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## **Certificate of Analysis**

MRA Report #: M17-050T  
Report Date: March 24, 2017  
Report Type: EESU Capacitor Performance Testing  
Prepared for: Mr. Ian Clifford  
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P.O. No: 2946-02'17

### **The following samples were submitted and identified on behalf of the client as:**

Sample ID's: Sample #1 – Densified ceramic disk, S/N #7c  
Sample #2 – Densified ceramic disk, S/N #8c  
Sample #3 – Densified ceramic disk, S/N #8ca  
Sample #4 – 3000Vdc packaged prototype capacitor, 16 layers, S/N EE16L02

Material types: Densified ceramic disks and prototype EESU capacitors  
Quantity: One per sample

Testing Period: February 23, 2017 – March 24, 2017

Objective: To independently illustrate the performance of EESstor capacitors across the range of operating conditions

Performed tests: **Test #1:** Electrical parameters such as Cap, DF, ESR, Z, and  $\theta$  at 1kHz, 1Vrms, room temperature;  
**Test #2:** Capacitance at 500V dc-bias, room temperature;  
**Test #3:** Insulation Resistance at 500V dc-bias, room temperature;  
**Test #4:** Capacitance at 500V dc-bias, 65°C;  
**Test #5:** Insulation Resistance at 500V dc-bias, 65°C;  
**Test #6:** Estimation of the dielectric constant based on physical dimensions and capacitance both at room temperature and at 65°C;  
**Test #7:** Stability of electrical parameters of the device before and after 1,000,000 charge/discharge cycles.

Summary: The results are given on the following pages for information only.

**Test Results:**

**Test #1: ELECTRICAL PARAMETERS**  
(@1kHz, 1Vrms, room temperature)

**Sample #1 – Densified ceramic disk, S/N #7c;**  
**Sample #2 – Densified ceramic disk, S/N #8c;**  
**Sample #3 – Densified ceramic disk, S/N #8ca;**

Electrical Parameters	Samples		
	Sample #1 “7c”	Sample #2 “8c”	Sample #3 “8ca”
Capacitance (C)	2.818nF	1.975nF	496.8pF
Dissipation Factor (DF)	0.623%	1.028%	1.764%
Equivalent Series Resistance (Rs)	351.8Ω	828.9Ω	5.6kΩ
Impedance (Z)	56.4kΩ	80.6kΩ	320.4kΩ
Phase Angle (θ)	-89.64°	-89.41°	-89.00°

Used equipment: Keysight E4980A precision LCR meter.  
Measured uncertainty: C, DF, Rs, Z, and θ ±0.1%.  
Room temperature: 19.6°C. Relative humidity: 17.7%.

**Test #2: CAPACITANCE**  
 (@500Vdc, room temperature)

**Sample #1 – Densified ceramic disk, S/N #7c;**  
**Sample #2 – Densified ceramic disk, S/N #8c;**  
**Sample #3 – Densified ceramic disk, S/N #8ca;**

Electrical Parameters	Samples		
	Sample #1 "7c"	Sample #2 "8c"	Sample #3 "8ca"
Capacitance (C)	3.48nF	2.64nF	0.69nF
Used equipment: ViTREK 951i electrical safety compliance analyzer. Measured uncertainty: Capacitance $\pm 0.25\%$ . Room temperature: 19.6°C. Relative humidity: 17.7%.			

**Test #3: INSULATION RESISTANCE**  
 (@500Vdc, room temperature)

**Sample #1 – Densified ceramic disk, S/N #7c;**  
**Sample #2 – Densified ceramic disk, S/N #8c;**  
**Sample #3 – Densified ceramic disk, S/N #8ca;**

Electrical Parameters	Samples		
	Sample #1 "7c"	Sample #2 "8c"	Sample #3 "8ca"
Insulation Resistance (IR)	> 260GΩ	> 270GΩ	> 280GΩ
Used equipment: ViTREK 951i electrical safety compliance analyzer. Measured uncertainty: Capacitance $\pm 0.25\%$ . Room temperature: 19.6°C. Relative humidity: 17.7%.			

**Test #4: CAPACITANCE AT TEMPERATURE**  
 (@500Vdc, 65°C)

**Sample #2 – Densified ceramic disk, S/N #8c;**

Electrical Parameters	Samples
	Sample #2 "8c"
Capacitance (C)	2.03nF
Used equipment: ViTREK 951i electrical safety compliance analyzer and Delta 9023 environmental chamber. Measured uncertainty: Capacitance $\pm 0.25\%$ . Room temperature: 19.6°C. Relative humidity: 17.7%.	

**Test #5: INSULATION RESISTANCE AT TEMPERATURE**  
 (@500Vdc, 65°C)

**Sample #2 – Densified ceramic disk, S/N #8c;**

Electrical Parameters	Samples
	Sample #2 "8c"
Insulation Resistance (IR)	> 270GΩ
Used equipment: ViTREK 951i electrical safety compliance analyzer and Delta 9023 environmental chamber. Measured uncertainty: Capacitance $\pm 0.25\%$ . Room temperature: 19.6°C. Relative humidity: 17.7%.	

**Test #6: ESTIMATION OF THE DIELECTRIC CONSTANT**  
(based on capacitance measured at 500Vdc at room temperature and at 65°C)

**Sample #1 – Densified ceramic disk, S/N #7c;**  
**Sample #2 – Densified ceramic disk, S/N #8c;**  
**Sample #3 – Densified ceramic disk, S/N #8ca;**

<b>Samples</b>	<b>Thickness, in</b>	<b>Electrode Area, in<sup>2</sup></b>	<b>Estimated K at room temperature</b>	<b>Estimated K at 65°C</b>
<b>Sample #1 “7c”</b>	<b>0.183</b>	<b>0.200</b>	<b>14,150</b>	<b>-</b>
<b>Sample #2 “8c”</b>	<b>0.138</b>	<b>0.200</b>	<b>8,100</b>	<b>6,230</b>
<b>Sample #3 “8ca”</b>	<b>0.077</b>	<b>0.030</b>	<b>7,880</b>	<b>-</b>

**Test #7: STABILITY OF ELECTRICAL PARAMETERS OF THE DEVICE  
 BEFORE AND AFTER 1,000,000 CHARGE/DISCHARGE CYCLES**  
 (@1Vrms, room temperature)

**Sample #4 – 3000Vdc packaged prototype capacitor, 16 layers, S/N EE16L02**

Electrical Parameters	Frequency							
	100Hz		120Hz		1kHz		10kHz	
	Before cycle test	After cycle test						
<b>Capacitance (C)</b>	2.963 nF	2.965 nF	2.958 nF	2.951 nF	2.912 nF	2.900 nF	2.857 nF	2.840 nF
<b>Dissipation Factor (DF)</b>	1.490 %	1.701 %	1.440 %	1.385 %	1.231 %	1.396 %	1.614 %	1.590 %
<b>Equivalent Series Resistance (Rs)</b>	7.9 kΩ	9.4 kΩ	6.5 kΩ	7.6 kΩ	673.2 Ω	764.7 Ω	89.9 Ω	90.1 Ω
<b>Quality Factor (Q)</b>	67.1	56.5	69.7	72.6	81.2	71.7	61.9	62.6
<b>Impedance (Z)</b>	536.9 kΩ	536.5 kΩ	448.2 kΩ	448.3 kΩ	54.6 kΩ	54.9 kΩ	5.6 kΩ	5.6 kΩ
<b>Phase Angle (θ)</b>	-89.14	-88.93	-89.17	-89.16	-89.29	-89.20	-89.07	-89.07

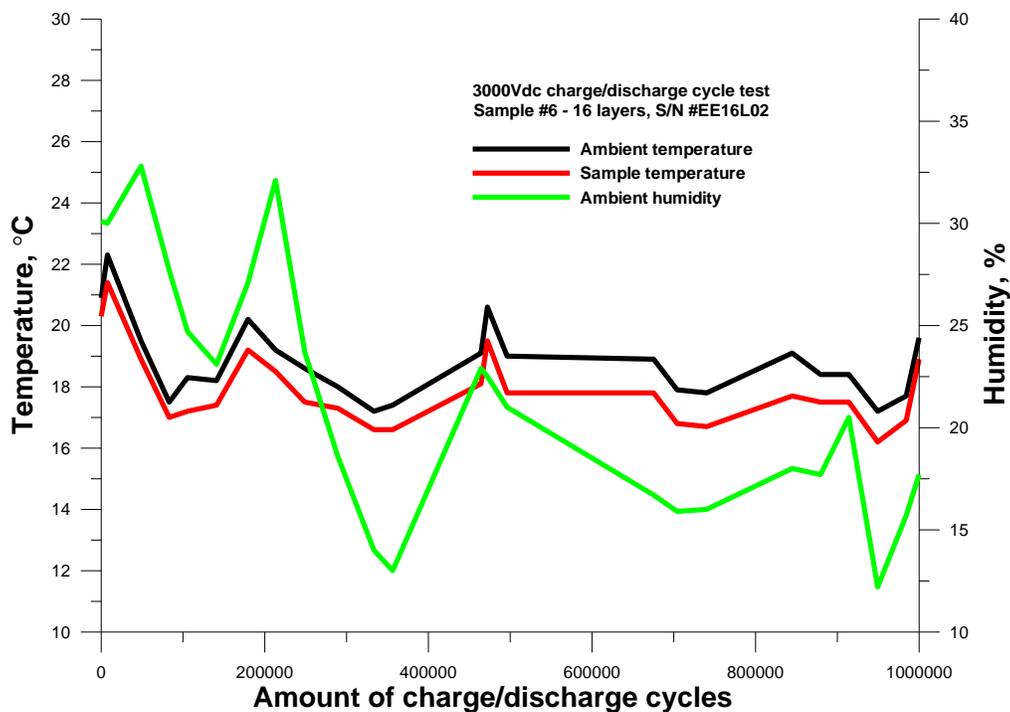
Used equipment: Keysight E4980A precision LCR meter.  
 Measured uncertainty: C, DF, Rs, Q, Z, and θ ±0.1%.  
 Room temperature: 20.0°C. Relative humidity: 32.3% (before cycle test).  
 Room temperature: 19.6°C. Relative humidity: 17.7% (after cycle test).

Sample ID	ac voltage					
	500Vac		1500Vac		2120Vac	
	Capacitance					
	Before cycle test	After cycle test	Before cycle test	After cycle test	Before cycle test	After cycle test
<b>Sample #6 (16 layers, S/N #EE16L02)</b>	3.12nF	3.18nF	4.22nF	4.21nF	4.61nF	4.69nF

Used equipment: ViTREK 951i electrical safety compliance analyzer.  
 Measured uncertainty: Capacitance  $\pm 0.25\%$ .  
 Room temperature: 20.0°C. Relative humidity: 32.3% (before cycle test).  
 Room temperature: 19.6°C. Relative humidity: 17.7% (after cycle test).

Sample ID	dc-bias	Insulation Resistance	
		Before cycle test	After cycle test
<b>Sample #6 (16 layers, S/N #EE16L02)</b>	3000Vdc, 60 min	240GΩ	170GΩ

Used equipment: ViTREK 951i electrical safety compliance analyzer.  
 Measured uncertainty: Insulation resistance  $\pm 0.25\%$ .  
 Room temperature: 20.0°C. Relative humidity: 32.3% (before cycle test).  
 Room temperature: 19.6°C. Relative humidity: 17.7% (after cycle test).



## **Test Methods**

The below methods were used to perform the tests.

### **General**

All measurement equipment was powered up at least 30 minutes prior to testing and allowed to reach a stable temperature.

### **Test #1: Electrical Parameters at 1kHz**

Electrical parameters at 1kHz were measured using Keysight E4980A Precision LCR Meter. The measurements were performed at room temperature and 1Vrms voltage conditions utilizing variable internal functions of the meter. Open/short correction was performed prior to measurements in order to compensate for stray admittance and residual impedance in the probe. The measurements were performed one time per sample.

### **Test #2: Capacitance at DC Voltage**

Capacitance at dc voltage measurements were performed by ViTREK 951i Electrical Safety Compliance Analyzer utilizing the “DCCAP” test function. The DC voltage was gradually ramped to a desire voltage with the ramp rate 50Vdc/sec at room temperature. The capacitance was recorded after 30 seconds of the voltage stabilization. The measurements were performed one time per sample.

### **Test #3: Insulation Resistance at DC-Bias**

Insulation resistance at dc-bias measurements were performed by ViTREK 951i Electrical Safety Compliance Analyzer utilizing the “DCIR” test function. The DC voltage was gradually ramped up to 3000Vdc level during 60 seconds at room temperature, and the insulation resistance was recorded after a prolonged period of time, necessary for the insulation resistance data stabilization. The measurements were performed one time per sample.

#### **Test #4: Capacitance at DC Voltage and Temperature**

Capacitance at dc voltage and temperature measurements were performed by ViTREK 951i Electrical Safety Compliance and Delta 9023 Environmental Chamber. 40 minutes were allowed for the temperature stabilization inside the chamber before each measurements. The DC voltage was gradually ramped to a desire voltage with the ramp rate 50Vdc/sec at room temperature. The capacitance was recorded after 30 seconds of the voltage stabilization. The measurements were performed one time per sample.

#### **Test #5: Insulation Resistance at DC-Bias and Temperature**

Insulation resistance at dc-bias measurements were performed by ViTREK 951i Electrical Safety Compliance Analyzer and Delta 9023 Environmental Chamber. 40 minutes were allowed for the temperature stabilization inside the chamber before each measurements. The DC voltage was gradually ramped up to 3000Vdc level during 60 seconds at room temperature, and the insulation resistance was recorded after a prolonged period of time, necessary for the insulation resistance data stabilization. The measurements were performed one time per sample.

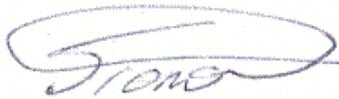
#### **Test #6: Estimation of the Dielectric Constant**

The dielectric constant of the densified ceramic pellets was estimated by using parallel plate capacitor model. The thickness of the samples and the area of sputtered gold electrodes were measured using a precision micrometer, while the capacitance was taken from measurements of the capacitance at 500Vdc bias both at room temperature and at 65°C.

#### **Test #7: Stability of Electrical Parameters of the Device Before and After 1,000,000 Charge/Discharge Cycles**

The electrical parameters of the device, were measured before and after charge/discharge cycle test. The cycle test was performed by QuadTech Guardian 12kV DC Hipot Tester and an external counter. The cycle consisted of ramp to 3000Vdc during ~0.1seconds followed by hold at 3000Vdc for ~0.1seconds and fast discharge. The total duration of one cycle, including Pass/Fail computation by the Hipot tester, was about 1 second. The counter triggered the new cycle after receiving the “Pass” signal from the Hipot tester. The ambient temperature and humidity as well as the temperature of the device was monitored during the cycle test using Omega HH314A Humidity-Temperature Meter.

**Affirmation:** I certify the above to be true and correct and to have witnessed the testing as described



Anton Polotai, Senior Scientist

Cc: RM, SM, JW

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