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## Capacitors for High Temperature Applications

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## **INTRODUCTION**

Traditionally, the main market for high temperature electronics is the downhole oil and gas industry. However, the avionics, automotive and many other industries also have applications which share the same key requirements of reliability under harsh operating conditions, including high humidity and dust, and the ability to withstand shock and vibration.

Resistors and capacitors are ubiquitous in any electronic device and system. The lack of reliable high-temperature, high value capacitors has almost certainly limited growth in these newer applications. Most current capacitor technologies on the market, such as aluminium electrolytics or film capacitors, are limited to a maximum temperature range of 125°C - 150°C or even lower. To achieve higher temperature ratings, ceramics and tantalum capacitors are used.

## **HIGH TEMPERATURE APPLICATIONS**

### **Downhole**

In downhole electronics, high temperature is usually classified as 150°C and above. In the past, temperatures of 150°C to 175°C were the maximum ratings typical for drilling operations. The need to drill deeper and explore hostile locations has significantly increased this and temperatures in today's wells can exceed 200°C, under pressures greater than 25kpsi [1].

**1. MWD - Measurement While Drilling (Sperry)** – MWD tools are attached directly to the back of the drillhead (drilling bit). Typical deep downhole temperatures are 210°C and above and in very deep natural gas wells the potential temperature can increase up to 250°C. In addition to withstanding extreme heat, electronic devices used in this application must be able to cope with continuous vibrations of 15G and extreme shock of 100 to 2000Gs [2].

**2. Logging tools / Wired measurement** – A device is attached to a wire and lowered into the existing well for data collection. Tools powered by high temperature batteries store the information in internal memory, while other types of device provide on-line measurement via a conducting cable. Typical maximum operating temperature is 225°C and this increase from ambient can be reached in less than 30 minutes.

**3. Completion tools, production monitoring** – Pump and valve controls tools are operated by permanently installed devices. In general, these systems monitor pressure, flow, density and temperature. As they are designed for a long operational life, the very highest reliability and performance components must be used. This application has very low shock and vibration requirements and temperatures in the range of 105°C to 175°C.

### **Avionics**

The operating temperature can vary significantly depending on where the electronics are located. For example, the ambient temperature of engine control systems placed very close to the engine itself range from – 55°C to 200°C. With the prospect of more electrical aircraft, power electronics will replace existing hydraulic systems. Power electronics for fuel pumps, motor controls, electric braking and landing systems will require high temperature capacitors that can withstand extensive thermal cycling over a long operating life.

### **Automotive**

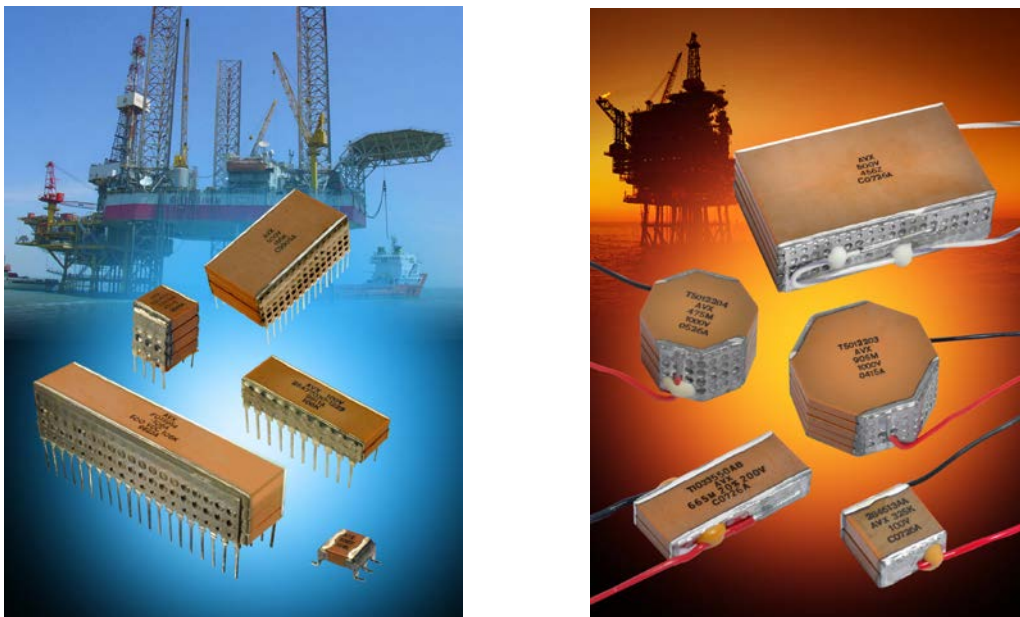
Automotive electronics is a fast and continuously growing area of the automotive industry. High temperature devices are replacing mechanical or hydraulics systems. Temperature conditions can vary, the most demanding locations being in the engine, transmission and brake systems. Engine and transmission temperatures are typically less than 200°C, but some of the wheel-mounted components can reach 250°C.

## HIGH TEMPERATURE CAPACITORS

The need for capacitors with stable electrical performance at high temperatures has increased in recent years. As described above, applications for high temperature electronics are also high reliability applications - the key requirements are maintaining optimum performance within specification and ensuring a long operating life. However, given the wide range of commercially available capacitor technologies, there are only a few that can reliably operate at elevated temperatures. In general, tantalum and ceramic capacitors are the most frequently used for applications operating at temperatures above 175°C.

### Ceramic capacitors

Most MLCC high temperature offerings are designed to operate at maximum temperatures of 150°C or 200°C. There are practical size limitations which prohibit reliable direct mounting of chip capacitors larger than 2225 to a substrate. These large chips could be subject to thermal shock, cracking and thermal cycling solder joint fatigue. In order to achieve the required capacitance stacked X7R or COG ceramics are common in high temperature applications (Fig 1). In order to limit the mismatch of thermal expansion (CTE) between the ceramics chip and the PCB, N-lead through-hole or J-lead/L-lead surface mountable configurations are commonly used.



*Fig 1: SMPS (Switched Mode Power Supply) stacked MLC high temperature capacitors, AVX SMX style rated up to 200°C; a) standard design b) custom design*

Many designs use custom parts with soft Teflon coated wires (Fig 1b). This option typically requires mechanical securing of the component, but allows flexibility of soldering with high melting point (HMP) solder without the use of a PCB. The additional benefit of such a design is the ability to solder at a safe distance from large ceramic capacitors. This effectively eliminates the need for preheat and eliminates any risk of thermal shock to the components.

**A. X7R (Class II) type** – these feature good volume efficiency and lower cost. The X7R type of dielectric is usually considered as a semi-stable. The capacitance over the temperature range from minus 55°C to +125°C is relatively flat; nevertheless the capacitance drop off at 200°C can be very significant, depending on the CV (capacitance/voltage) of the part (Fig. 2). The other important factor to consider is the drop of capacitance with applied voltage. Small capacitance loss also happens due to ageing, but this is not significant in comparison to temperature coefficient of capacitance (TCC) and voltage coefficient of capacitance (VCC).

**B. COG (Class I) type** – these have very low TCC compare to X7R. Capacitance is very stable with reference to temperature and voltage; however, capacitance values are lower in comparison to Class II X7R, so a much larger building block might be needed in order to achieve sufficient capacitance.

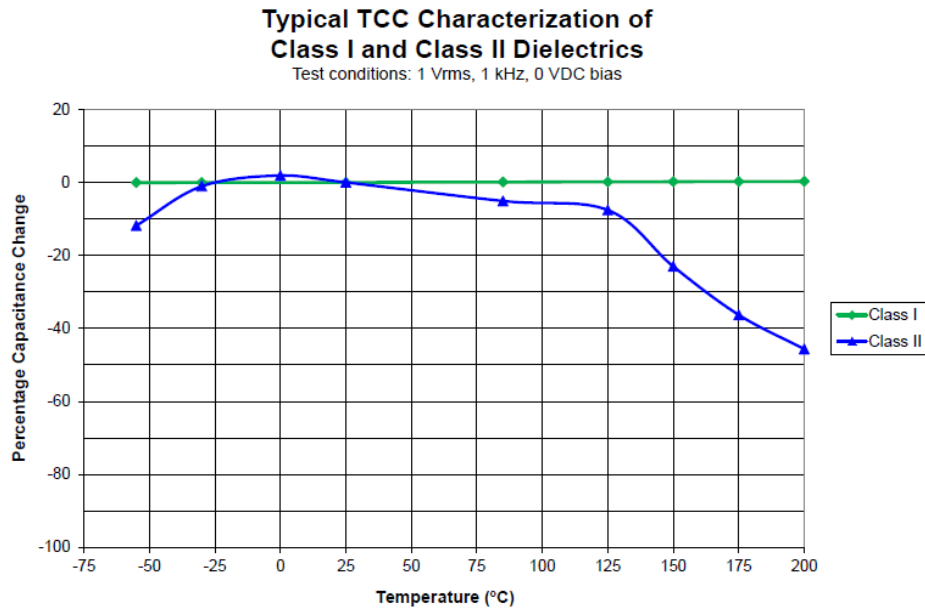


Figure 2: Typical TCC Characterization of Class I and Class II Dielectrics (1VRms, 1 kHz, 0 VDC bias)

The standard stacked MLC capacitors are generally quite large and as a result of their size, precautions must be taken before subjecting the parts to any soldering operation in order to prevent thermal shock. Preheat prior to soldering is essential. On the other hand, due to the nature of the technology and its multilayer construction, they benefit from very low ESR, high ripple and inrush current capability.

### Solid and Wet Tantalum capacitors

Tantalum capacitors have been known for their excellent reliability, robustness and stable parameters. Standard tantalum capacitor technologies have an operating temperature range of -55°C to +125°C, which covers the needs of consumer electronics and also in-cabin automotive electronics. Professional tantalum chips are currently capable of meeting the specifications of the automotive industry for high temperature capacitors up to 175°C. Advanced, high temperature tantalum capacitors can currently meet specifications up to 200°C while respecting the requirements for high reliability. Therefore this is a very suitable capacitor technology for further research and development aimed at enhancing operating temperatures above 200°C. The latest development, focused on solid tantalum capacitors in hermetically sealed ceramics package, has resulted in a new 230°C rated SMD capacitor.

**A. Moulded SMD 175°C and 200°C solid tantalum capacitors** - AVX 175°C THJ (Fig 3) suits the most demanding automotive and industrial applications. It meets AEC-Q200 requirements and enables continuous operation at temperature up to 175°C, with a basic reliability of 0.5%/1000 hours [3]. At its present stage it is widely used in many high reliability circuits, such as brake and steering control, tyre pressure monitoring systems, engine control units and engine cooling systems. Long experience with 175°C capacitor production enabled AVX to specify materials (powder, silver, moulding resin, etc.), designs and procedures that resulted in highly reliable moulded capacitors rated up to 200°C. All tantalum capacitors require voltage derating to operate at high temperature. Maximum operating voltage considering actual operating temperature is called category voltage (Fig 4).



Fig 3: Moulded SMD 175°C THJ solid tantum capacitors

Category voltage at 175°C is 0.5V<sub>r</sub> (half of the rated voltage), at 200°C is equal to 0.3V<sub>r</sub> (thirty percent of rated voltage at room temperature). Considering this rule, the 16V capacitor is suitable for 5V analog circuits at 200°C and the 10V capacitor can be used for 2.5V and 3.3V digital circuits at 200°C in systems such as drilling heads [4].

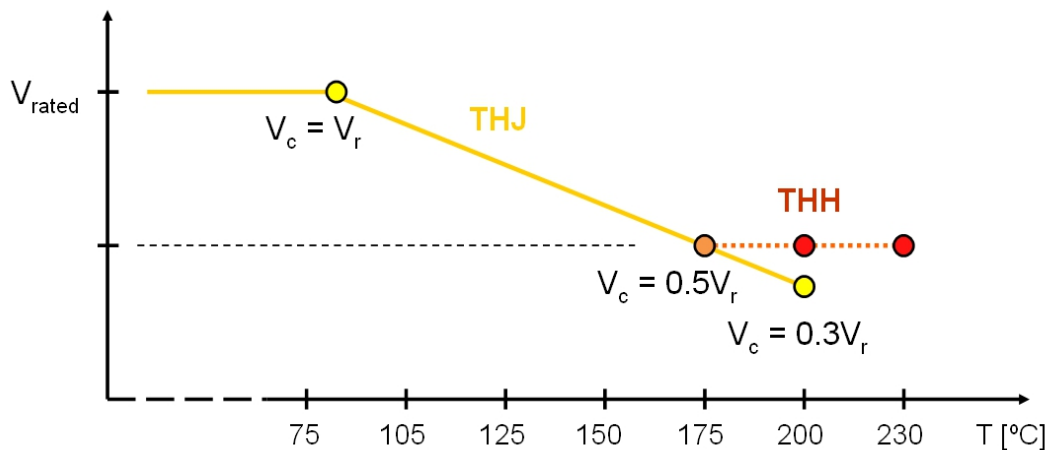


Fig 4: Category voltage of SMD tantalum capacitors vs temperature

**B. Wet tantalum 200°C capacitors** - wet electrolytic tantalum capacitors have been around for approximately 50 years [5]. High temperature wet tantalum products are primarily designed for use in down-hole drilling equipment and avionic engine control – they are ideal for input and output filtering due to high ripple current capabilities. High bulk capacitance and low ESR also provide excellent use for energy storage and discharge, with the additional benefit of lower leakage current values compared to solid tantalum technology. AVX TWC-Y and TWA-Y wet tantalum capacitors packaged in a hermetically sealed case are available in high temperature designs suitable for use up to 200°C with a category voltage of 60% the room temperature rated voltage (0.6V<sub>r</sub>).

**C. 230°C Hermetically sealed SMD tantalum capacitors** – several studies have been launched to assess the stability parameters of tantalum surface mounted capacitors at temperatures above 200°C. Nonetheless further increase of rated temperature is proving to be a real challenge, due to exceeding the glass transient temperature of epoxies and also other mechanisms related to humidity and oxygen deterioration. Higher stability can be achieved by placing the capacitor into a hermetically-sealed SMD case filled with an inert gas. A new hermetically-sealed SMD tantalum capacitor structure has been designed where the capacitor element is enclosed in a ceramic housing. Nitrogen is used inside the hermetic package as an inert gas inner atmosphere to inhibit oxidation of the solid electrolyte. To test mechanical robustness, mechanical shock of 1.500g (0.5ms, 5x, XYZ planes) and 20g vibration (10 to 2000Hz at 125°C) was used. An operating life test (2000hrs, 230°C, 0.5Vr) and moisture resistance test (64hrs, 120°C, 85%RH, Vr) were carried out to test electrical stability. The tests performed on these devices have demonstrated excellent performance in comparison to the same capacitors moulded in standard epoxy resin. A detailed description of testing and its results can be found in [6].

Based on these positive results, a THH 230°C high temperature hermetically-sealed tantalum series is being developed by AVX. Operation at 230°C combined with enhanced reliability under harsh environment could be the new solution for high temperature electronics, impossible to achieve with any other products currently on the market.



*Fig 5: Hermetically sealed SMD THH solid tantalum capacitors rated up to 230°C*

Available in two case sizes - 9 (11.8 x 12.5 x 5.8)mm and I (11.8 x 6 x 2.6)mm, the THH series offers very a high capacitance range up to 470uF and wide voltage ratings of 16 to 50V. Given the capacitance stability over the whole temperature range up to 230°C (capacitance actually increases with the temperature) and lower voltage derating, using THH capacitors can achieve significant size reduction, lower component count and reliability improvements in high temperature electronics. This series offers undertab termination for general use as well as 'J-lead' termination for applications operating under extreme mechanical conditions.

## SUMMARY AND CONCLUSIONS

Ceramic SMPS capacitors are generally used in higher voltage and higher power applications. Due to their construction, they offer ultra-low ESR and very good ripple and inrush current capability. The downside is larger capacitor blocks, sensitivity to thermal shock and mechanical damage, as well as lower capacitance values. In order to achieve the required capacitance, stacked X7R or COG ceramics are common in high temperature applications. Class II (X7R) ceramics offer the benefit of higher dielectric constant and thus higher capacitance, nevertheless there is significant capacitance loss at high temperatures. Class I types offer a very stable temperature range but much smaller capacitance values. Standard as well as customized parts are available with temperature ratings currently up to 200°C, with possible development to 260°C.

Tantalum capacitors do not exhibit capacitance drop off at high temperatures and their value is stable over the whole temperature range. Based on the fact that this technology offers excellent volumetric efficiency, higher capacitance values can be achieved in much smaller packages. The highest voltage ratings of 125V are offered by wet tantalum technology. Both wet and solid tantalum capacitors require derating due to temperature. ESR is typically much higher compared to ceramics. This may however be an advantage in circuits with a limited range of permissible ESR, such as some power supplies, in which too low series resistance can lead to circuit instability. Stacked ceramics might require additional series resistors to avoid this possibility. The latest developments in tantalum capacitor technology has proved 230°C temperature capability is possible using hermetical packaging and offers a new solution for applications where temperatures above 200°C are required.

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