Ceramic Capacitors with Base Metal Electrodes for Power Electronics Applications

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Outline

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  - Power Converter Capacitors
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- Base Metal Ceramic Capacitor Development
  - Ni BME C0G MLCC
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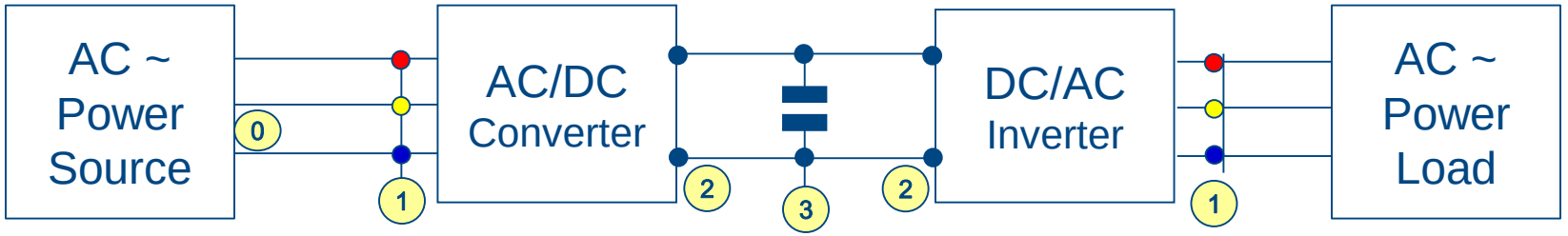
    - **High Voltage and High Temperature Extensions**
    - **DC-Link Opportunities**
  - U2J BME MLCC Development
    - **Key Characteristics**
    - **Ripple Current Comparisons**
- Summary

Power Electronics Trends

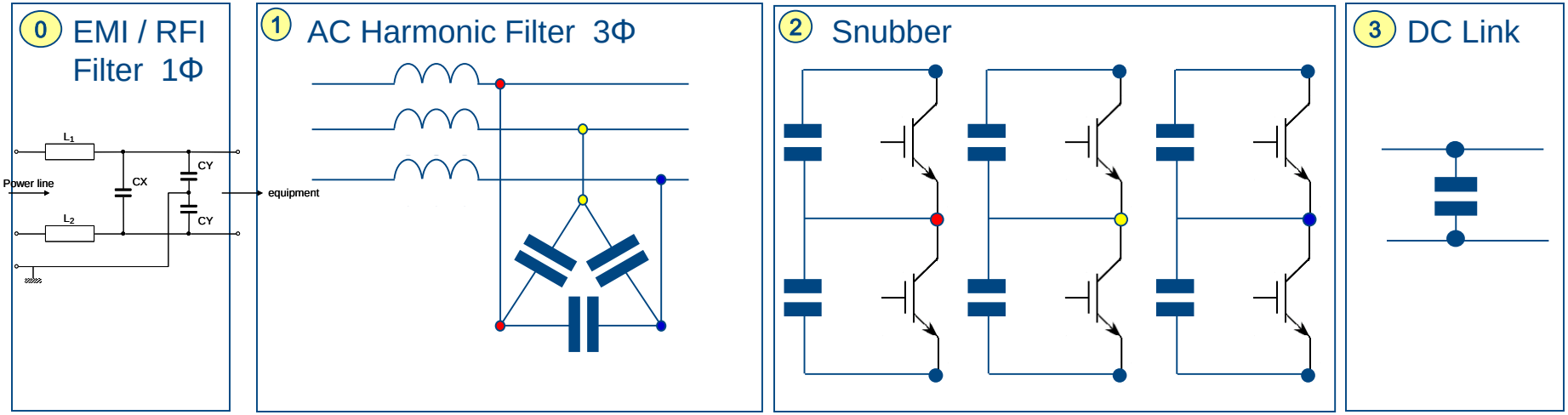
- Improved power conversion efficiency is driving the development of new systems and components
- The adoption of Wide Band Gap (WBG) Semiconductors (SiC & GaN) for more efficient power conversion is challenging traditional Si-technology
- These trends are changing the requirements for capacitors used in Power Electronics:
  - Higher switching frequencies → Need Low Loss MLCC with high ripple current capability
  - High operating voltages → GaN (to 650V), SiC (to >1700V)
  - Higher temperatures → 125°C, 150°C, > 200°C for SiC

Power Converter Capacitors

System Overview:



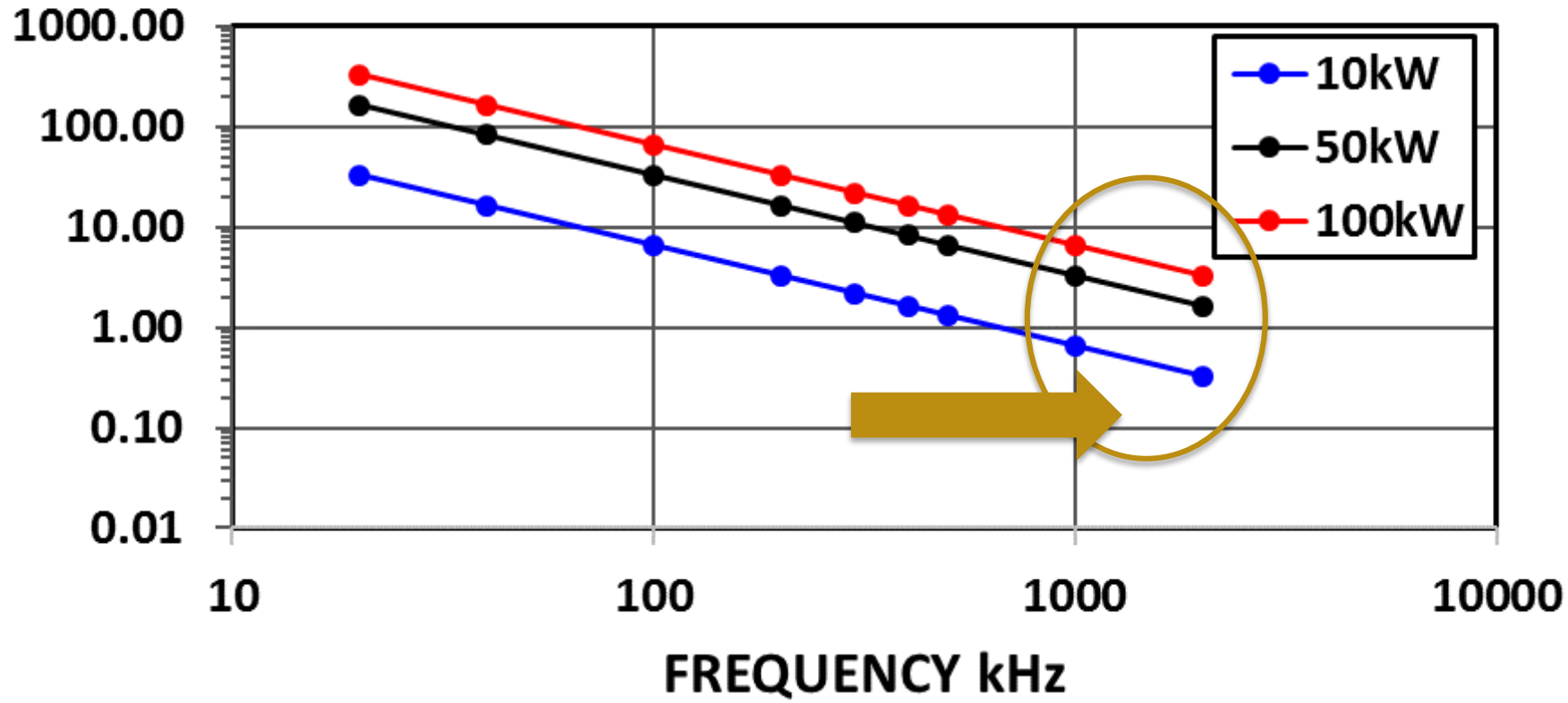
Typical Capacitor Types:



Capacitance Vs. Switching Frequency

Example: DC Link for 400V with 10% Ripple

$$C = \frac{P_{load}}{U_{ripple} * \left(U_{max} - \frac{U_{ripple}}{2}\right) * f_{rectifier}} \quad *$$

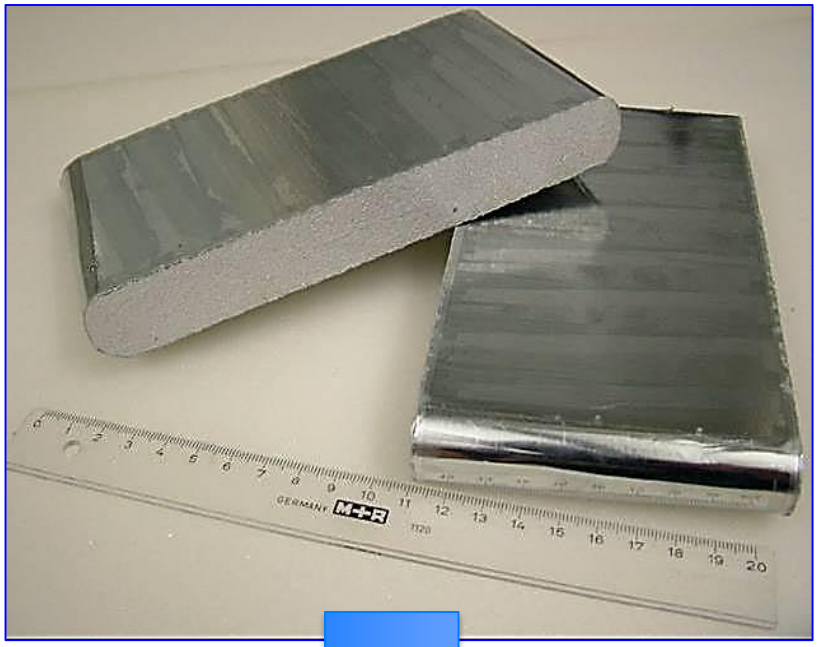


**** Source: Prof. R. Kennel, Technical University Munich, Germany***

Capacitance Vs. Switching Frequency

Polypropylene Film to MLCC

- For DC-Link Capacitors:
  - Lower capacitance requirement promotes miniaturization due to:
    - Increasing switching frequency
    - Higher voltages
- Lower capacitance needed are within the range of MLCC
  - But these MLCC (**Multi-Layer Ceramic Capacitors**) must be:
    - Extremely reliable
    - Over-Temperature and Over-Voltage Capable
    - High current capable
    - Mechanically Robust

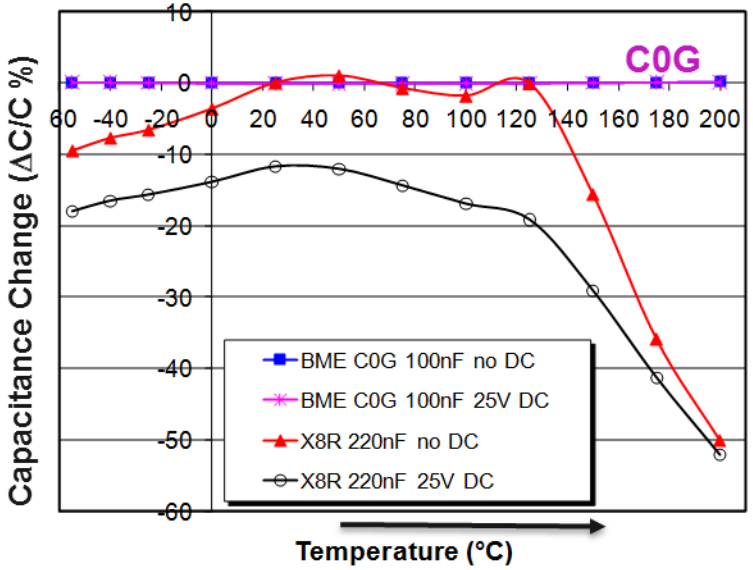


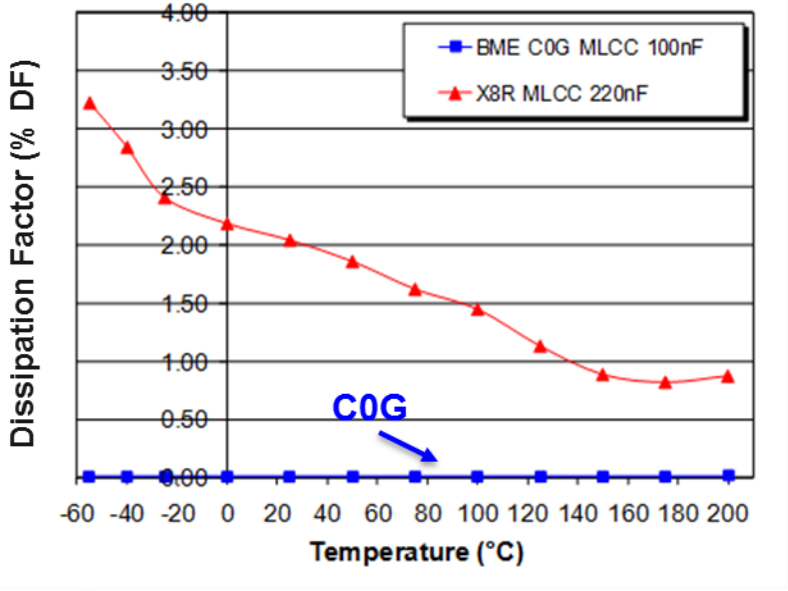
Base Metal Electrode (BME) Ceramic Capacitors

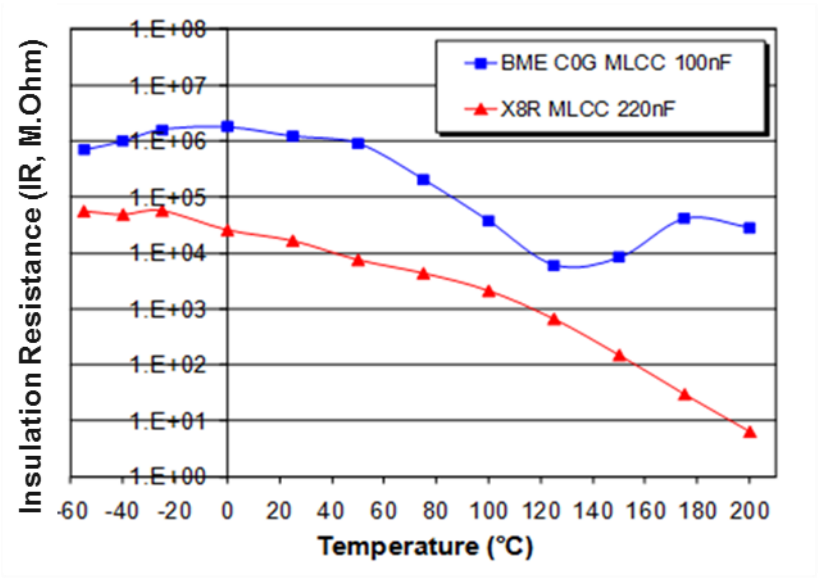
- Multi-Layer Ceramic Capacitors (MLCC) with base metal nickel inner electrodes were commercialized in the 90's to replace more expensive palladium based inner electrodes
- KEMET launched **BME MLCC** using Ni Electrodes in 1990's and a **Class-I** Para-electric calcium zirconate based **C0G** dielectric in 2005
- A new range of 200°C C0G NP0 rated ≤ 200V was added in 2010
  - Much higher capacitance values than PME C0G equivalents
  - No change with temperature or voltage bias (flat TCC and VCC to 200°C)
  - Available capacitance at 200°C equivalent to many Class-II MLCC with lower DF, higher IR and much higher voltage breakdown
  - Testing at 260°C and 300°C continues and is showing robust reliability
- The key characteristics of these C0G MLCC are compared to a competitor X8R (150°C rated) on the following slide

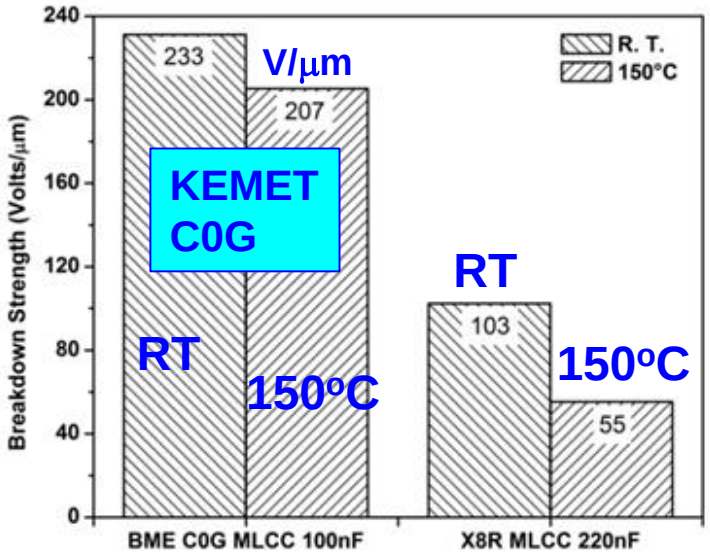
Ni BME C0G MLCC Vs Competitor X8R

1206 Case Size Comparison









High Voltage Ni BME C0G MLCC Extensions

Typical Properties

- In 2013 a catalog range was launched rated for voltages 500-2000V and 200ºC in case sizes 0805 to 2225
- Larger case sizes extensions 2824 to 4540 were added in 2016

Properties & Reliability Tests

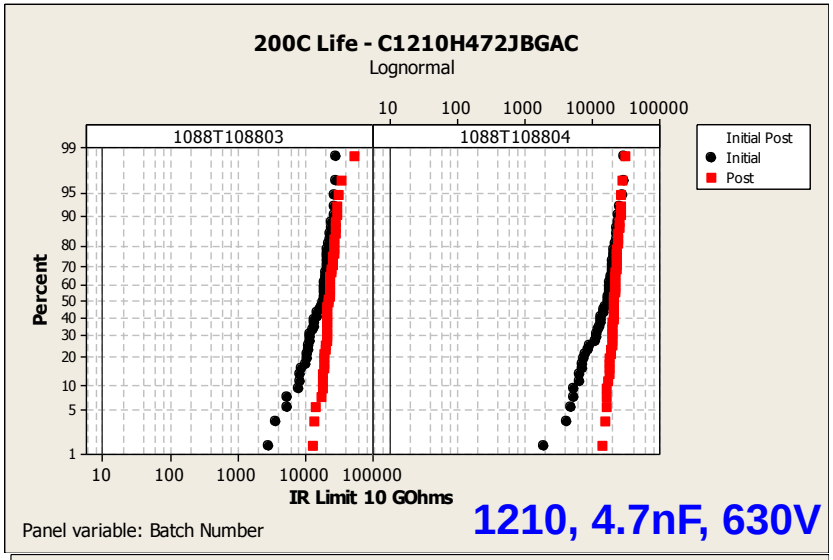
KEMET Part Number	Voltage Rating Vr	Average Capacitance (nF)	Average DF (%)	IR (GΩ)		TCC (PPM/°C)		Mean Voltage Breakdown in Air	Life Test 1000hr @ Vr 200°C	Thermal Cycling (-55 to +200°C)	Board Flex to 5mm	Mechanical Shock & Vibration
				25°C	125°C	-55°C	125°C					
C1206H332JCGAC	500	3.29	0.020	37,900	23	-10.56	10.65	1825	0/100	0/100	NA	0/30
C1210H472JBGAC	630	4.81	0.018	25,000	47	-10.96	10.17	2000	0/100	0/100	NA	0/30
C1808H292JDGAC	1000	4.75	0.021	21,500	60	-12.05	10.01	2931	0/100	0/100	NA	0/30
C1813H332JFGAC	1500	2.70	0.020	75,800	183	-10.63	11.05	3519	0/100	0/100	NA	0/30
C2220H332JGGAC	2000	3.31	0.020	56,300	35	-11.77	9.42	4116	0/100	0/100	NA	0/30
C2824H333KBGAC	630	34.30	0.010	13,430	30	-7.35	19.14	1783	0/100	0/231	0/30	0/90
C3040H393KDGAC	1000	39.03	0.010	8,982	18	-6.34	23.57	2678	0/150	0/231	0/30	0/90
C3640H153KGGAC	2000	15.36	0.009	6,509	10	-5.15	14.08	3919	0/100	0/231	0/30	0/90
C4540H273KFGAC	1500	27.95	0.010	2,125	6	-6.31	19.07	3608	0/150	0/231	0/30	0/90

Pb-Free RoHS

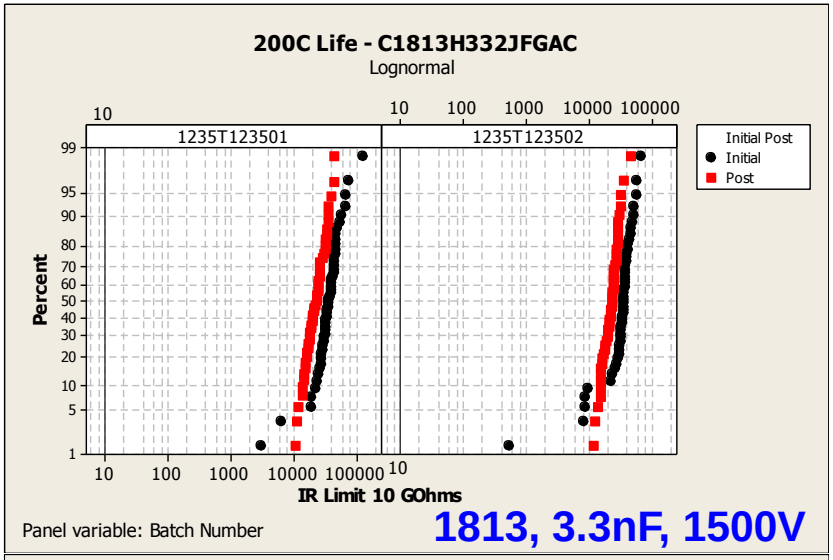
High Voltage Ni BME C0G MLCC Extensions

Life Testing @ 200°C for 1000hrs at Rated Voltage

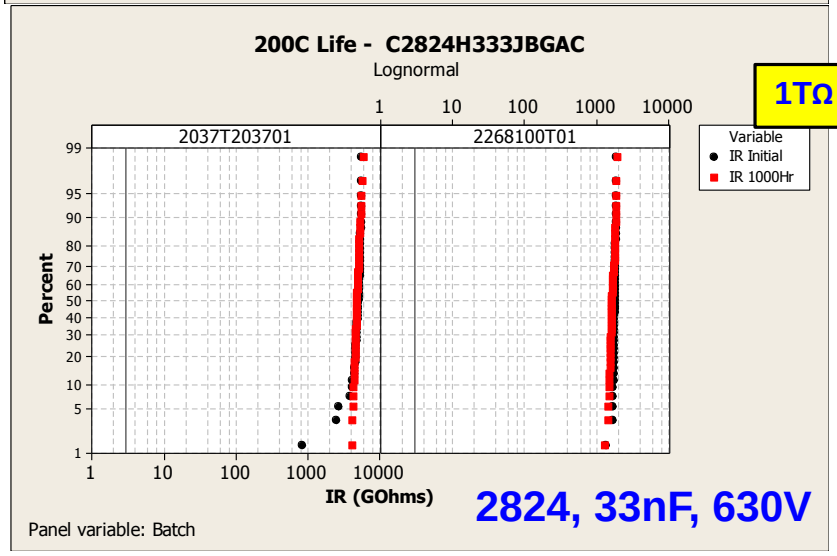
No IR degradation after 1000hr Life Test at 1xRV at 200°C



1210, 4.7nF, 630V

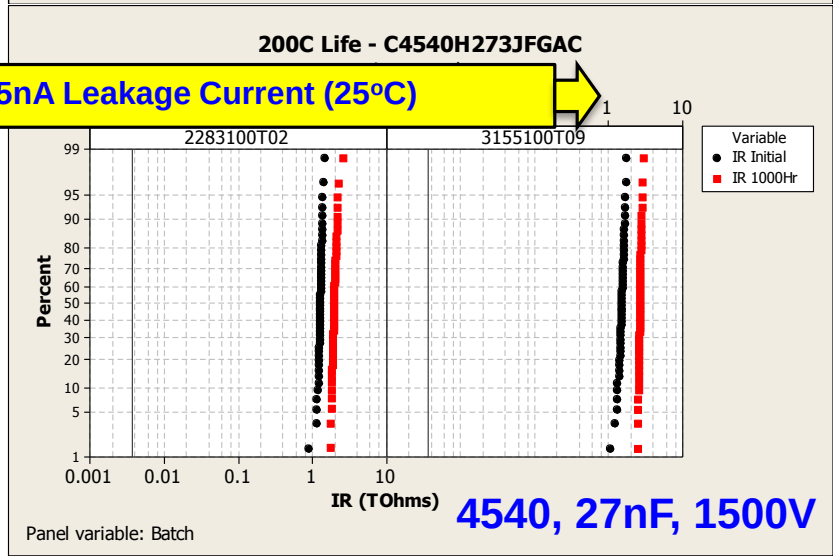


1813, 3.3nF, 1500V



2824, 33nF, 630V

1TΩ = 1.5nA Leakage Current (25°C)

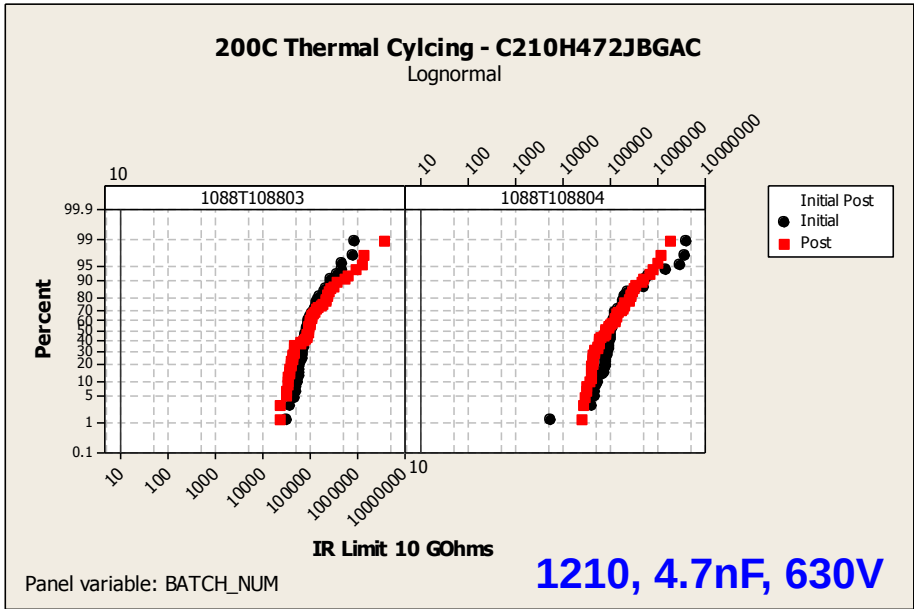


4540, 27nF, 1500V

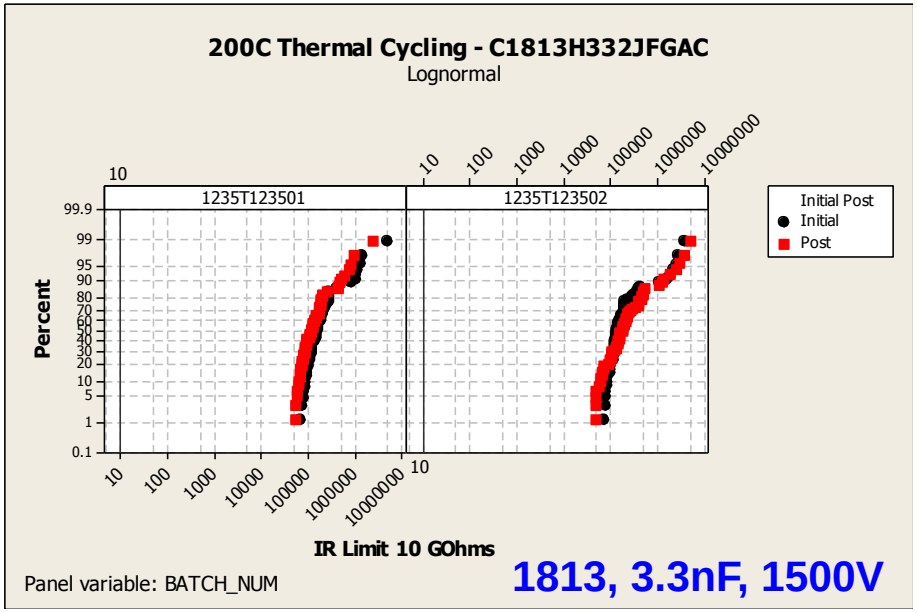
High Voltage Ni BME C0G MLCC Extensions

Thermal Cycling -55°C to 200°C

No IR degradation after 50 thermal cycles (-55°C to 200°C)



1210, 4.7nF, 630V



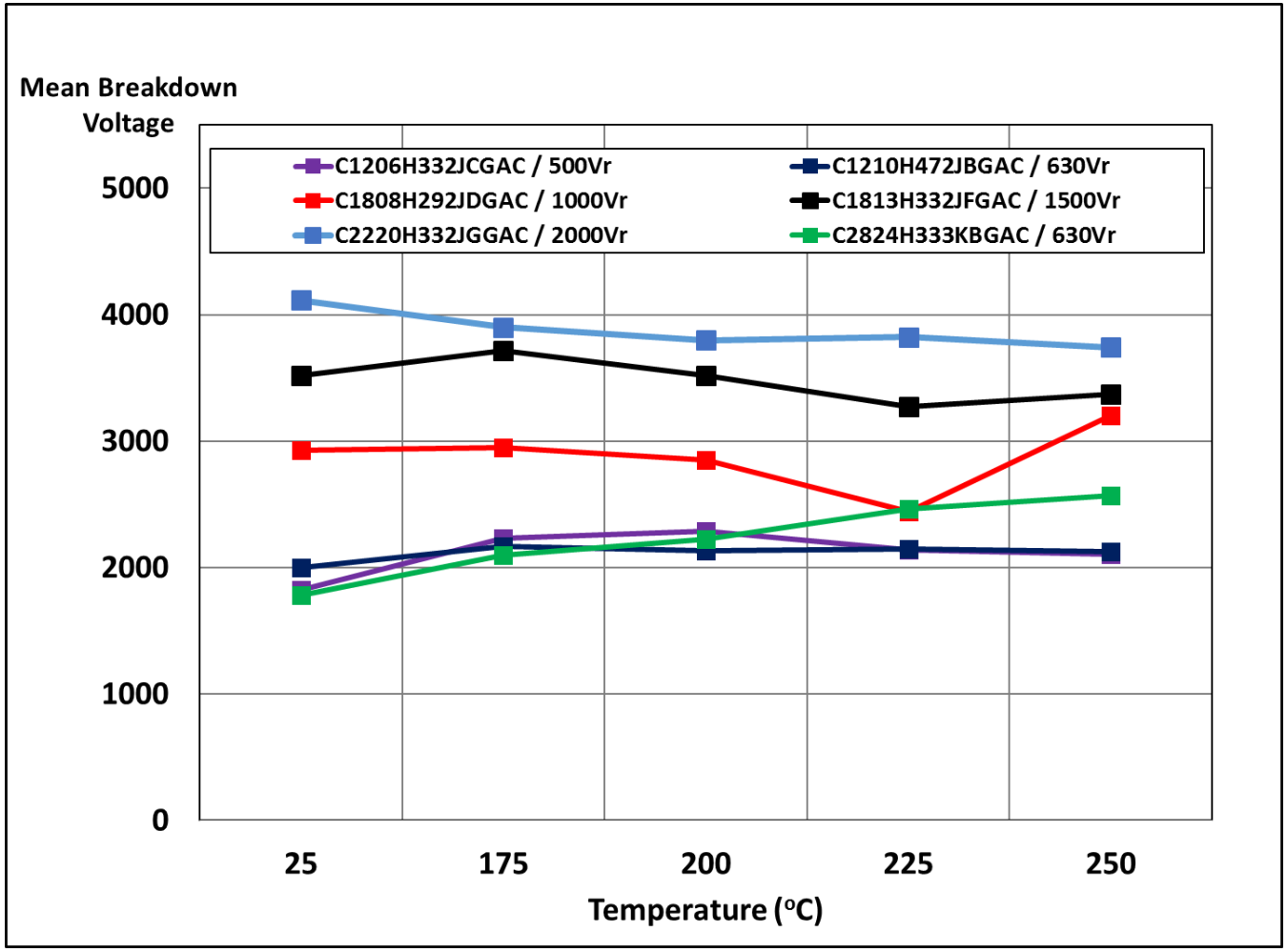
1813, 3.3nF, 1500V

3°C/min with 1hr Soak

High Voltage Ni BME C0G MLCC Extensions

Voltage Breakdown Vs. Temperature

Voltage Breakdown remains high even at 250°C



High Voltage Ni BME C0G MLCC Examples

Ripple Current Capability Comparisons

Case Size 2824, 33nF, 630Vr C0G @ 500kHz

- The temperature rise of the C2824H333KBGAC parts were measured at different Vrms

Voltage (Vrms)	57.7	93.9
Current (Arms)	**6.1**	**10.0**
Part Temperature (°C)	33.5	50.4
Ambient Temperature (°C)	24.2	24.2
Temperature Rise (°C)	**9.3**	**26.2**

- **Temperature rise < ~30°C is considered in a safe region so these parts have ≥ 10Arms capability @ 500kHz**

Case Size 2220, 100nF, X7R Vs. C0G @ 150kHz

- The temperature rise of new 630Vr C0G were compared to 1000Vr X7R

Part Type	X7R	C0G
Voltage (Vrms)	20.0	131
Current (Arms)	**1.95**	**10.0**
Part Temperature (°C)	64.0	55.8
Ambient Temperature (°C)	26.0	25.5
Temperature Rise (°C)	**38.0**	**30.3**

- **New C0G cap has 5X higher ripple current capability than the standard X7R @ 150kHz**

High Voltage Ni BME C0G MLCC Extensions

Performance Summary

High Voltage Ni BME C0G MLCC are an excellent choice in power applications because of their:

- Reliable performance even at high temperatures (200°C)
- Stable capacitance with temperature and voltage
- High voltage ratings (no derating required!)
- **Very low dissipation factors**
- **High IR (low leakage) & high breakdown voltages**
- **High ripple current capability**

However DC-Link applications need higher capacitance values, so work is underway to extend the cap offerings

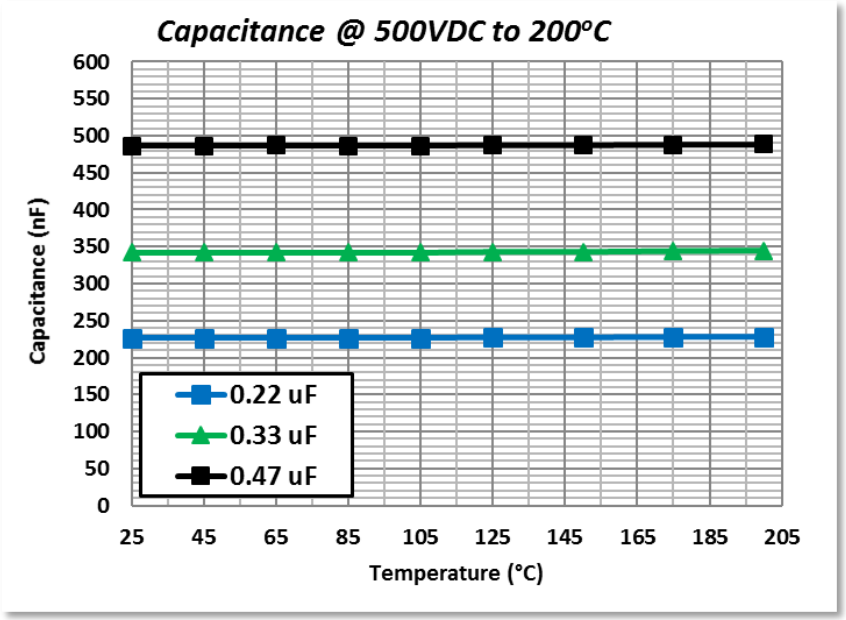
DC-Link Extensions

Ni BME C0G 3640 Case Size

Case Size 3640
L x W x TH
0.36” x 0.40” x 0.10”
9.1mm x 10.2mm x 2.5mm
Volume = 0.23cm^3

	Ni BME C0G 3640 Prototypes		
Capacitance (nF)	**0.22 µF**	**0.33 µF**	**0.47 µF**
DF (%)	0.0080	0.0117	0.0110
IR @ 25°C (GΩ)	458	277	242
IR @ 125°C (GΩ)	7.42	6.47	6.24

- Ni BME C0G 3640 have:
  - Low DF
  - High IR
  - Stable Capacitance at high temperatures & voltages



Ref. J. Bultitude et al; Proc. Intl. Symposium on 3D Power Electronics, NC State, June 13-15, 2016

DC-Link Extensions

3640 0.22µF 500V 150ºC Ripple Current

- Lower DF & ESR reduce the power dissipated

$$P = \frac{i^2 d}{2\pi f C} = i^2 R$$

P = power dissipated

i = current

d = dissipation factor

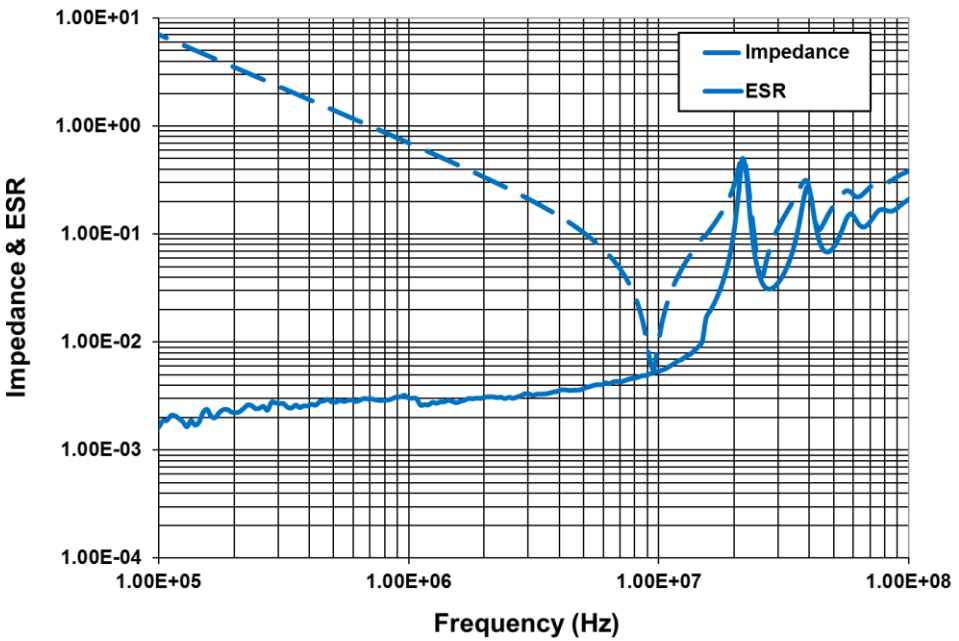
f = frequency

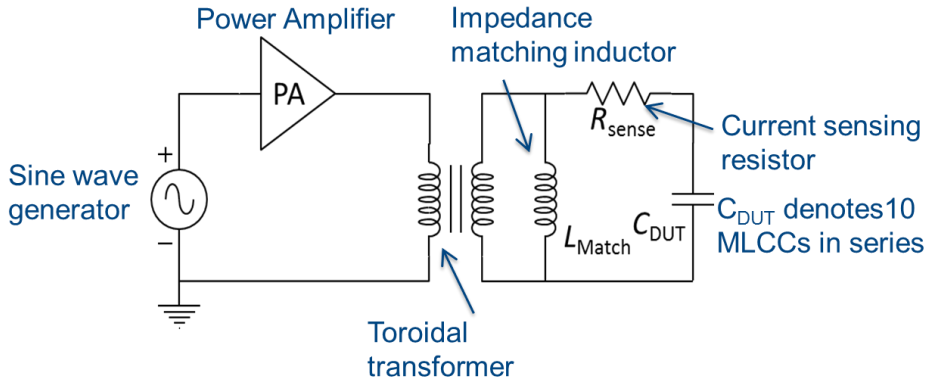
C = capacitance

R = resistance, ESR

- No failures after 1000hrs testing @ 150ºC 15A_{RMS} 100kHz

≈ 75 A_{RMS}/µF or ≈ 65 A_{RMS}/cm^3





Ref. J. Bultitude et al; Proc. Intl. Symposium on 3D Power Electronics, NC State, June 13-15, 2016

U2J MLCC Development

- Although the BME C0G capacitors perform well in power electronics applications, the need for higher capacitance values in smaller sizes continues
- KEMET has recently commercialized U2J MLCC that extends the Class-I capacitance range up to 50V ratings making them suitable for 48V DC-DC power supply applications
  - Temp Range -55°C to +125°C, Pb-Free, RoHS and REACH compliant
  - Low dissipation factor DF < 0.1%
  - Low ESR & ESL
  - No piezoelectric noise similar to C0G
  - High thermal stability, Pb-free soldering compatible
  - High ripple current capability
  - Small, predictable and linear capacitance change vs temperature
  - Non-polar device, minimizing installation concerns

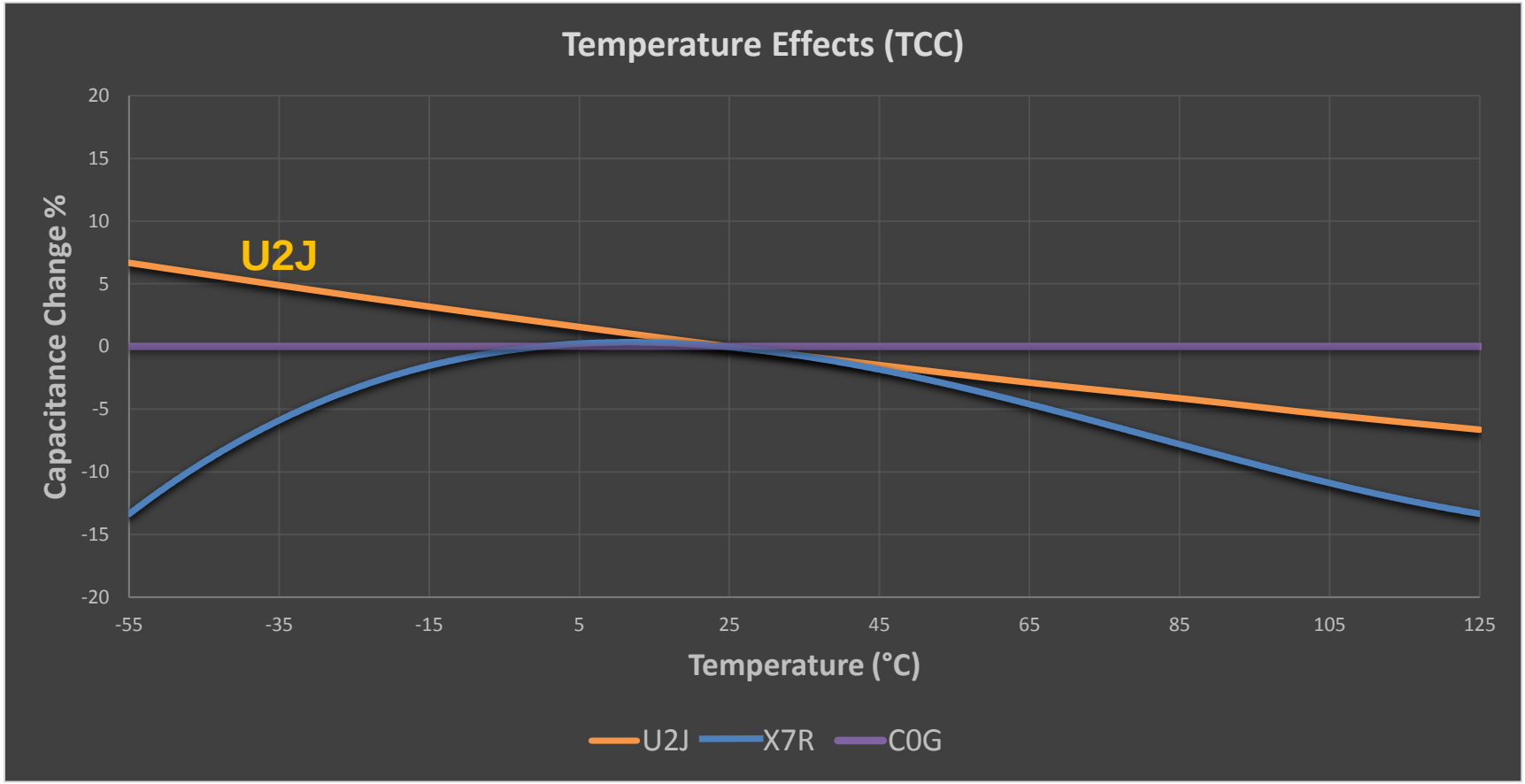
Dielectric Classification (Temperature Performance) Class I (Per EIA – 198)

Class-I Dielectrics (Examples C0G: 0±30ppm/°C vs. U2J: -750±120ppm/°C)

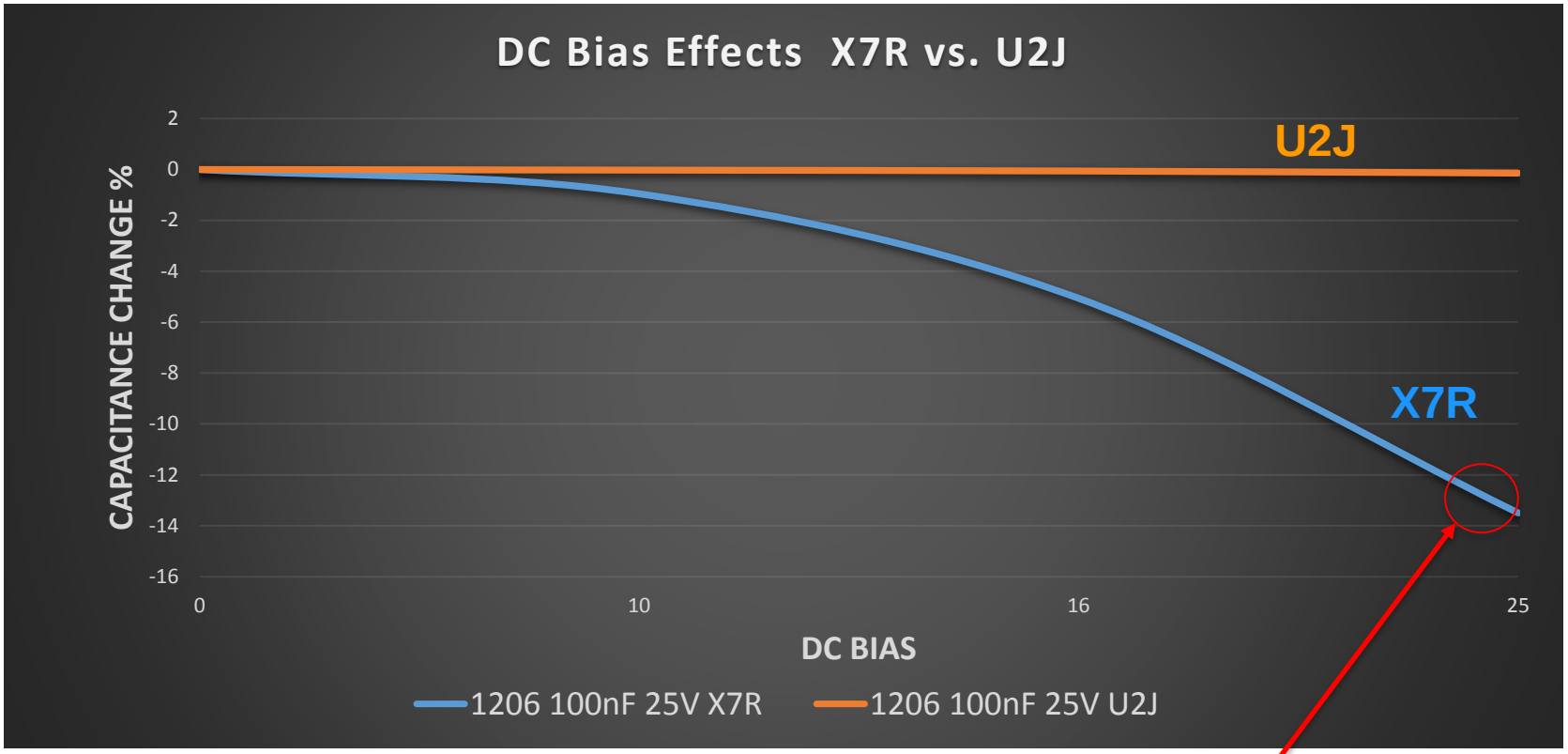
Temperature coefficient α 10^{-6}/K Letter code	Multiplier of the temperature coefficient Number code	Tolerance of the temperature coefficient Letter code
C: 0.0	**0: -1**	**G: ±30**
B: 0.3	1: -10	H: ±60
L: 0.8	**2: -100**	**J: ±120**
A: 0.9	3: -1000	K: ±250
M: 1.0	4: +1	L: ±500
P: 1.5	6: +10	M: ±1000
R: 2.2	7: +100	N: ±2500
S: 3.3	8: +1000	
T: 4.7		
V: 5.6		
U: 7.5		

Temperature Range: -55ºC to +125ºC

KEMET U2J Dielectric
Relative Capacitance vs. Temperature

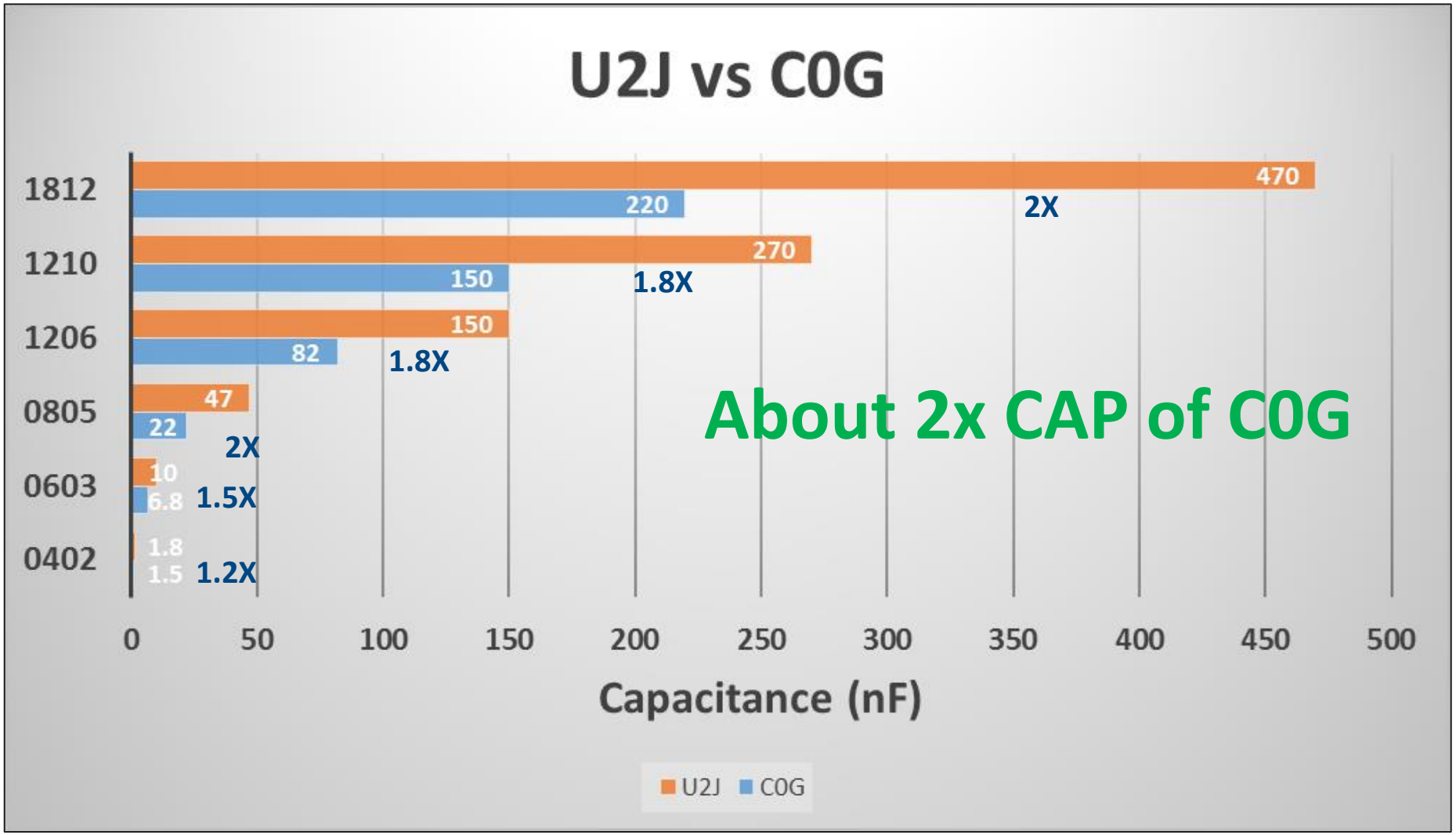


Effective Capacitance
X7R vs. U2J

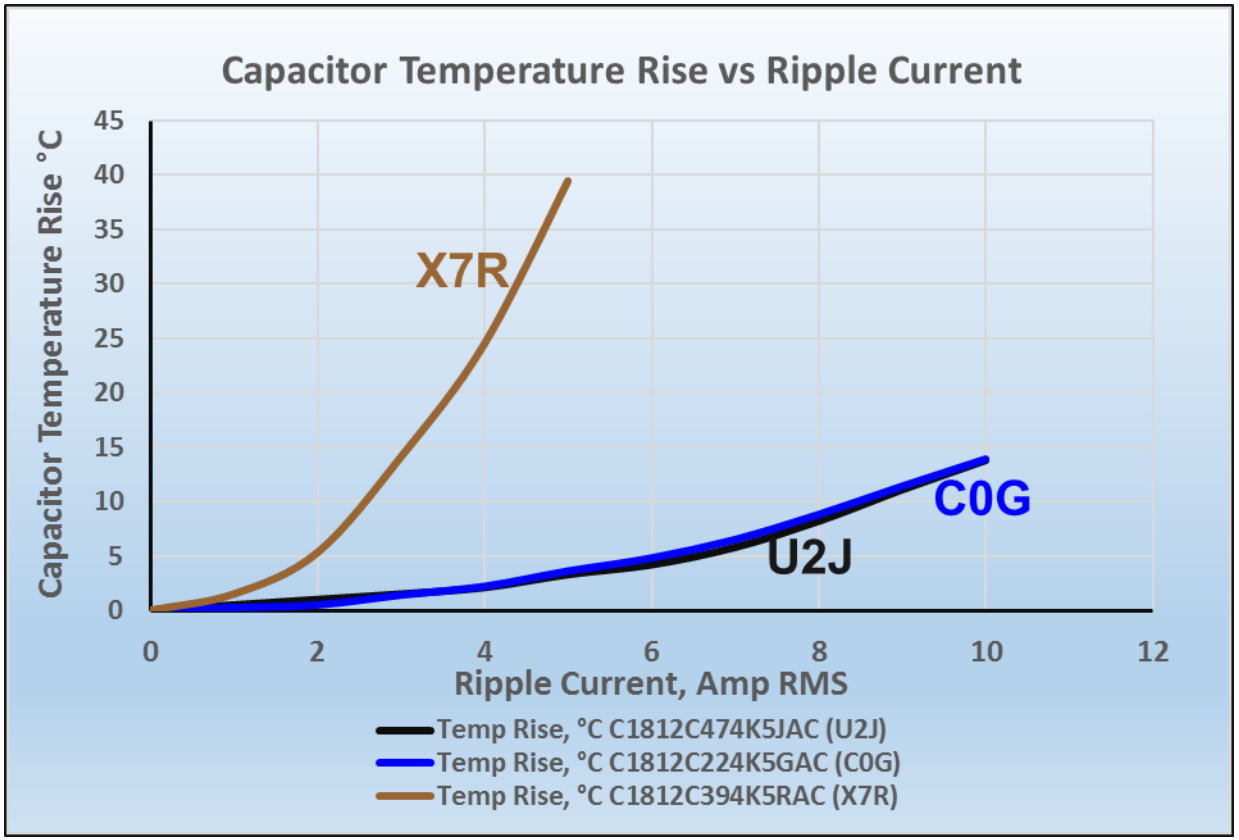


~13.8% capacitance loss
Effective capacitance of ~86nF

U2J Development 50V



Temperature Rise vs. Ripple Current



- BME C0G and BME U2J both show high current carrying capability
- Temperature rise <14°C up to ripple current of $10A_{rms}$

Summary

- Increase in switching frequency change capacitor needs:
  - Need Lower Capacitance Values
  - High Current Carrying Capability
  - Higher Voltage Capability (450-2000V)
  - Reliable at High Temperatures (125°C, 150°C, > 200°C)
- BME C0G MLCC have:
  - High reliability at high temperatures and voltages
  - High ripple current capability with ultra-low losses and ESR
- BME U2J MLCC:
  - Extend the capacitance values available in Class-I, 50 V ratings
  - Have similar ripple current performance to C0G allowing at higher frequency enabling further miniaturization for higher power density

Thank You!