



Representative Test Procedures for Customer Evaluations

Ioxus characterizes its products with constant current, constant voltage charge and constant current discharge cycles. This document details tests which will produce results that are closest to specifications listed in Ioxus' data sheets. Customers may find such tests useful in evaluating Ioxus products prior to application specific testing.

The following list details equipment typically required to perform characterization tests:

- Programmable bi-directional DC power supply and load or separate programmable DC power supply and programmable load
- Voltage vs. time measurement and recording device capable of ≥ 100 samples/s acquisition rates (digital oscilloscope, high speed DAQ, etc.)
- Current vs. time measurement and recording device (current can be measured by voltage recording device via a DC current to voltage transducer or shunt)
- 1 kHz impedance tester, LCR meter, or 1 kHz sine wave signal generator and oscilloscope

It should be noted that other analogs for the above described equipment can be used to achieve reasonable results. For example a properly sized and characterized resistor combined with a relay/contacter can be used in place of the programmable load bank or a properly sized battery could be used as a DC power supply, etc. The procedures in this document assume use of the equipment listed above, how the tests are actually implemented is up to the end user.

Unless otherwise noted, all measurements are to be taken in atmospheric conditions of $23 \pm 3^\circ\text{C}$, 25% - 75% relative humidity, and pressure 86 - 106 kPa.

Setup

Set the voltage and current limits on the DC power supply/load and turn the supply output off. The upper voltage limit is the rated cell voltage times the number of cells in series. The lower voltage limit is 0.1 V. The current limits can be anything less than the 1 second discharge rated current for the cell. Calculate the discharge current for the tests using the following formulas. Any digits after the first two significant digits shall be truncated for calculated discharge currents.

For Capacitance:

$$I_d \text{ Capacitance} = (4 * V_{RU} * C)/1000$$

For DC-ESR:

$$I_d \text{ DC ESR} = 10 * I_d \text{ Capacitance}$$

Values for the discharge current are given in table 1 for typical Ioxus products. These currents should be used for single cell or series only module configurations (1P configurations only). For parallel module configurations the formulas above should be used directly with the module rating information.

Single Cell Capacitance	I_d DC ESR	I_d Capacitance
100 F	10 A	1.0 A
350 F	37 A	3.7 A
600 F	64 A	6.4 A
1200 F	120 A	12 A
2000 F	210 A	21 A
3000 F	320 A	32 A

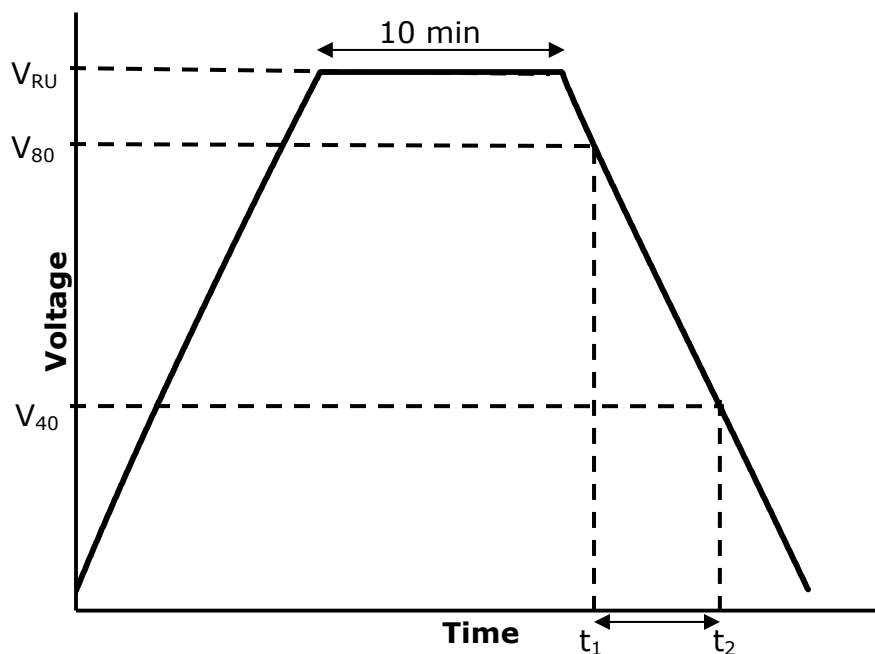
Table 1: Discharge Currents for Testing
 (Single Cell or 1P Module Configurations only)

Charge current can be anything less than the maximum continuous current specification. Ioxus typically uses the I_d Capacitance current.

Connect the load cables and voltage sense leads to the device under test. Use 4-wire connections for voltage sense at device terminals when possible to eliminate measurement error due to voltage drop in load cables. Connect voltage data acquisition equipment to device terminals and current data acquisition equipment to current transducer. A data acquisition rate of 1 – 10 samples/s can be used for most tests. However, for 10 ms ESR measurement, set the acquisition rate to 100 samples/s or faster.

IEC 62391-1 Capacitance Test

Start data acquisition at ≥ 1 samples/s and verify that recorded data is valid. Turn power supply output on and observe until power supply changes from constant current to constant voltage control. Start a timer and let power supply apply constant voltage for 10 minutes. After 10 minutes, turn off charging output and turn on discharge load. Discharge load current should be set to I_d Capacitance. Turn off discharge load upon reaching the minimum voltage limit or as low as the load can be controlled.

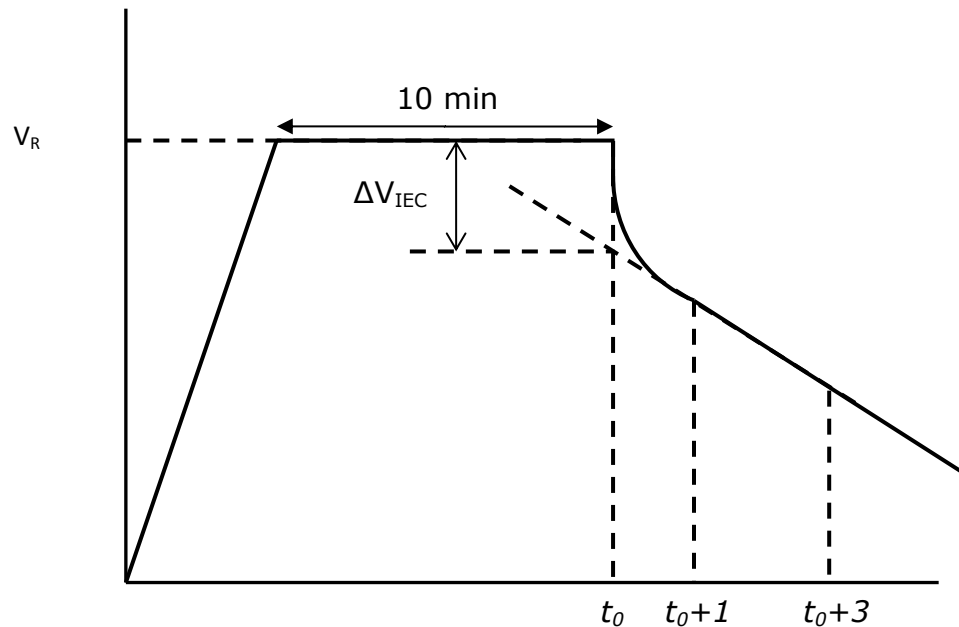


Capacitance is calculated from the discharge time from 80% of V_{RU} to 40% of V_{RU} multiplied by discharge current divided by the change in voltage from 80% to 40% of V_{RU} . V_{RU} is the upper rated voltage limit or upper voltage limit the device is charged to. I_d is the nominal discharge current and $(t_2 - t_1)$ is the time in seconds for the device to discharge from 80% to 40% of V_{RU} at current I_d .

$$Capacitance = I_d * \frac{(t_2 - t_1)}{V_{80} - V_{40}}$$

IEC 62391-1 DC ESR Test

Start data acquisition at ≥ 10 samples/s and verify that recorded data is valid. Turn power supply output on and observe until power supply changes from constant current to constant voltage control. Start a timer and let power supply apply constant voltage for 10 minutes. After 10 minutes, turn off charging output and turn on discharge load. Discharge load current should be set to I_d DC-ESR. Turn off discharge load upon reaching the minimum voltage limit or as low as the load can be controlled.

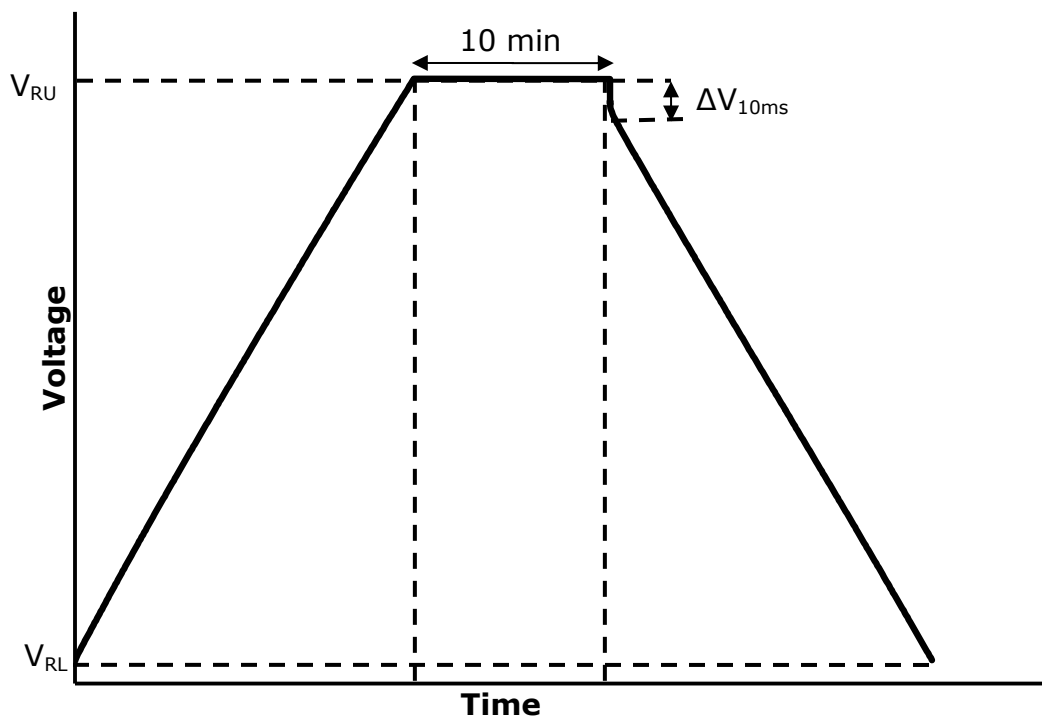


Draw a best fit line to the data from the straight portion of the discharge voltage curve and extrapolate to the discharge start time, t_0 . Ioxus recommends the straight portion of the discharge voltage curve between t_0+1 and t_0+3 seconds for the most accurate results. ΔV_{IEC} is the difference between voltage measured just prior to t_0 and the value of the best fit line at t_0 . I_d is the nominal current during the discharge. $DC\ ESR_{IEC}$ is calculated from the voltage difference calculation divided by discharge current.

$$DC\ ESR_{IEC} = \frac{\Delta V_{IEC}}{I_d}$$

10 mS DC ESR Test

Start data acquisition at ≥ 100 samples/s and verify that recorded data is valid. Turn power supply output on and observe until power supply changes from constant current to constant voltage control. Start a timer and let power supply apply constant voltage for 10 minutes. After 10 minutes, turn off charging output and turn on discharge load. Discharge load current should be set to I_d DC-ESR. Turn off discharge load after ΔV_{10ms} measurement has been obtained or upon reaching the minimum voltage limit or as low as the load can be controlled.



10 ms DC ESR is calculated from the measured voltage drop at 10 ms into a discharge divided by discharge current. ΔV_{10ms} is the difference between voltage measured just prior to discharge and the voltage measured at the device terminals at 10 ± 5 ms into a discharge. I_d is the nominal current during the first 10 ± 5 ms of discharge. The 10 ms DC ESR measurement can be taken by equipment which is designed to supply a short burst of dc current pulses and measure & average the voltage drops at the end of 10 ms pulses.

$$DC\ ESR_{10\ ms} = \frac{\Delta V_{10ms}}{I_d}$$

AC 1 kHz Impedance Test

Set impedance test equipment to generate a 1 kHz ± 20 Hz AC signal. Using a 4-wire connection, connect the impedance tester cables to the terminals of the device. Set signal amplitude such that RMS current is between 1 – 10 mA. AC impedance is calculated as the ratio between effective AC RMS voltage and AC RMS current across the terminals of the device.

$$AC\ Impedance = \frac{V_{rms}}{I_{rms}}$$

Leakage Current Test

Discharge device to lower rated voltage and hold at lower rated voltage, or connect a shorting wire across the terminals in the case of Ultracapacitors, for a minimum of 12 hours. Connect device to power supply and charge to rated voltage in 30 minutes or less. Disconnect the power supply cables from one side of the device and connect a 1 Ω $\pm 1\%$ resistor between the disconnected power supply cable and device terminal. Continue to provide constant voltage charge through the resistor for 72 hours. The voltage measured across the 1 Ω resistor after 72 hours of constant voltage charge is the leakage current in Amps.

For optimal results a 5½ digit or better digital multimeter or voltage data acquisition device should be used to measure voltage across the resistor. Use a ¼ W or higher power rated resistor so that the resistor's maximum power dissipation is not exceeded at initial connection between cell and power supply. Automated data acquisition can be used to obtain leakage current vs. time or to average several sequential data points to reduce measurement error. Multiple devices of same voltage can be tested in parallel using same power source if each is connected through an independent resistor. It should be noted that leakage current is temperature sensitive, on the order of a factor of 2 change in value for a 10°C increase in temperature, so a well regulated environment will produce the most consistent results.

Additional (Non-Specification) Testing:

Self-Discharge Test

Discharge device to lower rated voltage and hold at lower rated voltage, or connect a shorting wire across the terminals of a discharged ultracapacitor, for a minimum of 12 hours. Connect device to power supply and charge to rated voltage in 30 minutes or less. Continue to provide constant voltage charge for 8 hours. Disconnect the power supply and let device sit at open circuit for 24 hours. Measure voltage at the device terminals after 24 hours and record as V_{SD} . Testing may be continued beyond 24 hours if desired. Optionally, automated data acquisition equipment may be used to record the voltage during the test.

$$\%_{SD} = 100 * \frac{(V_{RU} - V_{SD})}{V_{RU}}$$

Where: $\%_{SD}$ = Percentage change in voltage during test (%)

V_{SD} = Voltage measured at end of test (V)

Calculations:

Maximum Energy Density:

$$E_{MAX} = \frac{1}{2} \frac{CV_{RU}^2}{3600}$$

$$E_{Max}^{Grav} = \frac{E_{Max}}{m}$$

$$E_{Max}^{Vol} = \frac{E_{Max}}{v}$$

Where: E_{Max} = Maximum energy available (Wh)

E_{Max}^{Grav} = Maximum gravimetric energy density (Wh/kg)

E_{Max}^{Vol} = Maximum volumetric energy density (Wh/L)

m = Mass (kg)

v = Volume (L)

Impedance Matched Power Density:

$$P_d^{Max,Grav} = \frac{V_{RU}^2}{4 * ESR_{AC} * m}$$

$$P_d^{Max,Vol} = \frac{V_{RU}^2}{4 * ESR_{AC} * v}$$

Where: P_d^{Max} = Maximum Power density at impedance match (W/kg) or (W/L)

Usable Power Density:

$$P_d = \frac{0.12 V_{RU}^2}{ESR_{DC,10mS} * m}$$

Where: P_d = usable power density as defined by IEC 62391-2 (W/kg)

Peak Current (1 sec):

$$I_{peak}^{1sec} = \frac{\frac{1}{2} C V_{RU}}{C * ESR_{DC,10mS} + 1}$$

Where: I_{peak}^{1sec} = Peak current for 1 sec discharge from V_{RU} to $\frac{1}{2} V_{RU}$ (A)

Short Circuit Peak Current:

$$I_{Short\ Circuit} = \frac{V_{RU}}{ESR_{DC,10mS}}$$