

New Ripple Current Guidelines for Very Low ESR Tantalum Capacitors

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Abstract

During the last decade, the equivalent series resistance (ESR) of surface mount tantalum chip capacitors has fallen dramatically. Typical performance of low-ESR capacitors with EIA 7343 footprint has fallen from around 100 m Ω to less than 20 m Ω , sometimes much less. A major driving force behind this ESR reduction is the steady evolution of electronic circuits that operate at lower voltages, faster switching speeds, and higher currents. The ESR of tantalum chip capacitors was reduced by manufacturers to satisfy the performance requirements of such circuits.

In general, lower ESR permits capacitors to be exposed to higher ripple currents, but how much higher? Ripple current specifications in manufactures' data sheets are assigned in a conservative fashion. A small surface temperature rise is tolerated and a corresponding maximum dissipated power is specified assuming "typical" mounting conditions. Given the maximum allowed power and the maximum allowed ESR, the maximum allowed ripple current is easily calculated.

But are these conservatively derived ripple current limits absolute? Can a clever designer safely exceed these limits if he uses heat sinks, forced cooling, and/or low ambient temperatures? What must a savvy circuit designer know about the capacitors to get the most electrical performance from them without compromising long-term reliability?

This paper discusses a more sophisticated approach to analyzing the ripple current capability of very low ESR tantalum chip capacitors. A simple thermal model of tantalum chip capacitors is suggested. A methodology for finding the parameters of the thermal model is described. Laboratory data are presented for two versions of tantalum polymer capacitors: those constructed from typical, non-optimized materials and those constructed from higher-performance materials.

Hypothetical circuit designs are analyzed to demonstrate application of these concepts for both non-optimized and improved-performance capacitors.

The discussion ends with a warning that even though the manufacturer's specified power dissipation and ripple current ratings can generally be safely exceeded when careful thermal design is employed, considerable risk is involved if assumptions made during the design process do not hold in the final application.

Introduction

During the last decade, the equivalent series resistance (ESR) of surface mount tantalum chip capacitors has fallen dramatically. State of the art devices have been manufactured with ESR less than 4 m Ω . Manufacturers have designed capacitors with lower ESR to satisfy the needs of circuits that operate at lower voltages, faster speeds, and higher currents.

Circuits that operate at lower voltages require stricter absolute control of the power supply voltage that feeds them if for no other reason than to maintain similar percentage regulation. Capacitors play a crucial role in the regulation of low-voltage switch-mode power supplies by limiting the change in power supply voltage that occurs while the supply is switching and when the load current changes. This regulation behavior depends on low ESR since voltage change across the capacitor at critical moments is proportional to ESR for a given transient current. So a lower voltage circuit inherently requires lower-ESR capacitors, even if its current requirements are the same as the higher-voltage circuit. But if the required current for a lower-voltage circuit is also higher, then the ESR must be even lower still.¹⁻⁴ It is common for lower-voltage circuits to require more current than higher voltage circuits. This is most evident in central processing units (CPUs) for computer systems. Early

CPUs operated at 5V and just a few amperes. Some modern CPUs operate at voltages below 1V and at currents approaching 100 amperes.

Circuits that operate at higher clock speeds tend to draw more current than similar circuits operating at lower clock speeds. The early CPU typically operated at speeds less than 100 MHz, while modern CPUs operate at speeds in excess of 1 GHz. These realities apply additional pressure on circuit designers to employ ever-lower-ESR capacitors, and on capacitor manufacturers to develop them.

When capacitors are employed in circuits that require low ESR, they are necessarily exposed to large ripple currents. These currents dissipate power in the ESR of the capacitor and this power generates heat in the capacitor that causes its temperature to rise. High temperatures are bad because they reduce the reliability of capacitors, a situation that could lead to failures.⁵ So manufacturers must specify limits on the allowed power dissipation and ripple current for safe capacitor operation.

Origin of Ripple Current Ratings

The author cannot comment authoritatively on the origin of competitors' ripple current ratings, but he has some knowledge of the evolution of the rating system at KEMET. While small details may vary, it is not likely that much difference exists from manufacturer to manufacturer.

Power dissipation limits for capacitors are governed by the desire to limit device temperature rise to a safe level. Historically, a 10-20°C temperature rise was considered "safe." This guideline was in place long before capacitor ESR and ripple current were routinely specified in KEMET data sheets (at least more than 28 years).

In the late 1970s, manufacturers of military equipment began to use hermetically sealed tantalum capacitors and polycarbonate film capacitors in high ripple current circuits and pressed for specification of ripple current limits as well as guidelines to reduce those ratings at higher ambient temperatures. Some specifications were directly negotiated with these manufacturers. DESC formulated MIL-C-39003/9 which specified 100 kHz ESR limits, ripple current limits, and a 40 kHz ripple current life test for proof of capability. MIL-C-83421 specified ripple current

limits, and ripple life tests for polycarbonate film capacitors.

It was not long before commercial customers wanted guaranteed ESR and ripple current too. At KEMET, the methodology for producing these limits was fairly straightforward. Power dissipation limits were assigned to various case sizes according to a combination of laboratory investigation (temperature rise versus power dissipation testing), interpolation (if a new part's size fell between two already rated parts, the new part got an intermediate rating that was proportional to its size), and competitive positioning (the ratings shouldn't differ too much from the competition). In any event, the resulting power dissipation limits were always consistent with a "safe" device temperature rise of 10-20°C and laboratory testing was always performed in a conservative manner in a still-air environment with minimal heat-sinking (to protect against worst-case customer application technique).

During the 1990s, customers began to demand very low ESR as they started to use tantalum capacitors in high-power switching power supplies. One consequence of this new, more aggressive application was that customers began to use the capacitors at higher ambient temperatures. In response to customer's needs, specifications were written to allow some fraction of the 25°C ripple current rating to be applied at ambient temperatures of 85°C, and a smaller fraction at either 105°C or 125°C, depending on the capacitor style.

Inconsistency in the Ripple Rating System

One KEMET specification allows roughly 90% of the 25°C ripple rating to be applied at 85°C. An astute customer asked, "if I can apply 90% of the 25°C ripple rating at 85°C, why am I limited to only 100% of the 25°C ripple rating at 25°C?" He reasoned that 90% of the 25°C ripple rating would produce $(0.9)^2=81\%$ of the power dissipation specified at 25°C. This power dissipation would cause roughly $0.81*20^\circ\text{C} = 16.2^\circ\text{C}$ temperature rise. This temperature rise plus the 85°C ambient temperature would raise the capacitor's temperature to approximately 100°C. He further reasoned that 100°C must be "safe" since we allowed it by the wording of our specification.

Working backward, he wanted to know why he was limited to only the original 20°C rise when the ambient temperature was 25°C. The resulting

capacitor temperature would be only 45°C, less than half of the “safe” 100°C that was allowed if the ambient temperature were 85°C. Why was he penalized for operating at 25°C? Couldn’t he apply more ripple current at 25°C than the specification allowed, at least enough more to get the capacitor’s temperature to 100°C, and still be “safe”? Was there something other than temperature rise that forced us to limit the ripple current at 25°C to such a low level?

This customer had discovered an inconsistency in our ripple current rating system. The simple explanation of this inconsistency is that KEMET wants to be very conservative with ripple current and power dissipation limits to avoid heat-related reliability problems in customer’s applications. But KEMET also wants to provide some ripple current capability when the capacitors are used in hot ambient environments such as switching power supplies. KEMET also wants to be competitive in the marketplace. Finally, KEMET wants the rating system to be simple. These conflicting objectives have created a rating system that is not internally consistent.

A More Enlightened Approach

Many ripple current lifetests have been performed by KEMET on low-ESR capacitors. Several observations have been made based on the data:

- Simple existence of ripple current in a tantalum capacitor does not create new failure mechanisms.
- Capacitor reliability is affected by peak applied voltage and peak core temperature, not specifically the presence or magnitude of the ripple current.
- DC lifetests produce similar rates of failure as are seen on ripple lifetests at similar peak voltage and temperature.
- There is no theoretical reason to arbitrarily limit temperature rise from ripple current at low ambient temperatures as long as the core temperature remains at an acceptable level.

So it should be possible to expose the capacitor to ripple current above the specification limit as long as the ambient temperature is low enough that the peak core temperature of the capacitor stays below some “safe” level. “Safe” does not mean the same thing to everyone. In this context, “safe” means a temperature

that allows **adequate** reliability at the peak applied voltage.

It must be clearly stated that reliability suffers as temperature rises. A very crude estimate is that the failure rate doubles with every 10°C rise in core temperature. KEMET designs its capacitors to have **competitive** reliability at their maximum rated temperature and voltage, but it is well known that many applications require even higher reliability. The only way to achieve this additional reliability is to reduce temperature and voltage.⁵

In order for the designer to limit temperature to a “safe” level, he must be able to predict the capacitor’s temperature in his application. The temperature rise caused by ripple current depends on the thermal conductivities of the materials from which the capacitor is fabricated and the thermal resistance of the path from the capacitor’s core to the ambient environment. The thermal behavior of capacitors can be experimentally determined and will remain valid unless the capacitor’s design changes. But the thermal resistance of the path from the capacitor to the ambient environment can vary dramatically from one application to another and must be separately determined for each design.

Specifically, if the copper traces that lead to and from the capacitor are thick and wide, ripple-generated heat will be readily conducted away from the capacitor where it can be dissipated by the surface of the circuit board into the ambient environment. Such circuit board design efforts reduce the thermal resistance from the capacitor core to the ambient environment. Moreover, if air is moving over the surface of the circuit board and the capacitor, heat can be removed even more effectively.

To facilitate practical thermal calculations, a simple thermal model of the capacitor and the circuit board is needed. A simple thermal model and a methodology for determining the constants of the model are described below.

A Simple Thermal Model of a Capacitor

It is common to model heat flow as though it were current flow in an electric circuit. In such a model, power dissipation is modeled as a current source. Thermal resistance is modeled as electrical resistance and temperature is modeled as voltage.

The advantage of such a model is that the simple analysis techniques of electric circuits can be directly and intuitively applied to the solution of a thermal problem. Of course, just as lumped-element circuit analysis is oversimplified for many real-life electric circuits, the same is true for thermal circuits, and the accuracy of the resulting analysis is only as good as the precision of the model employed. There is always a tradeoff between accuracy and simplicity in such models.

In Figure 1 is a suggested thermal model (drawn as an electric circuit) for a capacitor mounted on a circuit board. Also included in Figure 1 is a sketch of the corresponding capacitor and the circuit board that it is mounted to. Thermal capacitance which results from the specific heat of the various materials that make up the thermal path has been ignored since it is the steady-state rather than transient performance that is of interest in most high-ripple applications.

The escape routes for heat are shown pictorially in the capacitor sketch. A large amount of the heat escapes through the terminations because of their superior thermal conductivity as compared to that of the molded epoxy case. However, the short length of the path through the epoxy and its much larger cross-sectional area compensate significantly for low thermal conductivity, and a significant amount of heat is nevertheless dissipated from the surface of the epoxy case.

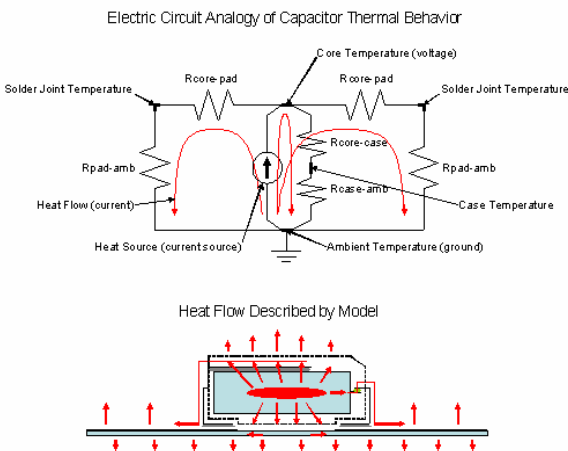


Figure 1. Simplified Thermal Model of Tantalum Chip Capacitor Mounted to a Circuit Board Given as an Electric Circuit Analogy.

In the circuit diagram of Figure 1, three distinct heat escape routes appear. They are the negative and

positive terminals and heat loss through the epoxy case. Each escape route is modeled as two series resistances, one that is contained within the capacitor and one that exists outside the capacitor. Thermal resistances outside the capacitor are defined by the circuit design. These resistances can be lowered by use of thermally conductive materials, heat sinking techniques, and circulation of cooling air.

The simplified model represents heat loss via the epoxy case as being totally independent of heat loss via the terminals. This is not strictly true as can be seen in the sketch of the capacitor in Figure 1. Heat loss through the case and heat loss via the terminals influence each other because the heat escape routes share common material. The error caused by this oversimplification is generally small and will encourage a conservative design. Modeling the coupling between the heat escape routes is beyond the scope of this paper.

Finding the Thermal Resistances in the Model

The basic strategy to find the thermal resistances is to quantify the power dissipated in the capacitor and measure key resulting temperatures. The analogous electric circuit problem is then solved to find the resistances and heat flows that must exist for the power and temperatures to be consistent.

Power in watts is given by the formula $P=I^2 \cdot ESR$, where the current is in root-mean-square (rms) amperes, and the ESR is in ohms. Since ESR is commonly specified at 100 kHz, all measurements and calculations reported here were made at 100 kHz.

Accurate current measurements are challenging at 100 kHz. Two strategies were employed in this investigation. In one case, the voltage drop across a precision, low-inductance 10 mΩ chip resistor was measured, while in other cases, the voltage drop across the capacitor's impedance was measured. The second approach was used when it was not practical to include the 10 mΩ resistor in the electric circuit.

Since the capacitor's impedance varies with temperature, this temperature dependence was characterized for each device so that current measurements via capacitor voltage drop could be properly corrected for temperature and inductance. The precision 10 mΩ resistor (determined to be within 1% accuracy at 100 kHz) was used as the calibration reference during these measurements.

Accurate temperature measurements are also challenging when the object being measured is the small size of a tantalum chip capacitor. The measurement sensors chosen were very fine-gage thermocouples. The wire diameter was chosen to be 0.005 inches to minimize heat-sinking through the thermocouple wires. This is the smallest wire size that is practical to work with without specialized tooling. Another benefit of small wire diameter is that the thermocouples have very fast response.

One thermocouple was placed in the solder joint at the negative terminal and a second at the positive terminal. A third thermocouple was inserted into a small-diameter hole that was drilled into the core of the capacitor element. A fourth thermocouple was used to measure the ambient air temperature in the immediate neighborhood of the capacitor.

Figure 2 is an x-ray photograph of one of the test capacitors which shows the location of the test hole for the third thermocouple. For reference, the terminations of the capacitor are roughly 7.3 mm (0.287 inch) apart, the hole diameter is about 0.6 mm (0.023 inch), and the wire diameter (the wire shadow is only barely visible in the x-ray) is about one-fifth the diameter of the hole. The intent was to locate the thermocouple in the hottest location. The strategy was to aim for roughly the center of the element while staying away from the tantalum wire since it is a heat escape path. The thermocouple was fixed in place with silver filled adhesive for good thermal conduction.

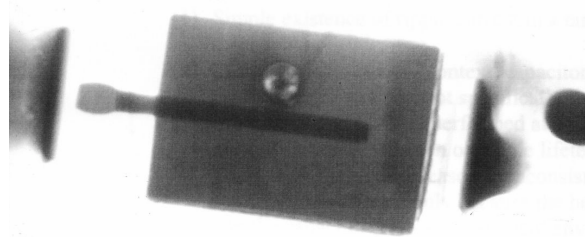


Figure 2. X-Ray Photograph of a Mounted Tantalum Polymer Capacitor with a Hole for Core Temperature Measurement.

Drilling a hole in the capacitor element does damage to the dielectric in the neighborhood of the hole, but the resulting dc resistance at this “wound” is still considerably larger (by a factor of 100-1000) than the 10-25 mΩ ac impedance of the capacitor at 100 kHz.

As long as this dc resistance to ac impedance ratio is large, there is only a small amount of additional heating around the cylindrical surface of the “wound” that can exaggerate the final measurement of core temperature.

The ac test signal was generated by an oscillator and separately amplified. The amplifier was impedance matched to the capacitor by means of a ferrite-core toroidal transformer.

Finding Core-to-Pad Thermal Resistances

The strategy for finding the core-to-pad thermal resistances involves connecting two equal heat sinks to the capacitor’s leads, insulating the capacitor’s case from heat loss to simplify the circuit model, heating the capacitor with ripple current, and measuring key temperatures. Then 6 simultaneous equations are solved using these data to find 6 unknowns that include the desired thermal resistances. The simplified circuit diagram and related equations appear in Figure 3.

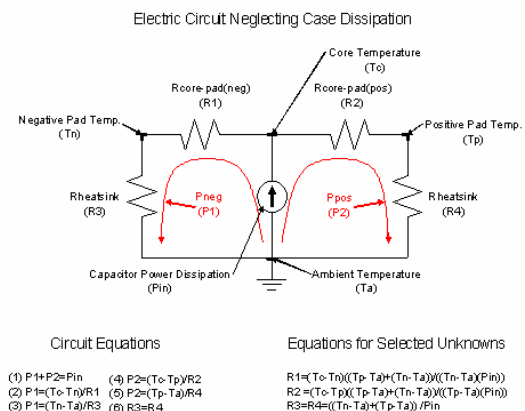


Figure 3. Diagram of a Simplified Circuit and Related Equations for Calculating Thermal Resistances from a Capacitor’s Core to its Solder Connections, Neglecting Case Dissipation.

Photographs of the laboratory apparatus employed to collect the data per Figure 3 appear in Figures 4-6. The photographs start with an overview of the work area, then focus in on details of the capacitor’s mounting, excitation, cooling, and shielding from case-to-ambient cooling.

The copper heat sink is divided into two separate but equal sections, one for each terminal. A gap between

the heat sink halves is covered with a narrow strip of high-temperature tape to block airflow. Ambient air is blown onto the back-side of the heat sinks and the air's temperature is measured with a thermocouple. The capacitor is covered with thin plastic tape to block contact with circulating air. The intent is to minimize heat dissipation via the epoxy case while maximizing heat dissipation via the capacitor's terminals.



Figure 4. General Overview of the Apparatus for Finding Thermal Resistance from the Capacitor's Core to Terminals.



Figure 5. Detailed View of Fan, Capacitor on Split Heat Sink, Support Vise, Matching Transformer, and Current Sense Resistor with Fins.

Thermocouples are embedded in both the negative and positive solder joints as well as in the core of the capacitor. Current from the impedance matching transformer is coupled to the capacitor through the copper heat sinks. The precision 10 m Ω , low-inductance resistor is visible in the current path. Fins were attached to the resistor to control its temperature

at high current. The sense terminals of the resistor are connected to the oscilloscope via 50 Ω coaxial cable which is terminated in 50 Ω to prevent reflections.

A second coaxial cable is connected across the capacitor's terminals with a short twisted pair of 0.005 inch diameter wires to monitor the ac voltage across the capacitor. This cable was also terminated in 50 Ω . Because of the very low source impedances of the precision resistor and capacitor, loading errors from the 50 Ω termination are negligible.



Figure 6. Close-up of Capacitor Soldered to Negative and Positive Heat Sinks. Capacitor is Covered with Thin Plastic Tape to Minimize Heat Dissipation via Convection.

Finding Core-to-Ambient and Core-to-Case Thermal Resistances

Two thermal resistances are of interest with respect to power dissipation via the capacitor's molded epoxy case. The first is the total thermal resistance from the core to the ambient environment when there is no deliberate heat-sinking of the capacitor's case. This is the most common configuration.

Since it is possible to attach a small heat sink directly to the surface of the capacitor, the designer would also like to know the thermal resistance that exists only between the core and the capacitor's surface when a heat sink is attached to it. Once found, $R_{\text{core-case}}$ can be added to the known thermal resistance of the attached heat sink to find the overall thermal resistance from core to ambient.

The strategy for finding these thermal resistances involves thermally isolating the capacitor's negative

and positive terminals from the ambient environment so that heat can only escape through the molded epoxy case. This simplifies the thermal model in a manner complementary to the previous technique. The capacitor is then heated with ripple current and key temperatures are measured. The simplified circuit is analyzed to find thermal resistances that are consistent with the power and measured temperatures.

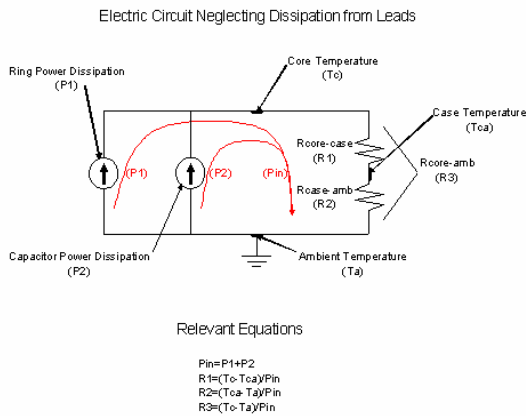


Figure 7. Diagram of a Simplified Circuit and Relevant Equations for Calculating Thermal Resistances from a Capacitor's Core to Ambient and Core to Case.

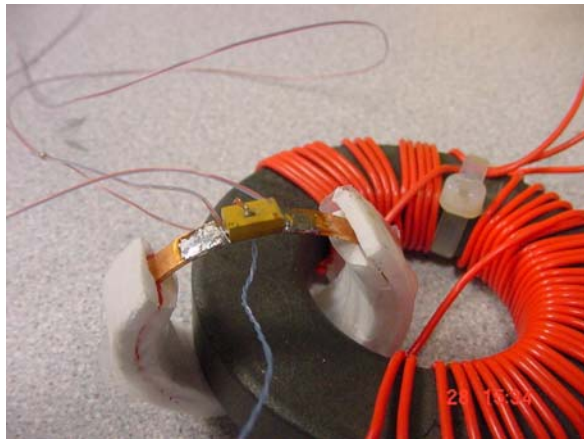


Figure 8. Picture of Copper Ring Connected to Capacitor and Partially Insulated, including Thermocouples and Twisted Voltage Sense Wires.

One challenge involved in finding these case-related thermal resistances is the problem of conducting electric current into the capacitor without conducting heat out of the capacitor's terminals via the electrical connections. A successful solution was to insert a thermally-insulated copper ring through the matching

transformer and to connect its two ends to the terminals of the capacitor. This way, heat conducted out of the capacitor through its terminals could not escape to the environment.

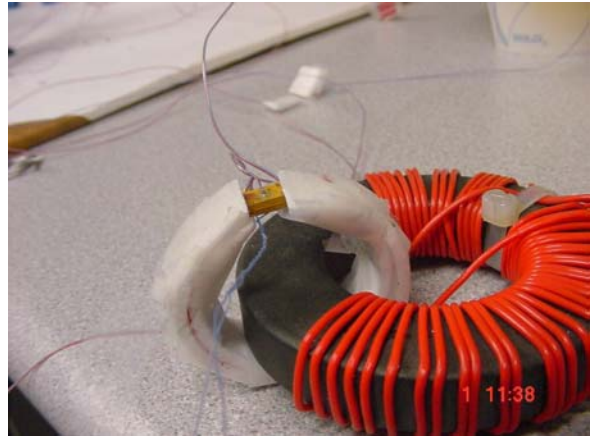


Figure 9. Picture of Copper Ring Fully Insulated.

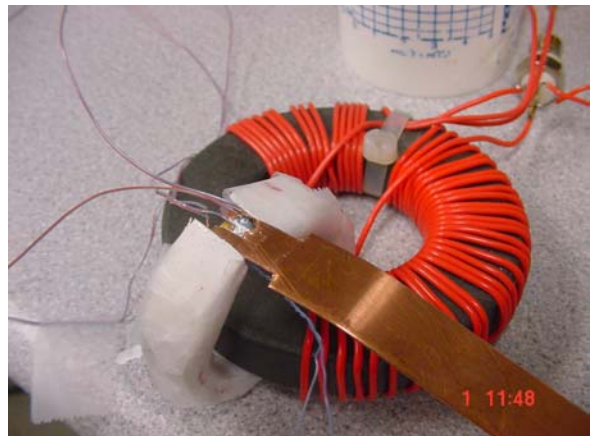


Figure 10. Addition of Copper Heat Sink to Aid Determination of Thermal Resistance from Core to Case.

One additional factor was considered. The current induced in the copper ring dissipates power in the ring's resistance. This heat is conducted into the capacitor via the capacitor's terminals where it contributes to the capacitor's temperature rise. This additional power must be accounted for when the total power dissipated by the capacitor is calculated. For this reason, current was measured as the voltage drop across the capacitor's impedance. This choice was driven by the desire to minimize the resistance of the ring and the resulting heat generation due to the ripple current. The ring's resistance was only 1.4 mΩ,

which would have risen by another 10 mΩ had the current sensing resistor been included.

The simplified circuit diagram and related equations needed to calculate the core-to-ambient and core-to-case thermal resistances appear in Figure 7. The insulated copper ring, capacitor, matching transformer, and thermocouples appear in Figures 8 and 9.

To find the core-to-case thermal resistance, a copper heat sink is attached to the surface of the capacitor. A picture of this heat sink appears in Figure 10. A small quantity of thermal compound is applied between the capacitor's top surface and the heat sink as is the usual practice. The heat sink makes the temperature across the top surface of the capacitor more uniform as is only true when a heat sink is attached. Also, the copper surface provides a convenient attachment point for the thermocouple.

Thermal Resistance Data

For this paper, tantalum polymer capacitors were characterized because they represent the leading edge of performance in miniature low-ESR capacitors. Two styles were studied, capacitors manufactured with conventional materials and capacitors manufactured with superior materials. Capacitors from the "conventional" group were specified to have ESR less than 40 mΩ, while capacitors from the optimized group were specified to be less than 15 mΩ. The actual ESR performance of the conventional capacitors was about 23 mΩ while that of the optimized capacitors was about 11 mΩ. Otherwise the two styles had similar capacitance (330 uF) and case size (EIA 7343-31).

Construction of the superior capacitors involves use of more conductive terminal metal, thicker tantalum wire in the capacitor element, and proprietary improvements of the carbon and silver paint layers. KEMET tantalum polymer capacitors with specified ESR of 25 mΩ or less are almost always manufactured with the superior material set while those with specified ESR greater than 25mΩ are generally not.

Changes that improve ESR also tend to improve thermal conductivity since these properties are closely linked. This generalization held true for these tantalum polymer capacitors. Thermal resistance data collected by means of the methodology described above appear in Table 1. These data are averaged

values from measurements of several representative devices from each style.

Because there is variation in the manufacturing process, there is necessarily some variation in thermal performance from device to device and from batch to batch. So the data of Table 1 are not to be construed as *guaranteed* performance specifications, but rather as *typical* performance for the conventional and superior versions of these tantalum polymer capacitors.

	Conv. Materials ESR _{max} >25mΩ	Sup. Materials ESR _{max} ≤25mΩ
R _{core-neg}	128°C/W	46°C/W
R _{core-pos}	115°C/W	47°C/W
R _{core-amb}	104°C/W	77°C/W
R _{core-case}	37°C/W	29°C/W

Table 1. Typical Measured Thermal Resistances for Conventional and Superior KEMET Tantalum Polymer Capacitors.

It is clear from the data of Table 1 that not only do the optimized capacitors have lower ESR, they also have substantially reduced thermal resistances. One interesting comparison is the total parallel thermal resistance of all three heat escape routes if no heat sink is attached to the capacitor's surface. For the conventional parts this combined thermal resistance is about 38°C/W, while for the superior parts this value is about 18°C/W, about a 2:1 ratio. It is interesting that this ratio is quite similar to the ratio of ESRs of the two groups of capacitors, both specified and actual. The ratio of specified ESRs is 2.7:1 while the ratio of actual ESRs is 23mΩ/11mΩ, or 2.1:1. This correlation is not expected to hold this well in general, but there is more than mere coincidence in the similarity of the ratios.

Example Calculations with the Thermal Resistance Data

Two quick example calculations are done to introduce application of the thermal resistance data of Table 1 to real-world applications. They are also done as a reality check of the thermal resistance data in light of the KEMET-specified "safe" power dissipation limit that should produce between 10-20°C temperature

rise. These calculations do not assume any aggressive heat sinking and the ripple current and power dissipation levels do not exceed catalog limits. After these examples, a few more aggressive cases are analyzed to explore what can be done with the thermal data of Table 1 and some attention to the thermal design of the circuit.

The first example is the hypothetical case where rated ripple current is made to flow (by hypothetical wires that do not conduct heat) in a conventional tantalum polymer capacitor that is not connected to any heat sink at all. In this case, the only thermal resistance of interest is $R_{\text{core-amb}}$ which is $104^{\circ}\text{C}/\text{W}$. The objective is to find the core temperature rise.

Rated ripple current produces rated power dissipation in a capacitor. For the capacitors characterized in this paper, the rated power is 0.15 W. The core temperature rise is then $0.15\text{W} \times 104^{\circ}\text{C}/\text{W} = 15.6^{\circ}\text{C}$ for this case where no heat can escape from the capacitor's terminals. This temperature rise easily falls into the $10\text{-}20^{\circ}\text{C}$ "safe" temperature rise zone. Had an optimized tantalum polymer capacitor been used, the temperature rise would have been $0.15\text{W} \times 77^{\circ}\text{C}/\text{W} = 11.6^{\circ}\text{C}$. This example validates the connection between the rated power dissipation and temperature rise between $10\text{-}20^{\circ}\text{C}$, as is indicated in KEMET's catalogs.

A second example is the case of a non-optimized tantalum polymer capacitor mounted on a small test substrate and subjected to a ripple current lifestest at 25°C . Assume the test substrate is very small, having dimensions $1.0 \times 0.25 \times 0.062$ inches (these exist in real life). The copper traces on the substrate are thin and narrow and the thermal resistance to ambient from the mounting pads is high, say $300^{\circ}\text{C}/\text{W}$ for each of the two pads. The ESR of the capacitor is $35 \text{ m}\Omega$ at 100 kHz and the catalog ripple current limit at 25°C is 1.9 amperes. What is the core temperature of the capacitor?

The analysis that follows ignores any heating in the resistance of the traces of the test substrate. The dissipated power in this case is given by $P = I^2 \times \text{ESR}$ and is 0.126 W. Of course this is below the maximum power rating of 0.15 W because we used the specified ripple current and ESR is below the specified value.

The total thermal resistance along the route from core to ambient via the negative terminal is $428^{\circ}\text{C}/\text{W}$, and via the positive terminal is $415^{\circ}\text{C}/\text{W}$. The thermal resistance from core to ambient via the case is

$104^{\circ}\text{C}/\text{W}$. According to the circuit diagram in Figure 1, these three paths are electrically in parallel and the effective thermal resistance of these parallel resistances is $69.6^{\circ}\text{C}/\text{W}$. So the temperature rise of the core is 8.8°C , which is quite low and safe.

Pushing the Limits with Conventional Tantalum Polymer Capacitors

A circuit designer has performed lifestests on tantalum polymer capacitors and has determined that a core temperature of 85°C is a safe enough temperature for his purposes. He designed his circuit board to use thick, wide traces on both the front and back of the board. Redundant traces of like potential are connected together with numerous vias. A fan circulates air over the board.

In tests similar to the tests described above, the thermal resistance of his circuit board was found to be $25^{\circ}\text{C}/\text{W}$ from each pad to ambient. The ambient temperature is 40°C and there is no heat sink attached to the surface of the capacitor. The ESR of the capacitor is $35 \text{ m}\Omega$ at 100 kHz . The designer wants to know how much ripple current can he safely apply without exceeding the "safe" core temperature of 85°C .

Following the path of the previous example, the thermal resistances of the parallel thermal paths are $153^{\circ}\text{C}/\text{W}$, $140^{\circ}\text{C}/\text{W}$, and $104^{\circ}\text{C}/\text{W}$ for a total effective thermal resistance of $43^{\circ}\text{C}/\text{W}$. The temperature rise that can be tolerated is $85^{\circ}\text{C} - 40^{\circ}\text{C} = 45^{\circ}\text{C}$. So dividing the temperature rise by the effective thermal resistance yields a "safe" power dissipation level of 1.04 W. Clearly this power is much higher than the catalog limit of 0.15 W!

The safe ripple current is found by solving $P = I^2 \times \text{ESR}$ for I which is 5.5 A. This current is almost three times the catalog limit of 1.9 A. Again, the key to this process is that the designer knows the "safe" core temperature for his application, the thermal resistances of the capacitor, and the thermal performance of his circuit board design. Superior performance is achieved through superior knowledge.

Of course, the designer also needs to establish some safety factor in his design and needs to anticipate the unexpected, such as a cooling fan failure or use of his circuit in a very hot environment. The problem with exceeding catalog limits is that you are removing a portion of the safety factor. But if the concepts in this

paper are applied with caution, one can safely use higher ripple currents than are specified in the catalog.

Just out of curiosity, the designer fabricates a small copper heat sink with several fins that he attaches to the top surface of the capacitor with thermal compound and a clamp. A separate investigation revealed to him that the thermal resistance to ambient of this heat sink was 30°C/W with the same airflow that is expected in his design. He now wants to know how much he has increased the power dissipation and ripple current capability of the conventional tantalum polymer capacitor by adding the heat sink.

The resistances of the thermal paths through the capacitor's terminals are still 153°C/W and 140°C/W as before. But the core-to-ambient thermal resistance, via the epoxy case, must be recalculated. This resistance is now found by adding the core-to-case thermal resistance to the thermal resistance of the heat sink. $R_{\text{core-amb}}$ now decreases from 104°C/W to 67°C/W, causing the total effective thermal resistance to fall from 43°C/W to 35°C/W. Now the "safe" power dissipation level increases from 1.04 W to 1.29 W, a 24% increase.

With the given 100 kHz ESR of 35 mΩ, the newly "safe" ripple current rises from 5.5 A to 6.1 A, or about 11%. The percentage increase in ripple current is always smaller than the percentage increase in power dissipation because current is squared in the power formula.

Pushing the Limits with Optimized Tantalum Polymer Capacitors

In this example, the designer substitutes an optimized tantalum polymer capacitor for the conventional capacitor. The optimized capacitor's ESR is 11 mΩ at 100 kHz and the specified 25°C ripple current is 3.2 A. The designer wants to know just how much ripple current he can safely apply.

The thermal resistances of the parallel thermal paths now become 71°C/W, 72°C/W, and 77°C/W for a total effective thermal resistance of 24.4°C/W. The temperature rise that can be tolerated is still 45°C. So dividing the tolerable temperature rise by the effective thermal resistance yields an acceptable power of 1.84 W. This is 12 times the catalog limit of 0.15 W and almost twice the power that can be safely dissipated by the conventional tantalum polymer in the same application.

The allowable current is calculated to be 12.9 A. This current is 4 times higher than the catalog limit of 3.2 A and more than twice the current allowed for the conventional tantalum polymer capacitor in the same circuit. The reason for this high calculated current is that the optimized capacitor's ESR is lower by a factor of three **and** its thermal resistances are roughly half those of the conventional capacitor.

An Ugly Surprise

Unfortunately, when the designer installs his optimized tantalum polymer capacitor and turns the circuit on, the core temperature ends up higher than predicted. What went wrong?

It turns out that he didn't have quite enough information. It seems that the traces leading to the pads on the board were not made of superconductors and instead had electrical resistance of about 5 mΩ (each) in the neighborhood of the capacitor. Each of these traces carries the 12.9 amperes and dissipates an additional 0.83 W of power right next to the capacitor. So the circuit board and capacitor actually have to dissipate about 3.5 watts of total power and the core temperature becomes close to $45^{\circ}\text{C} + 3.5\text{W} * 24.4^{\circ}\text{C}/\text{W} = 130^{\circ}\text{C}$ instead of the "safe" 85°C that was expected.

Recall that in the method for finding the thermal resistance from core to ambient via the epoxy case, the power dissipated in the resistance of the ring (same as the resistance of the traces on the board) was added to the power dissipated in the capacitor to find the total dissipated power. The same logic applies to power dissipated in the circuit traces near the capacitor in the example above. This is because the heat generated in the traces raises the temperature of the traces which raise the temperature of the capacitor.

The exact analysis of how "close" the trace resistance has to be to the capacitor to matter and exactly how much additional temperature rise results from the extra dissipated power is beyond the scope of this paper. The problem of the power dissipated in the ring was made much simpler by the fact that the power could only escape to ambient via the capacitor's case because the ring was thermally insulated. In practical applications, the conservative approach would be to assume that all of the power dissipated in the trace resistance must be added to the power dissipated in the capacitor.

Summary and Conclusions

The paper starts with a statement that capacitors with lower ESR can tolerate higher ripple current levels safely. But, then a question is asked, how much higher? KEMET's ripple current rating system for tantalum capacitors is described and its highly conservative nature is revealed. Also, an inconsistency in the system is identified. The inconsistency suggests that there are circumstances where published ripple current limits can be safely exceeded. But calculating safe ripple current levels in excess of published limits requires thermal information about the capacitor and designer's circuit.

To assist the designer, a simple thermal model of tantalum capacitors is provided. Then a method to find the thermal resistances in the model is described and typical thermal data for tantalum polymer capacitors are presented. Various hypothetical and practical examples are presented to illustrate the concepts and to demonstrate the utility of the model. Throughout, the reader is warned of the dangers of significantly exceeding published ripple current limits, but encouraged to thoughtfully explore the true ripple current capability of tantalum polymer capacitors in carefully designed circuits.

Some specific conclusions are now stated. First, existing catalog power dissipation and ripple current limits are based on very conservative assumptions. The rating system is not always internally consistent, and the limits can frequently be exceeded if the designer has the right information to work with.

It is within the grasp of the designer to model the thermal behavior of the capacitors and of his circuit. In this way the designer can determine for himself "safe" ripple current levels for his circuit.

Steps taken to reduce the ESR of tantalum capacitors frequently have the effect of improving the thermal performance of the capacitors as well. This is clearly

true for the low-ESR tantalum polymers discussed in this paper.

The further a designer strays from the safety of catalog specifications, the more informed and careful he must be. But this shouldn't discourage the savvy designer from stretching the boundaries. The information provided in this paper should provide the concepts, models, performance data, and warnings needed to successfully exceed the published ripple current and power dissipation limits of tantalum polymer capacitors.

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