DOE/ID-10491

Electric Vehicle Capacitor Test Procedures Manual

Revision 0

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Published October 1994

Prepared for the Idaho National Engineering Laboratory
Under Subcontract C92-120319
and for the
U. S. Department of Energy
Assistant Secretary for Energy Efficiency and Renewable Energy (EE)
Under DOE Idaho Operations Office
Contract DE-AC07-94ID13223

ACKNOWLEDGMENT

Acknowledgment and special thanks are expressed to the following individuals who assisted in the preparation of this report.

- E.J. Dowgiallo and P.A. Brookshier of the U.S. Department of Energy for their support.
- T. C. Murphy and Pat Smith for editorial and publication assistance.

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DEFINITION OF TERMS

Average Discharge Power: The average power is obtained from the product of the average current and average voltage.

Capacitor/Unpackaged: A single or multicell test capacitor assembled for the purpose of electrode, electrolyte, construction material, or construction design evaluation. This includes devices suitable for testing in flooded conditions ("breaker tests") and those having o-ring seals with external clamping fixtures.

Capacitor/Packaged: A complete single or multicell capacitor that has an enclosing package This device is fully functional and ready for evaluation without the use of any auxiliary fixtures. Commercial capacitors fall into this category.

Capacitor Module: A grouping of interconnected capacitors in a series and/or parallel arrangement. For example, an interconnected assembly of commercial electrochemical capacitors forms a capacitor module.

Capacitor System: A completely functional capacitor comprised of capacitor modules, interconnects, and related support equipment. Support hardware includes any voltage balancing components, gas-release systems, constraining hardware, and thermal-management accessories.

Cycle: A series of operations (charge and discharge) that change the capacitor voltage, ending finally at the initial voltage.

Cycle Efficiency (e): The ratio in percent of the energy delivered by a capacitor to the energy that was supplied to it during a specified cycle.

Discharge Energy: The energy obtainable from a capacitor during discharge. It is calculated by integrating (adding) the product of voltage times current for each time increment during the discharge.

Equivalent Series Resistance (ESR): The value of the resistance element when a capacitor is modeled as a series RLC circuit. ESR can be measured using current interrupt methods or ac impedance techniques. It contributes to dynamic losses in the capacitor, that is, losses experienced only during charge or discharge. ESR is a lumped element value that arises from the leads, current collectors, electrodes, separators, contacts, and other resistance elements.

Ideal Stored Energy (E_W): The ideal value of the electrical energy stored in a capacitor. For the first-order model of a capacitor, it is equal to $0.5 \bullet C \bullet V_W^2$ where C is the capacitance and V_W is the working voltage on the capacitor.

Impedance (Z): The ratio V/I of a capacitor where V is a voltage (periodic in time) applied to the component and I is the resultant current. Z is a complex quantity, having real and imaginary parts. It represents the opposition to current flow for an applied time-dependent voltage.

Leakage Current (1_L): The steady-state current drawn by a capacitor after being charged. is responsible for static energy losses. The leakage current is established by resistor R_P, the resistance in parallel with the capacitor which is sometimes referred to as the self-discharge resistance.

Maximum Power Transfer: The condition where a matched load is attached to the capacitor. Then, the initial peak power delivered to the load is $V^2/4R_L$ where V is the initial capacitor voltage and R_L is the ESR of the capacitor.

Matched Load: A load having an impedance equal to the complex conjugate of the capacitor's impedance Z. For resistive loads, it is a resistor having a value equal to the ESR of the capacitor. A matched load provides maximum-power transmission from the capacitor to the load. It is rarely used in systems shuttling large blocks of energy because a matched load has only 50% power transfer efficiency (i.e., one-half of the stored energy in the capacitor is dissipated as heat within the capacitor).

Nominal Discharge/Charge Current (I_n): This is the current at which the average power during a constant current charge or discharge is 200 W/kg or a higher specified value for advanced devices.

Phase Angle: The angle between the current and the voltage in an ac circuit. For an ideal capacitor, voltage lags the current by 90°, producing a -90° phase angle. An ideal inductor has a +90° phase angle. A resistor has a 0° phase angle.

PSFUDS Cycle: A test cycle (power versus time) intended to simulate in the laboratory the operation of a capacitor being used to load level a battery in a vehicle being driven on the Federal Urban Driving Cycle (FUDS).

Resonance Frequency: The frequency in Hertz equal to the reciprocal of $2\,\pi[\,(LC)^{1/2}$ where C is the component's capacitance and L is its inductance. A capacitor is purely resistive at this frequency.

Round-trip Cycle Efficiency: The percentage of energy supplied to a capacitor that can be delivered to the vehicle in a cycle. The energy output-to-input ratio, in percent, is defined as the cycle efficiency.

Time Constant (RC): The product RC of an ideal resistor-capacitor series combination. This is the time required for the capacitor to reach 63.2% of its full charge after a voltage is applied. Most electrochemical capacitors have an ill-defined time constant due to the distributed nature of their resistance and stored charge. In other words, such devices cannot be accurately represented by a single time constant.

Useable Energy (E): The useable energy from a capacitor depends on both its discharge characteristics and the voltage window. For an ideal capacitor,

$$E_u = \frac{1}{2} C V_W^2 \left[1 - \left(\frac{V_f}{V_W^2} \right) \right]$$

where V_f is the lowest voltage at which the capacitor is to be operated in the electric drive system. For $V_f = V_W/2$, $E_u = 0.75\ E_W$; for $V_f = V_W/4$, Eu = 0.9375 E_W. The energy density and round-trip efficiency of capacitors should be rated for a voltage window of \n/2 unless specific application indicates that a wider or narrower voltage window should be used. When that is the case, the constant-power and PSFUDS tests should be done using the non-standard voltage window and that departure from standard test procedures noted on the data sheets/report.

Voltage Window: The range in voltage over which the capacitor is operated and/or must provide specified functional performance. For the EV application, this is often defined as $V_W/2$ to V_W where V_W is the working voltage of the capacitor.

Working Voltage (V_W): The maximum (rated) voltage that can be continuously applied to i capacitor. V_W depends on temperature and factors relating to design-life and reliability. It usually is specified by the manufacturer, often with temperature derating factors.

Electric Vehicle Capacitor
Test Procedures Manual

INTRODUCTION AND OBJECTIVES

This manual was written to provide a consistent set of test methods for use in evaluating the performance of electrochemical capacitors intended for use in electric drivelines to load level the battery. Presently, available test procedures for capacitors (i.e., DOD-C-29501) were developed to characterize capacitors intended for low-rate applications such as memory backup. They fall short of providing the comprehensive test procedures needed to characterize high-power devices to be used in electric vehicles (EVs).

The manual was prepared with four objectives in mind:

1. Provide a means to determine the performance of capacitors being developed for the electric vehicle (EV) application.
2. Develop a consistent and accepted yardstick that can be used to compare one technical approach or capacitor product configuration with another.
3. Formulate test methods that identify critical performance deficiencies, thereby providing direction for subsequent development activity.
4. Standardize the test sequence and reporting format to facilitate performance comparisons between capacitor products and technologies.

The test procedures in this manual are designed to be as simple and straight forward as possible, and be capable of being followed in a number of laboratories. They are suitable for small, unpackaged, single-cell capacitors, as well as for large multicell modules. Use of these procedures on early prototypes will make it possible to project, at a high confidence level, anticipated performance of similarly-constructed full-size EV capacitor units.

The test procedures rely primarily on large-signal dc measurements. These provide functional performance information that is directly linked to anticipated use of the capacitors in vehicles. The dc measurements use constant-current charging and discharging, as well as constant-power and transient cycle approaches, to better approximate actual use conditions. The later test cycles require special test equipment not available in all laboratories. The constant-current test approaches are such that they can be followed in most laboratories involved with electrochemical capacitor development. One of the test procedures uses small-signal impedance techniques to obtain important capacitor properties which leads to an equivalent circuit model. This model is a two-terminal representation of the electrical response of the capacitor.

This manual includes definitions of important terms, properties, and characteristics of capacitors as well as the detailed test procedures, and a recommended test sequence. Data reporting requirements are also specified. Descriptions of specialized equipment needed to perform the specified tests are provided.

TECHNICAL BACKGROUND

General Characteristics of Electrochemical Capacitors As a Circuit Element

The circuit schematic shown in Figure 1 represents the first-order model for an electrochemical capacitor. It is comprised of four ideal circuit elements, which include a capacitor C, a series resistor R_s, a parallel resistor R_p, and a series inductor L. R_s is called the equivalent series resistance (ESR) and contributes to energy loss during capacitor charging and discharging. R_p simulates energy loss due to capacitor self-discharge. It is often referred to as the leakage-current resistance. Inductor L results primarily from the physical construction of the capacitor and is usually small. However, it cannot be neglected in many applications, particularly those operating at high frequencies or subject to hard switching.

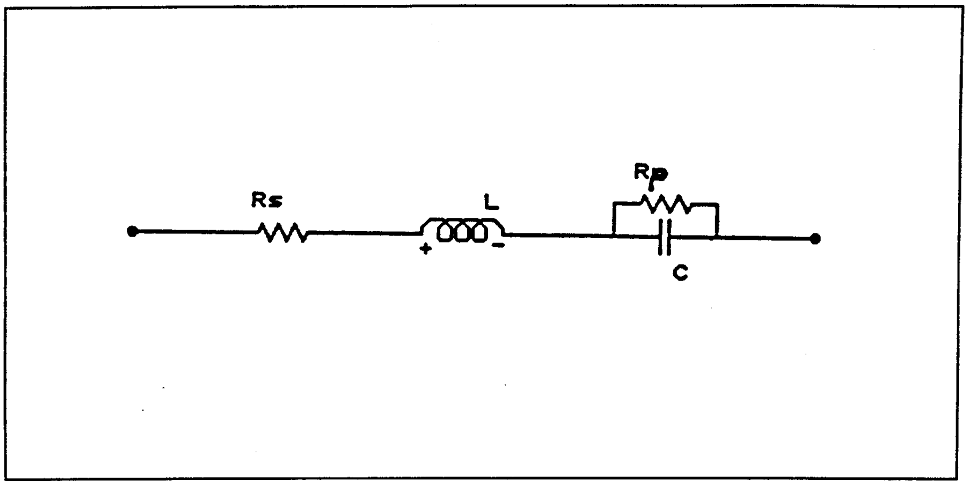


Figure 1. The first-order circuit model of a capacitor. Each of the four circuit elements is ideal.

The impedance Z of a circuit element is defined as Z = V(t)/I(t) where V is the applied potential (voltage) and I is the resultant current. Z is a complex quantity, having real and imaginary parts. For a resistor, Z = R, where R is the resistance in ohms. For a capacitor, $Z = -i/2 \pi fC$ where $i = (-1)^{1/2}$, f is the frequency in Hertz, and C is the capacitance in Farads. Current leads the voltage by 90° in an ideal capacitor. And for an inductor, $Z = i2 \pi fL$, where L is the inductance in Henrys. Current lags the voltage by 90° in an ideal inductor.

Resistor Rp is always much greater than Rs in practical capacitors. Thus it can often be neglected, particularly in high-power applications. In that case, the impedance of the Figure 1 circuit model (shown in Figure 1) is $Z = R + i\,(2 \pi fL - 1/2 \pi fC)$. Figure 2 shows the magnitude of the real and the imaginary parts of the capacitor's impedance versus frequency using this equation. The impedance is purely resistive when $2 \pi fL - 1/2 \pi fC = 0$, or $f = 1/2 \pi (LC)^{1/2}$. This particular frequency is referred to as the resonance frequency of the capacitor. Thus, the impedance of the circuit is simply the resistance at self-resonance At lower frequencies, the device is capacitive (negative phase angle). At higher frequencies, it is not capacitive but rather inductive (positive phase angle).

Electrochemical capacitors exhibit non-ideal characteristics beyond those represented by the circuit model shown in Figure 1. These result primarily from the porous material used to form the electrodes that causes the resistance and capacitance to be distributed such that the electrical response mimics transmission line behavior (References 1 and 2). Figure 3 shows the magnitude of the real and imaginary parts of the impedance of a typical electrochemical capacitor. The dashed lines show the predicted behavior from the first-order model. (Note: The dashed lines in Figure 3 show the behavior predicted using the first-order model shown in Figure 1.)

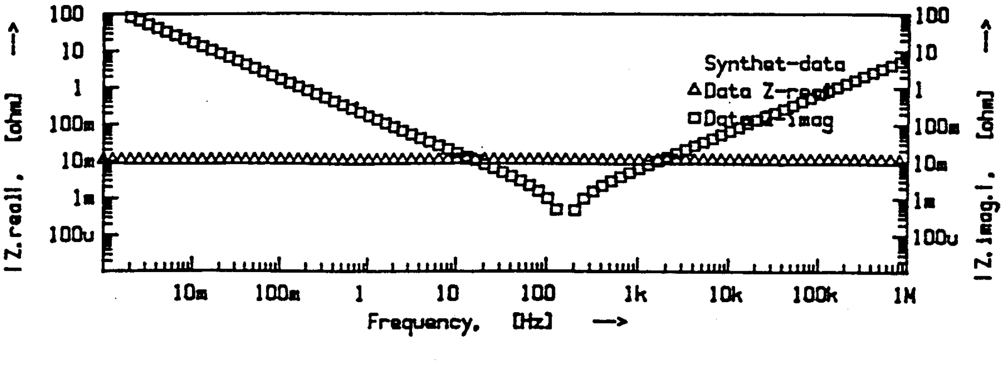


Figure 2. Impedance characteristics of a capacitor based on the first-order model shown in Figure 1 with R_p neglected.

Deviations from the first-order model, evident in Figure 3, take three forms. These include a change in the slope of Z_{imag} at frequencies above ~0.3 Hz. Thus, the capacitance of the device, which is proportional to 1/Zimag, declines above 0.3 Hz. Second, Z_{real} is not independent of frequency. It is relatively flat above ~100 Hz, but increases as the frequency is reduced. This increase creates additional energy dissipation at low charge/discharge rates. Cycle efficiency is thus lower than predicted using the first-order circuit model. And third, self-resonance occurs at an increased frequency. The frequency shift above the $1/2\ \pi\ (LC)^{1/2}$ value reflects decreased capacitance at higher frequencies.

Figure 4 shows one circuit model that can be used to represent an electrochemical capacitor. This five-time-constant equivalent circuit is generally adequate for representing the

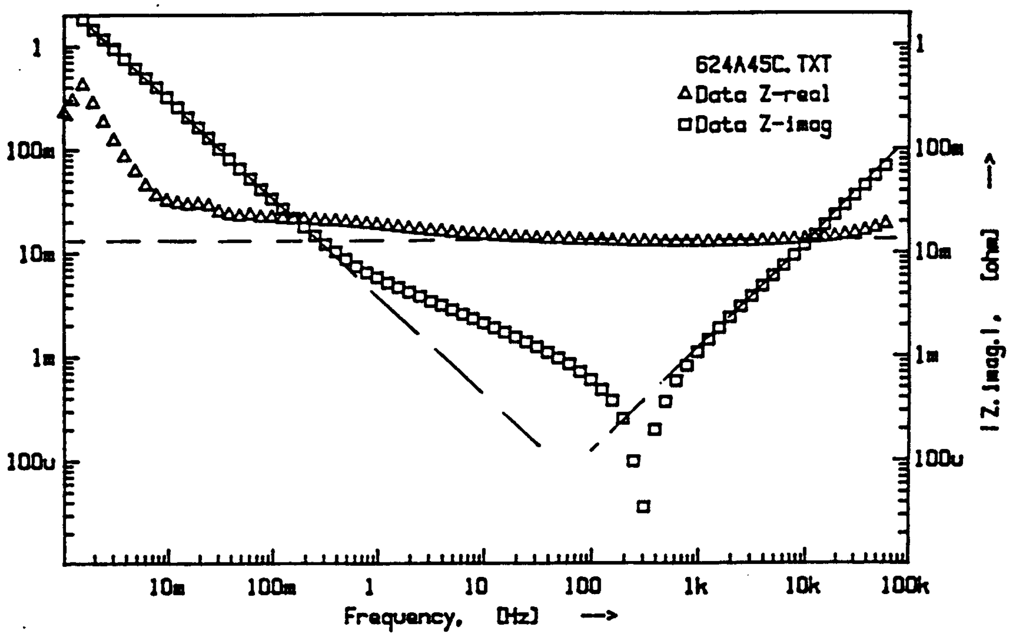


Figure 3. The magnitude of the real and the imaginary parts of the impedance of a typical electrochemical capacitor.

capacitor's electrical response. A fit of this model to the Figure 3 data is shown in Figure 5. The model provides a good representation of the device's electrical response over a span of seven decades in frequency. Many other circuit configurations could have been used to provide an equally-good fit.

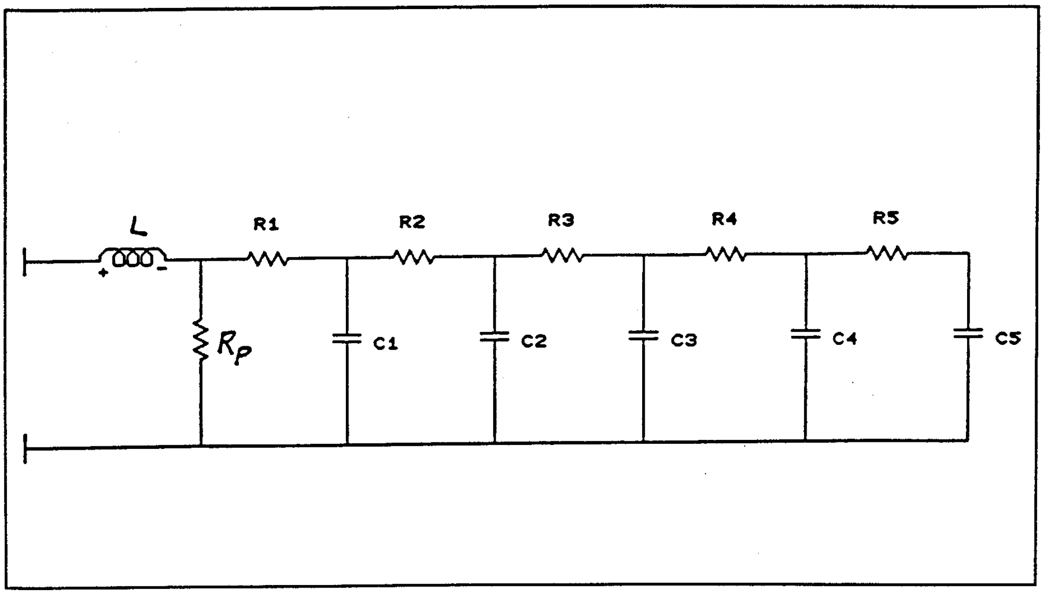


Figure 4. A five-time-constant model used to represent the equivalent circuit of an electrochemical capacitor. Each circuit element is ideal.

In summary, the non-ideal behavior of electrochemical capacitors cannot be neglected, particularly when used in high power applications. Resistive losses will generally be greater than those predicted from the first-order circuit model. Capacitance, and thus energy storage capability, is affected by the energy input rate. Consequently, energy density, power density, and charge/discharge cycle efficiency measurement procedures must be carefully specified. Then, meaningful test data that is suitable for evaluating the capacitors for electric driveline applications will be obtained. Test procedures in this manual are intended to meet this requirement.

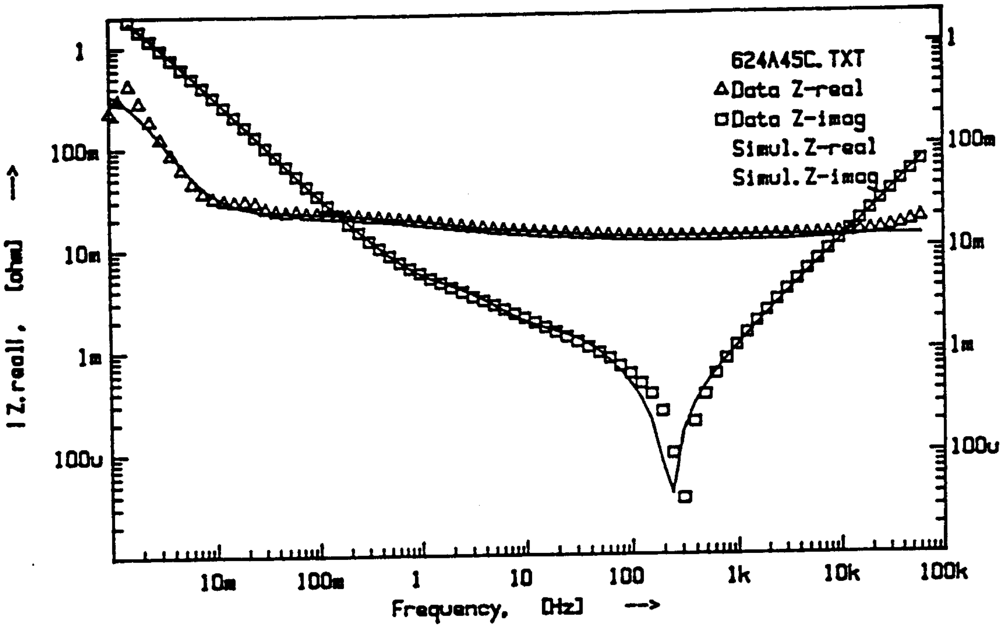


Figure 5. Fit of the Figure 4 equivalent circuit model to the electrochemical capacitor impedance shown in Figure 3.

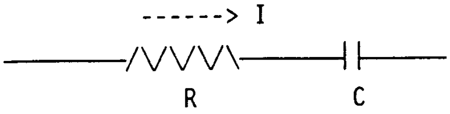
DC Behavior of Electrochemical Capacitors

Electrochemical capacitors used in electric drivelines to load-level the battery experience large non-steady (transient) direct currents (dc), much like the battery, rather than small amplitude, alternating current (ac) signals. The dc charge or discharge time (t_{dc}) of the capacitor is related to the fundamental characteristic frequency (f_{ac} in Hz) of the ac voltage on the capacitor by:

$$t_{dc} = \frac{1}{4 f_{ac}}$$

Hence for the electric vehicle applications, the ac signals of most interest (remembering that ~5 odd harmonics are needed to synthesize an arbitrary waveform) are those in the frequency range of 0.02 to 2.5 Hz. As indicated in Figure 3 and 4, electrochemical capacitors can have non-ideal characteristics in this frequency range.

In testing electrochemical capacitors, it is convenient to model them as a simple series RC circuit when inductive effects are unimportant.



In this case,

$$Q = CV$$

$$E = 1/2\, CV^2$$

$$V_0 - V = IR + \frac{Q_0 - Q}{C} \quad -$$

where

Q - charge on the capacitor
V - voltage on the capacitor
E - energy stored in the capacitor
V_0 Q_0 - voltage and charge at time t = 0

Voltage V and current I change with time as the capacitor is charged and discharged between voltage limits (e.g., V_W, and $V_W/2$ where V_W is the working voltage of the capacitor). For electrochemical capacitors, the capacitance C and resistance R in this model vary with charge/discharge rate as discussed in the previous section. One of the objectives of the testing described in this manual is to determine C and R for the charge/discharge times of interest in electric vehicle applications. These times are generally between 2 to 100 seconds.

The test conditions for the capacitors to be evaluated are expressed in terms of the following parameters:

- charge/discharge time
- power density (W/kg)
- capacitor voltage window

These parameters are more closely related to those used in battery testing than in evaluations of capacitors or electrochemical electrodes or cells using ac impedance. It can be expected that over the next few years, the relationship between dc testing and ac impedance testing of electrochemical capacitors being developed for electrical vehicle applications will become more completely understood.

GENERAL CONSIDERATIONS FOR TESTING

Test Equipment

DC Testing

The test equipment used for the dc testing of capacitors is closely related to that available for testing battery cells and modules. These testers are programmable and permit cycling the capacitors at constant-current, constant-power, and on a prescribed transient cycle, such as the PSFUDS. The battery testers are specified in terms of maximum voltage and current, for example, 20 V and 12 A. State-of-the-art battery testers, such as those available from Maccor, permit capacitor testing at voltage, current, and power as low as a fraction of a volt, ampere, and watt, respectively, and discharge times as low as one second. State-of-the-art battery testers are computer-controlled and have as integral components data acquisition systems that permit data sampling at 10 to 100 ms rates and real-time computations of charge (A-s) and energy (W-s) during the capacitor tests for sub-steps of complicated transient cycles (e.g., the PSFUDS). Hence, it follows that test equipment is presently commercially available to perform all the dc test procedures given in this manual.

AC Impedance Testing

Measurement equipment used for ac impedance testing must be capable of measuring the complex impedance of a capacitor from 0.001 Hz to above its self-resonance frequency. This upper frequency limit is typically 5 kHz or less for electrochemical capacitors. The magnitude of the impedance over this range is typically between 10 Mohms and 100 ohms. Therefore, the impedance equipment must be capable of making these measurements. An ac signal amplitude of 0.02 V per capacitor cell or less should be used. Measurements must be in a true four-lead configuration.

Commercial equipment is available that meets these impedance test requirements for electrochemical capacitors. The digital correlation approach, also known as frequency response analysis or transfer function analysis, is well suited for these measurements. Equipment relying on this approach is available from Solartron (models 1280A, 1260, 1255, and 1250). It provides highly accurate impedance measurements over the frequency range of interest. Models 1255 and 1250 must be used with a potentiostat, such as the Solartron Models 1286 or 1287, or the model 273A unit sold by EG&G PAR. Model 1260 can be used with a potentiostat to increase its current capability. Model 1280A is a complete impedance measurement system by itself.

An alternate means for obtaining impedance data is to combine a phase sensitive detection approach with a Fast Fourier Transform (FFT) approach. The first, which uses a lock-in amplifier, measures impedance down to ≈ 10 Hz while the FFT approach, which uses a computer-controlled potentiostat, measures impedance to lower frequencies. An EG&G PAR, Model 5120, lock-in amplifier with a Model 273A potentiostat and an IBM-compatible personal computer, is one example of the equipment needed.

Other approaches, such as ac-bridge or oscilloscope (Lissajous figures) methods, are unsuitable for measuring the impedance of electrochemical capacitors. These approaches generally do not have sufficient accuracy over the frequency range of importance nor the capability to make true four-lead impedance measurements.

Physical Characteristics of Capacitors

Capacitor/Unpackaged

Single or multicell test capacitor assembled for the purpose of electrode, electrolyte, construction material, or construction design evaluation. They include devices suitable for testing in flooded conditions ("beaker tests") and those having o-ring seals with external clamping fixtures. This configuration is suitable for electrical performance tests, but is unsuitable for environmental tests like vibration and life. For specific property calculations the mass and volume should include device electrodes, separators, current collectors and the electrolyte between the current collectors.

Capacitor/Packaged

A complete single or multicell capacitor that has an enclosing package. This device is fully functional and ready for evaluation without the use of any auxiliary fixtures. Most commercial electrochemical capacitors fall into this category. Such devices can be subjected to all tests. The measured mass and volume of the device is used for energy and power density calculations.

Capacitor Module

Groups of capacitors that are interconnected in a series and/or parallel arrangement. A capacitor module could be formed, for example, from an assembly of commercial electrochemical capacitors. Energy and power density calculations should be based on the total measured mass and volume of the module. All electrical interconnects must be included.

Capacitor System

A completely functional capacitor comprised of capacitor modules, interconnects, and related support equipment. Support hardware may include, but is not limited to, voltage balancing components, gas-release systems, constraining hardware, and thermal-management accessories. The measured mass and volume of the total system shall be used for energy and power density calculations.

Procedure for Determining the Physical Characteristics

Determine the mass and volume of the test capacitor using the above definitions. Estimations based on information from the manufacturer may be required for the unpackaged capacitor. If so, use the volume and mass of the constituent materials that are provided by the manufacturer to derive these numbers. Provide a detailed description of the methodology used for the estimates. When possible, weigh and measure the volume of the capacitors (cells, modules, etc.) independent of manufacturers' information.

Selection of Test Parameters

In general, in preparing to test a capacitor, it is necessary to develop a test plan, which involves the selection of test parameters for the evaluation of the device. For dc testing, this includes selection of the current (A) and power (W) at which the device will be charged and discharged, and the initial and final voltages for the tests. The currents and powers to be used in the testing depends on the manufacturers' (developers') rating (capacitance and voltage) of the device and its mass. The nominal charge/discharge current 1^ can be determined from the rated capacitance and voltage of the device from the relationship

$$I_n = \frac{(C_p)\ (wt)}{V_{W/2}}$$

C_p = nominal power density (W/kg) for the testing using 200 W/kg for present devices, but this can be adjusted upward as devices improve.

wt = device weight in kg

V_W = device working voltage

The corresponding nominal discharge time t_n is:

$$T_n = \frac{C\ V_W}{I_n}$$

where t_n is a nominal charge/discharge time and V_W is the working voltage of the device.

Tests will be performed at currents higher and lower than I_n (e.g., 0.25, 0.5, 1.0, 2.0, 4.0, 8.0 I_n).

Selection of the power (W) levels for the tests would depend on the mass (M) of the device to be evaluated. For capacitor devices having an expected energy density less than 5 W-h/kg, the tests could be performed at specific power values of 50, 100, 200, 500, 800, 1200 W/kg. The power (P) value for each test is simply

$$P = (P/M)\ M\ (W)$$

between a specified initial voltage (V_0) and final voltage (V_f). For the PSFUDS cycle test (see Procedure 4 for a definition of this test), the power (charge or discharge) for each step is also determined based on the mass of the device to be tested.

In the case of ac impedance testing of devices, the characteristics of the device are less important in selecting the test parameters. In most cases, one selects the a frequency range of 1 mHz to 10 kHz and limits the amplitude of the voltage signal to 20 mV per cell.

Test Sequence

This manual contains procedures for a number of tests. The procedures are written to characterize capacitors under development for the electric vehicle applications. The various capacitor technologies are in different states of development and consequently not all tests and procedures are applicable for each test device.

Procedures are listed below in five groups. The test sequence should proceed from Group I and Group II to any of the final three groups depending on the state of development the device and the information needed to evaluate it.

Group I

dc Tests

- Constant current charge/discharge
- Equivalent series resistance
- Leak current
- Self discharge

Group II

ac Impedance characterization

Group III

dc Tests

- Constant power discharge
- Transient power cycles (PSFUDS)

Group IV

Life cycle tests
Life stability
Temperature effect tests

Group V

Shock and vibration

All capacitors should be evaluated using the Group I tests and Group II if ac impedance equipment is available. Group III procedures should be performed on all capacitors that perform satisfactorily in the Group I and II tests. These establish baseline electrical and physical characteristics. Significant discrepancies between test data and information received from the device supplier may be reason to terminate testing at this point. For example, a low-rate capacitance value that is much different from the device's rating may indicate defective behavior. Further tests on such a capacitor would then not be warranted.

Group IV procedures constitute life-cycle testing of devices/modules. These tests should be performed on all capacitors that perform satisfactorily in the tests of Groups I through III.

Test procedures contained in Group V should be performed only on fully packaged devices/modules.

In summary, testing should proceed in order from Group I through Group V as the devices show satisfactory performance in proceeding tests.

REPORTING FORMAT

The data presentation for each of the test procedures is discussed separately in the manual. The series of tests on a device is likely to result in a comprehensive test report for the device. The reporting format given in Tables 1 and 2 is intended to provide a summary of the test results that show clearly the status of the device/technology development and permits rapid and clear comparisons with program goals and other electrochemical capacitor technologies. Tables 1 and 2 indicate the complete set of data needed for each device/technology, but the complete set is not likely to be available from a single test series except near the end of the development cycle for the device. For a particular series of tests, it is acceptable to present incomplete tables if all the tests needed to complete the tables were not performed.

Table 1. Device test summary.

Device Name:	
Device Supplier:	
Technology Description:	
Device Physical Characteristics:	
Status:	(unpackaged, packaged, module, system, single cell, multicell stack, etc.
Mass:	kg or gm (basis)
Dimensions: Area (A) Volume (v)	 cross-sectional area (cm^2) cm^3
Working Voltage:	volts
Voltage Window	fraction of working voltage (0.5 is standard)
Tests completed:	list of tests
Performance/Design Deficiencies:	List

Table 2. Summary of device performance and life-cycle characteristics.

Low Rate (> 30 sec, 0 —> V_W)						
	Capacitance (F)	ESR (ohms)	ESR (ohms)	ESR · A (Ohm-cm2)	E_W/M (Wh/kg)	E_W/v (W-h/L)
Charge						
Discharge						
High Rate (5 sec, 0 --> V_W)						
	Capacitance (F)	ESR (ohms)	ESR (ohms)	ESR · A (Ohm-cm2)	E_W/M (W-h/kg)	Ew/v (W-h/L)
Charge						
Discharge						
AC Impedance (series RC model)						
	Capacitance (F)			R (Ohm)	Phase Angle (°)	
1 Hz						
10^{-1} Hz						
10^{-2} Hz						
10 Hz						
Constant Power (discharge) Vw —> Vw/2 (or non-standard value)						
P/M(W/kg)	Eu/M (W-h/kg)			Eu/v (W-h/L)	e round trip (%)	
50						
100						
200						
500						
800						
1200						
Transient Power Cycle (PSFUDS)						
Setup: (W/kg)max =____, W-h/kg =____, voltage window (V_W)						
Data: (W-h/kg)total charge = ____, ____(Wh/kg)total discharge =____						
round-trip efficiency =____%						

Table 2. Summary of device performance and life-cycle characteristics, (cont'd)

Leakage Current (@ Vw)		
Time{hrs)	I(mA)	I • A (A-cm^2)
0.5		
1.0		
3.0		

Self Discharge (from Vw)		
Time (hrs)	Voltage (v)	Fraction of Initial Energy
1		
8		
24		
36		
72		

Life-Cycle Test				
Cycle No.	Capacitance (F)	ESR(ohm)	Eu/M (Wh/kg) @ 800 W/kg	Eu/M Degradation (%)
0				
1,000				
4,000				
20,000				
40,000				
100.000				
200.000				

Temperature Effect on Performance						
Temp (°C)	Capacitance (F)	ESR (ohms)*	Ew/M. (W-h/kg)*)	I_L (mA) @ 1 hr	% Ew/M Change	PSFUDS e_{cycle} (%)
65						
25						
-30						
* all data for I = 1^						

Life Stability (70 C, vw)*						
Aging Time (hrs)	Capacitance (F)	ESR (ohms)'	I_L(mA) @ 1 hr	Eu/M (W-h/kg) @800 W/kg	Eu/M change from 0 hr (%)	PSFUDS e_{cycle} (%)
0						
250						
500						
1000						
2000						
* all data for I = I_n						

CAPACITOR TEST PROCEDURES

DC Tests (large signal)

Procedure 1: Constant-Current Tests

1. **Purpose**

This procedure specifies a method for determining the constant-current charging and discharging characteristics of the capacitor. It is the first set of tests that should be performed on a device.

2. **Approach**

A range of currents is selected such that the charge and discharge times for voltages between 0 and V_W is 2 to 100 seconds. The voltage is held for 10 s at the end of the charge and discharge portions of the test cycle to establish a constant voltage level for all tests. Three consecutive charge/discharge cycles at a specified current constitutes a single test. The reported data should be the average of the second and third cycles.

3. **Procedure**

- Based on the manufacturers' specified working voltage (V_W) and capacitance (C), a nominal characteristic current L is calculated for a 30 s charge/discharge.

$$In = C\ V_W /30\ (A)$$

- Tests are then performed at the following constant currents: 0.25, 0.5, 1.0, 2.0, 4.0, 8.0 In

- This should result in a range of charge/discharge times of 2 to 100 seconds. A typical charge/discharge voltage trace is shown in Figure 1. If the charge/discharge times are not in the desired range, adjust I_n after the first several constant-current tests.

4 Data Presentation

For each constant-current test, determine the capacitance from the relation

$$C_{test} = \frac{I_{test}\, t_{test}}{V_W}$$

and the energy density E_W/M and E_W/v from the relationships

$$\frac{E_W}{M} = \frac{I_{test} t_{test} V_W / 2}{3600M} \left(\frac{Wh}{kg} \right)$$

$$\frac{E_W}{v} = \frac{I_{test} t_{test} V_W / 2}{3600v} \left(\frac{Wh}{L} \right)$$

where M is in kg and v is in liters.

Calculate C_{test} and E_W/M and E_W/v for the charge and discharge portions of each .of the constant-current tests. Determine the repeatability (%) of the three charge/discharge cycles of each test and average the data for cycles 2 and 3 for presentation in the following table:

	Charge					Discharge			
	I_{test} (A)	t_{test} (S)	C (F)	E_W/M (W-h/kg)	E_W/v (W-h/L)	t_{test} (S)	C (F)	E_W/M (W-h/kg)	E_W/v (W-h/L)
0.25 In									
0.50 In									
—									
—									
—									
8.0 In									

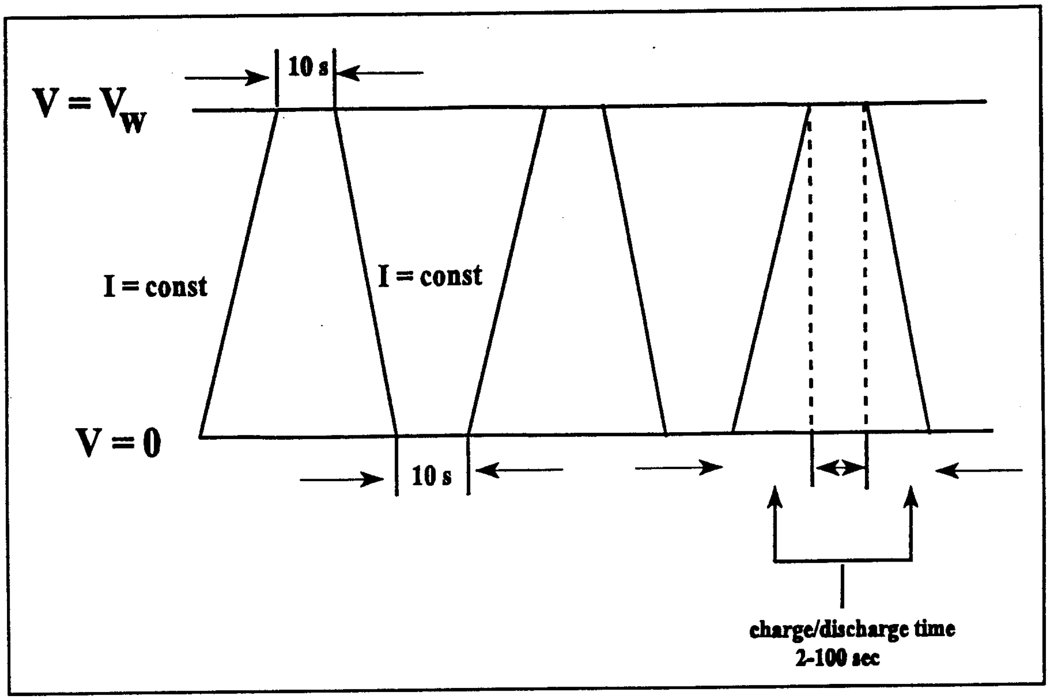


Figure 6. Diagram showing the waveform used to determine the constant-current characteristics of a capacitor.

Procedure 2: Equivalent Series Resistance Tests

1. Purpose

This procedure specifies a method of determining the equivalent series resistance (ESR) of a device by utilizing the test data from the constant-current tests.

2. Approach

The ESR is determined using the current interrupt method. It entails measuring the change in voltage on the capacitor, immediately after the current to the capacitor has been changed. This voltage change is often referred to as the "IR Step."

3. Procedure

In the constant-current tests, the current (I) is interrupted or suddenly changed at the beginning and end of the charge/discharge portions of the cycle. In this procedure, the ESR is calculated from the IR Step at the beginning of charge and the beginning of discharge from the relationship

$$ESR = \frac{(\Delta V)_{IRStep}}{I}$$

Experience has shown that consistent values of ESR are obtained if AV is determined from the readings at the end of the 10-s hold-period prior to charge or discharge, and within 10 msec (0.01 s) after the initiation of charge or discharge (see Figure 2). The ESR should be calculated for the beginning of charge and discharge for each of the constant-current test cycles of Procedure 1. It should be independent of current.

4. **Data Presentation**

The resistance data should be presented in tabular form as follows:

	Charge			**Discharge**	
I	**(A)**	**ΔV**	**ESR (Ω)**	**ΔV(V)**	**ESR (Ω)**
0.25 I_n					
0.50 I_n					
-					
-					
-					
8.0 I_n					

The repeatability of the ESR values for the three charge/discharge cycles at each current should be determined and the average value of ΔV used to determine the value reported in the above table.

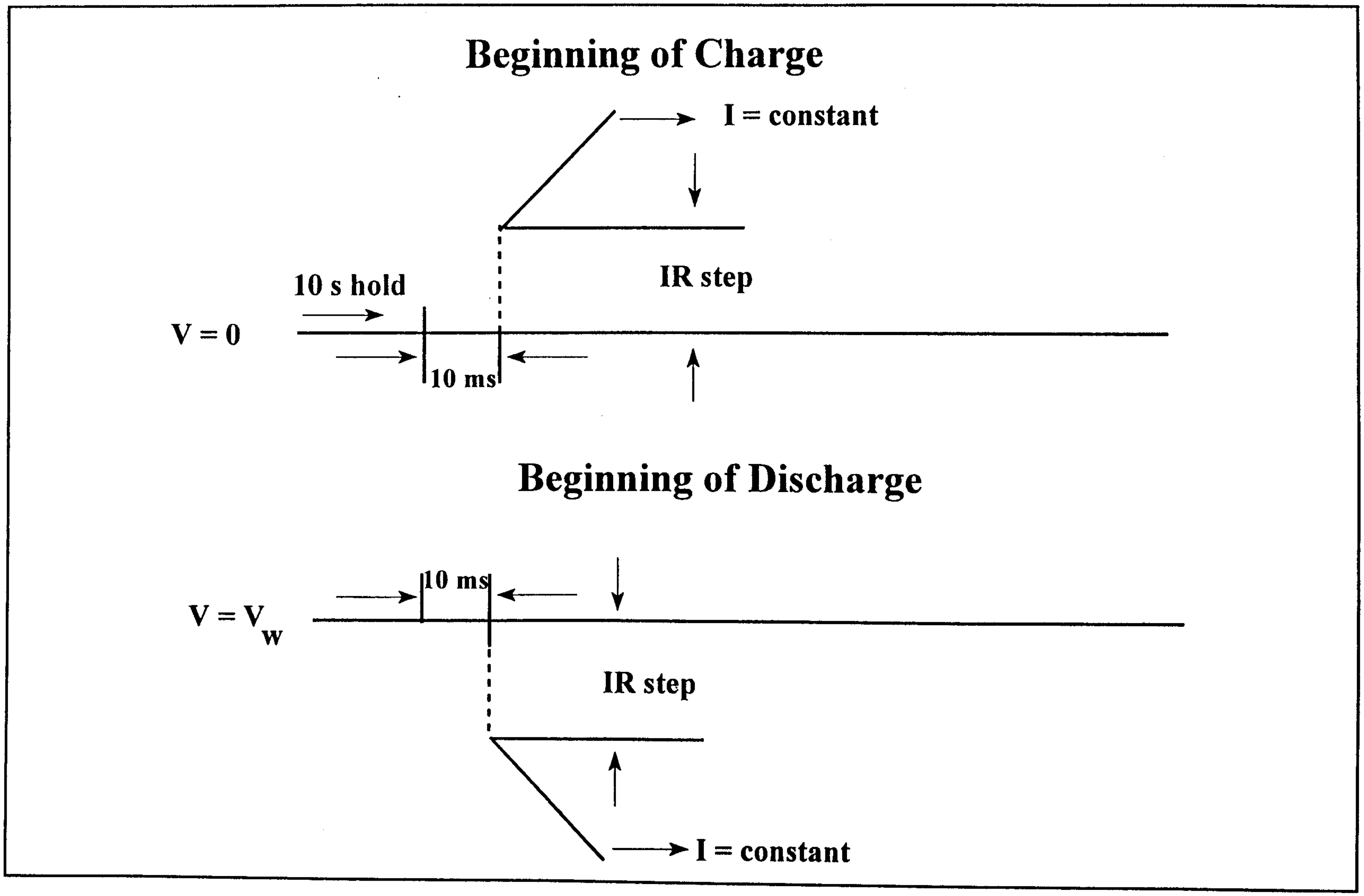


Figure 7. Diagrams showing the procedure for measuring the equivalent series resistance (ESR) of a capacitor.

Procedure 3: Constant Power Tests

1. Purpose

This procedure specifies a method to determine the discharge characteristics of the capacitor at different discharge power levels.

2. Approach

A range of discharge rates (powers) is selected such that they correspond to power densities (P/M) between 50 and 1200 W/kg (or higher for advanced devices). The discharge is performed between V_W and $V_W/2$. This would drain 75 of the energy in an ideal capacitor. The capacitor should be charged at constant-current (I_n) and held at V_W for 10 s before the constant power discharge is initiated. The capacitor will also be held for 10s at $V_W/2$ before charging is initiated. Three consecutive charge/discharge cycles at each specified constant power constitutes a single test. (A larger or smaller voltage than $V_W/2$ can be used for a particular device with permission of the DOE Program Manager.)

3. Procedure

Based on the manufacturer's specified working voltage (V_W) and the mass (M) of the device (mass agreed to by the manufacturer and the test lab), discharge powers (watts) are calculated for specific power densities of M 50, 100, 200, 500, 800, and 1,200 W/kg. Tests are performed at each of these discharge powers. The discharge times for these tests should be in the same range as the constant current tests of Procedure 1. For each constant power test, the energy (W-s) during charge and discharge will be calculated by summing $VI\Delta t$ during the charge/discharge portions of the cycle. The usable energy densities (E_u /M and E_u/v) are calculated from

$$\frac{E_u}{M} = \frac{\left(\sum VI\Delta t\right)_{disch\arg e}}{3600\,M} \left(\frac{Wh}{kg}\right)$$

$$\frac{E_u}{v} = \frac{\left(\sum VI\Delta t\right)_{disch\arg e}}{3600\,V} \left(\frac{Wh}{L}\right)$$

and the round-trip efficiency (r|^) is calculated from

$$\eta_{rt} = \frac{\left(\sum VI\Delta t\right)_{discharge}}{\left(\sum VI\Delta t\right)_{charge}}$$

4. Data Presentation

The constant power discharge data for the capacitor should be presented in tabular form as follows:

P/M (W/kg)	Power (W)	E_W/M (W-h/kg)	E_W/v (W-h/L)	η_{rt}
50				
100				
200				
500				
800				
1200				

Note that for an ideal capacitor ($E = CV^2/2$), energy density at constant power would nominally be 75% of the value determined in the constant current tests because of the difference in the voltage window of the two tests ($V_W/2$ for constant power tests and V_W for the constant current tests).

Procedure 4: Transient Power Tests (PSFUDS)

1. Purpose

This procedure specifies a transient power test cycle that is intended to simulate the use of a capacitor to load level the battery in a vehicle being driven on the Federal Urban Driving Cycle (FUDS). This test cycle is designated as the pulsed SFUDS (PSFUDS) cycle.

2. Approach

As in the case of the SFUDS battery test cycle, the PSFUDS cycle is given as a series of power-time steps involving both charge and discharge of the device being tested. The power levels and length of time for each step should be specified such that the test cycle is applicable to different size and performance capacitors intended for use in vehicles of varying performance.

The original PSFUDS cycle (Table 3), which was first presented in Reference 3, was specified in terms of a W/kg and time for each step. The maximum power density for the cycle is 500 W/kg, and the times for the steps were selected such that the 3 V Panasonic power capacitor (2 W-h/kg) could store sufficient energy to complete the cycle at voltages between V_W and $V_W/2$. For a particular capacitor device, the power (watts) for each step was calculated by multiplying the P/M for the step by the mass M(kg) of the device. In some cases, it was necessary to reduce the $(W/kg)_{max}$ from 500 to 300 so that the device could complete the cycle within the desire voltage limits. (A larger or smaller voltage window than $V_W/2$ can be used for a particular device with the permission of the DOE Program Manager.)

A number of capacitor devices have been tested using the original PSFUDS cycle. Based on that experience, it became clear that the cycle should be generalized for application to devices with higher energy density and peak power capabilities than had previously been the case. The generalized PSFUDS cycle is given in Table 4. The new cycle was obtained by normalizing the power for each step by 500 W/kg and multiplying the time in each step by the factor of 5/2 to account for an increase in energy density from 2 W-h/kg to 5 W-h/kg. Originally, the PSFUDS cycle had been intended to simulate the use of a capacitor unit storing 500 W-h having an energy density of 5 W-h/kg. The time steps were reduced for the test cycle given in Table 3, because the energy density of available devices was 2 W-h/kg or less. For the generalized PSFUDS cycle (Table 4), the time steps have been increased to the values shown for testing high-energy density devices and should be reduced when testing devices having lower energy density.

3. Procedure

The generalized PSFUDS cycle (Table 4) should be used for all transient power tests. The power level and time for each step is determined using the energy density W-h/kg (at 100 W/kg) and the $(W/kg)_{max}$ for the device to be tested. The energy density is the value measured in the constant power test (Procedure 3). The maximum power density $(W/kg)_{max}$ depends on the application of the device and should be agreed upon between the test lab and the DOE-program manager. For near-term devices, $(W/kg)_{max} = 500$. The maximum power for the test is given by

$$P_{max} = (W/kg)_{max} \, M_{(w)}$$

The time for each step is the value given in Table 4 if W-h/kg ≥ 5 or the value reduced by the factor $(W\text{-}h/kg)_{device}/5$, if W-h/kg is < 5.

The device is tested using the transient power cycle defined in the previous paragraph. The test is started by charging the capacitor to V_W, and holding for 10 s. The test cycle is repeated three times with the capacitor returned to V_W at the end of each complete cycle as indicated in Table 4. The device should be held at V_W for 10s between cycles. If the voltage on the device remains at $V_W/2$ or lower for a significant time during the cycle, the value of $(W/kg)_{max}$ should be reduced and the test repeated.

The voltage and current should be measured and recorded at one-second time intervals during the test cycle. The A-s and W-s sums for each power step should be calculated and recorded for later use in determining the round-trip efficiency for the cycle.

4. Data Presentation

The primary purpose of the transient power cycle test is to determine the round-trip efficiency for charge and discharge of the capacitor while it is load leveling a battery. The efficiency η_{rt} is given by

$$\eta_{rt} = \frac{(W-s)_{discharge}}{(W-s)_{charge}}$$

with the capacitor voltage being the same at the beginning and end of the cycle. $(W\text{-}s)_{discharge}$ is determined by adding up the W-s values from all the discharge power steps. $(W\text{-}s)_{charge}$ is determined by adding up the W-s values for all the charge power steps. The A-h efficiency can be calculated similarly from

$$(Ah)_{effic} = \frac{(A-s)_{discharge}}{(A-s)_{charge}}$$

$(Ah)_{effic}$ should be very close to 1.0.

Table 3. Power profile for the original PSFUDS test cycle

Time Step (s)	W/kg	Mode
3	100	Discharge
5	200	Discharge
5	50	Discharge
20	50	Charge
5	100	Discharge
5	300	Discharge
3	200	Discharge
20	100	Charge
5	100	Discharge
5	200	Discharge
7	50	Discharge
20	100	Charge
3	100	Discharge
5	300	Discharge
5	50	Discharge
20	125	Charge
3	100	Discharge
5	300	Discharge
15	100	Charge
5	200	Discharge
5	100	Discharge
>20	125	Charge (to V^)
Total 189 s		

Table 4. Generalized PSFUDS (W-h/kg $\geq$5)

Time Step (s)	**P/P_{max}**	**Charge (c) or Discharge (D)**
12	0.4	D
12	0.1	D
50	0.1	C
12	0.2	D
12	1.0	D
8	0.4	D
50	0.2	C
12	0.2	D
12	0.4	D
18	0.1	D
50	0.2	C
8	0.2	D
12	1.0	D
12	0.1	D
50	0.25	C
8	0.20	D
12	1.0	D
38	0.20	C
12	0.4	D
12	0.2	D
$\geq$50	0.25	C to V_W
Total 470 s		

Procedure 5: Leakage Current

1.Purpose

This test is performed to measure the self-dissipation rate of the capacitor under steady-state conditions, i.e. the static loss rate. Referring to the first-order circuit model in the Technical Background Section, this procedure determines the value of parallel resistor Rp. Leakage current can arise from charge-transfer reactions at the electrodes or from shunt paths that are in parallel with some of the capacitor cells. This type of loss is different from the dissipation processes associated with dynamic losses, which arise from the series resistor Rs and occur only during capacitor charge and discharge.

2.Approach

The leakage current (l_L) is the current required to maintain the capacitor at the working voltage V_W. It is time-dependent and only approaches a constant value after the voltage has been applied to the capacitor for several hours. Hence, to determine the leakage current characteristics of a device, it is necessary to measure the current to the capacitor over a relatively long time (up to 3 hours). This can be done using a standard battery tester if it is sufficiently stable and has the capability to measure small currents (down to a fraction of mA for small devices). Otherwise, it is necessary to use a stable power supply and a shunt resistor in series with the capacitor being tested.

3.Procedure

The capacitor is charged to its working voltage (V_W) and maintained at that voltage for 3 hours. The current should be measured at one-minute intervals for the first hour on the test and then at 5-minute intervals during the remainder of the test. The voltage applied to the capacitor should be maintained at $V_W \pm 0.01$ V.

4. **Data Presentation**

The data from the test should be presented in graphical form as current versus time for the complete three hours of the test. The parallel resistance Rp, should be calculated a 0.5, 1.0, 2.0, 3.0 hours from the relationship

$$R_p = \frac{V_W}{I_L}$$

Procedure 6: Self-Discharge Tests

1. Purpose

This test is performed to measure the self-discharge of the capacitor after it has been charged to its working voltage V_W,. The decrease in voltage experienced after the device is open-circuited is a measure of its self-dissipation and is an indicator of the extent of the occurrence of non-ideal energy storage/transfer mechanisms.

2. Approach

The capacitor is charged to its working voltage (V_W) and held at that voltage for 30 minutes. It is then placed on open-circuit and the voltage measured over a period of 72 hours. The voltage will decrease more rapidly over the first hour (or less) and then decrease at a slower rate for the remainder of the test.

3. Procedure

The capacitor should be charged to the working voltage and held at that voltage for 30 (± 1) min. After placing the device on open-circuit, the voltage should be measured over a 72-hour period. For the first three hours, the time increment between measurements should be one minute or less. For the remainder of the test, measurements should be made every 10 min. Voltage measurement equipment should have high input impedance to minimize its effects on discharge.

4. **Data Presentation**

The data from the test should be presented in graphical form as voltage versus time for the complete 72 hours of the test. The self-discharge energy loss factor (SDLF) should be calculated from the relationship

$$SDLF = 1 - \left(\frac{V}{V_W} \right)^2$$

for t = 0.5, 1, 8, 24, 36, 72 hours.

Procedure 7: Cycle-Life Tests

1. Purpose

Long cycle-life is needed for capacitors used in the electric vehicle applications. Stable performance during more than 100,000 charge/discharge cycles is desired. This procedure measures capacitor performance stability during cycle tests.

2. Approach

The capacitors are characterized initially and then periodically throughout the cycle test. Individual capacitor failures, and the number of cycles completed before failure, should be recorded. Constant-current charging and discharging are used. A symmetric charge/discharge cycle, somewhat more strenuous than expected in the electric vehicle application, is used to accelerate property and performance changes.

3. Procedure

Condition the capacitor at 25 ± 3°C until thermal equilibrium is reached. Initialize the voltage on the capacitor at $V_W/2$. Then charge the capacitor at a current $I_n = (V_W/40)$ to V_W or at the value of I_n determined experimentally so that the voltage reaches V_W in 20 (± 1) s. Maintain voltage V_W on the capacitor for 10 ± 0.50 s. Then discharge the capacitor to $V_W/2$ at current I_n. Hold at V_W for 10 ± 0.50 s. This defines a cycle (see Figure 8). Repeat this cycle throughout the testing, adjusting I_n as needed in order to maintain the initial charge/discharge times.

Capacitors shall be characterized using the procedures listed below initially, and after 1000 ± 25; 4000 ± 100; 10,000 ± 250; 40,000 ± 1000; 100,000 ± 2500; 150,000 ± 2500; and 200,000 ± 2500. Capacitor failure, and the number of cycles to failure, shall be recorded. Failed capacitors should be removed from test.

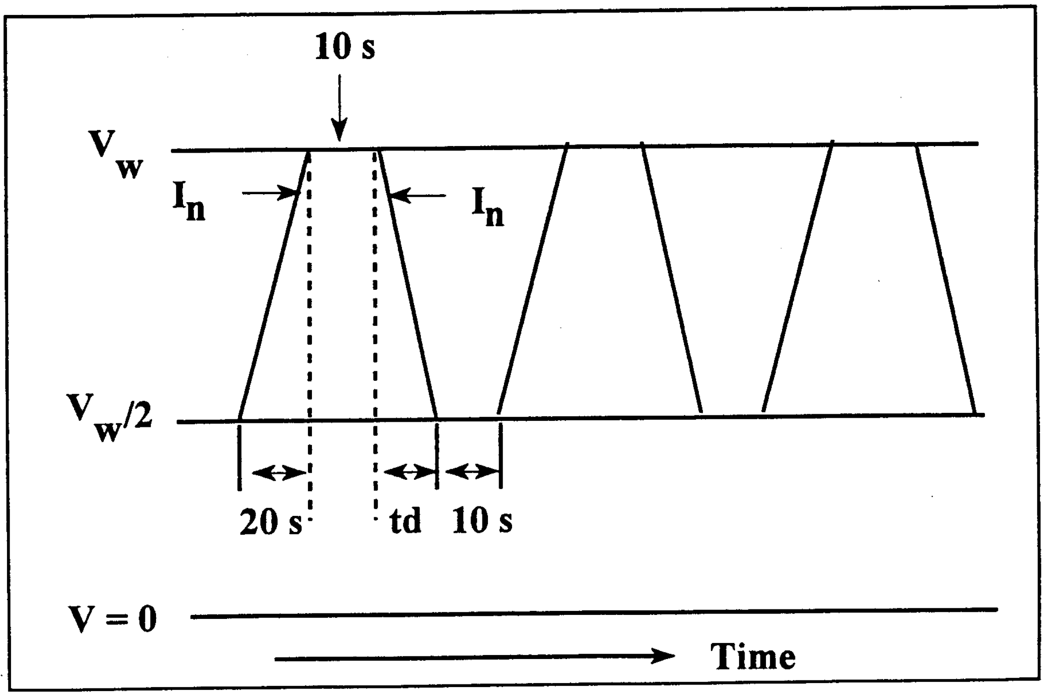


Figure 8. The waveform used during cycle-life testing of a capacitor.

Characterization tests to be performed at each measurement cycle include:

1. Constant-Current Charge/Discharge (0.25 I_n, 2 I_n)
2. ESR (from constant-current test data)
3. Leakage Current
4. Constant Power Discharge (200 W/kg, 800 W/kg)
5. Self-Discharge

The life-cycle tests should be run continuously (24 hrs/day, 7 days/wk) resulting in 1,000 to 2,000 cycles/day. Voltage, current, and temperature data should be recorded for each cycle, but the data needs to be recorded only periodically (every 500 to 1000 cycles). The charge/discharge current I_n should be adjusted periodically (at least weekly) to maintain constant charge/discharge cycle times (tc, td, see Figure 8). When capacitance decreases by 20 or when I_n is decreased by 20 from the value at the beginning of the life-cycle test, the life-cycle test should be terminated.

4. Presentation of Data

The charge and discharge times (tc, td) and the I_n should be tracked during the tests, and the results shown graphically. The results of the characterization tests (1 to 5) at cycles 1000, 4000, 10,000, 40,000, 100,000, 150,000, and 200,000 should be tabulated. and the degradation factors calculated based on the initial values of all the parameters.

Procedure 8: Temperature Performance

1. **Purpose**

Temperature influences the energy that can be stored in a capacitor as well as the power it can deliver. Charge/discharge cycle efficiency is also dependent on temperature. This procedure determines the performance characteristics of a capacitor over the temperature range expected for electric vehicle operation.

2. **Approach**

Capacitor property and performance measurements are performed at three temperature; in this procedure.

3. **Procedure**

Step 1 - Condition the capacitor at 25 + 3°C and perform the tests listed below. Data from previous measurements at this test temperature may be used provided that they were acquired within the previous thirty (30) days.

Tests

1. Constant-Current Charge/Discharge Tests
2. ESR (from constant-current charge/discharge tests)
3. Leakage Current Tests
4. Constant Power Discharge (200 W/kg, 800 W/kg)
5. Transient Power Tests (PSFUDS)

Step 2 - Condition the capacitor at 65 ± 3°C until thermal equilibrium is reached. Perform the above tests at this temperature in the order listed.

Step 3 - Condition the capacitor at -30 ± 3°C until thermal equilibrium is reached. Perform the above tests at this temperature in the order listed.

Step 4 - Condition the capacitor at 25 ± 3°C and repeat the tests listed above. This test data will provide information about the stability of the capacitor under thermal cycling conditions.

Step 5 - Perform a visual inspection of the capacitors to identify any damage caused by the thermal cycle.

4. Presentation of the Data

Prepare a graphical presentation of the following parameters as a function of temperature: ESR at $I = I_n$; leakage current at 1 hr; capacitance at 0.25 I_n, I_n, and 2 I_n, round-trip efficiency on the PSFUDS cycle.

Procedure 9: Life Stability

1. Purpose

Long operational life is needed for capacitors used in the electric vehicle. Stable performance is desired over the specified temperature range during an anticipated life of 10 years. This procedure characterizes capacitor life properties and performance using an accelerated aging condition.

2. Approach

Capacitor properties and performance are measured initially and then periodically throughout the aging period. Individual capacitor failures and the times to failure are recorded. Voltage equal to V_W, the working voltage, is applied and maintained excep during specified characterization tests.

3. Procedure

Age the capacitors in a suitable oven or environmental chamber maintained at 70 ± 3°C with an applied voltage equal to V_W. The voltage source must be capable of supplying a current of at least ten times more than the steady state current draw of the capacitor at 70°C. This will help insure that device failure is not limited by the tester should shunt paths develop or cell shorts occur.

Characterization tests of the capacitors should be performed at the start of the test sequence, and after 250 ± 10, 500 ± 25, 1000 ± 50, and 2000 ± 100 hours. Measurements are made at 25 ± 3°C. Capacitor failures and the time to failure should be recorded. Failed capacitors should be removed from test.

The characterization tests to be performed at each measurement time include:

1. Constant-Current Charge/Discharge

2. ESR
3. Leakage Current
4. Constant Power Discharge (200 W/kg, 800 W/kg)
5. Transient Power Tests (PSFUDS)

4. Presentation of Data

Prepare a graphical presentation of the following parameters as a function of time (hrs) at 70°C: ESR at $I = I_n$, leakage current at 1 hr, capacitance at 0.25 I_n, I_n, 2 I_n, round-trip efficiency on the PSFUDS cycle.

AC Impedance Testing

Procedure 10: Impedance

1. **Purpose**

Many important capacitor properties can be determined using ac impedance spectroscopy. Impedance spectra can be used to determine capacitance and the equivalent series resistance. They can also identify the self-resonance frequency of a capacitor. Importantly, impedance data can be used to create a two-terminal equivalent circuit which models the electrical response of the capacitor in detail.

2. **Approach**

Impedance measurements at one or two frequencies, which is common practice in the electrolytic capacitor industry, are of limited use in characterizing electrochemical capacitors. This is due to the distributed resistance and capacitance in electrochemical capacitors. But impedance data over a broad range of frequencies can provide a wealth of information. This procedure describes methods for obtaining electrochemical impedance spectra.

3. **Procedure**

The capacitor should be conditioned at the specified test temperature until thermal equilibrium is reached. Initialize the capacitor voltage at the specified voltage for a minimum of 1 hr before each test. Longer times may be necessary to stabilize the voltage on some capacitors. Test voltages are 0.02 V_W, $V_W/2$, and V_W Measure the capacitor's impedance at a minimum of 5 frequencies per decade, over the range 0.001 Hz to above the self-resonance frequency (at least to 1000 Hz). The amplitude of the applied sinusoidal signal must be set so that the average value applied to each cell is less than or equal to 0.02 V. The real and imaginary parts of the impedance at each measurement frequency shall be recorded. Equipment limitations may preclude tests at $V_W/2$ and V_W for high-voltage devices.

4. Presentation of Data

Data should be presented on a log-log plot of the magnitude of the real and the imaginary part of the impedance versus frequency at each of the voltages. Figure 3 in the Background Section is an example of this format. Three frequencies should be identified:

1. The frequency where the real and the imaginary parts of the impedance are equal.
2. The Frequency where deviations from ideal-capacitor behavior occurs (see the Background Section).
3. The self-resonance frequency.

These frequencies are important when comparing one capacitor or technology with the next.

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3. Burke, A.F., "*Laboratory Testing of High Energy Density Capacitors for Electric Vehicles*," EG&G Idaho. Inc. Report No. EGG-EP-9885, October 1991.