MRA Laboratories, Inc.

ISO 9001:2008
BUREAU VERITAS
Certification

# ***Certificate of Analysis***

| | |
|---|---|
| MRA Report #: | M16-112T |
| Report Date: | November 12, 2016 |
| Report Type: | EESU Capacitor Performance Testing |
| Prepared for: | Mr. Ian Clifford<br>EEStor, Inc.<br>715 Discovery Boulevard #107<br>Cedar Park, TX 78613 |

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

| | |
|---|---|
| Sample ID's: | Sample #1 – 3000Vdc rated bare prototype capacitor layer (single dot)<br>Sample #2 – 3000Vdc rated bare prototype capacitor layer (double dot)<br>Sample #3 – 3000Vdc rated packaged prototype capacitor, 4 layers<br>Sample #4 – 3000Vdc rated packaged prototype capacitor, 8 layers<br>Sample #5 – 3000Vdc rated packaged prototype capacitor, 16 layers |
| Material types: | Prototype EESU capacitors |
| Quantity: | One per sample |
| Testing Period: | November 9, 2016 – November 11, 2016 |
| Objective: | To independently illustrate the performance of EEStor capacitors across the range of operating conditions |
| Performed tests: | Capacitance vs. DC Voltage<br>Insulation Resistance vs. DC Voltage<br>Capacitance vs. Frequency |
| Summary: | The results are given on the following pages for information only. |

**Test Results:**

**CAPACITANCE VS. DC VOLTAGE**

**Sample #1 - 3000Vdc rated bare prototype capacitor layer (single dot)**

| **Voltage, Vdc** | **Time Constant, ms** | | | **Discharge Resistor, MΩ** | **Estimated Capacitance, nF** | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **$\tau_1$** | **$\tau_2$** | **$\tau_3$** | | **$C_1$** | **$C_2$** | **$C_3$** | **Mean** | **σ** |
| **500** | 14.4 | 13.4 | 13.7 | 12.120 | 1.19 | 1.11 | 1.13 | 1.14 | 0.042 |
| **1000** | 14.3 | 13.1 | 13.7 | 12.120 | 1.18 | 1.08 | 1.13 | 1.13 | 0.050 |
| **2000** | 12.2 | 13.0 | 12.7 | 12.120 | 1.01 | 1.07 | 1.05 | 1.04 | 0.033 |
| **3000** | 11.9 | 11.7 | 11.8 | 12.120 | 0.98 | 0.97 | 0.97 | 0.97 | 0.008 |
| Measured uncertainty: Capacitance ±0.07nF, Voltage ±1.0Vdc | | | | | | | | | |

**Sample #2 - 3000Vdc rated bare prototype capacitor layer (double dot)**

| **Voltage, Vdc** | **Time Constant, ms** | | | **Discharge Resistor, MΩ** | **Estimated Capacitance, nF** | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **$\tau_1$** | **$\tau_2$** | **$\tau_3$** | | **$C_1$** | **$C_2$** | **$C_3$** | **Mean** | **σ** |
| **500** | 13.1 | 12.9 | 13.1 | 12.120 | 1.08 | 1.06 | 1.08 | 1.08 | 0.010 |
| **1000** | 12.7 | 13.4 | 12.7 | 12.120 | 1.05 | 1.11 | 1.05 | 1.07 | 0.033 |
| **2000** | 12.0 | 11.6 | 12.4 | 12.120 | 0.99 | 0.96 | 1.02 | 0.99 | 0.033 |
| **3000** | 12.2 | 11.2 | 10.8 | 12.120 | 1.01 | 0.92 | 0.89 | 0.94 | 0.059 |
| Measured uncertainty: Capacitance ±0.07nF, Voltage ±1.0Vdc | | | | | | | | | |

*15 Print Works Drive*
*Adams, MA 01220*
*Tel: [413] 743-3927 Fax: [413] 743-0305*
Email: *mra@mralabs.com* *www.mralabs.com*

**Sample #3 - 3000Vdc rated packaged prototype capacitor, 4 layers**

| Voltage, Vdc | Time Constant, ms | | | Discharge Resistor, MΩ | Estimated Capacitance, nF | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | $\tau_1$ | $\tau_2$ | $\tau_3$ | | $C_1$ | $C_2$ | $C_3$ | Mean | σ |
| **500** | 16.4 | 15.5 | 16.0 | 12.120 | 1.35 | 1.28 | 1.32 | 1.32 | 0.037 |
| **1000** | 16.7 | 15.4 | 15.4 | 12.120 | 1.38 | 1.27 | 1.27 | 1.31 | 0.062 |
| **2000** | 15.3 | 16.9 | 15.6 | 12.120 | 1.26 | 1.39 | 1.29 | 1.31 | 0.070 |
| **3000** | 16.2 | 16.1 | 16.0 | 12.120 | 1.34 | 1.33 | 1.32 | 1.33 | 0.008 |
| Measured uncertainty: Capacitance ±0.08nF, Voltage ±1.0Vdc | | | | | | | | | |

**Sample #4 - 3000Vdc rated packaged prototype capacitor, 8 layers**

| Voltage, Vdc | Time Constant, ms | | | Discharge Resistor, MΩ | Estimated Capacitance, nF | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | $\tau_1$ | $\tau_2$ | $\tau_3$ | | $C_1$ | $C_2$ | $C_3$ | Mean | σ |
| **500** | 42.0 | 38.8 | 37.6 | 12.120 | 3.47 | 3.20 | 3.10 | 3.26 | 0.188 |
| **1000** | 39.6 | 38.1 | 38.8 | 12.120 | 3.27 | 3.14 | 3.20 | 3.20 | 0.062 |
| **2000** | 39.6 | 36.8 | 37.3 | 12.120 | 3.27 | 3.04 | 3.08 | 3.13 | 0.123 |
| **3000** | 36.8 | 36.8 | 36.6 | 12.120 | 3.04 | 3.04 | 3.02 | 3.03 | 0.010 |
| Measured uncertainty: Capacitance ±0.08nF, Voltage ±1.0Vdc | | | | | | | | | |

**Sample #5 - 3000Vdc rated packaged prototype capacitor, 16 layers**

| Voltage, Vdc | Time Constant, ms | | | Discharge Resistor, MΩ | Estimated Capacitance, nF | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | $\tau_1$ | $\tau_2$ | $\tau_3$ | | $C_1$ | $C_2$ | $C_3$ | Mean | σ |
| **500** | 90.0 | 88.0 | 88.0 | 12.120 | 7.43 | 7.26 | 7.26 | 7.32 | 0.095 |
| **1000** | 93.1 | 86.1 | 85.5 | 12.120 | 7.68 | 7.10 | 7.05 | 7.28 | 0.349 |
| **2000** | 91.0 | 89.5 | 92.5 | 12.120 | 7.51 | 7.38 | 7.63 | 7.51 | 0.124 |
| **3000** | 93.0 | 94.0 | 92.0 | 12.120 | 7.67 | 7.76 | 7.59 | 7.67 | 0.083 |
| Measured uncertainty: Capacitance ±0.10nF, Voltage ±1.0Vdc | | | | | | | | | |

## INSULATION RESISTANCE VS. DC VOLTAGE

**Sample #1 - 3000Vdc rated bare prototype capacitor layer (single dot)**

| Voltage, Vdc | Leakage Current, nA | | | Estimated Insulation Resistance, GΩ | | | | | Estimated Mean Capacitance, nF | Estimated Self-Discharge Time Constant, s |
|---|---|---|---|---|---|---|---|---|---|---|
| | $I_1$ | $I_2$ | $I_3$ | $IR_1$ | $IR_2$ | $IR_3$ | Mean | σ | | |
| **500** | 5.5 | 1.2 | 1.3 | 90.9 | 416.7 | 384.6 | 297.4 | 179.54 | 1.14 | 339.0 |
| **1000** | 14.2 | 5.9 | 5.2 | 70.4 | 169.5 | 192.3 | 144.1 | 64.80 | 1.13 | 162.8 |
| **2000** | 26.2 | 17.2 | 15.4 | 76.3 | 116.3 | 129.9 | 107.5 | 27.83 | 1.04 | 111.8 |
| **3000** | 47.6 | 39.6 | 29.9 | 63.0 | 75.8 | 100.3 | 79.7 | 18.97 | 0.97 | 77.3 |
| Measured uncertainty: Leakage Current ±1.6nA, Voltage ±1.0Vdc | | | | | | | | | | |

**Sample #2 - 3000Vdc rated bare prototype capacitor layer (double dot)**

| Voltage, Vdc | Leakage Current, nA | | | Estimated Insulation Resistance, GΩ | | | | | Estimated Mean Capacitance, nF | Estimated Self-Discharge Time Constant, s |
|---|---|---|---|---|---|---|---|---|---|---|
| | $I_1$ | $I_2$ | $I_3$ | $IR_1$ | $IR_2$ | $IR_3$ | Mean | σ | | |
| **500** | 5.9 | 1.3 | 1.2 | 84.7 | 384.6 | 416.7 | 295.3 | 183.08 | 1.08 | 318.9 |
| **1000** | 17.2 | 6.1 | 5.7 | 58.1 | 163.9 | 175.4 | 132.5 | 64.66 | 1.07 | 141.8 |
| **2000** | 27.4 | 19.5 | 16.8 | 73.0 | 102.6 | 119.0 | 98.2 | 23.34 | 0.99 | 97.2 |
| **3000** | 43.2 | 37.1 | 29.5 | 69.4 | 80.9 | 101.7 | 84.0 | 16.35 | 0.94 | 79.0 |
| Measured uncertainty: Leakage Current ±1.6nA, Voltage ±1.0Vdc | | | | | | | | | | |

Note: Estimated mean capacitance value taken from average measurements on page #2.

**Sample #3 - 3000Vdc rated packaged prototype capacitor, 4 layers**

| Voltage, Vdc | Leakage Current, nA | | | Estimated Insulation Resistance, GΩ | | | | | Estimated Mean Capacitance, nF | Estimated Self-Discharge Time Constant, s |
|---|---|---|---|---|---|---|---|---|---|---|
| | $I_1$ | $I_2$ | $I_3$ | $IR_1$ | $IR_2$ | $IR_3$ | Mean | σ | | |
| **500** | 9.9 | 0.16 | 0.21 | 50.5 | 3125.0 | 2381.0 | 1852.2 | 1604.01 | 1.32 | 2445 |
| **1000** | 19.8 | 6.6 | 6.5 | 50.5 | 151.5 | 153.8 | 118.6 | 59.00 | 1.31 | 155 |
| **2000** | 39.7 | 23.6 | 19.9 | 50.4 | 84.7 | 100.5 | 78.5 | 25.63 | 1.31 | 103 |
| **3000** | 59.9 | 57.4 | 53.7 | 50.1 | 52.3 | 55.9 | 52.7 | 2.92 | 1.33 | 70 |
| Measured uncertainty: Leakage Current ±1.6nA, Voltage ±1.0Vdc | | | | | | | | | | |

**Sample #4 - 3000Vdc rated packaged prototype capacitor, 8 layers**

| Voltage, Vdc | Leakage Current, nA | | | Estimated Insulation Resistance, GΩ | | | | | Estimated Mean Capacitance, nF | Estimated Self-Discharge Time Constant, s |
|---|---|---|---|---|---|---|---|---|---|---|
| | $I_1$ | $I_2$ | $I_3$ | $IR_1$ | $IR_2$ | $IR_3$ | Mean | σ | | |
| **500** | 12.3 | 0.2 | 0.3 | 40.7 | 2500.0 | 1666.7 | 1402.4 | 1250.78 | 3.26 | 4572 |
| **1000** | 22.7 | 7.3 | 5.8 | 44.1 | 137.0 | 172.4 | 117.8 | 66.29 | 3.20 | 377 |
| **2000** | 48.1 | 29.2 | 23.8 | 41.6 | 68.5 | 84.0 | 64.7 | 21.48 | 3.13 | 203 |
| **3000** | 76.5 | 64.4 | 59.2 | 39.2 | 46.6 | 50.7 | 45.5 | 5.81 | 3.03 | 138 |
| Measured uncertainty: Leakage Current ±1.6nA, Voltage ±1.0Vdc | | | | | | | | | | |

**Sample #5 - 3000Vdc rated packaged prototype capacitor, 16 layers**

| Voltage, Vdc | Leakage Current, nA | | | Estimated Insulation Resistance, GΩ | | | | | Estimated Mean Capacitance, nF | Estimated Self-Discharge Time Constant, s |
|---|---|---|---|---|---|---|---|---|---|---|
| | $I_1$ | $I_2$ | $I_3$ | $IR_1$ | $IR_2$ | $IR_3$ | Mean | σ | | |
| **500** | 18.4 | 0.3 | 0.3 | 27.2 | 1666.7 | 1666.7 | 1120.2 | 946.56 | 7.32 | 8200 |
| **1000** | 39.1 | 15.7 | 9.0 | 25.6 | 63.7 | 111.1 | 66.8 | 42.85 | 7.28 | 486 |
| **2000** | 84.1 | 51.3 | 44.6 | 23.8 | 39.0 | 44.8 | 35.9 | 10.87 | 7.51 | 270 |
| **3000** | 147.2 | 122.5 | 100.1 | 20.4 | 24.5 | 30.0 | 24.9 | 4.81 | 7.67 | 191 |
| Measured uncertainty: Leakage Current ±1.6nA, Voltage ±1.0Vdc | | | | | | | | | | |

Note: Estimated mean capacitance value taken from average measurements on page #3.

## CAPACITANCE VS. FREQUENCY

**Sample #1 - 3000Vdc rated bare prototype capacitor layer (single dot)**

| **Frequency, kHz** | **Capacitance, nF** |
|---|---|
| **1000** | 0.949 |
| **800** | 0.951 |
| **600** | 0.955 |
| **500** | 0.957 |
| **400** | 0.961 |
| **300** | 0.966 |
| **200** | 0.973 |
| **100** | 0.985 |
| **80** | 0.989 |

**Sample #2 - 3000Vdc rated bare prototype capacitor layer (double dot)**

| **Frequency, kHz** | **Capacitance, nF** |
|---|---|
| **1000** | 0.888 |
| **800** | 0.890 |
| **600** | 0.894 |
| **500** | 0.896 |
| **400** | 0.899 |
| **300** | 0.904 |
| **200** | 0.912 |
| **100** | 0.923 |
| **80** | 0.927 |

## ACTIVE DIELECTRIC LAYER THICKNESS
**(For reference only. Data provided by EEStor, Inc.)**

| **Sample #** | **Active Dielectric Layer Thickness, µm** |
|---|---|
| Sample #1 | 64.7 |
| Sample #2 | 75.0 |
| Sample #3 | 72.1 |
| Sample #4 | 75.4 |
| Sample #5 | 69.2 |

*15 Print Works Drive*
*Adams, MA 01220*
*Tel: [413] 743-3927 Fax: [413] 743-0305*
Email: *mra@mralabs.com* *www.mralabs.com*

## Test Methods

The below methods are used to perform the tests.

### General

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

### Capacitance vs. DC Voltage

Capacitance is measured with capacitors charged to a desired voltages. The method employed is based upon determination of the time constant, $\tau$ of an RC circuit, by means of a controlled discharge.

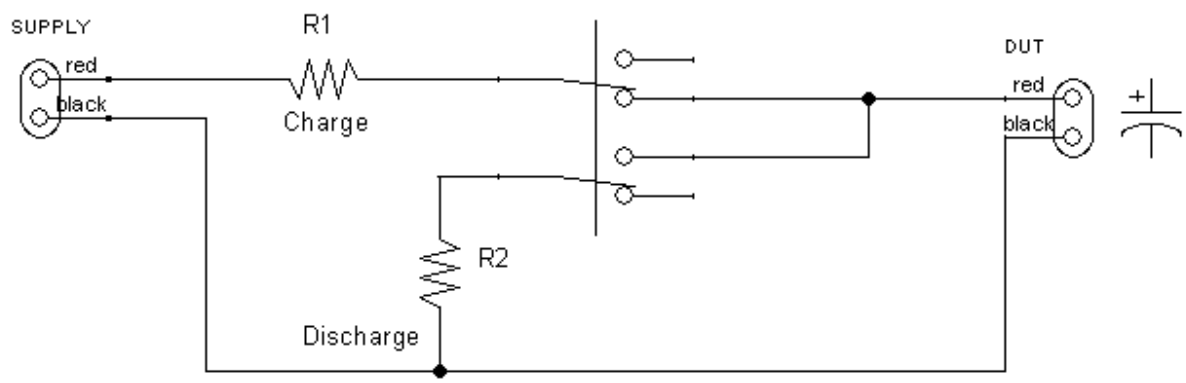


Figure 1: Capacitor charge/discharge circuit.

An oscilloscope (Tektronix TDS 2004B) is connected across the device under test using a 1000x probe (Tektronix P6015A) to provide necessary voltage rating and sufficiently high probe impedance. The contribution of the oscilloscope probe and any other parasitic resistance is taken into account for the purposes of final calculations by means of a direct resistance measurement of the discharge path.

The capacitors is charged to operating voltage using a high voltage power supply (Stanford Research Power Supply PS350). The oscilloscope is used to measure the discharge time in which the voltage between the capacitor terminals is reduced by 63.2%.

Based on the measured resistance and time constant, capacitance is determined using the below equation:

$$C = \frac{\tau}{R}$$

Each measurement is taken three times for each test voltages.

**Insulation Resistance vs. DC Voltage**

The leakage through the dielectric is measured by means of applying a static voltage using a high voltage power supply (Stanford Research Power Supply PS350) across the device under test with a sensitive current meter (Keithley Picoammeter 6485) connected in series. In accordance with the manufacturer's recommendations, a network of diodes and a resistor are used to protect the meter from potential voltages in excess of 200V.

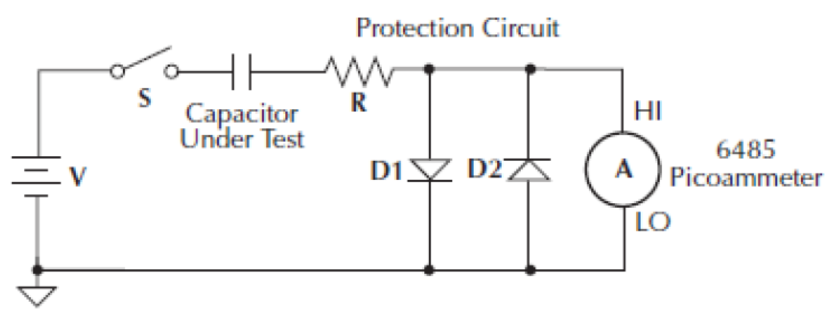


Figure 2. Manufacture recommended circuit for >200V capacitor measurement.

The capacitor is allowed to settle after application of voltage for a minimum of 5 minutes before the leakage current is recorded.

**Capacitance vs. Frequency**

The dependence of capacitance versus frequency is measured a commercial impedance analyzer (Keysight E4980A Precision LCR Meter). Capacitance is measured in parallel mode in a frequency range from 80kHz to 1.0MHz at 1Vrms, 0V dc-bias test conditions using a tweezers contact probe. Open/short correction is performed prior to measurement in order to compensate for stray admittance and residual impedance in the probe.

Measurements were conducted both at MRA Laboratories, Inc, 15 Print Works Drive, Adams, MA 01220 and at EEStor, Inc. 715 Discovery Blvd, Ste. 107, Cedar Park, TX 78613.

**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

**NOTICE:** *MRA Laboratories, Inc. strives to maintain a high standard in the conduct and reporting of its testing and professional services. Best efforts are made to assure equipment is properly maintained and calibrated and that correct procedures are followed. All results are discussed and reviewed by the project lead and at least one other qualified technical person prior to reporting.*

*Test results are considered advisory and/or experimental in nature. Therefore, neither MRA, nor its employees, assume any obligation or liability for damages, including, but not limited to consequential damages, arising out of or in conjunction with the use, or inability to use, the resulting information. Questionable results should be called to the attention of MRA as soon as possible.*

*15 Print Works Drive*
*Adams, MA 01220*
*Tel: [413] 743-3927* *Fax: [413] 743-0305*
Email: *mra@mralabs.com* *www.mralabs.com*