A FERRO COMPANY

# ***Certificate of Analysis***

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|---|---|
| MRA Report #: | M18-091T |
| Report Date: | September 6, 2018 |
| Report Type: | EEStor, Inc. Samples Performance Testing |
| Prepared for: | Mr. Ian Clifford<br>EEStor, Inc.<br>715 Discovery Boulevard #107<br>Cedar Park, TX 78613 |
| P.O. No: | 3158-00'18 (Sample #4) |

**The following sample was submitted and identified on behalf of the client as:**

| | |
|---|---|
| Sample ID's: | CS-18-13-4 – Densified ceramic disk, Customer ID# L-3H |
| Material types: | Densified ceramic disk capacitor |
| Quantity: | One per sample |
| Testing Period: | August 21, 2018 – September 5, 2018 |
| Objective: | To independently illustrate the performance of EEStor materials across the range of operating conditions |

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

Performed tests:

**Test #1:** Capacitance & Dissipation Factor vs. Frequency (20Hz – 2MHz) @1Vrms, RT, 0V dc-bias;
**Test #2:** Capacitance & Dissipation Factor vs. dc-bias (up to 1000V) @1kHz, RT;
**Test #3:** Temperature Coefficient of Capacitance @ 1kHz, -55°C – 200°C temperature range, 0V dc-bias;
**Test #4:** Temperature Coefficient of Capacitance at dc-bias @ 1kHz, -55°C – 200°C temperature range, 300V dc-bias;
**Test #5:** Insulation Resistance @1000V, RT and 125°C;
**Test #6:** HALT @1000V, 180°C, 100h;
**Test #7:** Dielectric Breakdown Strength both at AC (up to 5000Vac) and DC (up to 6000Cdc) voltages;
**Test #8:** Cross-section and optical/SEM microstructure evaluation.

Summary:

The results are given on the following pages as tables and plots for information only.

**Customer Samples Dimensions**

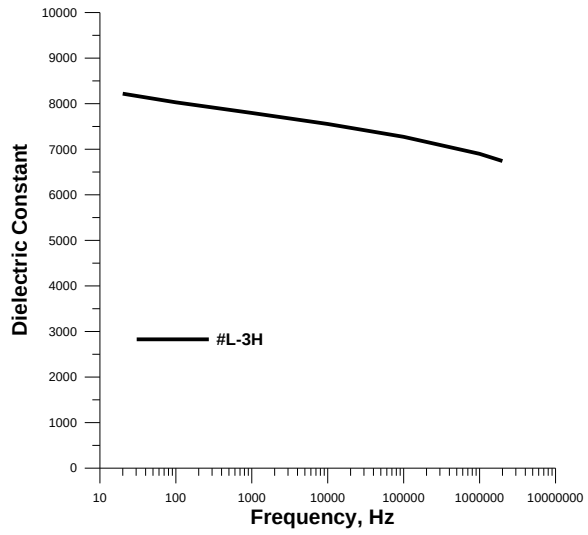
| Sample ID# | Customer ID# | Electrode dimensions (diameter or length and width), mm | Sample thickness, mm | Electrodes area, $mm^2$ |
|---|---|---|---|---|
| **CS-18-13-4** | **#L-3H** | 5.69 | 0.55 | 25.42 |
| Used equipment: Precision micrometer, 210-A.<br>Measured uncertainty: ±0.001mm.<br>Room temperature: 19.2°C. Relative humidity: 49.2%. | | | | |

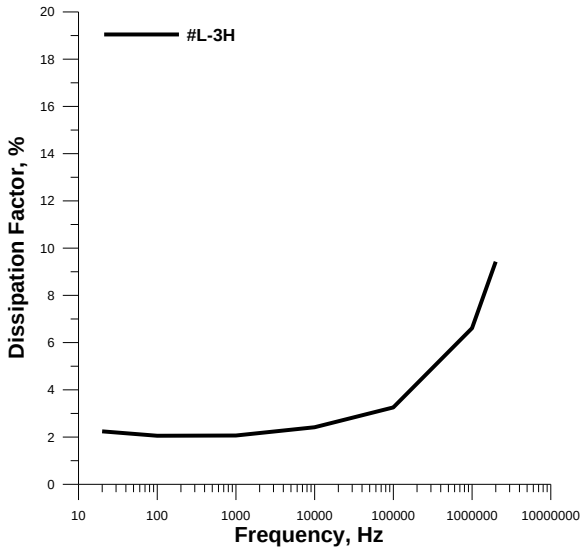
**Test Results:**

**Test #1: Capacitance & Dissipation Factor vs. Frequency (20Hz – 2MHz)**
(@ 1Vrms, 0V dc-bias, room temperature)

| Freq., Hz | CS-18-13-4 (#L-3H) | |
|---|---|---|
| | Cap, nF | DF, % |
| **20** | 3.386 | 2.239 |
| **100** | 3.308 | 2.052 |
| **1,000** | 3.212 | 2.065 |
| **10,000** | 3.112 | 2.412 |
| **100,000** | 2.996 | 3.252 |
| **1,000,000** | 2.842 | 6.608 |
| **2,000,000** | 2.777 | 9.423 |
| Used equipment: Keysight E4980A precision LCR meter.<br>Measured uncertainty: C, DF ±0.1%.<br>Room temperature: 19.2°C. Relative humidity: 49.2%. | | |

| Freq., Hz | CS-18-13-4 (#L-3H) |
|---|---|
| | Estimated Dielectric Constant |
| **20** | 8218 |
| **100** | 8029 |
| **1,000** | 7796 |
| **10,000** | 7553 |
| **100,000** | 7271 |
| **1,000,000** | 6898 |
| **2,000,000** | 6740 |

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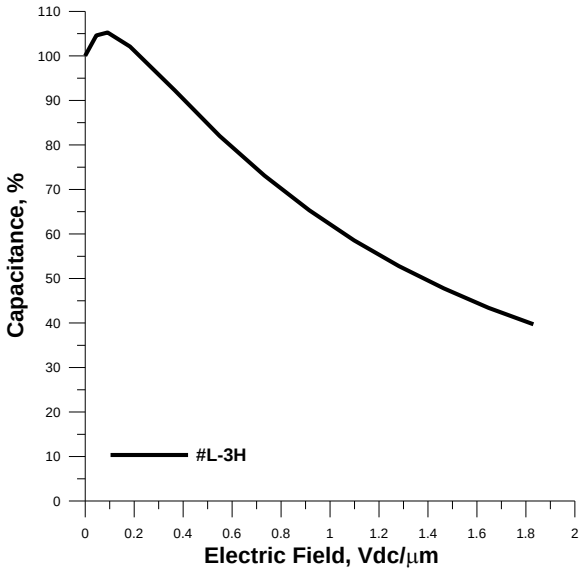
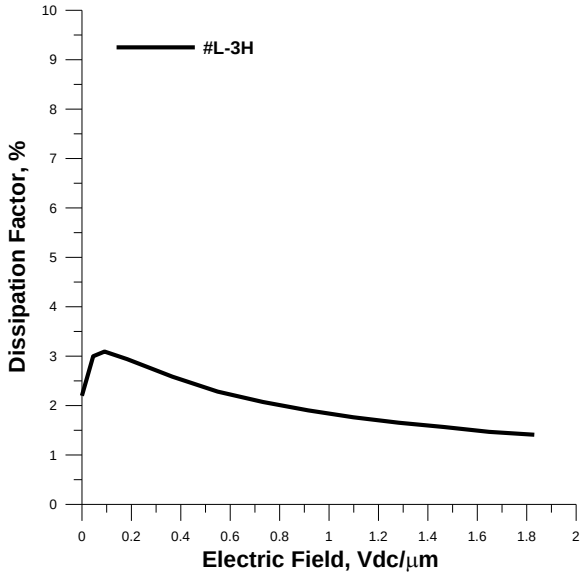
**Test #2: Capacitance & Dissipation Factor vs. dc-bias (up to 1000V)**
(@ 1 kHz, room temperature)

| dc-bias, V | CS-18-13-4 (#L-3H) | |
|---|---|---|
| | Cap, nF | DF, % |
| **0** | 3.089 | 2.197 |
| **25** | 3.231 | 2.996 |
| **50** | 3.251 | 3.091 |
| **100** | 3.154 | 2.938 |
| **200** | 2.849 | 2.584 |
| **300** | 2.533 | 2.281 |
| **400** | 2.258 | 2.071 |
| **500** | 2.017 | 1.901 |
| **600** | 1.808 | 1.762 |
| **700** | 1.630 | 1.652 |
| **800** | 1.475 | 1.565 |
| **900** | 1.340 | 1.467 |
| **1,000** | 1.226 | 1.408 |
| Used equipment: Keysight E4980A precision LCR meter.<br>Measured uncertainty: C, DF ±0.1%.<br>Room temperature: 19.2°C. Relative humidity: 49.2%. | | |

| dc-bias, V | CS-18-13-4 (#L-3H) | |
|---|---|---|
| | E, V/ μm | Cap, % |
| **0** | 0.000 | 100.000 |
| **25** | 0.046 | 104.597 |
| **50** | 0.092 | 105.244 |
| **100** | 0.183 | 102.104 |
| **200** | 0.366 | 92.230 |
| **300** | 0.549 | 82.001 |
| **400** | 0.732 | 73.098 |
| **500** | 0.916 | 65.296 |
| **600** | 1.099 | 58.530 |
| **700** | 1.282 | 52.768 |
| **800** | 1.465 | 47.750 |
| **900** | 1.648 | 43.380 |
| **1,000** | 1.831 | 39.689 |

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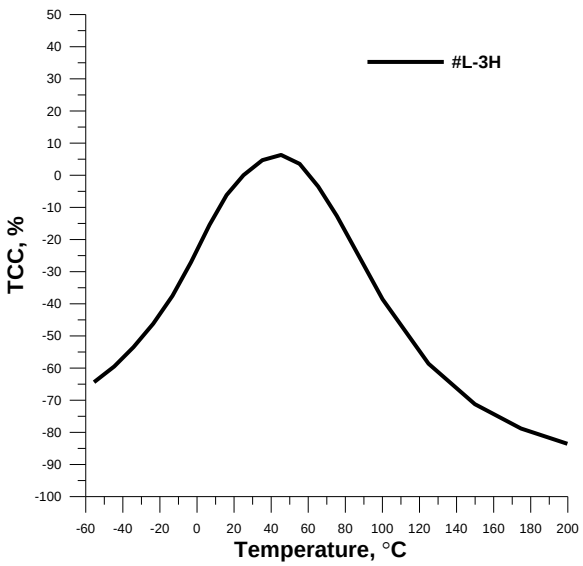
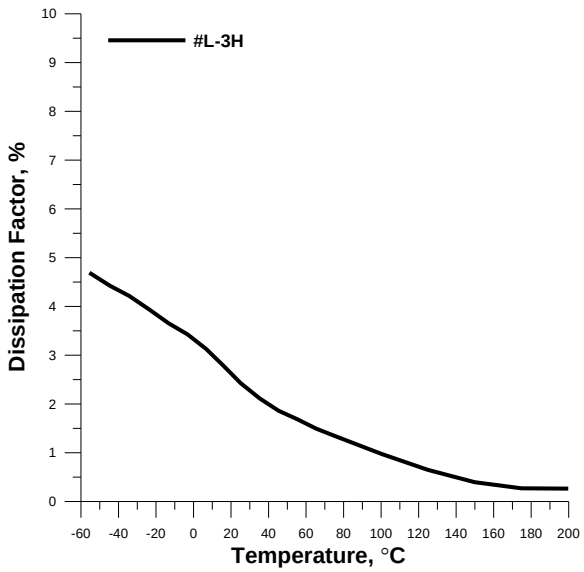
**Test #3: Temperature Coefficient of Capacitance**
(@ 1 kHz, -55°C – 200°C temperature range, 0V dc-bias)

| Temp., °C | CS-18-13-4 (#L-3H) | |
|---|---|---|
| | Cap, % | DF, % |
| **-55** | -64.41 | 4.69 |
| **-45** | -59.52 | 4.42 |
| **-35** | -53.49 | 4.21 |
| **-25** | -46.23 | 3.94 |
| **-15** | -37.54 | 3.65 |
| **-5** | -27.07 | 3.43 |
| **5** | -15.42 | 3.12 |
| **15** | -6.17 | 2.78 |
| **25** | 0.00 | 2.43 |
| **35** | 4.68 | 2.11 |
| **45** | 6.29 | 1.86 |
| **55** | 3.52 | 1.69 |
| **65** | -3.52 | 1.49 |
| **75** | -12.65 | 1.34 |
| **100** | -38.60 | 0.98 |
| **125** | -58.66 | 0.65 |
| **150** | -71.24 | 0.39 |
| **175** | -78.82 | 0.27 |
| **200** | -83.57 | 0.26 |

Used equipment: HP 4278A Capacitance meter and Delta 9023 environmental chamber.
Measured uncertainty: C, DF ±0.25%.
Room temperature: 19.2°C. Relative humidity: 49.2%.

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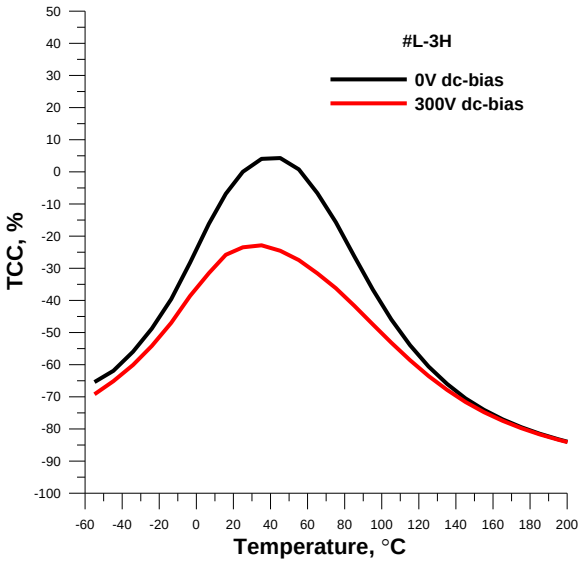
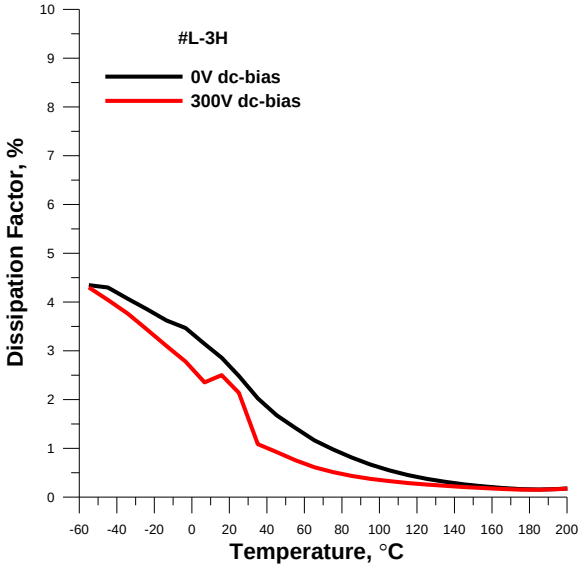
**Test #4: Temperature Coefficient of Capacitance at dc-bias**
(@ 1 kHz, -55°C – 200°C temperature range, 300V dc-bias)

| Temp., °C | CS-18-13-4 (#L-3H) | | | |
|---|---|---|---|---|
| | 0V dc-bias | | 300V dc-bias | |
| | Cap, % | DF, % | Cap, % | DF, % |
| **-55** | -65.44 | 4.35 | -69.23 | 4.30 |
| **-45** | -61.91 | 4.30 | -65.16 | 4.04 |
| **-35** | -55.98 | 4.06 | -60.10 | 3.76 |
| **-25** | -48.79 | 3.85 | -54.19 | 3.44 |
| **-15** | -39.63 | 3.62 | -47.00 | 3.10 |
| **-5** | -28.24 | 3.47 | -38.63 | 2.78 |
| **5** | -16.18 | 3.14 | -31.53 | 2.35 |
| **15** | -6.86 | 2.86 | -25.82 | 2.50 |
| **25** | 0.00 | 2.48 | -23.51 | 2.14 |
| **35** | 4.02 | 2.02 | -22.87 | 1.09 |
| **45** | 4.28 | 1.68 | -24.59 | 0.92 |
| **55** | 0.76 | 1.42 | -27.47 | 0.75 |
| **65** | -6.65 | 1.16 | -31.61 | 0.61 |
| **75** | -15.69 | 0.98 | -36.22 | 0.51 |
| **85** | -26.27 | 0.81 | -41.68 | 0.43 |
| **95** | -36.64 | 0.67 | -47.48 | 0.37 |
| **105** | -45.95 | 0.55 | -53.19 | 0.33 |
| **115** | -53.95 | 0.45 | -58.64 | 0.29 |
| **125** | -60.61 | 0.37 | -63.54 | 0.26 |
| **135** | -66.03 | 0.31 | -67.88 | 0.23 |
| **145** | -70.50 | 0.26 | -71.62 | 0.21 |
| **155** | -74.08 | 0.22 | -74.80 | 0.18 |
| **165** | -77.04 | 0.19 | -77.49 | 0.17 |
| **175** | -79.47 | 0.16 | -79.77 | 0.15 |
| **185** | -81.50 | 0.15 | -81.71 | 0.15 |
| **195** | -83.22 | 0.16 | -83.37 | 0.16 |
| **200** | -84.00 | 0.18 | -84.11 | 0.18 |

Used equipment: HP 4278A Capacitance meter and Delta 9023 environmental chamber.
Measured uncertainty: C, DF ±0.25%.
Room temperature: 19.2°C. Relative humidity: 49.2%.

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## Test #5: INSULATION RESISTANCE

(@ 1000V, RT and 125°C)

| **Electrical Parameters** | **CS-18-13-4 (#L-3H)** |
|---|---|
| | **Room Temperature** |
| **IR, Ω** | $9.23*10^{12}$ |
| **ρ, Ω*m** | $4.19*10^{11}$ |
| **R*C, MΩ*μF** | 28908.0 |
| | **125°C** |
| **IR, Ω** | $2.05*10^{12}$ |
| **ρ, Ω*m** | $9.31*10^{10}$ |
| **R*C, MΩ*μF** | 2569.6 |
| Used equipment: Beckman Megaohmmeter and Delta 9023 environmental chamber.<br>Measured uncertainty: IR ±0.25%.<br>Room temperature: 19.2°C. Relative humidity: 49.2%. | |

**Test #6: Highly Accelerated Life Test**
(@ 1000V, 180°C, 100h)

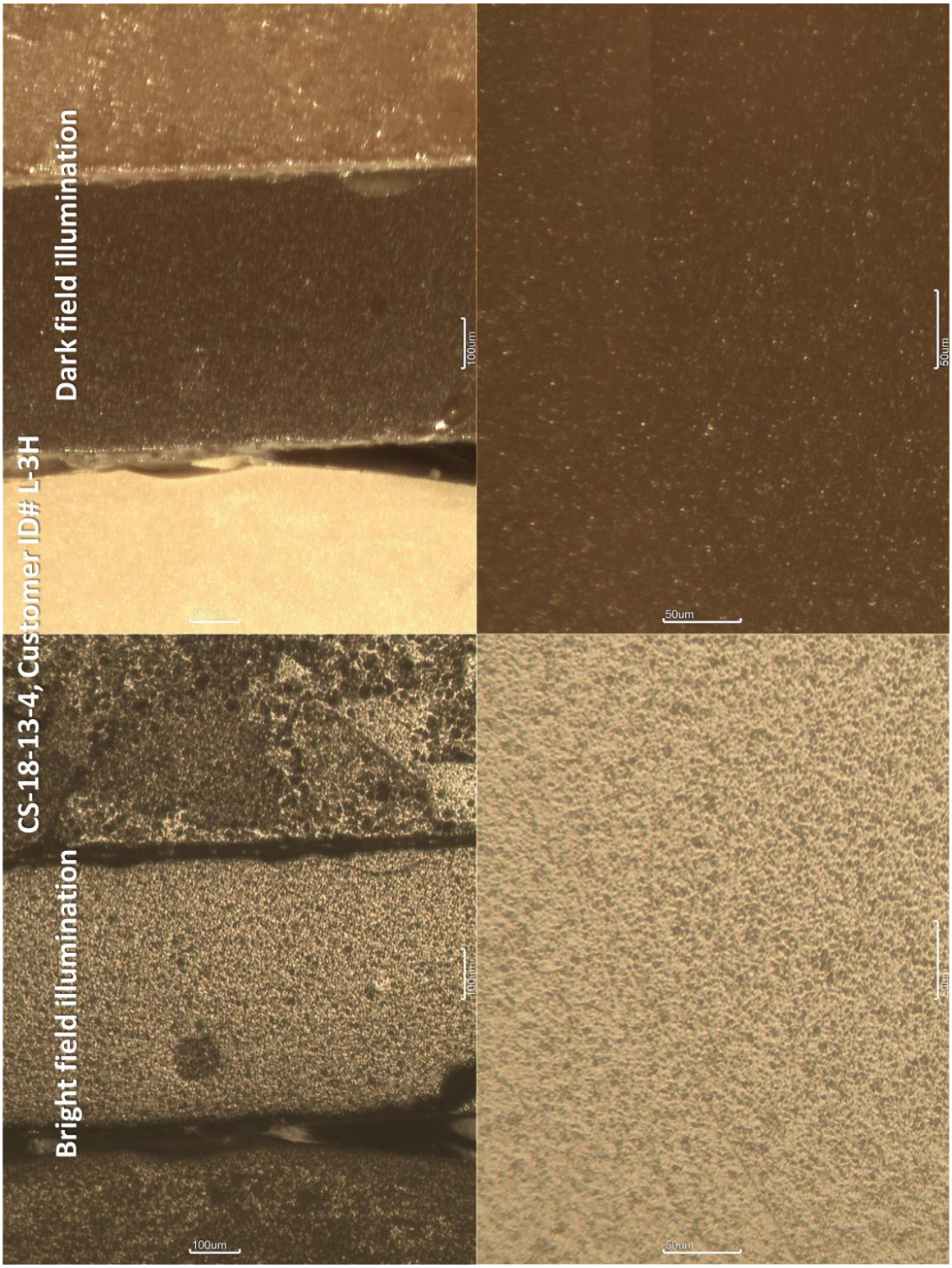
| **Time, h** | **CS-18-13-4 (#L-3H)** |
|---|---|
| | **IR, Ω** |
| **2** | $1.6*10^{11}$ |
| **12** | $8.9*10^{10}$ |
| **24** | $9.4*10^{10}$ |
| **36** | $9.6*10^{10}$ |
| **48** | $9.9*10^{10}$ |
| **60** | $9.9*10^{10}$ |
| **72** | $1.1*10^{11}$ |
| **84** | $1.3*10^{11}$ |
| **96** | $1.4*10^{11}$ |
| **100** | $1.5*10^{11}$ |
| Used equipment: Custom made HT-HALT system.<br>Measured uncertainty: IR ±0.25%.<br>Room temperature: 19.2°C. Relative humidity: 49.2%. | |

## Test #7: AC and DC Dielectric Breakdown Strength

(@ Room temperature)

| **Electrical Parameters** | **CS-18-13-4 (#L-3H)** |
|---|---|
| | **DC Dielectric Breakdown** |
| **Ultimate Dielectric Breakdown, Vdc** | **>6000** |
| **Dielectric Breakdown Strength, Vdc/μm** | **>11.0** |
| | **AC Dielectric Breakdown** |
| **Ultimate Dielectric Breakdown, Vac** | **3239** |
| **Dielectric Breakdown Strength, Vac/μm** | **5.9** |
| Used equipment: Chroma Sentry Plus HiPot tester 19073.<br>Measured uncertainty ±0.25%.<br>Room temperature: 19.2°C. Relative humidity: 49.2%. | |

**Test #8:** Cross-section and optical/SEM microstructure evaluation.

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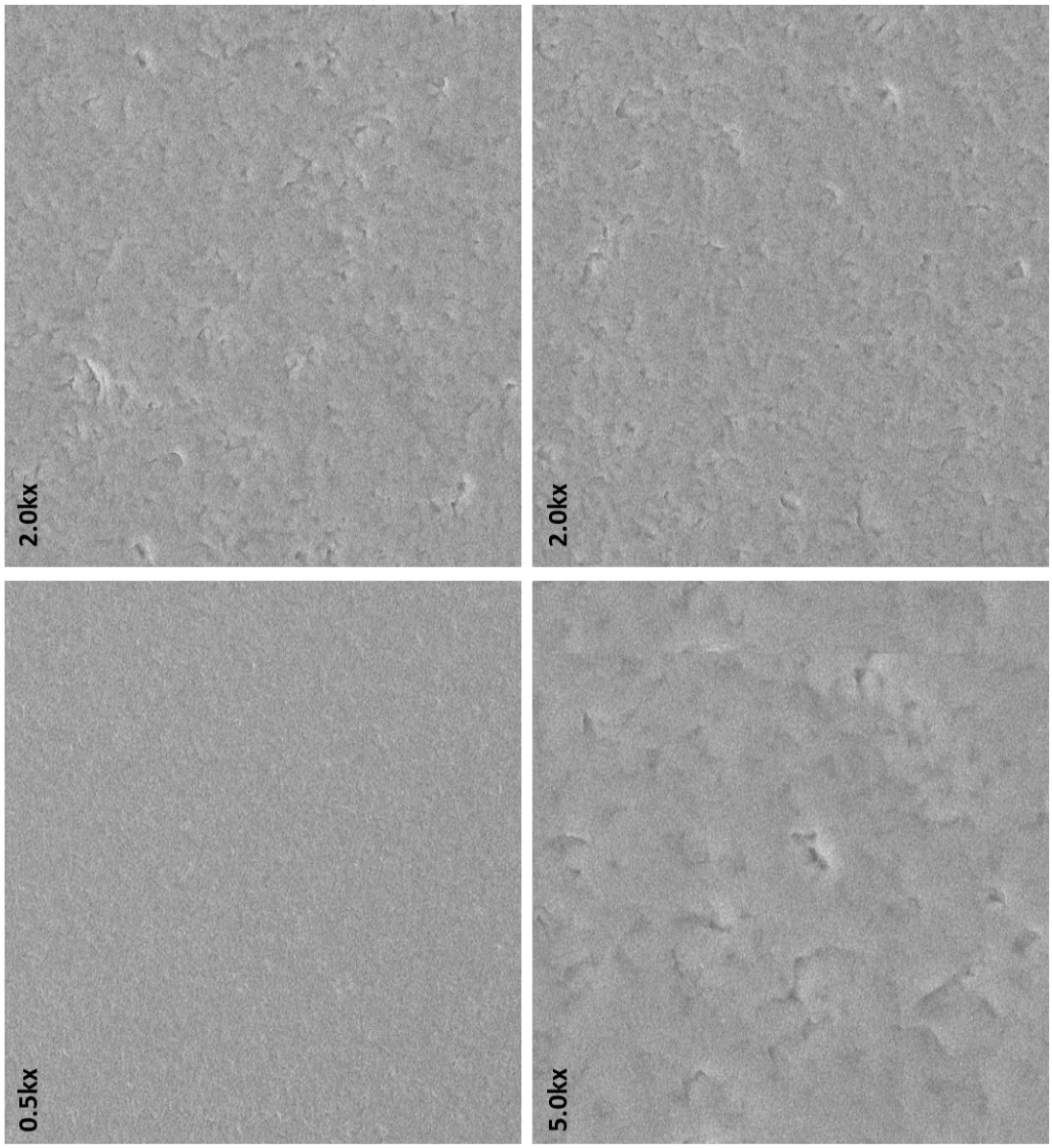
**CS-18-13-4, Customer ID# L-3H**

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## 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: Capacitance & Dissipation Factor vs. Frequency (20Hz – 2MHz)

Electrical parameters at variable frequencies were measured using Keysight E4980A Precision LCR Meter. The measurements were performed at room temperature at 1Vrms voltage condition. Open/short correction was performed prior to measurements in order to compensate for stray admittance and residual impedance of the probe. The measurements were performed one time per sample. Dielectric constant of the densified ceramic and polymer-ceramic disks was estimated by using parallel plate capacitor model. The thickness of the disks and the area of sputtered gold electrodes were measured using a precision micrometer, while the capacitance was taken from measurements of the capacitance at variable frequencies at room temperature.

### Test #2: Capacitance & Dissipation Factor vs. dc-bias (up to 1000V)

Electrical parameters at variable dc-biases were measured using Keysight E4980A Precision LCR Meter coupled with Acopian High Voltage Power Supply and ART ASY0360 HV Bias Module. The measurements were performed at room temperature at 1Vrms voltage condition. Open/short correction was performed prior to measurements in order to compensate for stray admittance and residual impedance of the probe. The measurements were performed one time per sample.

### Test #3: Temperature Coefficient of Capacitance

Temperature coefficient of capacitance was measured using HP 4278A 1kHz/1MHz Capacitance Meter coupled with Rokem Scanner and Delta 9023 Environmental Chamber. The measurements were performed in the temperature range from -55°C to 200°C. Three minutes were allowed for temperature stabilization prior to measurements of capacitance and dissipation factor at each temperature steps. Open/short correction was performed prior to measurements in order to compensate for stray admittance and residual impedance of the scanner. The measurements were performed one time per sample.

**Test #4: Temperature Coefficient of Capacitance at dc-bias**

Temperature coefficient of capacitance at dc-bias was measured using HP 4278A 1kHz/1MHz Capacitance Meter coupled with Rokem Scanner, Sorensen DLM 300-2 Programmable dc Power Supply, ART ASY0360 HV Bias Module, and Delta 9023 Environmental Chamber. The measurements were performed in the temperature range from -55°C to 200°C. Three minutes were allowed for temperature stabilization prior to measurements of capacitance and dissipation factor at each temperature steps with and without 300V dc-bias. Open/short correction was performed prior to measurements in order to compensate for stray admittance and residual impedance of the scanner. The measurements were performed one time per sample.

**Test #5: Insulation Resistance**

Insulation resistance at 1000V dc-bias was measured using Beckman Megaohmmeter coupled with Delta 9023 Environmental Chamber. The measurements were performed at room temperature and at 125°C. 10 minutes were allowed for the temperature stabilization inside the chamber before each measurements. The insulation resistance was recorded after 2 minutes of dc-bias being applied. The measurements were performed one time per sample.

**Test #6: Highly Accelerated Life Test (HALT)**

Highly Accelerated Life Test (HALT) was performed at 180°C under the applied 1000V dc-bias using a custom made high temperature HALT system consisting of Agilent 34972A LXI Data Acquisition / Switch Unit, Acopian High Voltage Power Supply, and Across Environmental Chamber. The insulation resistance of the samples was recorded every 30 minutes for the duration of 100 hours. The measurements were performed one time per sample.

**Test #7: AC and DC Dielectric Breakdown Strength**

AC and DC dielectric breakdown strength measurements at room temperature were performed using Chroma Sentry Plus HiPot tester 19073. The ultimate dielectric breakdown both for AC and DC conditions was recorded during the voltage ramp up with the constant rate of 100V/sec. The samples were coated with a silicon oil to prevent surface arcing. The measurements were performed one time per sample.

**Test #8: Cross-section and optical/SEM microstructure evaluation**

Microstructural evaluation of the samples were performed using both optical, Unitron TMS-3906, and scanning electron, ISI-100B, microscopes. The ceramic samples were cross-sectioned and polished down to 1 micron alumina powder finish. Both bright field and dark field illumination was used in the optical microscope to reveal different features of the samples' microstructure.

**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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