due to a larger surface area.
Heat transfer by radiation. 

\[ h_{\text{rad}} = \varepsilon \times \sigma \times S \times \left(T^2 + T_0^2\right) \times \left(T + T_0\right) \]

\[ R_{\text{th}}^{\text{rad}} = \frac{1}{h_{\text{rad}} \times S} \]

where \( \varepsilon \) is the surface emissivity, and \( \sigma = 5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4 \) is the Stefan-Boltzmann constant. For sleeved capacitors, \( \varepsilon = 0.9 \). For capacitors without sleeves \( \varepsilon = 0.1 \).

**Calculated Thermal Resistance**

<table>
<thead>
<tr>
<th>Case with sleeves</th>
<th>( R_{\text{th lead}} ), K/W</th>
<th>( R_{\text{th conv}} ), K/W</th>
<th>( h_{\text{rad}\Delta T=50} ), W/m( ^2)K</th>
<th>( R_{\text{th rad.}} ), K/W</th>
<th>( R_{\text{th total}} ), K/W</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>195</td>
<td>359</td>
<td>6.83</td>
<td>701</td>
<td>107.1</td>
</tr>
<tr>
<td>T2</td>
<td>195</td>
<td>186</td>
<td>6.83</td>
<td>329</td>
<td>73.8</td>
</tr>
<tr>
<td>T3</td>
<td>195</td>
<td>123</td>
<td>6.83</td>
<td>202</td>
<td>54.9</td>
</tr>
<tr>
<td>T4</td>
<td>195</td>
<td>94</td>
<td>6.83</td>
<td>154</td>
<td>44.9</td>
</tr>
<tr>
<td>THQA</td>
<td>195</td>
<td>128</td>
<td>5.5</td>
<td>280</td>
<td>60.5</td>
</tr>
</tbody>
</table>

- The three components of thermal resistance, \( R_{\text{conv}} \), \( R_{\text{rad}} \), and \( R_{\text{cond}} \), have comparable values.
- Thermal resistance related to radiation is 1.6 to 2 times greater than for convection.
- Heat transfer through the leads is more important for smaller parts.

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Experiment and IR Images
Test Set-up

- A PC-based set-up allowed for measurements of temperature, ripple current, ripple voltage, $V_r$, and phase angle between $I_r$ and $V_r$.
- Minco PDZ24A PRT temperature sensors were attached at the bottom of the case for #93026 and at the top for #04005 capacitors.

- Equipment:
  - AC generator: Agilent 81150A.
  - Power amplifier: Venable Instruments VLA1000.
  - DC PS: Agilent 6623.
  - Oscilloscope: Agilent Infinium.
  - Current probe and amplifier: Tektronix TCPA300/TCP312.

- Capacitors are soldered onto a PWB.
Part Types

- Seven types of high volumetric efficiency wet tantalum capacitors.
- Parts from Mfr. A and Mfr.E were without insulating sleeves.

### Specifications

<table>
<thead>
<tr>
<th>Type</th>
<th>Mfr.</th>
<th>C, uF</th>
<th>VR, V</th>
<th>case</th>
<th>Specified $I_{rm}$, A rms</th>
</tr>
</thead>
<tbody>
<tr>
<td>93026</td>
<td>V</td>
<td>470</td>
<td>75</td>
<td>T4</td>
<td>2.75</td>
</tr>
<tr>
<td>93026</td>
<td>A</td>
<td>470</td>
<td>75</td>
<td>T4</td>
<td>2.75</td>
</tr>
<tr>
<td>93026</td>
<td>V</td>
<td>470</td>
<td>50</td>
<td>T3</td>
<td>2.1</td>
</tr>
<tr>
<td>93026</td>
<td>V</td>
<td>220</td>
<td>50</td>
<td>T2</td>
<td>1.8</td>
</tr>
<tr>
<td>93026</td>
<td>V</td>
<td>120</td>
<td>25</td>
<td>T1</td>
<td>1.25</td>
</tr>
<tr>
<td>93026</td>
<td>V</td>
<td>33</td>
<td>75</td>
<td>T1</td>
<td>1.05</td>
</tr>
<tr>
<td>04005</td>
<td>E</td>
<td>210</td>
<td>125</td>
<td>THQA</td>
<td>2.7</td>
</tr>
</tbody>
</table>

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Heating and Cooling Curves

- Heating and cooling curves were measured at different ripple currents and frequencies in the range from 60 Hz to 100 kHz.
- Temperature was measured at the surface of the case and at the anode contact pad.
- In still air, at $T_{\text{case}} \sim 120 \, ^\circ\text{C}$ the contact pad had $\Delta T \sim 10 \, ^\circ\text{C}$.

Examples of heating and cooling curves

- Temperature stabilizes after 5 to 15 min of heating/cooling.
- Heating of the contact pads might increase the calculated conduction component of the thermal resistance by $\sim 10\%$. 

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Experiments with FLIR-600 IR camera

- To measure temperature on capacitors without sleeves a small piece of polyimide film was attached to the case.

- Both techniques, PRT sensor and IR resulted in similar heating and cooling curves.

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IR Imaging

- IR images were recorded with time during heating and cooling of the parts to check for a possible formation of hot spots.

✓ Analysis of temperature distributions did not reveal hot spots in any of the parts.
✓ Temperature distributions corresponded to the location of the anode slug.
Temperature Distributions

- Comparison between loose and soldered onto PWB capacitors.
- Loose parts and boards were placed horizontally in still air.

For loose parts, the temperature at the top of the case exceeded the temperature at the bottom by 1 to 2 °C.

For parts soldered onto PWB, the temperature difference was greater, ~ 5 °C.

Limited heat release and reflection from the board increase temperature at the bottom of the case.
Thermal resistance, $R_{th}$, can be calculated based on the characteristic time of cooling, $\tau$, and as a slope of $\Delta T(P)$ line.

**Method 1:**

$$\Delta T(t) = \Delta T_{\text{init}} \times \exp\left(-\frac{t}{\tau}\right)$$

- $\tau$ depends on the heat capacity, $C_t$, and $R_{th}$:
  $$\tau = C_t \times R_{th}$$
- Heat capacity, $C_t$, depends on the weight, $W$, specific heat capacity of tantalum, $c_{Ta}$, and electrolyte, $c_{el}$:
  $$C_t = 0.8 \times c_{Ta} \times W + 0.2 \times c_{el} \times W$$

$$R_{th} = \frac{\tau}{C_t}$$

**Method 2:**

$$\Delta T = P \times R_{th} = I_r \times V_r \times \cos(\phi) \times R_{th},$$

where $I_r$, $V_r$ and $\phi$ are ripple current, voltage and phase angle between $I_r$ and $V_r$.

$R_{th}$ is determined as a slope of the line approximating $\Delta T(P)$ dependence.

**Method 3:**

$$\Delta T = P \times R_{th} = I_r^2 \times ESR(T) \times R_{th},$$

where $ESR(T)$ is ESR corresponding to the stabilized temperature of the case.

$R_{th}$ is determined as in Method 2.

- Due to poor accuracy of the phase angle measurements, method 3 gave more reproducible results compared to method 2.
- Both, method 1 and method 3 gave similar results (within ~15%).
Effect of Ripple Currents in Still Air
Heating in Still Air

Comparison of self-heating at low and high frequencies

Variations of temperature rise with ripple currents at different frequencies

- At high frequencies, temperature stabilizes after ~10 min for T4 cases and after ~3 min for T1 cases.
- Heating at low frequencies (60 Hz and 120 Hz) occurs slower than at high frequencies, ~15 to 20 min.
- Temperature rise increases with ripple current according to a power law:
  \[ \Delta T = A \times I_r^m \]
  with the exponent
  \[ 1.2 < m < 1.6. \]
Heating in Still Air, Cont’d

- Exponent $m$ has a trend of increasing with frequency, from ~ 1.2 at 120 Hz to ~ 1.6 at 100 kHz.
- Maximum ripple currents specified for the parts results in temperature rise that is different for different part types and for #93026 capacitors varies from ~20 °C to ~50 °C.

The specified values for ripple currents are very conservative: experimental data that correspond to $\Delta T = 50$ °C are up to 2 times greater than the maximum ripple current.
Cooling in Still Air

- At $t < \tau$, temperature decreases with time exponentially.
- Characteristic times of cooling, $\tau$, were calculated for all test conditions.

- At high frequencies, above $\sim$1kHz, the characteristic times for T4 cases are $\sim$ 300 sec and for T1 cases $\sim$ 60 sec.
- At low frequencies, characteristic times are greater than at high frequencies.
Cooling in Still Air, Cont.’d

Variations of characteristic times with the temperature rise at different frequencies

\[ \tau = C_t \times R_{th} \]

- At low \( \Delta T \), the values of \( \tau \) increase at all frequencies due to decrease of the heat transfer coefficient (increase of \( R_{th} \)).

- At low frequencies, \( \tau \) is greater because the whole slug is heating up (increase of \( C_t \)).

- At HF, only part of the case is heated, mostly electrolyte, the shell of anode slug, and the case (decrease of \( C_t \)).
Effect of Power in Still Air

- Power was calculated for each $I_r$ and $\Delta T$ as $I_r^2 \times ESR(T_0 + \Delta T)$.

Variation of temperature rise with power at different frequencies and amplitudes of ripple currents

- The temperature rise at different frequencies follow a linear relationship with the same slope.
- The slope of the $\Delta T(P)$ line indicates thermal resistance: $R_{th} = \Delta T/P$. 

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Effect of Power in Still Air, Cont’d

**$\Delta T(P)$** at different frequencies and amplitudes of ripple currents

- At frequencies above 1 kHz, $R_{th}$ is frequency independent.
- At low frequencies (60 Hz and 120 Hz), $R_{th}$ is substantially, from 2 to 10 times, greater than at high frequencies.
- Per Evans, THQA2 capacitors have $R_{th} \sim 60$ K/W at 200 Hz.
- The anomaly corresponds to much larger $\tau$ at LF, and is likely due to different temperature distributions in the capacitor – PWB system.
- For low-size cases, contrary to the large-size cases, at low frequencies $\Delta T$ is noticeable at relatively low levels of the dissipated power.

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Thermal Resistance in Still Air

 Thermal resistances, $R_{th}$, were calculated using methods 1 and 3.

Weight of the parts, $W$, heat capacity, $C_t$, characteristic time, $\tau$, and thermal resistances, $R_{th}$, calculated at $f \geq 1$ kHz.

<table>
<thead>
<tr>
<th>Part</th>
<th>$W$, g</th>
<th>$C_t$, J/K</th>
<th>$\tau$, sec</th>
<th>$R_{th} = \frac{\tau}{C_t}$, K/W</th>
<th>$R_{th} = \frac{\Delta T}{P}$, K/W</th>
<th>$R_{th}$ still air avr., K/W</th>
</tr>
</thead>
<tbody>
<tr>
<td>470uF 75V T4 V</td>
<td>14.8</td>
<td>9.95</td>
<td>295</td>
<td>29.7</td>
<td>31</td>
<td>30.4</td>
</tr>
<tr>
<td>470uF 75V T4 A</td>
<td>14.8</td>
<td>9.95</td>
<td>305</td>
<td>30.7</td>
<td>33</td>
<td>31.9</td>
</tr>
<tr>
<td>470uF 50V T3 V</td>
<td>9.4</td>
<td>6.32</td>
<td>230</td>
<td>36.4</td>
<td>36</td>
<td>36.2</td>
</tr>
<tr>
<td>220uF 50V T2 V</td>
<td>5.7</td>
<td>3.83</td>
<td>120</td>
<td>34.5</td>
<td>40</td>
<td>37.3</td>
</tr>
<tr>
<td>120uF 25V T1 V</td>
<td>2.3</td>
<td>1.55</td>
<td>60</td>
<td>38.8</td>
<td>43</td>
<td>40.9</td>
</tr>
<tr>
<td>33uF 75V T1 V</td>
<td>2.3</td>
<td>1.55</td>
<td>55</td>
<td>35.6</td>
<td>34</td>
<td>34.8</td>
</tr>
<tr>
<td>210uF 125V E</td>
<td>8.5</td>
<td>5.41</td>
<td>100</td>
<td>18.6</td>
<td>30</td>
<td>24.3</td>
</tr>
</tbody>
</table>

✓ Both techniques give similar results within an error of $\sim 15\%$.
✓ For DWG93026 capacitors, $R_{th}$ increases from $31.1 \pm 1.4$ K/W for T4 cases to $37.9 \pm 4$ K/W for T1 cases.
✓ Experimental values of $R_{th}$ are 1.4 to 3 times less than calculated.
✓ The difference is due to substantial simplifications of the model.

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Effect of Ripple Currents in a Temperature Chamber with Forced Convection
Effect of Forced Convection

- The heat transfer coefficient increases with the air velocity.
- Experiments with loose 470 μF 75 V T4 capacitors showed a decrease of $\Delta T$ from 60 °C to 30 °C when a lab fan was turned on.

A substantial decrease in the temperature rise is expected when capacitors are tested in temperature chambers with forced air convection.
Effect of Forced Air Convection at 85 °C

- Temperature rise was measured in the Sigma M10 chamber at 85 °C at different frequencies and amplitudes of ripple currents.

Comparison of results in still air and in the chamber

- At the same ripple currents, temperature rise in the chamber at 85 °C is 2 to 5 times less than in still air.
- The result is due to a lesser ESR at higher temperatures, but mostly to the increased heat release at forced air convection conditions.

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Variations of temperature rise with ripple current in the chamber follow the same power law as at still air conditions: \( \Delta T = A \times I_r^m \). The exponent is on average \( \sim 1.8 \) and is less frequency dependent. Due to the forced convection, heat release is less dependent on the surface temperature that is varying in a relatively narrow range; hence \( \Delta T \sim P_{dis} = I_r^2 \times ESR \).
Characteristics times are from ~40% (for T1) to 150% (for T4) smaller than in still air, and less dependent on the initial temperature rise.

At low frequencies $\tau$ is greater than at high frequencies.
Effect of Power on Temperature Rise under Forced Air Convection

- Under forced air convection, $\Delta T$ is a linear function of power.
- Thermal resistance decreases from ~35 K/W for T1 cases to ~11 K/W for T4 cases.
Temperature rise and $R_{th}$ under Forced Air Convection

<table>
<thead>
<tr>
<th>Part</th>
<th>$\Delta T$ at $I_{rm}$, °C</th>
<th>$C_t$, J/K</th>
<th>$\tau_{conv}$, sec</th>
<th>$R_{th} = \tau/C_t$, K/W</th>
<th>$R_{th} = \Delta T/P$, K/W</th>
<th>$R_{th}$ conv. avr., K/W</th>
<th>$R_{th}$ still air/R$_{th}$ conv.</th>
</tr>
</thead>
<tbody>
<tr>
<td>470uF 75V T4 V</td>
<td>9.1</td>
<td>9.95</td>
<td>130</td>
<td>13</td>
<td>11.4</td>
<td>12.2</td>
<td>2.5</td>
</tr>
<tr>
<td>470uF 75V T4 A</td>
<td>14.6</td>
<td>9.95</td>
<td>115</td>
<td>12</td>
<td>11.5</td>
<td>11.8</td>
<td>2.7</td>
</tr>
<tr>
<td>470uF 50V T3 V</td>
<td>8.2</td>
<td>6.32</td>
<td>111</td>
<td>17.6</td>
<td>17.1</td>
<td>17.4</td>
<td>2.05</td>
</tr>
<tr>
<td>220uF 50V T2 V</td>
<td>15.6</td>
<td>3.83</td>
<td>70</td>
<td>18.3</td>
<td>18</td>
<td>18.2</td>
<td>1.96</td>
</tr>
<tr>
<td>120uF 25V T1 V</td>
<td>1.55</td>
<td>42</td>
<td>27.1</td>
<td>35</td>
<td>30.4</td>
<td>1.14</td>
<td></td>
</tr>
<tr>
<td>33uF 75V T1 V</td>
<td>18.9</td>
<td>1.55</td>
<td>40</td>
<td>25.8</td>
<td>35</td>
<td>30.4</td>
<td>1.14</td>
</tr>
<tr>
<td>210uF 125V E</td>
<td>31.3</td>
<td>5.71</td>
<td>80</td>
<td>14.0</td>
<td>14.1</td>
<td>14.1</td>
<td>1.72</td>
</tr>
</tbody>
</table>

- In the temperature chamber, $\Delta T$ at the specified $I_{rm}$ is substantially less than 50 °C, and varies for different part types from 8 to 31 °C.
- Average variations of $R_{th}$ calculated using two methods are ~15%.
- On average, $R_{th}$ values in the convection chamber are ~30% less for small-size cases (T1) and ~2.6 times less for large-size cases (T4).
Effect of Ripple Currents in Vacuum
**Heating in Vacuum**

Examples of $\Delta T$ variations with the amplitude of ripple currents for still air and vacuum conditions

- $\Delta T$ was measured in vacuum at $10^{-4}$ torr at different $I_r$ and $f$.
- Similar to still air conditions, $\Delta T$ in vacuum increases as a power of $I_r$ with the exponent $1.25 < m < 1.6$.

- Temperature rise in vacuum substantially, by 20 °C to 50 °C, greater than at still air conditions.

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Based on $\Delta T(I_r)$ approximations, $\Delta T = A \times I_r^m$, temperature rise for still air and vacuum conditions were calculated at rated ripple currents for different frequencies in the range from 60 Hz to 100 kHz.

Temperature rise at rated currents in vacuum and still air conditions

- At rated ripple currents, temperature rise in vacuum for 470 µF 75 V capacitors in case T4 was in the range from 100 °C to 130 °C for capacitors from Mfr.A and from 45 °C to 55 °C for Mfr.V.
- The major reason for a relatively small value of $\Delta T_{\text{vac}}(I_{rm})$ that is below ~ 60 °C for some parts, is a substantial underrating of capacitors at still air conditions: $\Delta T_{\text{air}}(I_{rm}) << 50$ °C.
Cooling in Vacuum

Examples of temperature variation during cooling after the parts were heated to steady-state conditions at different amplitudes and frequencies of ripple currents.

\[ \Delta T = \Delta T_0 \times \exp\left(-\frac{t}{\tau}\right) \]

Similar to still air conditions, temperature decreases exponentially with time.
Cooling in Vacuum, Cont.’d

Comparison of characteristic times of cooling in still air and vacuum conditions

- The most significant increase in $\tau$, ~ 3.5 times, was for T4 capacitors without sleeve and was due to a low emissivity of Ta.
- An increase in $\tau$, for T4 capacitors with sleeves was ~ 2.5 times.
- $\tau$ increased 2.5 to 3 times for T3, T2, and T1 cases.

- Depending on the case type, $\tau$ in vacuum increases from 2.5 to 3.5 times compared to still air.
**Effect of Power in Vacuum**

- In vacuum, the temperature rise increases linearly with power for all frequencies of ripple currents.

- Depending on the case type, the thermal resistance calculated as a slope of $\Delta T(P)$ curves varies from ~60 K/W to ~150 K/W.

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Thermal Resistance in Vacuum

- Heat release in vacuum is reduced compared to air conditions and is mostly due to conduction through the leads and radiation.
- Both $R_{th}$ methods give results within ~15% error.
- The difference between the calculated and experimental values of $R_{th}$ varies from 8% to 70%.

<table>
<thead>
<tr>
<th>Part</th>
<th>$C_t$, J/K</th>
<th>$\tau_{vac}$, sec</th>
<th>$R_{th} = \tau/C_t$, K/W</th>
<th>$R_{th} = \Delta T/P$, K/W</th>
<th>$R_{th}$ vac. avr., K/W</th>
<th>$R_{th}$ vac. calc., K/W</th>
</tr>
</thead>
<tbody>
<tr>
<td>470uF 75V T4 V</td>
<td>9.95</td>
<td>800</td>
<td>80.4</td>
<td>61</td>
<td>70.7</td>
<td>152.6</td>
</tr>
<tr>
<td>470uF 75V T4 A</td>
<td>9.95</td>
<td>1070</td>
<td>107.5</td>
<td>114</td>
<td>111</td>
<td>152.6</td>
</tr>
<tr>
<td>470uF 50V T3 V</td>
<td>6.32</td>
<td>600</td>
<td>95</td>
<td>83</td>
<td>89</td>
<td>99.2</td>
</tr>
<tr>
<td>220uF 50V T2 V</td>
<td>3.83</td>
<td>370</td>
<td>96.6</td>
<td>130</td>
<td>113.3</td>
<td>122.4</td>
</tr>
<tr>
<td>33uF 75V T1 V</td>
<td>1.55</td>
<td>175</td>
<td>112.9</td>
<td>148</td>
<td>130.4</td>
<td>152.6</td>
</tr>
</tbody>
</table>

- In vacuum, capacitors in T4 cases without sleeves (Mfr.A) have much greater values of $R_{th}$ compared to similar parts with sleeves.
- For capacitors with sleeves, $R_{th}$ increases from ~71 K/W for T4 case to ~130 K/W for T1 case.
Discussion
Temperature Rise at Different Test Conditions

Variations of temperature rise with ripple current at 40 kHz in still air, vacuum, and a temperature chamber with forced air convection.

- Ripple-current-induced temperature rise changes substantially depending on environmental conditions.
- Compared to still air conditions, temperature rise in vacuum can be more than 2 times greater, and ~3 times less in the forced air convection temperature chamber.
**R\textsubscript{th} and \(\Delta T\) at Different Environments**

- Average \(R_{th}\) values were calculated using two methods.
- Temperature rise, \(\Delta T\), was calculated for standard conditions: 40 kHz and specified values of \(I_{rm}\).

<table>
<thead>
<tr>
<th>Part</th>
<th>(R_{th\text{ still air, K/W}})</th>
<th>(R_{th\text{ conv.}, K/W})</th>
<th>(R_{th\text{ vac.}, K/W})</th>
<th>(\Delta T\text{ still air, }^\circ C)</th>
<th>(\Delta T\text{ conv., }^\circ C)</th>
<th>(\Delta T\text{ vac., }^\circ C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>470uF 75V T4 V</td>
<td>30.4</td>
<td>12.2</td>
<td>70.7</td>
<td>28.8</td>
<td>9.1</td>
<td>51.3</td>
</tr>
<tr>
<td>470uF 75V T4 A</td>
<td>31.9</td>
<td>11.8</td>
<td>111</td>
<td>47.5</td>
<td>14.6</td>
<td>114.3</td>
</tr>
<tr>
<td>470uF 50V T3 V</td>
<td>36.2</td>
<td>17.4</td>
<td>89</td>
<td>22.5</td>
<td>8.2</td>
<td>38.2</td>
</tr>
<tr>
<td>220uF 50V T2 V</td>
<td>37.3</td>
<td>18.2</td>
<td>113.3</td>
<td>43.4</td>
<td>15.6</td>
<td>81</td>
</tr>
<tr>
<td>120uF 25V T1 V</td>
<td>40.9</td>
<td>27.1</td>
<td>21</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>33uF 75V T1 V</td>
<td>34.8</td>
<td>30.4</td>
<td>130.4</td>
<td>27.9</td>
<td>18.9</td>
<td>52</td>
</tr>
<tr>
<td>210uF 125V E</td>
<td>24.3</td>
<td>14.1</td>
<td>50.9</td>
<td>31.3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Four out of 7 part types had low rated currents, \(\Delta T \ll 50^\circ C\).  
- In a convection chamber temperature rise decreases by 40\% to 60\% compared to still air conditions.  
- Temperature rise increases by 60\% to 140\% in vacuum and can exceed 100^\circ C.
Effect of Sleeve

- T4 case capacitors from Mfr.V have smaller $R_{th}$ compared to Mfr.A due to the presence of sleeve.
- The difference is especially substantial (~60%) in vacuum where radiation is the major heat transfer mechanism.
- Emissivity varies from ~0.1 for tantalum to ~0.9 for polymer sleeve.

\[ q_r = \varepsilon \times \sigma \times F_{1,2} \times A \times (T_1^4 - T_2^4) \]

Temperature rise was measured on loose parts with and without sleeve using an IR camera in still air.

- Sleeves reduce temperature rise in still air by a few deg.C.
- The effect of sleeve is less significant at forced convection and much more significant in vacuum where radiation thermal conduction prevails.
Thermal Run-Away at Low Frequencies

Failure in temperature chamber

Failure in vacuum chamber

- At low frequencies (≤ 1 kHz) and high temperatures ESR increases with temperature resulting in a thermal run-away.
- Thermal run-away in vacuum happened at a ripple current below $I_{rm}$.

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Effect of Low Frequencies and Temperatures

- Characteristic times of heating/cooling are greater at low frequencies compared to high frequencies.
- Contrary to HF conditions, when power is dissipated mostly in the surface area of the slug, at LF the power is dissipated more evenly across the anode.
- At LF, surface cooling in a convection temperature chamber is not as efficient as at HF.
- At HF and low temperatures, ESR, hence dissipated power, $P_{\text{dis}}$, are large. As the part heats-up, $P_{\text{dis}}$ decreases.
- Ripple currents applied at low temperatures create a thermal shock that might cause damage to $\text{Ta}_2\text{O}_5$ dielectric.

✓ Special care should be taken to avoid thermal run-away when capacitors are to be used at low temperatures and/or low frequencies.
✓ Power cycling creates multiple thermal shocks. However, the parts are not tested for power cycling applications.
How Stressful is Ripple Current Testing?

- Experience shows that ripple life testing does not generate more failures compared to a regular, DC bias only, life testing.

- At ripple life test conditions for M39006/33 capacitors (85°C, 40kHz, $I_{rm}$, 2/3VR), the temperature rise is from 10 °C to 20 °C only.

- Assuming acceleration factors for reliability testing for solid and wet capacitors are similar, AF can be expressed as:

$$ AF = \exp \left[ B \left( \frac{V}{VR} - 1 \right) \right] \times \exp \left[ -\frac{E_a}{k} \left( \frac{1}{T_2} - \frac{1}{T_1} \right) \right] $$

  where $B = 10$ to $20$, $E_a = 0.7$ to $2$ eV.

- At $T = 85$ °C, an increase in the case temperature by 10 to 20 °C would increase FR in 2 to 34 times; however, a decrease in DC bias from VR to 2/3VR would decrease FR in 30 to 785 times.

✔ Considering a 33% decrease in applied DC voltage and relatively minor self-heating, the level of stress during ripple life testing is below the level of stress during regular life testing at 85°C and VR.
Power Cycling Test (PCT)

- Power cycles at 40 kHz, 4.9 Arms, 15 min on and 15 min off, resulted in temperature rise, $\Delta T = 100 \, ^\circ C$.
- AC and DCL measurements were carried out periodically.

Heating and cooling curves during first 10 cycles

No substantial variations of heating/cooling curves during the testing.
Power Cycling Test, Cont.’d

- SN1 passed 200 cycles with $\Delta T = 100^\circ C$, SN2 failed after 140$^\circ C$.

Results show that PCT can cause failures, and this testing is a value-added test for qualification.
Test Methods for Rated Ripple Current, Typical ESR(T, f) and Thermal Resistance

The test methods described below are intended for qualification testing and the relevant characteristics should be presented in the specifications for each part type.

- Rated ripple current, $I_{rr}$, at 40 kHz.
  - Parts shall be soldered onto a PWB in a typical configuration.
  - Temperature sensor should be attached at the bottom of the case for the cylinder-style cases, and at the top for the button-style case capacitors.
  - $I_{rr}$ is determined at still air conditions when temperature rise is stabilized at $\Delta T = 50 ^\circ C \pm 2 ^\circ C$ for 10 min.

- Temperature and frequency dependencies of ESR.
  ESR shall be measured at $V_{DC} = 2.2 \, V$, $V_{AC_{rms}} \leq 1 \, V$, from -55 $^\circ C$ to +125 $^\circ C$ with 10 $^\circ C$ increments, at frequencies 120Hz, 400Hz, 1kHz, 4kHz, 10kHz, 40kHz, and 100kHz.

- Thermal resistance at 40 kHz.
  - $\Delta T$ values should be measured at 0.7, 1, and 1.3 times $I_{rr}$.
  - The relevant values of the power dissipation shall be calculated as $P = I_r^2 \times ESR(T)$.
  - The data should be approximated with a straight line crossing zero.
  - $R_{th}$ is calculated as an average based on measurements for three samples.

- Rated dissipated power at 40 kHz.
  - $P_{rr}$ is a power that causes temperature rise of 50 $^\circ C$ at 40 kHz in still air conditions.
  - $P_{rr}$ is calculated as a ratio of 50 $^\circ C$ to $R_{th}$. 

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Derating Requirements

- Ripple currents do not introduce new failure mechanisms, if the sum of DC and AC voltages remains within the limits, 
  \[ 0 < V_{DC} \pm V_{AC_{ampl}} < V_R. \]
- The effect of ripple currents on reliability is mostly due to self-heating, and for this reason, derating of ripple currents is based on temperature derating.
- Rating requirements for ripple currents should include (see p.62 for details):
  - Method for determining \( I_{rr} \) based on 50 °C temperature rise.
  - Temperature and frequency dependencies of ESR.
  - Thermal resistance in still air obtained at 40 kHz.
  - Rated power dissipation at 40 kHz that results in \( \Delta T = 50 \) °C
- The temperature derating is currently set to 70 °C ambient at 0.6×VR and to 110 °C at 0.4×VR.
- The requirements for ripple currents: the temperature rise shall not result in the case temperature exceeding 85 °C at 0.5×VR and 125 °C at 0.3×VR. Derate voltage linearly between 85 °C and 125 °C.
Requirements for Maximum Dissipated Power and Ripple Currents

- **Power derating for ground operation (still air):**
  The case temperature should be below 85 °C at 0.5×VR or 125 °C at 0.3×VR:
  \[
  T_c = P \times R_{th} + T_0 < 85 \quad \text{or} \quad I_r^2 \times ESR(f, T) \times R_{th} + T_0 \leq 85, \quad \text{at 0.5×VR}
  \]
  \[
  T_c = P \times R_{th} + T_0 < 125 \quad \text{or} \quad I_r^2 \times ESR(f, T) \times R_{th} + T_0 \leq 125, \quad \text{at 0.3×VR}
  \]
  where \( T_0 \) is the ambient temperature.

- **Power derating for operation in vacuum (conservative estimation):**
  \[
  P_{\text{max\_vac}} = 0.5 \times P_{\text{max\_still\ air}}
  \]

- **Power derating for forced air convection:**
  \[
  P_{\text{max\_forced\_convection}} = \alpha \times P_{\text{max\_still\ air}}, \quad \alpha \approx 2, \quad \text{but depends on specific conditions and might need verification.}
  \]

- **Notes:**
  - A special analysis and additional testing might be necessary to avoid thermal shock for parts that are powered-up at temperatures below 0 °C, (cold start-up).
  - Operating at low frequencies (below ~ 1 kHz) and high ripple currents have a higher risk of thermal run-away failures, need additional analysis and derating.
  - Estimations of \( ESR(f, T) \) for frequencies other than the measured can be calculated by a linear extrapolation of the \( ESR \text{ vs. } \ln(f) \) functions.
Conclusion

Existing requirements for ripple currents
- Ripple current specifications are not supported by the relevant methods.
- There is no specification for temperature rise measurements, so the existing requirements for $I_{rm}$ cannot be verified.
- Manufacturers’ requirements for $I_{rm}$ are mostly based on historic data and proprietary methods.
- Test conditions for ripple current life testing are confusing, and allowing ~3% of failures does not seem right.
- ESR has a complex dependence on temperature and frequency, which makes difficult development of requirements for current multiplying factors.
- The existing CM result in conservative estimations of ESR at high $T$ and $f$, but might cause substantial errors at low temperatures and frequencies resulting in $\Delta T >> 50$ °C.

Thermal model
- A simplified thermal model for estimations of case-to-ambient thermal resistances has been developed.
- An assessment of the internal thermal resistance indicates that the core temperature might be only ~ 6 °C maximum greater than the case temperature.
- All three components of $R_{th}$: conduction through the leads, convection, and radiation, have comparable values.
- In still air, $R_{th}$ caused by radiation is 1.6 to 2 times greater than the convection component. Heat transfer through the leads is more important for smaller case sizes.
Experiment and IR images

- No hot spots on the cases of wet tantalum capacitors were observed.
- For parts soldered onto a PWB, temperature at the bottom of the case in the area across the anode slug is ~ 5 °C greater than at the top.
- Two test methods for $R_{th}$ calculations are suggested: one is based on analysis of the cooling curves, and another on analysis of the temperature rise vs. power. Both techniques provided similar results within 15% error.

Effect of ripple currents in still air

- Characteristic times of heating and cooling at $f < 1$ kHz are 2 to 3 times greater than at high frequencies indicating that temperature distributions depend on frequency.
- Temperature rise increases with the ripple current according to power law with the exponent $1.2 < m < 1.6$.
- Temperature rise at rated currents varies from 20 °C to 50 °C for different part types.
- Four out of 7 part types had substantially under-rated currents.
- At $f \geq 1$ kHz, $\Delta T(P)$ does not depend on frequency.
- For DWG#93026 capacitors, $R_{th}$ varies from ~31 K/W for T4 to ~38 K/W for T1 cases.
Conclusion, Cont.’d

Effect of ripple currents in convection chamber
- At the same ripple current conditions, $\Delta T$ in the convection temperature chamber at 85 °C is 2 to 5 times less than in still air.
- The exponent in the $\Delta T(I_r)$ dependence is greater than in still air, $m \sim 1.8$, because the heat release does not depend that substantially on the surface temperature.
- In forced air convection chamber, $R_{th}$ is less than in still air: by $\sim 30\%$ for small-size cases (T1), and in $\sim 2.6$ times for large-size cases (T4).
- The existing ripple current life testing in convection chamber is not a value added test because the acceleration of the failure rate caused by the ripple current-induced temperature does not compensate for the reduction of the acceleration caused by decreased voltage.

Effect of ripple currents in vacuum
- Variations of $\Delta T$ with $I_r$ in vacuum follow the power law with the exponent $1.2 < m < 1.6$.
- The characteristic times of heating/cooling are from 2.5 to 3.5 times greater in vacuum than in still air.
- At rated ripple currents, the temperature rise, hence thermal resistance, in vacuum approximately 2 times greater than in still air.
- Parts without insulation sleeves have higher temperature rise that might exceed 100 °C.
- Thermal run-away in vacuum is more likely to happen at low frequencies.
Recommendations

- Manufacturers should provide the following information in the specification/data package for each part type:
  - Rated ripple current and dissipated power at 40 kHz, still air conditions that results in $\Delta T = 50 \, ^\circ\text{C}$. The value of $I_{rr}$ should be determined experimentally using a standardized temperature rise testing.
  - Typical variations of ESR with frequency in the range from 100 Hz to 100 kHz at temperatures $-55 \, ^\circ\text{C}$, $-25 \, ^\circ\text{C}$, $0 \, ^\circ\text{C}$, $+25 \, ^\circ\text{C}$, $+55 \, ^\circ\text{C}$, $+85 \, ^\circ\text{C}$, and $+125 \, ^\circ\text{C}$.
  - Typical values of $R_{th}$ determined at 40 kHz and still air conditions.

- Users should make sure that the ripple current during applications does not increase case temperature above $85 \, ^\circ\text{C}$ at $0.5 \times \text{VR}$ and $125 \, ^\circ\text{C}$ at $0.3 \times \text{VR}$.

- Special analysis and testing are required if a part is to be powered up at low temperatures to avoid failures related to overheating and thermal shock.

- Power cycling test should be used to assure reliable operation for applications when cold start-ups are possible.