High Temperature Ceramic Capacitors for Deep Well Applications

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Abstract

Temperature requirements for ceramic capacitors have increased significantly with recent advances in deep-well drilling technology. Increasing demand for oil and natural gas has driven the technology to deeper and deeper deposits resulting in extreme temperature environments up to 200°C and above. A novel capacitor solution utilizing temperature-stable base-metal electrode capacitors in a molded and leaded package addresses the growing market high temperature demands of (1) capacitance stability, (2) long service life, and (3) mechanical durability. A range of high-temperature C0G capacitors capable of meeting this 200°C and above high temperature environment has been developed. This paper will review the electrical, reliability, and mechanical performance of this new capacitor solution.

Introduction

A recent boom in the downhole oil and gas industry has resulted in a push for performance improvement in electronic component technology. This paper will discuss specifically the performance improvement trends in ceramic capacitor components. The increasing worldwide demand for oil and gas has pushed the industry to explore deeper and deeper wells resulting in increasingly higher temperatures and pressures. Traditional high-pressure/high-temperature (HPHT) wells, which have been characterized as having bottom well pressures up to 69MPa and temperatures of up to 177°C, have now been expanded to what has been characterized as "extreme high-pressure/high-temperature" (xHPHT) or "ultra HPTH," with pressures up to 138 MPa and temperatures of up to 204°C.[1] Additionally, passive cooling systems that may have been used in traditional HPHT wells may not be practical or cost-effective in xHPHT wells.[2] Developments in modern fracking and horizontal drilling have increased the shock and vibration exposure to drilling tools. The increasing depths to which the electronic instruments are submerged have also increased the importance of minimizing the losses of the components, especially at higher and higher temperatures. As more sophistication is added to the instrumentation, component size has become an increasingly important design consideration.

In recent years, high temperature (200°C-rated) surface mount base-metal electrode C0G multi-layered ceramic capacitors have been developed for extreme operating conditions. For some xHPHT environments, a leaded device is desired in order to design against severe shock and vibration environments, especially in the drilling tools and especially with larger case sizes (i.e. >0603). Temperature cycling resistance of logging tools and monitoring tools may also be improved by the strain relief features of a leaded device. This paper focuses on recent development of a range of high-temperature (200°C-rated) radial molded C0G capacitors. These devices will be characterized at high temperature and compared to existing industry standard X7R radial molded capacitors.

Capacitor Design

Figures 1 and 2 show the high-temperature C0G 062 and 052 size molded radial components. It can be seen from these figures that the larger 062 case size is similar in size to the smallest competitor X7R radial molded parts. The 052 case size, however, is significantly smaller – approximately 84% smaller by volume than the competitor X7R smallest radial molded parts. As electronic module complexity increases in drilling, logging, and monitoring tools, the size reduction of components becomes more and more important. Table 1 summarizes the dimensions of all the components tested.

The high-temperature radial molded C0G components also feature a gold-plated lead wire for temperature resistance. The molded case offers environmental protection and mechanical durability of the internal MLCC. An HMP solder is used to lead attach the gold-plated lead wires to the MLCC.

CARTS International 2013 Proceedings, March 25-28, Houston, Texas, USA

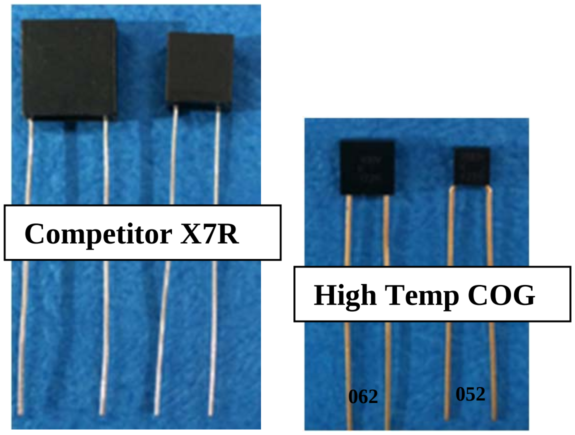

Figure 1. High-Temperature C0G Radial Molded Capacitors Compared to Competitor X7R

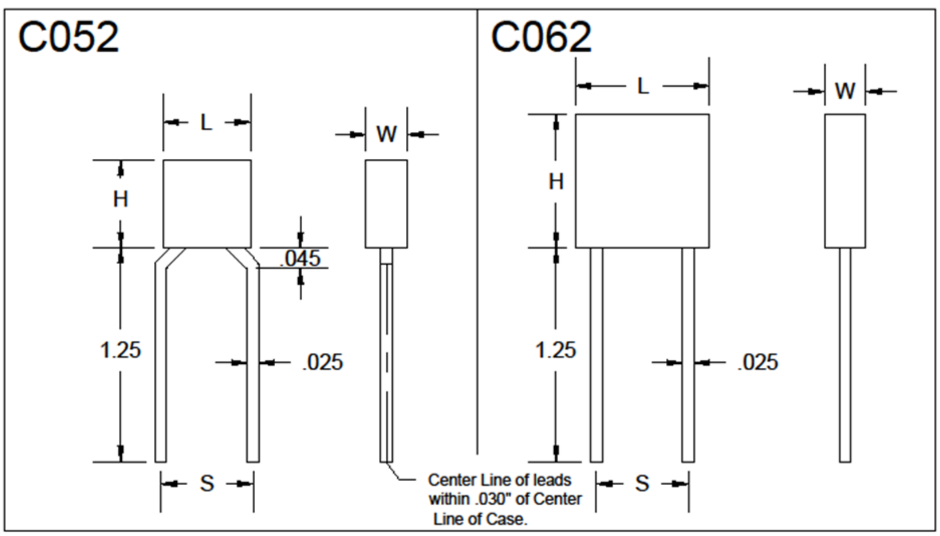

Figure 2. Schematic Layout of High-Temperature C0G Radial Molded C052 and C062 sizes.

Dimensions (mm)						
	High-Temperature C0G Radial			Competitor X7R Radial		
	062- 224-100V	062-274-50V	052-562-100V	684-100V	125-100V	185-100V
Capacitance (nF @25 C)	220	270	5.6	680	1200	1800
Length	7.4930	7.4803	5.0673	8.8646	11.4173	12.6873
Height	7.5438	7.6454	5.2578	8.8900	11.4046	12.7762
Width	2.5908	2.5273	2.4511	5.0800	5.0292	5.0419
Volume(mm3)	146.4468	144.5360	65.3043	400.3360	654.8508	817.2692

Table 1. Dimensions of Hi-Temp C0G Radial Molded Compared to Competitor X7R Radial Molded

Electrical Characterization at High Temperature

It is well-known that C0G dielectrics have much more stable capacitance over a temperature range than X7R dielectrics. However, most of the historical data has been taken in the -55°C to +125°C range or sometimes up to 150°C. The capacitance stability of high-temperature C0G surface mount capacitors has been characterized up to 200°C.[3] Figure 3 characterizes the new high-temperature C0G radial molded capacitors up to 250°C showing that the temperature stability remains intact even at these harsh temperatures. This may be critical in certain sophisticated electronic circuits in deep well monitoring and logging. Even though the starting capacitance of the C0G dielectric is much lower than comparable sized X7R dielectric capacitors, the fact that the loss in capacitance over temperature is very low (ppm level), allows the circuit designer to precisely predict the circuit performance in the deep well environment. In Figure 3, it can be seen that the percent change in capacitance for the C0G high-temperature radial molded capacitors as well is less than 1% all the way up to 250°C. The X7R radial molded capacitors show a typical X7R loss of capacitance up to 125°C (<15%). Above 125°C, however, a steep decline in capacitance can be observed. At 250°C, an approximate 58% capacitance loss was observed on the X7R parts.

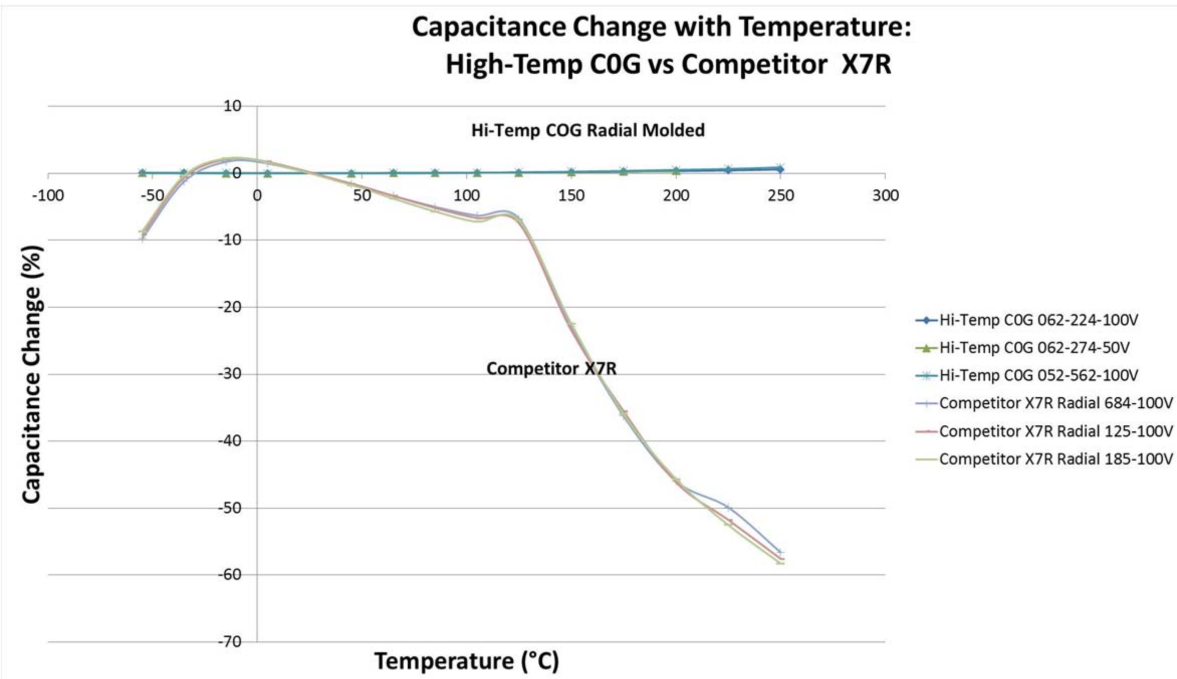

Figure 3. TCC of C0G vs. X7R Capacitors

In Figure 4, the effective capacitance at temperature and maximum rated voltage is shown. This would be the worst-case operating conditions of the capacitor. This figure shows the advantage of using a capacitance-stable COG capacitor at high temperatures. For example: it can be seen in Figure 4 that the competitor X7R-100V-684 (680 nF) capacitor at rated voltage has already degraded to 336 nF at 200°C and showed further degradation to 291 nF at 250°C. A comparable, although significantly smaller sized high-temperature C0G-100V-224 (220 nF) capacitor at 200°C and 250°C still maintained 221 nF capacitance – virtually no change from its starting capacitance at ambient.

When the size of the capacitor design is taken into account, it can be seen that the component manufacturer must design a much larger sized X7R with a much higher starting capacitance in order to overcome the high capacitance losses at extreme temperatures. This is evident in Figure 5 where it can be observed that the competitor X7R 100V-185 (1.8 µF) at maximum rated voltage degrades to 0.789 nF/mm^3 at 250°C, whereas the high-temperature C0G 100V-224 (220 nF) with a much lower starting capacitance (8 times less) and a much smaller volume (5 times smaller by volume) closely matched the volumetric efficiency of the much larger X7R capacitor with 0.82 nF/ mm^3 at 250°C. In fact, the lower voltage, 50V-274 high-temperature C0G radial molded capacitor, when normalized for volume, matched the capacitance of the competitor X7R 100V-185 (1.86 nF/ mm^3 for the C0G) and maintained virtually the same capacitance over the entire temperature range up to 250°C.

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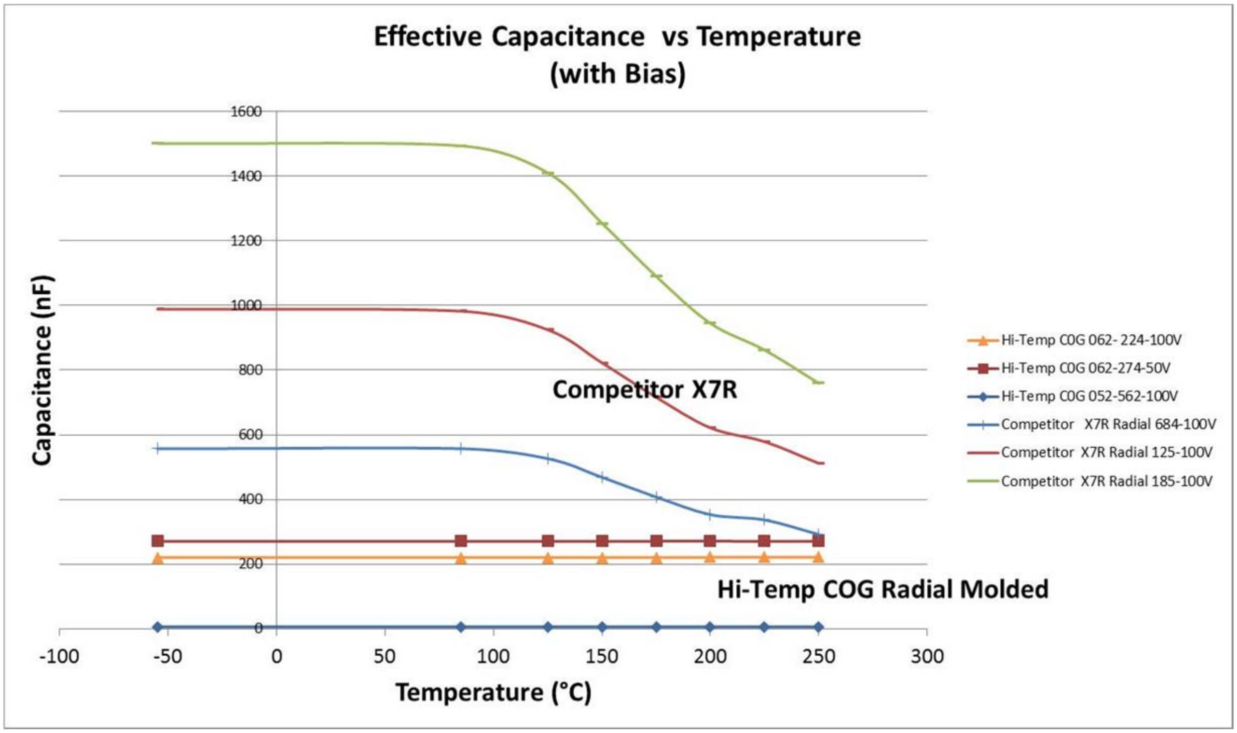

Figure 4. Capacitance at Maximum Rated Voltage vs. Temperature

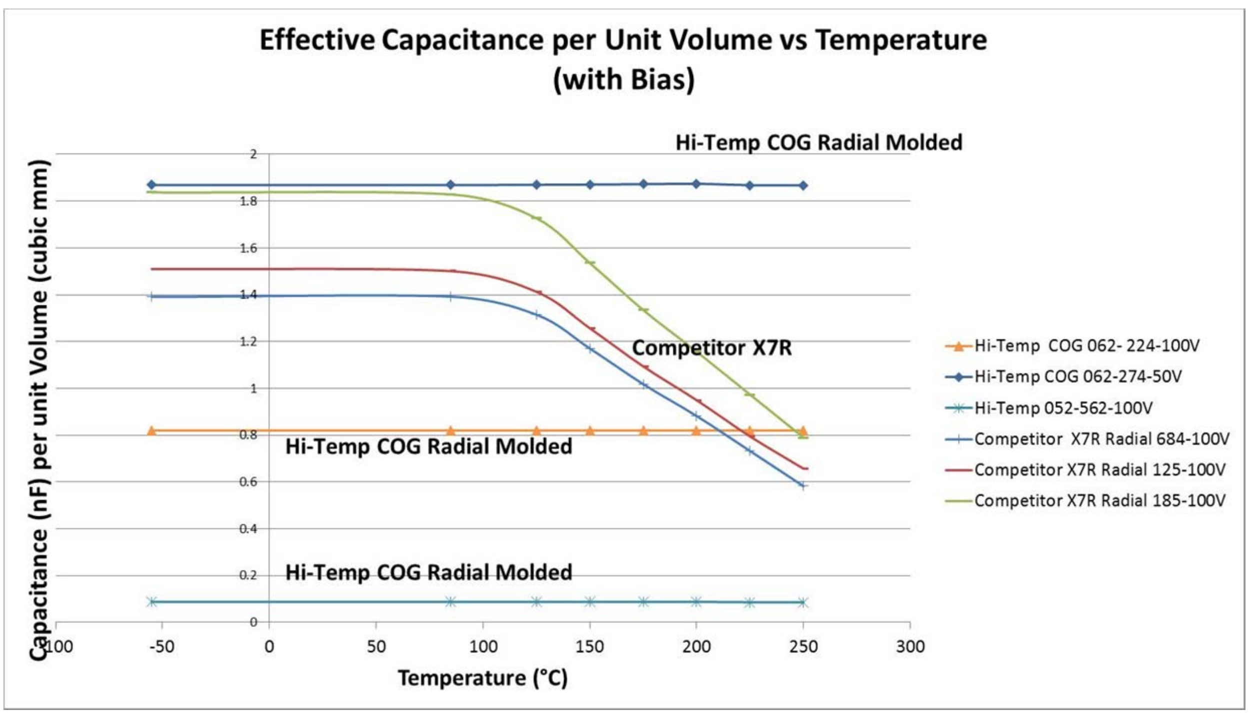

Figure 5. Capacitance at Maximum Rated Voltage per Unit Volume

High Temperature Insulation Resistance

In addition to the capacitance stability with temperature, one of the major advantages of the C0G high-temperature dielectric capacitors is the high insulation resistance. It can be observed in Figure 6, for example, that the high temperature C0G radial molded 274-50V capacitor has 18 times the starting insulation resistance than the competitor X7R radial molded 185-100V capacitor. And while the 185-100V X7R degrades to approximately 210 kilo-Ohms at 200°C, the 274-50V COG maintains almost a 3 Giga-Ohm IR at 200°C, more than three orders of magnitude higher than the competitor X7R. This can be significant in the reliability performance of these high temperature capacitors.

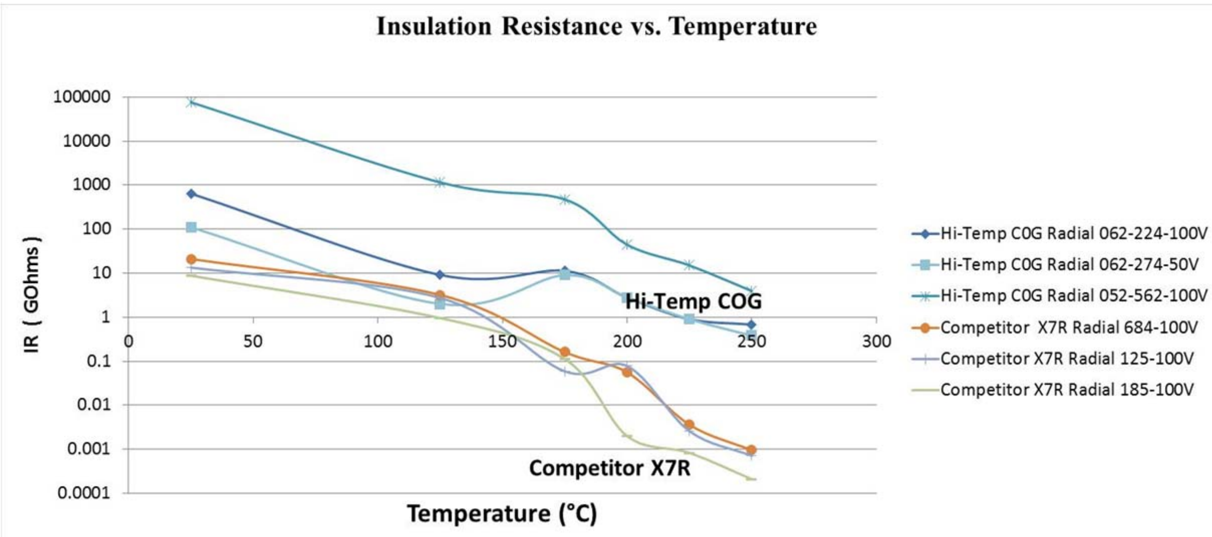

Figure 6. Insulation Resistance vs. Temperature

Mean Time-to-Failure Predictions

An important consideration in electronic circuit design for deep-well application is the long-term reliability of the components. The expense of operating a deep-well is on the order of millions of dollars per day. Therefore, any downtime to replace defective circuits due to component failure is significant financially. To characterize the predicted life of the COG high-temperature radial molded capacitors, an 052-size 100 nF-50V capacitor was tested using Highly Accelerated Life Testing (HALT) to determine the mean time to failure (MTTF) at different voltages (400V, 500V, 600V). All of the testing was performed at a fixed opertating temperature of 200°C. Using the Prokopowicz and Vaskas (P-V) equation below, and simplifying to one fixed temperature function, the values of A, n, and E_a werer determined for each voltage allowing the MTTF prediction.

$$t = A \frac{1}{V^n} \exp\left(\frac{E_a}{kT}\right)$$

A = time constant (min)

t	mean time to failure
V	voltage under condition
n	voltage stress exponential
E_a	activation energy for dielectric wear out
k	Boltzmann's constant (8.62 E^{-5} eV/K)
T	absolute Temperature in Kelvin

By taking the natural log of the equation, it can be rewritten in a more useful form for our modeling:

$$\ln(t) = \ln(A) - n\ln(V) + Ea/kT$$

Figure 7 shows the HALT test results for the three different voltage conditions. Using this data and the P-V equation, values for A and n were calculated as shown in Table 2, and the MTTF was predicted to be 8.64 x 10^7 years.

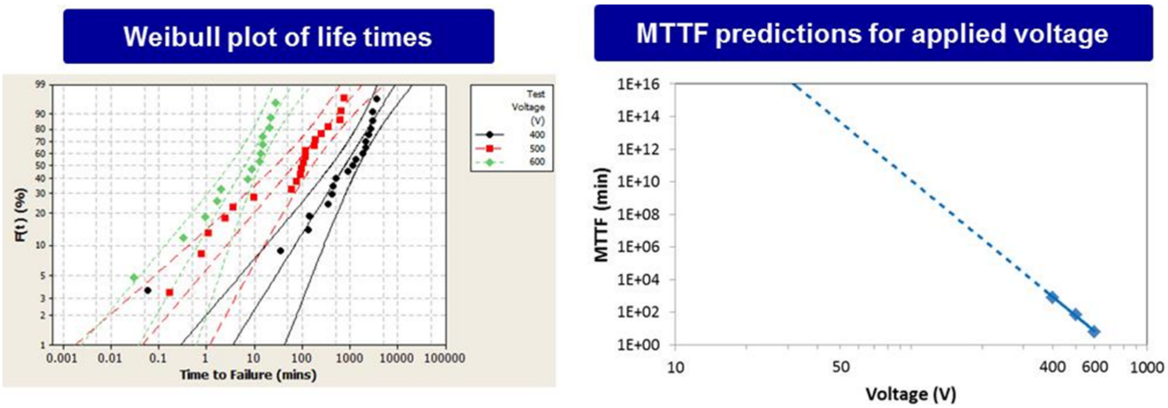

Figure 7. HALT Test results.

Part number	Dielectric	A (mins)	n	MTTF (Yrs.) 200°C, 50V
C052 100nF	C0G	7.50E+33	11.9	8.64E+07

Table 2. MTTF Calculations

200°C Life Testing and other Long-Term Reliability Testing

To further confirm the long-term reliability of the high-temperature COG radial molded capacitors, five part numbers (062-124-50V, 062-124-100V, 062-102-200V, 052-562-100V, 052-332-200V) were selected for 1000 hours of 200°C Life Testing at rated voltage. 82 piece sample sizes were tested. Insulation resistance was measured at 0, 250, 500, and 1000 hour intervals. Figure 8 shows a typical IR distribution plot of the life test. It can be seen that there were no IR failures over the 1000 hours testing at 200°C, and also no degradation in IR.

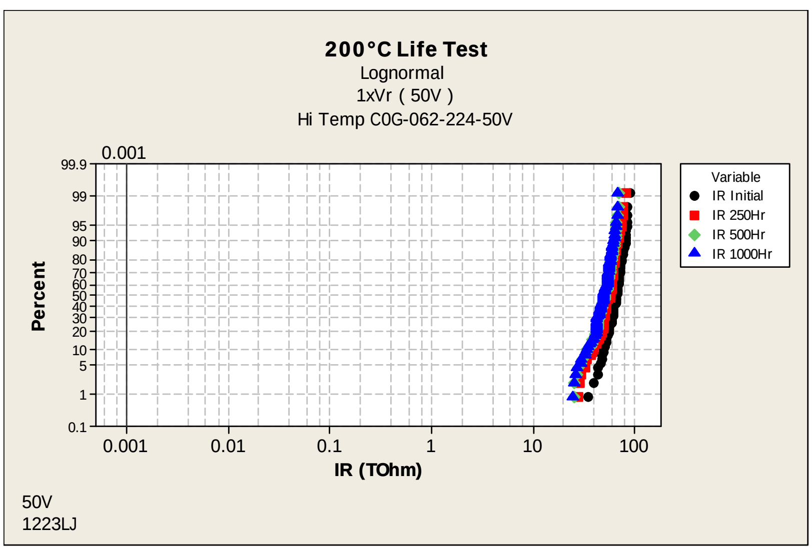

Figure 8. Typical 200°C Life Test IR Distribution

Additionally, as observed in Table 3, excellent performance was observed in other long-term testing including 85°C/85% humidity (1xVr), 200°C storage life (0V), low voltage humidity (1.5V), thermal shock -55°C +220°C, shock and vibration.

Part Type	High Temperature Storage (1000 hours@ 200°C)	Biased Humidity (1000 hours: 85°C/85% RH @ 1xVr)	Low Voltage Humidity (1000 hours: 85°C/85% RH @ 1.5V)	Thermal Shock (50 cycles: -55°C +220°C @ 0 Volts)	Vibration	RTSH	Solderability	Resistance to Solvents	Immersion
	MIL-STD-202 Method 108	MIL-STD-202 Method 103	MIL-STD-202 Method 103	JESD22 Method JA-104; (-55°C to 220°C), 50 cycles. 8 minutes maximum transition time	MIL-STD-202 Method 204	MIL-STD-202 Method 210; condition B	J-STD-002; AECQ-200: Method A @ 235°C, category 3	MIL-STD-202 Method 213	MIL-STD-202 Method 104; MIL-PRF-39014: Test condition B
High-Temp-C0G-562-100V	0/87	0/87	0/87	0/87	0/40	0/30	0/15	0/5	0/28
High-Temp-C0G-332-200V	0/87	0/87	0/87	0/87	0/40	0/30	0/15	0/5	0/28
High-Temp-COG-062-102-200v	0/87	0/87	0/87	0/87	0/40	0/30	0/15	0/5	0/28
High-Temp-COG-062-124-100V	0/87	0/87	0/87	0/87	0/40	0/30	0/15	0/5	0/28
High-Temp-COG-224-50V	0/87	0/87	0/87	0/87	0/40	0/30	0/15	0/5	0/28

Table 3. Other Long-Term Reliability Testing and Functional Testing

Modulus of Rupture and Drop Shock Testing

One important attribute of components for deep-well applications is the ability to withstand impacts with high G-forces. As a design consideration for deep-well applications as well as horizontal drilling applications, shock and vibration resitance is of increasing importance as the drilling conditions become more severe. It has been shown that for surface mount capacitors that reducing the case size (i.e. to 0603 and smaller) improves the resistance to drop/shock forces on the MLCC.[4] The new high-temperature C0G radial molded capacitor improves the shock resistance by using a higher break-strength dielectric[5] along with compliant lead wires in a temperature-resistant durable molded case.

To test the durability of the components, a test board was designed as shown in Figure 9 below. A single-side polyimide circuit board, 7.93 in. x 0.92 in. x 0.06 in., was designed to test 20 pieces per board of both radial-molded and surface mount capacitors for comparison on the same board. The surface mount capacitors were mounted directly onto the board pads, and the radial molded parts were through-hole soldered with a 0.02 inch stand-off using HMP solder 93.5%Pb-5%Sn-1.5%Ag. C0G dielectric was compared to X7R dielectric in addition to radial-molded vs surface mount.

Drop/shock testing was performed by screwing the test boards into a suport jig which was clamped to the drop tester platen. A drop was performed creating 500 G-force for 2 m-s duration for a total of 120 drops. The samples were tested in the X,Y, and Z directions. Table 4 shows that 4/40 crack failures were observed on the surface mount X7R compared to 0/40 on the surface mount C0G (higher MOR). Figure 10 shows an example of the cracked capacitor. However, when strain-releiving leads were soldered to the components, even the X7R survived 120 drops of 500G's force. The modulus of rupture (MOR) of the high-temperature C0G dielectric is more than twice that of the industry benchmark X7R.[5] This, along with the compliant lead wires provide improved shock-resistance of the molded radial C0G capacitor.

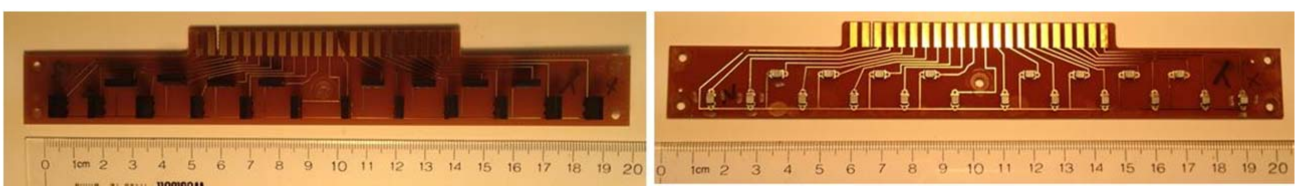

Figure 9. Drop/Shock Test Board Design

	C0G		X7R
Case size	C052	C062	C062
Radial molded	0/40	0/40	0/40
Surface mount	0/40	0/40	4/40

Table 4. Drop/Shock Test Results

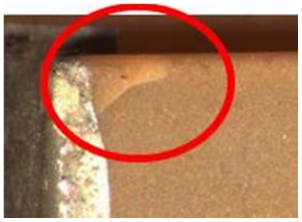

Figure 10. Drop/Shock Test Crack Failure on Surface Mount X7R

Attaching leads to the capacitor improves the mechanical durability by providing strain-relief. However, care must be taken to ensure that the solder joint is capable of withstanding high service temperatures. To test the high-temperature adhesion of the C0G radial-molded capacitors, a high temperature adhesion test was designed where the pull test on an Instron Force Tester was performed with a 200°C stream of hot forced air blowing on the sample. Figure 11 shows the pull strength of the high-temperature C0G radial molded parts tested at 200°C to be well in excess of the room temperature specification limit (1.8 kg).

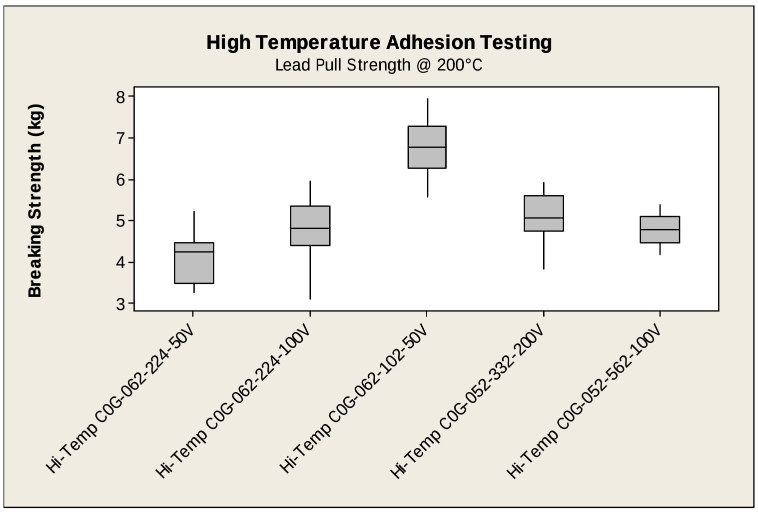

Figure11. 200°C Lead Adhesion

Summary and Conclusions

The C0G high-temperature radial-molded capacitor solution provided improved performance over traditional X7R capacitors by providing a predictable, stable capacitance over the -55°C to +250°C temperature range. The C0G has higher insulation resistance even at elevated temperatures (>200°C). Although the C0G capacitor size is smaller than the X7R alternatives, the available capacitance per unit volume at temperatures > 200°C and rated voltage is comparable to that currently available. Highly Accelerated Life Tests (HALT) as well as 200°C life testing proved the C0G capacitors have good reliability for long-term service. The higher MOR of the C0G MLCC along with the attached lead wires and molded case provide an extra level of mechanical durability for harsh drilling, logging, and monitoring conditions found in xHPHT wells.

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