Note: Revision history dates and details contained in final section of this document

Note: **Refer to the relevant PDM system for complete approval history and details**

Capacitance and ESR Test Procedure - UCAP

Standard Approvers for Changes to this Document	
Standard approver(s) (List by position title) ▪ Director of Test and Validation ▪ Director of Product & Manufacturing Engineering	3888 Calle Fortunada, SAN DIEGO, CA 92123, USA Capacitance and ESR Test Procedure - UCAP

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1013823	**9**			**68911**	

Table of Contents

1. Purpose

The purpose of this test is to evaluate the Capacitance and ESR characteristics of an Ultracapacitor cell or module.

2. Scope

This document provides a standard test procedure that is capable of measuring and calculating CAP and ESR on both Ultracapacitor cells and modules with the Maxwell Six Step and IEC methods.

3. Reference Documents

- Maxwell Ultracapacitor Safety Data Sheet (DOC No: 3000389-EN)
- IEC 62391: Fixed electric double-layer capacitors for use in electronic equipment
- IEC 62576: Electric double-layer capacitors for use hybrid electric vehicles
- Maxwell Ultracapacitor Data Sheet
- Application Note: Maxwell Harmonized CAP and ESR Test
- Released_Scripts (DOC No: 3002136)

4. Definitions

- **UCAP:** A Maxwell Ultracapacitor cell or module
- **CAP:** Capacitance of a cell or module
- **ESR:** The equivalent series resistance of a cell or module
- $\boldsymbol{C_R}$**:** The rated CAP of the cell or module at 25°C in farads
- $\boldsymbol{R_N}$**:** The rated ESR of the cell or module at 25°C in Ohms
- $\boldsymbol{V_R}$**:** The rated voltage of the cell or module in volts
- $\boldsymbol{V_M}$**:** $\frac{1}{2}V_R$ or the minimum discharge voltage for the measurement specified in volts
- $\boldsymbol{Vs}$**:** The storage voltage of the cell or module in volts
- $\boldsymbol{I_D}$**:** The discharge test current in amps
- $\boldsymbol{T_R}$**:** The rest time after discharge for voltage rebound to be measured in seconds
- $\boldsymbol{N_S}$**: T**he number of the cells in series of the module
- $\boldsymbol{V, I, \ T, and\ N}$**:** The voltage, current, time, and sample number, at a single measurement point

5. Safety

The general safety warnings and material hazard information included in Maxwell Ultracapacitor Safety Data Sheet (DOC No: 3000389-EN) should be read and understood by the test operator.

6. Test Equipment

A charge/discharge tester with high speed data acquisition system is required. If the capacitance and ESR measurements are under certain temperature other than room temperature, the test unit must be placed in a temperature controlled thermal chamber.

Requirements of Tester:

- Programmable charge and discharge cycler
- Data acquisition sample rate: equal to or faster than 100ms/sample
- Voltage measurement accuracy: ±0.1% (or better) of the rated voltage
    - Voltage measurement resolution: 1mV or better per cell

- Current measurement accuracy: ±0.1% or better of the test current
- Current slew rate from 0 to rated current: less than 100ms

Requirements of Temperature Control:

- Room temperature: 20-25°C
- Temperature other than room temperature: control accuracy ± 2°C or better

7. Test Setup

Please see the pictures below for the test setup, connection method and standard test fixtures in the test & validation lab and production lines for each test unit group.

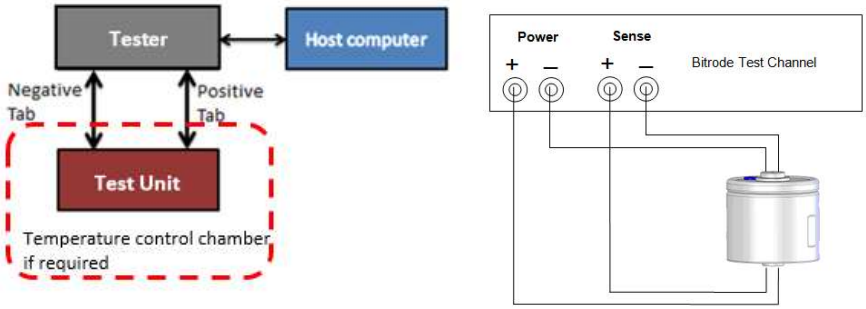

Figure 7.1 Test Setup and 4 Point Connection

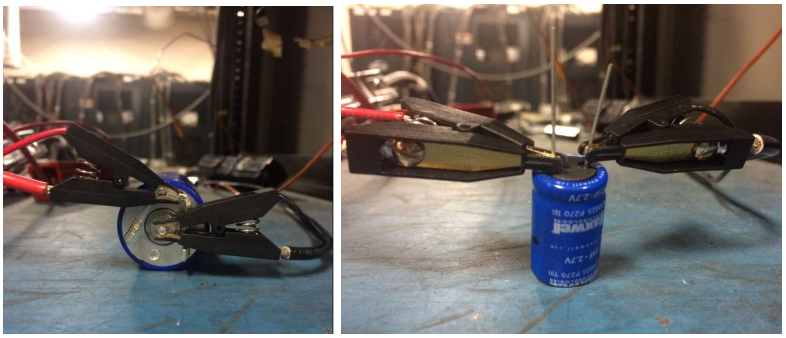

Figure 7.2 Small Cell 4 Point Connection

Figure 7.3 Module 4 Point Connection

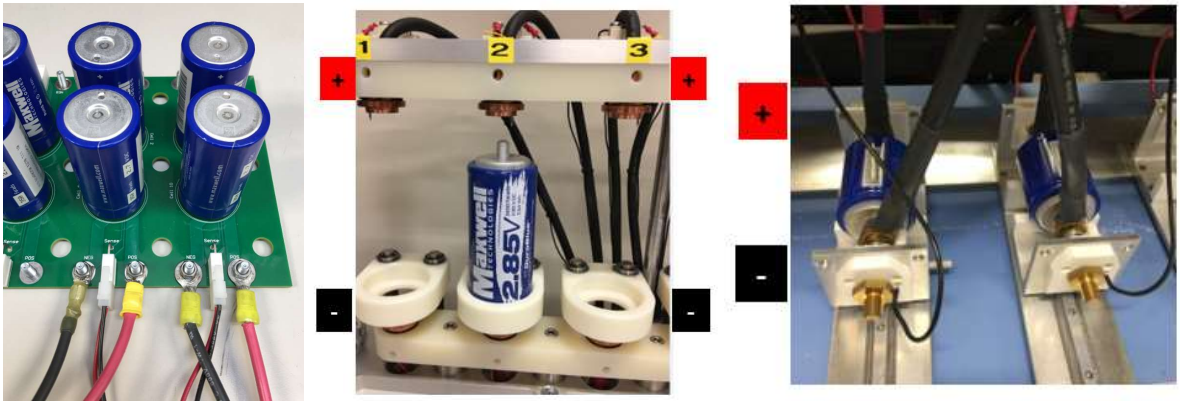

Figure 7.4 : D Cell and Large Cell Fixtures - T&V

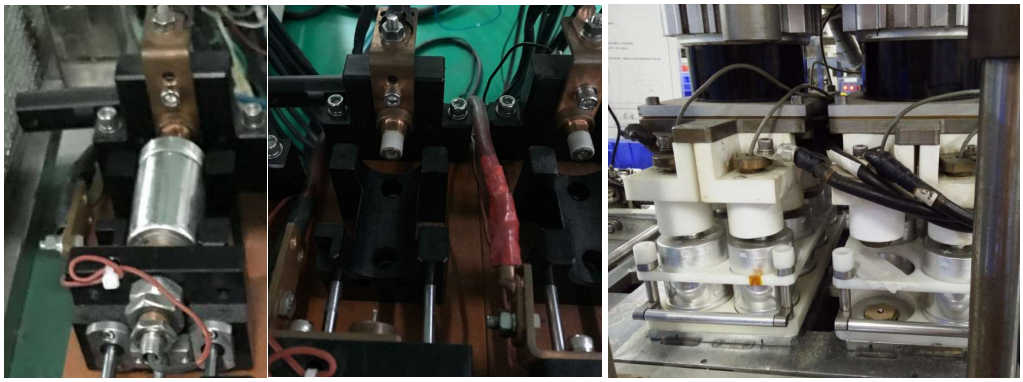

Figure 7.5 D Cell and Large Cell Fixture - Production

8. Test Program

8.1. Test Current & Voltage Profile

Below are the program steps written for the Bitrode charge/discharge cycle scripts to perform CAP/ESR. The scripts are released as an Access database under document number 3002136. Only current revision scripts released under this document number shall be used for qualifying tests.

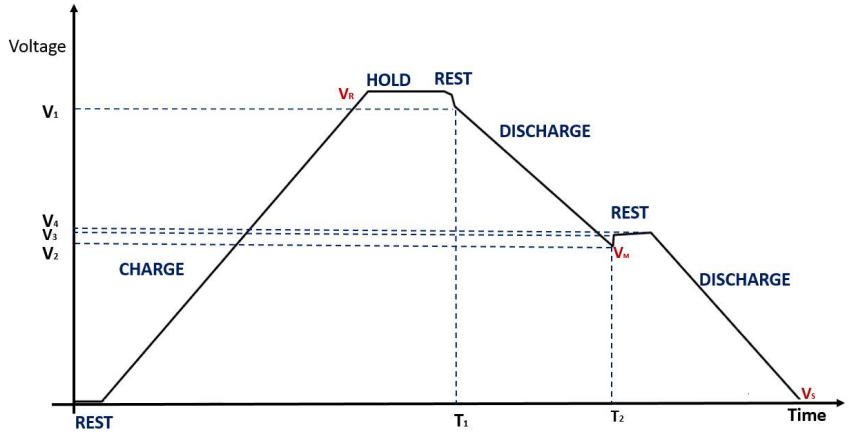

Figure 8.1 Voltage Profile for CAP&ESR Test

- ***Step 1**: **REST** for 1 sec*
  - *Sample: end of step*

- *Go to next step when step time reaches 1sec*

- ***Step 2: CHARGE** at current of I_D to a small voltage to check the sense wire connection*
  - *Constant Current at I_D*
  - *Voltage at V_R*
  - *Power at I_D*V_R*2*
  - *Sample: end of step*
  - *If Step time greater than 20 second, halt the test*
  - *Go to next step when voltage reaches 0.1 X V_R(or specified)*
- ***Step 3: CHARGE** at current of I_D to a voltage of V_R(or specified)*
  - *Constant Current at I_D*
  - *Voltage at V_R(or specified)*
  - *Power at I_D*V_R*2*
  - *Sample: end of step*
  - *Go to next step when voltage reaches V_R(or specified)*
- ***Step 4: HOLD** at voltage of V_R for 10 sec*
  - *Current at I_D*
  - *Voltage at V_R*
  - *Power at I_D*V_R*2*
  - *Sample: end of step*
  - *Go to next step when step time reaches 10 sec*
- ***Step 5**: **REST** for 1 sec*
  - *Sample: end of step(V_0,T_0)*
  - *Go to next step when step time reach 1 sec*
- ***Step 6**: **DISCHARGE** at current of I_D to a voltage of V_M*
  - *Current at I_D*
  - *Voltage at 0V*
  - *Power at I_D*V_R*2*
  - ***Sample: every 100 ms (I_1,V_1,T_1 : first sample when current reaches I_D)***
  - ***Sample: end of step(I_2,V_2,T_2)***
  - *Go to the next step when voltage is equal or less than V_M*
- ***Step 7**: **REST** for 5 sec*
  - ***Sample: every 100 ms (V_3,T_3 : sample at the first 100ms)***
  - ***Sample: end of step(V_4,T_4)***
  - *Go to next step when step time reaches 5 sec*
- ***Step 8: DISCHARGE** at current of I_D to a voltage of V_S + 0.1*
  - *Current at I_D*
  - *Voltage at V_s*
  - *Power at I_D*V_R*2*
  - *Sample: None*
  - *Go to next step when voltage reaches 0.1V*
- ***Step 9: DISCHARGE** at current of I_D to a voltage of V_S*
  - *Current at I_D*
  - *Voltage at V_s*
  - *Power at I_D*V_R*2*
  - *Sample: None*
  - *End test when voltage reaches V_S for more than 10sec*

where:

- I_D

- *Standard value for released product please refer to Maxwell product data sheet (100mA/F*CR) or test request specified*
- *Others refer to test request specified*
- *Required tester current accuracy: ≤ 0.1% of I_D*

- ***V_R***
  - *Rated voltage please refer to Maxwell product data sheet*

- ***V_M***
  - *½ of Rated voltage and please refer to Maxwell product data sheet or test request specified*
- ***V_S***
  - *Minimum voltage of cell (typical value: 0V) specified in the data sheet or test request specified*

8.2. Temperature Profile for Temperature Characterization Test (if required)

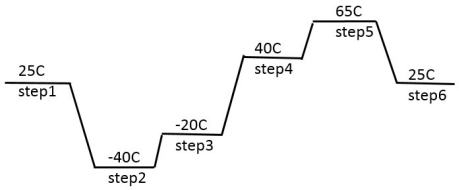

Figure 8.2 Temperature Profile for Temperature Charaterization

- Time at each step before CAP&ESR measurement: 4 hours
- Fully discharge cells before and after CAP&ESR test
- Temperature increase 1-5C/min between step

9. Test Sequence

1) Connect test unit to test hardware as shown in **chapter 7** using the four-point connection method or test fixture for power and sense lines.
2) Program tester per detailed test procedure in **chapter 8** .
3) Place the test unit in the test chamber if temperature control is required
4) Test unit must have been at test temperature for at least 4 hours
5) Test unit is fully discharged before the test
6) Perform test
7) Make sure the test unit back to its storage state of charge before removing from test.
8) Record output data and calculate Cap and ESR per detailed test procedure in the following section
9) **Pass Criteria**
   - **Room temperature**
     - **CAP: ≥ minimum value specified in the datasheet of the product or the test requirement specified**
     - **ESR: ≤ maximum value specified in the datasheet of the product or the test requirement specified**
   - **Other temperature**
     - **CAP: < ±10% of room temperature value or the test requirement specified**
     - **ESR: <±100% of room temperature value or the test requirement specified**

10. Maxwell Standard Capacitance and ESR Calculation

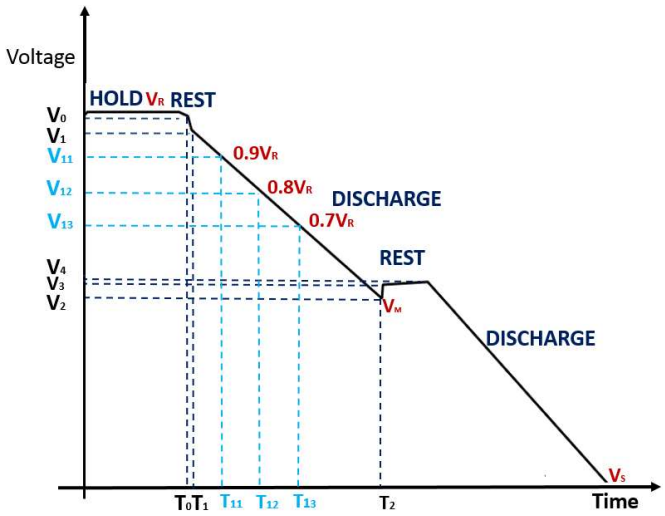

Figure 10.1 Capacitance and ESR Calculation Samples

The following formulas provide the CAP and ESR values with CAP calculated over the full current discharge time, and ESR calculated from the voltage rebound 5 second after current release. In addition, the ESR due to voltage rebound 100ms after current release can be calculated as it is indicative of the purely ohmic losses within the cell.

$$CAP = |I_2| \frac{T_2 - T_1}{V_1 - V_2} \text{ (F)}$$

$$5sec\ ESR = \frac{V_4 - V_2}{|I_2|} (\Omega)$$

$$100ms\ ESR = \frac{V_3 - V_2}{|I_2|} (\Omega)$$

Equation 10.1 Maxwell 6 Step CAP and ESR

11. CAP and ESR Calculation with IEC Method as Reference

If the discharge step at step 7 is sampled at 100 ms or less, the same test data can be used to calculate the CAP and ESR values according to IEC method.

11.1. IEC 62391 CAP and ESR

The following formulas provide the IEC 62391 CAP and ESR values. The IEC 62391 CAP is calculated using the charge released between $0.8\mathrm{U_R}$ and $0.4V_R$, and the ESR is found by the voltage drop at start of discharge as backwards projected from the slop between the $0.8\mathrm{U_R}$ and $0.4\mathrm{U_R}$ (or $\mathrm{U_M}$ by using the above 6 step test data) voltage points .

$$CAP = |I_2| \frac{T_2 - T_{12}}{V_{12} - V_2} \text{ (F)}$$

$$ESR = \frac{V_0 - V_{12} - (T_0 - T_{12}) \cdot \frac{V_2 - V_{12}}{T_2 - T_{12}}}{|I_2|} \text{ (Ω)}$$

Equation 11.1 IEC 62391 CAP and ESR

11.2. IEC 62576 CAP and ESR

The following formulas provide the IEC 62576 CAP and ESR values. The IEC 62576 CAP is calculated using the energy released between $0.9\mathrm{U_R}$ and $0.7V_R$, and the ESR is found by the voltage drop at start of discharge as backwards projected from the slope between the $0.9\mathrm{U_R}$ and $0.7\mathrm{U_R}$ voltage points.

$$CAP = 2 \frac{\sum_{i=N_{11}}^{N_{13}} I_i V_i (T_i - T_{i-1})}{{V_{13}}^2 - {V_{11}}^2} \text{ (F)}$$

$$ESR = \frac{V_0 - V_{11} - (T_0 - T_{11}) \cdot \frac{V_{13} - V_{11}}{T_{13} - T_{11}}}{|I_2|} \text{ (Ω)}$$

Equation 11.2 IEC 62576 CAP and ESR

12. Revision History

The table below contains detailed revision history for this document.

Rev.	Date	CO #	Revision Description	Originator
1	07/31/08	N/A	Production Release	Kenn Nugent
2	01/08/11	4738	Revised to current format and product models	Kenn Nugent
3	08/24/11	5040	Revised current table	Kenn Nugent
4	10/15/12	5244	No change to document (transfer back into IFS)	S. Zuiderweg
5	06/07/17	ECO-05114	Update to the modified 6 step method to remove the ESR impact to the capacitance calculation, add 100ms ESR and IEC CAP and ESR calculation values as reference.	R. Yan
6	10/20/17	ECO-05477	Update the test currents to align with datasheet specs. Revised room temperature to 20-25C to align w/ typical lab temperature.	R. Yan
7	11/10/17	ECO-05535	Add procedure for CAP&ESE temperature charaterization	R. Yan
8	3/2/2018	ECO-05728	Modified script profile to accommodate Bitrode ramp rate. Remove the test current table and refer to the production datasheet.	M. Wilk
9	7/30/2018	ECO-06122	Added information in regards to released Bitrode scripts.	M. Wilk