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High-Temperature Capacitors Push Performance To 200°C And Beyond

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Capacitors are among the most widely used passive components in electronics, so naturally they find their way into many applications in harsh operating environments. In certain applications such as those in oil logging, jet aircraft, nuclear power generation, and other industrial applications, these components are subject to extremely high temperatures, often somewhere in the range of 180°C to 300°C.

For MLCCs and tantalum capacitors, which are among the most popular capacitor types, the traditional 125°C limit on operating temperature for military components is problematic. When these military-grade components are subject to the extremes of high-temperature applications, a large percentage of the components will fail. This undermines the reliability of the end applications, since capacitors usually fail short and thereby short power or signals to ground, causing the end equipment to fail.

This problem was recognized in the early days of the U.S. space program, which led to R&D efforts by the U.S. Department of Energy and concerned parties in industry to develop capacitors with higher temperature ratings. In this article, we review the history of the early efforts to address the need for more-robust capacitors, which included the launch of the High Temperature Electronics Conference (HiTEC) as a forum for fostering the development of high-temp capacitors and other components.

We then discuss the high-temperature options available for MLCCs and tantalum capacitors; the material systems, manufacturing processes and terminations which enable these parts; and how the different material systems affect key performance parameters such as capacitance stability and voltage rating. In addition to examining the various dielectric types for MLCCs and tantalum electrolytics, options for achieving higher capacitance values through stacking or modular configurations are noted.

History And Early Days

The earliest activities in high-temperature component development can be traced to the 1950s and 1960s with the need for harsh environment parts for the space program.[1] Progress was made on a variety of devices but early improvements combined with huge advances in thermal shielding quickly moved immediate focus and work away from high-temperature electronics.

Around 1975, a second wave of high-temperature electronics work came from the U.S. Department of Energy Division of Geothermal Energy’s funding to sponsor pioneering R&D efforts for the development of high-temperature electronics at national labs, universities and certain companies. Sandia, Oak Ridge, Los Alamos (and others laboratories) all participated to varying degrees. This effort yielded solid wins such as thin film ink products, lower loss magnetics, improved packaging and more.

This was followed in 1977 by a request for Sandia National Labs to consolidate these efforts into the Geothermal Logging Instrument Development Program.[2] At the time, electronic technology only had the upper temperature limit of 125°C from military specifications.

Early high-temperature electronic designs using 125°C-rated components exhibited early failures many times dominated by failing capacitors. Failures were generally explained by the Arrhenius equation which that says for every 10ºC increase in temperature, the failure rate in capacitors doubles. Early high temperature designs found that some 125°C capacitors survived high-temperature use but many others did not. Further, multiple manufacturers had dramatically different performance on similar material systems, and similarly rated and sized capacitors. Even worse, multiple lots of devices from a single manufacturer could have vastly different failure rates.

These unpredictable performance results brought together a group of end users needing action. Users discussed the need for the 125°C limit to scale upwards to the region of 180°C to 300°C for electronics destined for more than just the oil logging sector. Other common areas included control electronics for combustion system efficiency control, safety systems in jet aircraft, nuclear reactor control operations and thermal conversion processes.

Successful results were produced under Sandia's direction where end users, researchers and producers initiated focused efforts on problem components that improved some device availability and performance across a multiple-year time frame. However, the promise of faster growth of high-temperature electronic systems highlighted the need for quicker developments and a broader supplier network for off-the-shelf high-temperature devices. It was roughly at that point that Sandia held what many consider to be the first official industry event—the High Temperature Electronics Conference of 1979.

The inaugural High Temperature Electronics Conference, which was later to become known as HiTEC, had well over 300 attendees and was tailored to address the needs of the oil logging industry by identifying common application and performance needs and matching those to existing or potential evolutionary products. R&D needs and funding were recognized as next steps where no options existed.

This conference had concentrated discussions on hybrid circuits, electronic devices, transducers, cables, connectors, materials, tools and thermal protection. The High Temperature Electronics Conference successfully matched end users, suppliers and researchers to create the framework of harsh environment electronics.

Fast Forward To Today

The HiTEC conference[3] is now under the organizational sponsorship of the International Microelectronics Assembly and Packaging Society (IMAPS). It is a widely attended biennial conference dedicated to the advancement and dissemination of knowledge of the high-temperature electronics industry. As expected, this conference succeeded in defining an emerging and evolving industry with an ever-expanding supplier base.

The conference's scope has expanded to include the needs of sectors such as geothermal energy production, underhood automotive electronics, high-reliability military and space.

Traditional passive component technologies such as resistors, capacitors, inductors, connectors and oscillators are widely discussed. Active device sessions have significant concentration on materials such as Si, SOI, SiC, diamond, GaN and GaAs. Electronic packaging discussions are centered on materials, processing, solders/brazes, pc boards, wire bonding, flip chip, insulation and thermal management. Reliability remains a focus with strong efforts aimed at advances in failure mechanism prediction and avoidance through experimentation and modeling.

The COVID pandemic impacted the conference by temporarily forcing it to become a virtual event. COVID further reduced the rate of technology development from prior expectations due to reduced demand for oil. That in turn had a ripple effect upon oil exploration and the demand for further advanced electronics.[4] The high-temperature electronics sector has experienced such swings in demand previously and is arguably in better position today to return to high rates of technical advances quickly due to the massive need for high-temperature electronics in the transportation sector.

High-Temperature Components—Capacitors

The topic of high-temperature electronics is so broad and involves so many active and passive component types we must narrow our scope to that of a single part—capacitors. An overview of the high-temperature capacitors available today is shown in Table 1.

Capacitors were chosen to be this article's topic because—as was learned in the earliest years of high-temperature electronics—capacitors can be among the most unreliable components, if not optimized for the high-temperature environment. Capacitor failures are especially concerning because capacitors are among the most commonly used passive components in electronics. Capacitor failures usually involve a direct short of power or signals to ground thus rendering the equipment inoperable.

Table 1. High-temperature capacitor options.

Temperature range (°C)	Capacitor availability
300	MLCC stack
250	MLCC chip MLCC modules
230	Solid tantalum Wet tantalum
200	MLCC chip MLCC stacked MLCC custom module Wet tantalum Solid tantalum EMI filters
175	RF MLCC MLCC chip MLCC stacked Wet tantalum Solid tantalum
150	Solid tantalum MLCC chip

The two most widely used capacitor types—multilayer ceramic capacitors (MLCCs) and tantalum capacitors—have both nearly doubled their operating temperature range in recent years while dropping failure rates to near zero. With this in mind, a closer look into device options and performance is warranted.

High-temperature capacitors are based on uniquely formulated material systems with the highest of purity. A combination of conservative design rules (typically lower electric field stress across dielectrics) and tightly controlled manufacturing steps help these devices meet intended reliability levels of commercial, AEC Q200 (automotive) and COTS use in a wide array of end industry sectors.

MLCCs

Ceramic capacitors are built by stacking alternate layers of ceramic and metal electrodes vertically until the desired capacitance value is obtained. The resulting stack is fired in ovens that can exceed 1000°C. After high-temperature sintering, a base termination metal is fired onto the ends of the capacitor at temperatures around 800°C. Although the materials of MLCCs are able to be exposed to extreme temperatures, MLCCs have very specific operating-temperature windows.

High-temperature SMT MLCCs are commonly available in 0603 to 2225 case sizes in three temperature ranges:

- -55°C to +150°C
- -55°C to +200°C
- -55°C to +250°C.

Ceramic capacitors intended for -55°C to +150°C are manufactured with dielectrics ranging from C0G and X8R to X8L dielectric material. These dielectrics provide a highly reliable capacitor with low loss and multiple capacitance stability characteristics over temperature. Capacitors built using C0G dielectrics exhibit capacitance stability of 0 ±30 ppm/°C.

Capacitors based on X8R material have a capacitance variation of ±15% between -55°C and +150°C. The X8L material has a capacitance variation of ±15% between -55°C to 125°C and +15/-40% from +125°C to +150°C. A high-level summary of common dielectrics, operating temperature range and stability is shown in Table 2.

Table 2. Temperature range and stability of ceramic capacitors with various dielectrics.

Ceramic dielectric type	Operating temperature range	Stability characteristics
C0G	-55°C To +150°C	0 ±30 ppm/°C
X8R	-55°C To +150°C	±15%
X8L	-55°C To +150°C	±15% -55°C to 125°C +15/-40% +125°C to +150°C
VHT PME COG	-55°C To +200°C	0 ±30 ppm/°C
VHT PME COG	-55°C To +250°C	0 ±30 ppm/°C
VHT BME COG	-55°C To +200°C	0 ±30 ppm/°C
VHT BME COG	-55°C To +250°C	See Fig. 1
VHT PME 200	-55°c To +200°c	±15% -55°C To 150°C
		>150°C (see Fig. 1)
VHT PME 250	-55°C To +250C	±15% -55°C To 150°C
		>150°C (see Fig. 1)

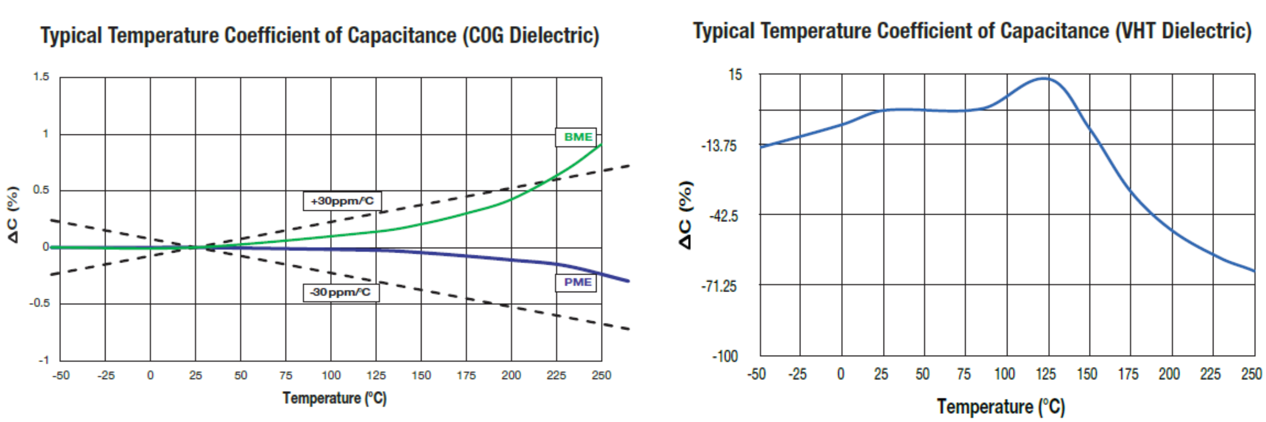


Fig. 1. Temperature coefficients of VHT BME COG (left graph), and VHT PME 200 and VHT PME 250 dielectrics (right).

In addition to the capacitors' temperature coefficient of capacitance, designers should pay close attention to dc bias characteristics since that number can range from zero (as in the case of COG-based dielectrics) to well over >20% in the case of X8R or X8L capacitors.

MLCC Termination Options

The traditional high-temperature MLCC termination options for 250°C have been PdAg, Sn/Ni and Ni/Au. However, recent expansion of automotive electronic content helped drive MLCC manufacturers to create a termination that has been optimized to negate CTE mismatch and PCB flexure stress.

These X8R/X8L devices are rated for operation in the -55°C to +150°C range and are used in high-temperature, high-vibration, high-thermal cycle applications underhood, on drive trains and in almost all other high-thermal-cycle-rate transportation applications. High-flexure-capable MLCCs are achieved through the addition of a conductive epoxy layer placed under the final termination finish and the MLCC core as shown in the cross section in Fig. 2.

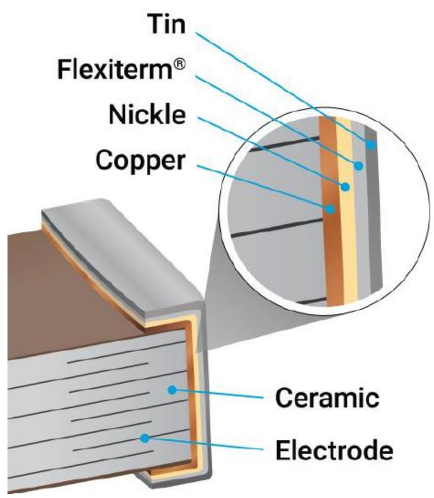


Fig. 2. Cross section of a flexible termination developed for MLCCs.

Capacitors based upon FlexiTerm technology have the capability to withstand board flexure >5 mm across a 90-mm span and withstand >3000 thermal cycles per AEC Q200 temperature cycle procedures. Most importantly there is no penalty paid in terms of increased ESR or ESR instability over time or environmental conditions. Flexible terminations are a very attractive termination choice for high-temperature MLCCs used up to 150°C.

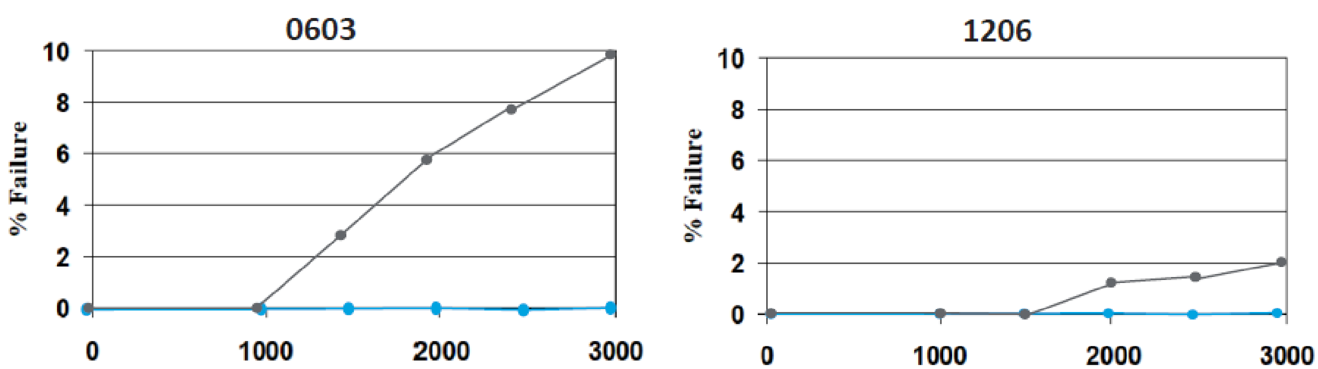


Fig. 3. Failure rates as a function of thermal cycles for MLCCs employing the FlexiTerm termination (blue curve) versus those produced with a conventional Sn/Ni termination (gray curve) .

MLCCs—Stacking For Bulk Capacitance

High-temperature MLCCs can be stacked to form ultra-low ESR bulk capacitors that have values up to ~ 270 µF and voltages that range up to 500 V dc. These capacitors are available in DIP, J, L and DIP-formed configurations to absorb high shock and vibration.

Solid And Wet Tantalum Capacitors

Tantalum capacitor technology is well understood and exhibits excellent reliability, robustness and stable parameters in small, light, and simple to place and process case sizes. What's more, end users find that tantalum capacitors exhibit small size, light weight and ease of use regardless of the technology platform (solid MnO_2, polymer, wet, hermetic) the particular device is based upon.

Standard tantalum capacitor devices have been successfully used in applications ranging from consumer to automotive applications and have an operating temperature range of -55°C to +125°C. These devices served as a platform to build upon and create a professional grade of tantalum capacitors that are capable of meeting expectations for automotive electronics reliability and operation up to 175°C. As those 175°C devices' design, processes and materials expanded, even higher-temperature tantalum-based capacitors were developed using either solid MnO_2, polymer, wet, or hermetic technology and operating up to 230°C.

At this point in time, high-temperature tantalum capacitors are available in five temperature ranges:

- -55°C to +125°C
- -55°C to +135°C
- -55°C to +150°C
- -55°C to +175°C
- -55°C to +230°C.

Capacitance Stability And Voltage Derating

For high-temperature tantalums, the temperature coefficient of capacitance varies less than that of most MLCC technologies and is a positive temperature coefficient as temperatures exceed 25°C. Designers tend to gravitate to these devices in high-temperature designs because of the availability of small case-size parts with high, stable capacitance values. The specific capacitance variation is dependent on the technology type, rated voltage and capacitor size as shown in Fig. 4.

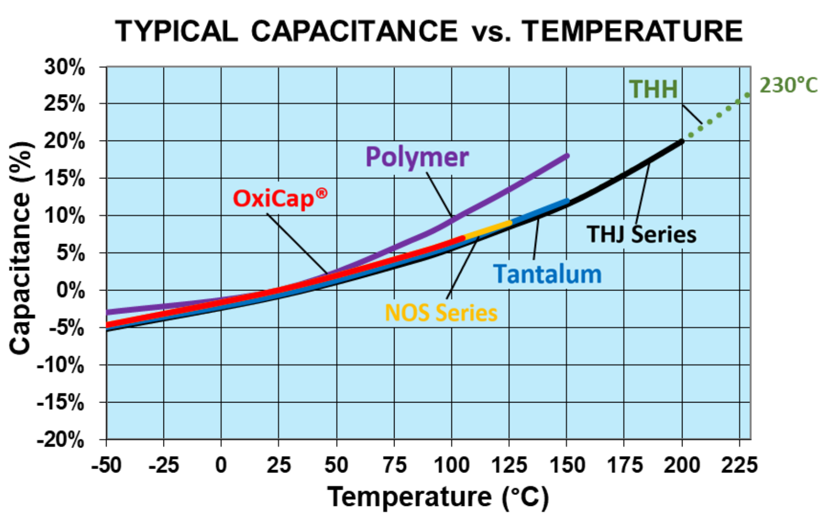


Fig. 4. Comparing temperature coefficients of capacitance for different types of tantalum capacitors.

Rated Voltage V_R Versus Category Voltage V_C

With high-temperature tantalum capacitors, voltage derating is an area of great interest to designers. Tantalum capacitors actually have a varying voltage rating based on the temperature of use.

The rated voltage (V_R) of high-temperature tantalum capacitors is the steady-state dc voltage allowed for continuous operation. The V_R of typical high-temperature tantalum capacitors is specified at 85°C. This voltage is comprised of the sum of the dc bias voltage and the peak ripple voltage. Beyond 85°C the maximum applied voltage becomes a term called category voltage (V_C). The category voltage varies for different technology tantalum capacitors. Examples are shown in Fig. 5.

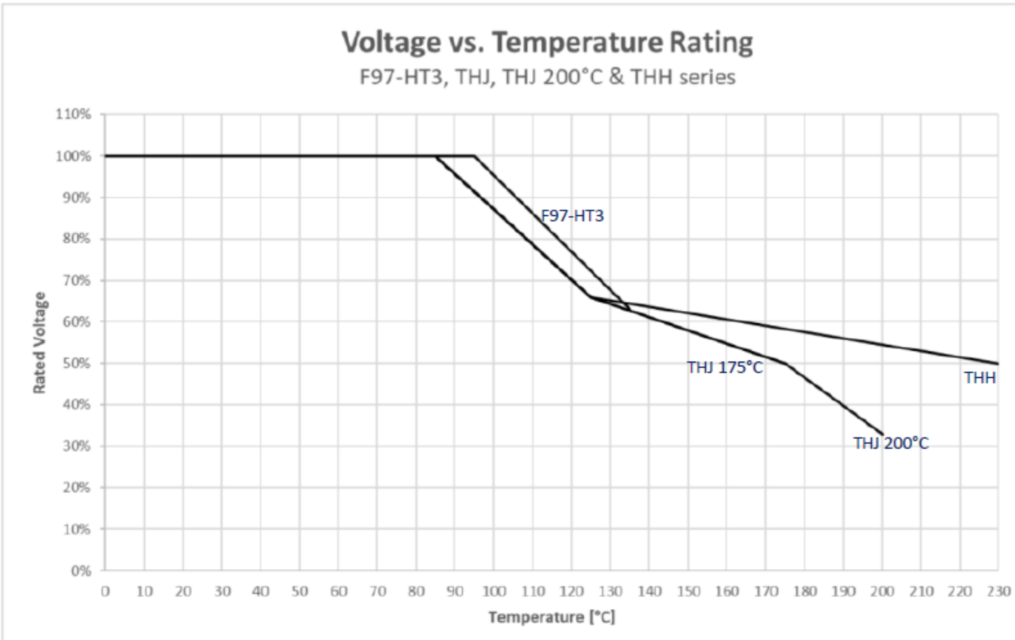


Fig. 5. Category voltage for tantalums of different technologies.

Solid, Polymer, Hermetic And Wet Tantalum Options

Wet tantalum capacitors have been in existence for over five decades and offer higher capacitance and higher voltage ratings than solid tantalum capacitors. Wet tantalums are now available in temperature ratings up to 230°C.

A particular wet tantalum series has been designed for minimum ESR and is rated at 175°C for use in applications where high capacitance is used in voltage hold-up for circuit operation. These products are hermetically sealed and available in axial-leaded and modular configurations. The components of a wet tantalum capacitor are depicted in Fig. 6 along with the drawing of a module containing several of these wet tantalum capacitors.

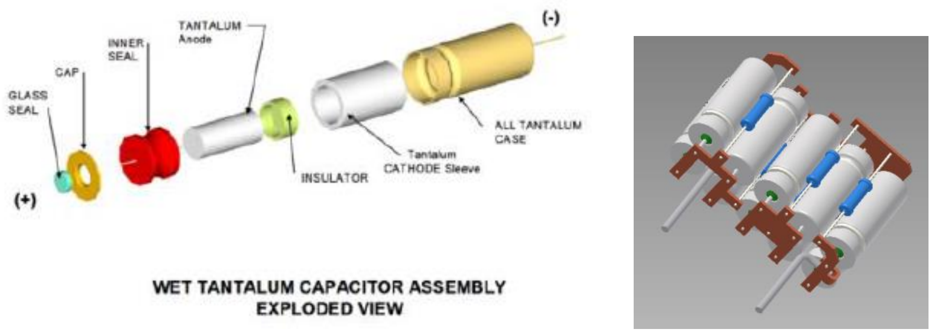
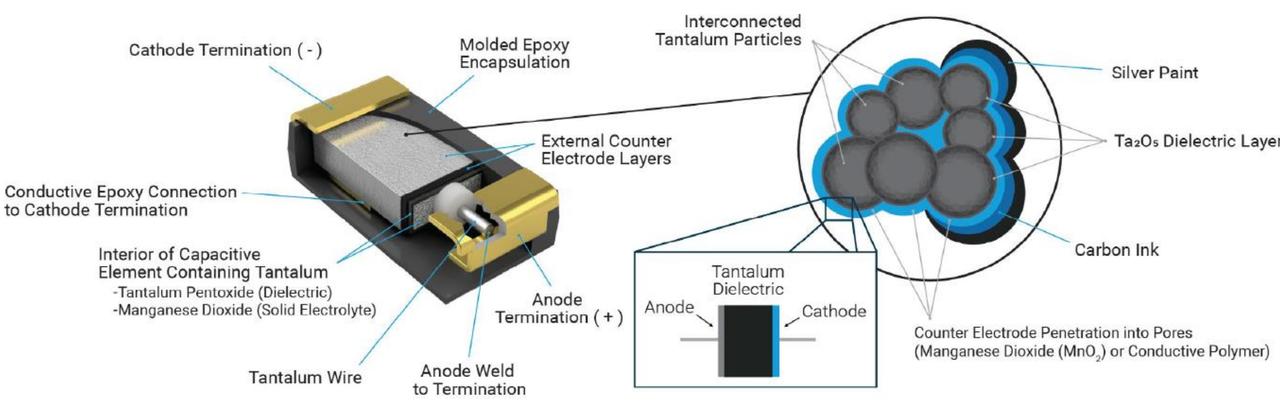


Fig. 6. The exploded view on the left shows the components that make up a single wet tantalum capacitor. Besides being available as discrete devices, these capacitors are offered in modular configurations with devices paralleled to provide higher levels of capacitance, as shown on the right. Modules also allow for series or series-parallel configurations to provide higher voltage ratings.

Tantalums in molded SMDs are available in temperature ranges from -55°C to 200°C. As previously mentioned these capacitors came about through optimized material systems, conservative design and exacting manufacturing methods, which were achieved in the last 12 to 18 months. Material improvements range from increased purity to totally novel tantalum powder, silver, molding resin and conductive epoxy. As Fig. 7 illustrates, the construction of a tantalum polymer capacitor differs markedly from that of a wet tantalum as depicted in Fig. 6.



Tantalum Conductive Polymer Cross Section

Fig. 7. Tantalum conductive polymer package and anode/dielectric/cathode cross section.

Hermetically sealed SMD tantalum capacitors came about from extensive experimentation on hermetic and near-hermetic packages aimed at assessing the stability parameters of tantalum surface-mount molded capacitors at temperatures of 230°C. These experiments showed that glass transition temperature of epoxies and also other mechanisms related to humidity and oxygen deterioration would prevent high-reliability 230°C operation.

However, it was determined that a new hermetically-sealed SMD tantalum capacitor structure would exponentially increase performance of 230°C tantalum capacitors with strong promise to increase temperature ratings to 250°C in the near future. These components have the capacitor element completely encapsulated in a ceramic hermetic housing with the internal environment being a high purity nitrogen.

Summary

The world of high-temperature capacitors has progressed greatly in recent decades to the point where capacitors are among the more reliable components in high-temperature electronics. Improvements were a result of improved material systems, conservative design and advanced manufacturing methods.

High-temperature ceramic dielectrics are NPO/C0G, X8R/X8L and other advanced dielectrics such as VHT that are specifically formulated for extreme temperature use. High-temperature capacitor use at 150°C is primarily driven by automotive designs and accelerating in frequency of use.

Discrete high-temperature MLCCs can be stacked and packaged in DIP packages and used at 230°C and 250°C to provide bulk capacitance functions. Stacked capacitors have multiple lead-frame options that can be specifically designed to increase the shock and vibration capability of the ceramic structure.

High-temperature tantalum capacitors are available in multiple technologies (solid MnO_2, polymer, wet and hermetic). Operating temperature range is a direct result of the various technologies used in high-temperature tantalum capacitor design.

Further temperature increases are expected for both MLCC and tantalum technology.

Reference

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About The Authors

Currently a KYOCERA AVX Senior Fellow, Ron Demcko manages the TSG team at KYOCERA AVX headquarters in Fountain Inn, S.C. This role centers on projects ranging from simulation models for passive components to product support/new product identification and applied development. Prior to that Ron was the EMC lab manager for AVX in Raleigh, N.C. This lab concentrated on subassembly testing and passive component fixes for harsh electrical and environmental applications. Before the EMC lab work, he held an application engineering position at AVX. Product work included integrated passive components, EMI filters and transient voltage suppression devices.

Previously Ron worked as a product engineer and later as a product engineering manager at Corning Glass Works' electronics division. In this role he supported production, sale and development of pulse-resistant capacitors, high-temperature capacitors and radiation-resistant capacitors. He developed high-frequency test methods and co-developed high-temperature test systems. Ron received a BSEE from Clarkson College of Technology. He can be reached at ron.demcko@kyocera-avx.com.

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Prior to AVX, Slavo spent two years at SONY TV as a production engineer. He graduated from the military aviation university in Kosice, Solvakia with a specialization in airborne radio and airborne radar equipment. Slavomir can be reached at slavomir.pala@kyocera-avx.com.

For more information on capacitors, see How2Power's Design Guide, locate the Component category and click on "Capacitors". Or for more on high-temperature components for power electronics, locate the Extreme Environments category and select "Extreme heat".