APPLICATION NOTE

How to Test and Validate Batteries

Battery Testing with Keysight Power Product Solutions

KEYSIGHT

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Introduction

Battery testing is critical for verifying performance, safety, and longevity across various applications, from small Internet of Things (IoT) devices to electric vehicles. It involves assessing key parameters such as capacity (the total amount of charge the battery can deliver), internal resistance (which influences efficiency, heat generation, and aging), and safety, under both normal and stress conditions (including overcharge, short-circuit, and thermal events). These assessments must be carried out in controlled environments to ensure accuracy, and they require precise instrumentation capable of adapting to the specific characteristics of different chemistries — such as lithium-ion, nickel-cadmium, lead-acid, or alkaline — each of which exhibits unique behaviors, degradation mechanisms, and safety considerations.

Batteries and Main Chemistries

A battery is a device that stores and releases electrical energy through electrochemical reactions, consisting of one or more cells with positive and negative electrodes and an electrolyte to facilitate ion movement. This table summarizes the types of batteries and their characteristics.

Battery Type	Characteristic
Lithium-ion (Li-ion)	A rechargeable battery is known for high energy density, light weight, and long cycle life. It is commonly used on smartphones, laptops, and electric vehicles.
Nickel-cadmium (NiCd)	A rechargeable battery with lower energy density but known for durability and reliability in extreme temperatures, and used in power tools, cameras, and medical devices. It suffers from the "memory effect," reducing capacity over time.
Lead-acid	A robust, cost-effective battery commonly used in automotive applications (for example, car batteries) and backup power systems. It has a lower energy density and shorter life cycle compared to newer technologies but remains widely used because of its affordability and reliability.
Alkaline	A non-rechargeable battery with a higher energy density than older zinc-carbon batteries. It is commonly used in everyday consumer devices, such as remote controls, flashlights, and toys. Alkaline batteries offer a long shelf life but cannot be recharged.

Why Battery Testing Matters

Battery testing is essential for ensuring the performance, safety, and longevity of batteries. Some of the reasons for testing batteries are:

- **Performance verification**: Ensures that the battery meets its specified capacity in ampere-hours (Ah) and output power, confirming its ability to power devices effectively.
- **Safety**: Identifies potential issues such as overheating, leakage, or short circuits, reducing the risk of accidents like fires or explosions.
- **Longevity assessment**: Tests how well the battery maintains its performance over time, predicting lifespan and identifying when it needs replacement.
- **Quality control**: Ensures that batteries meet manufacturer standards and are free from defects before they are used in consumer products.

Considering the above, it is evident that battery testing is crucial for optimizing performance, preventing safety hazards, and ensuring reliable, long-term operation in various applications ranging from low-power IoT devices to high-power battery packs in electric vehicles.

Test Challenges for Battery Testing

Key challenges when performing electrical tests on batteries are as follows:

- **Safety risks**: Batteries can overheat, leak, or explode under improper test conditions, especially during high current or short-circuit tests, so they need to be tested in a dedicated, safe enclosure.
- **Accuracy and repeatability**: Variations in temperature, test setup, and equipment calibration can affect the consistency and reliability of results.
- **Time-consuming procedures**: Battery capacity and life cycle tests require extended periods, delaying validation and increasing costs.
- **Temperature sensitivity**: Battery performance is highly temperature-dependent, requiring controlled environments for accurate testing.
- **Complex battery chemistries**: Different chemistries (for example, Li-ion, NiMH, lead-acid) require specific test protocols, complicating standardization.
- **State-of-health (SoH) estimation**: Accurately predicting battery aging and degradation remains complex and often requires advanced algorithms and modeling.
- **Accurate and versatile testing equipment**: Accurate and multifunctional electrical test equipment is essential to test batteries. Equipment must support various chemistries, voltage / current ranges, dynamic range, bandwidth, emulation modes, and communication protocols to ensure flexibility and reliability in testing.

These challenges must be addressed to ensure reliable, safe, and meaningful battery evaluation.

Main Battery Electrical Tests

The main electrical tests commonly performed to validate battery performance are as follows:

- **Open Circuit Voltage (OCV) test**: Measures the battery's voltage without a load to estimate its State of Charge (SoC).
- **Load test**: Applies a load to evaluate the battery’s ability to maintain voltage under demand, simulating real use.
- **Internal resistance test**: Assesses the battery’s internal series impedance, which affects efficiency and heat generation. Higher resistance may indicate aging or damage.
- **Capacity test**: Measures the total charge a battery can deliver under specific conditions (for example, different temperatures, power loading), confirming whether it meets rated capacity.

  Short-circuit test (controlled): Ensures safety by testing the battery’s response to a short-circuit condition, typically done under controlled lab settings.
- **Charge / discharge cycle test**: Repeatedly charges and discharges the battery to evaluate performance over time and assess degradation.

These tests help determine battery health, performance, and safety compliance.

Test Equipment Requirements

As mentioned above, a multitude of electrical tests need to be performed on batteries. To reliably complete such tests, you need testing equipment that meets certain performance specifications and requirements, such as these:

Remote Sensing / Four-Wire Configuration

Wiring resistance can cause voltage drops between the power supply and the battery being charged / discharged, resulting in the battery receiving a lower voltage than intended and inaccurate measurements. To correct this, the two-quadrant power supply can be configured in a four-wire configuration. This setup configuration measures voltage directly at the battery terminals, allowing the power supply to compensate for any voltage drop and deliver the programmed voltage to the battery terminals. Additionally, the voltages measured by the two-quadrant power supply measurement system will accurately reflect the voltage at the battery terminals.

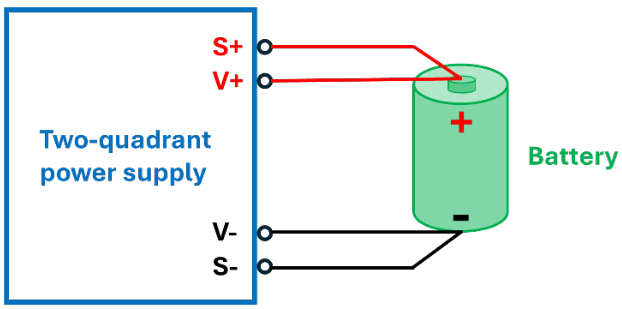


Figure 1. Remote sense test configuration

High Accuracy and Resolution

Equipment must provide precise voltage, current, and resistance measurements to ensure reliable test results, especially for small cells or sensitive applications.

Wide Voltage and Current Range

The ability to handle various battery sizes and chemistries requires flexible voltage and current capabilities, including support for both low-power cells and high-capacity packs.

Programmable High-Bandwidth Load with Arbitrary Waveform Generation

Testers should offer controlled charging and discharging profiles with arbitrary waveform capabilities to simulate real-world use and perform standardized tests like capacity and cycle life.

Safety Features

Built-in protections such as overvoltage, overcurrent, thermal cutoffs, watchdog timers, and emergency shutdowns are critical to prevent hazardous conditions. Watchdog functionality provides an additional safeguard by continuously monitoring the system's operation and automatically stopping or resetting tests if abnormal conditions or communication failures are detected.

Temperature Monitoring and Control

Integration with temperature sensors or chambers allows accurate testing under controlled thermal conditions, as temperature greatly affects battery behavior.

Data Logging and Communication Interfaces

Equipment should support high-resolution data acquisition and interfaces (such as USB, Ethernet, CAN) for real-time monitoring, analysis, and integration with test systems.

Multichannel Capability

For efficient testing of multiple cells or packs simultaneously, multichannel systems enhance productivity and throughput.

Battery Emulation Mode

Allows the tester to simulate a battery's electrical behavior, enabling system-level validation of battery-powered devices without using actual batteries — critical for R&D and hardware testing.

These requirements ensure test accuracy, safety, and flexibility across different battery types and applications.

Keysight Power Products for Battery Testing

Keysight offers several power products that can be used for battery testing, each with varying specifications, features, characteristics, and performance to match different testing needs. Some are better suited for low-power IoT device batteries, while others are designed for high-power electric vehicle batteries. The same equipment and test setup can be used to model, charge, discharge, and cycle batteries. This flexibility enables engineers to choose the right tools based on the complexity and demands. Figure 2 shows how various Keysight power products fit into the battery test setup.

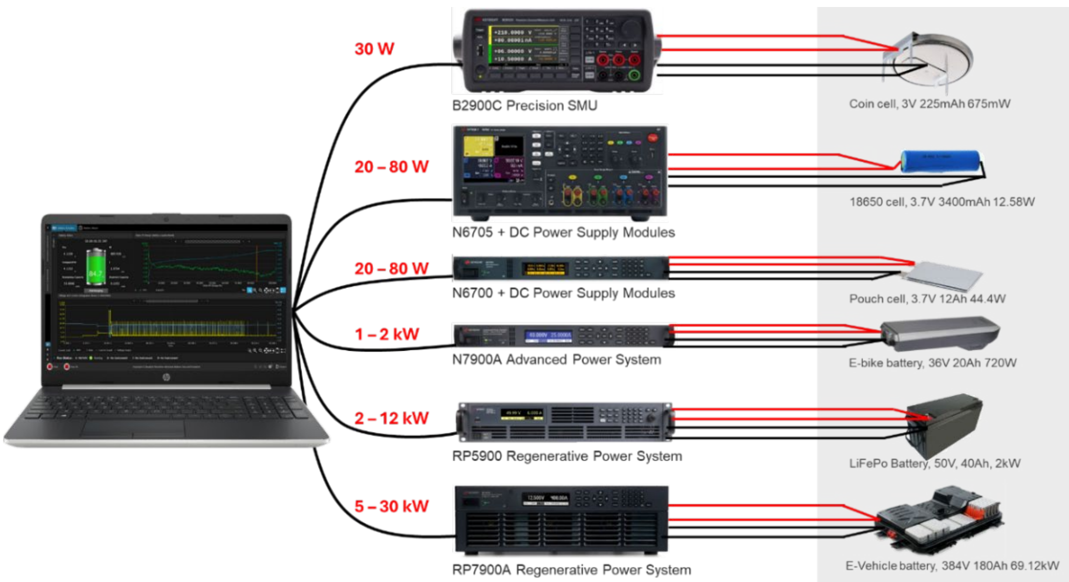


Figure 2. Battery testing setup with Keysight power products

When paired with Keysight Advanced Power Application Suite software, control and measurement of the instruments can be leveraged through software, enabling precise control for battery testing, profiling, charging, discharging, cycling, data visualization, logging, and analysis.

Figure 3. Keysight PathWave Advanced Battery Test and Emulation (PW9253A)

Two-Quadrant Power Supply Portfolio

The Keysight power portfolio offers a range of products that fulfill the battery testing requirements. From low-power benchtop to regenerative high-power automated test equipment, Keysight provides a flexible and scalable selection of two-quadrant power supplies for both charging and discharging batteries.

Two-Quadrant DC Power Supplies

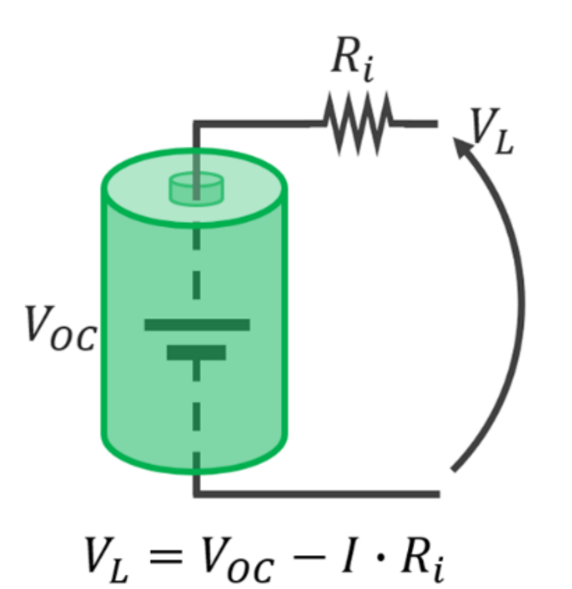
Parameters	B2900C	N6700C	N7900	RP7900	RP5900
Power	31.8 W	20 W – 500 W	1 kW / 2 kW	5 kW – 30 kW	2 kW – 12 kW
Voltage	± 210 V	0 – 150 V	0 – 160 V	0 – 2,000 V	0 – 800 V
Current	0 – 10.5 A	0 – 50 A	0 – 200 A	0 – 800 A	0 – 240 A
Outputs	1 – 2	4	1	1	1
Size	2U	1U / 4U	1U / 2U	3U / 5U	1U / 2U
Volt. prog. resolution	100 nV – 1mV	6 µV – 43 mV	0.21 mV – 1.68 mV	191 µV – 21 mV	1 mV – 10 mV
Curr. prog. resolution	10 fA – 100 µA	0.1 µA – 16 mA	0.24 mA – 1.9 mA	190 µA – 15.5 mA	1 mA – 10 mA
Volt. meas. resolution	100 nV – 100 µV	1 µV – 77 mV	0.21 mV – 1.68 mV	191 µV – 20 mV	1 mV – 10 mV
Curr. meas. resolution	10 fA – 10 µA	0.1 nA – 10 mA	0.24 mA – 1.9 mA	190 µA – 15.5 mA	1 mA – 10 mA
Voltage rise / fall time	50 µs	12 µs – 20 ms	0.5 ms / 0.35 ms	75 µs – 33 ms	15 ms – 60 ms
Transient recovery time	Not specified	35 µs – 250 µs	100µs	300 µs / 500 µs	1 ms
Minimum sampling interval	10 µs – 200 µs	5 µs / 10 µs	5 µs	5 µs	100 µs
Measurement bandwidth	Not specified	2 kHz – 30 kHz	25 kHz	Not specified	Not specified
CD arb points	10k / 100k points	Up to 65,535	Up to 65,535	Up to 65,535	Up to 65,535
CD arb dwell time	10 µs / 200 µs to 100,000 s	10.24 µs	10.24 µs	10.24 µs to 0.30 seconds	1 ms to 3,600 seconds
Data logging integration period	100 µs	100 µs	100 µs	100 µs	100 µs
Output relays	Yes	Yes	Yes	Yes	No
PathWave support	Yes	Yes	Yes	Yes	Yes
Datasheets	B2900C	N6700C	N7900	RP7900	RP5900




Battery Modeling

Battery modeling involves determining the electrical parameters of a battery at various states of charge. A battery model is an electrical representation of a battery's behavior. It enables simulation and prediction of performance under different conditions. A comprehensive electrical model uses resistors, capacitors, and voltage sources to simulate a battery's dynamic load voltage response.

The Keysight's solution uses a first-order approximation, electrically modeling the battery as an ideal voltage source with open circuit voltage (VOC) and series internal resistance (Ri) as shown in the schematic below. A fully charged battery is discharged down to the specified cut-off voltage corresponding to 0% State of Charge (SoC). The open circuit voltage and internal resistance are periodically measured at intervals of either 1% or 0.5%, resulting in a data set and battery model comprising 100 or 200 points, respectively.



SoC(%)	Voc(V)	Ri(ohm)
100.00	4.18	0.086
99.50	4.14	0.086
99.00	4.12	0.086
98.50	4.11	0.085
98.00	4.10	0.085
....	....	....
....	....	....
1.50	3.04	0.085
1.00	3.01	0.085
0.50	2.97	0.085
0.00	2.93	0.085

Figure 4. Battery equivalent electric circuit (left) and extracted parameters, table (right).

The internal resistance Ri is measured with very short pulses to make sure we are capturing only the resistive response of the battery, while the open circuit voltage VOC is measured at rest with no load. Longer current pulses will result in a longer voltage drop tail, corresponding to the dynamic capacitive behavior of the battery. When modeling your batteries for emulation purposes for a given device, it is thus important to tune the current pulse width according to the typical pulse duration of that device. Different pulse widths will result in different voltage drops, and thus a different resistance value. Both the current pulse width and the rest time can be tuned by the user according to their needs, mimicking the device's behavior.

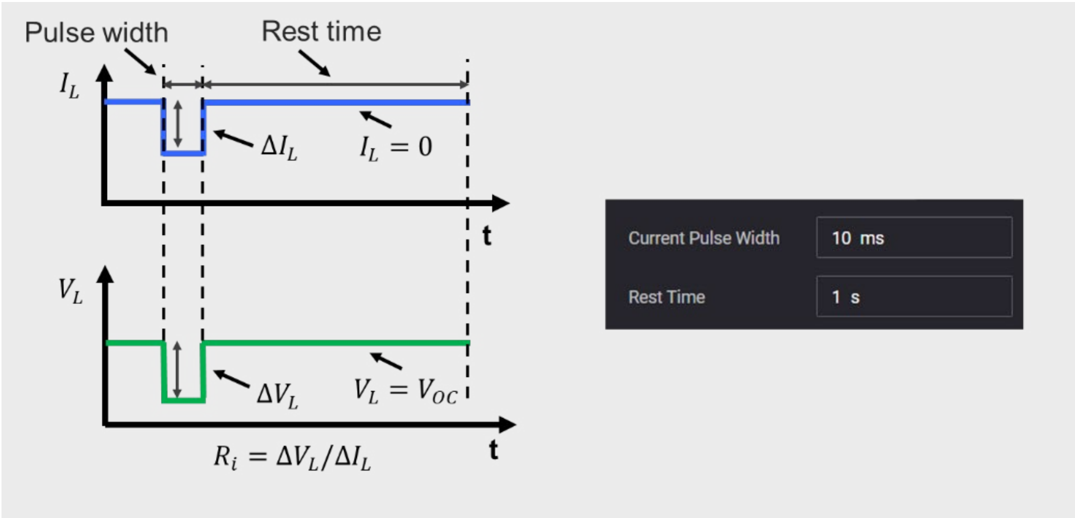


Figure 5. Internal series resistance (Ri) and open circuit voltage (VOC) measurements and settings.

Keysight power supplies can discharge the batteries with constant or dynamic arbitrary load profiles, enabling engineers to validate their behavior with real-life scenarios and obtain the most realistic and accurate results.

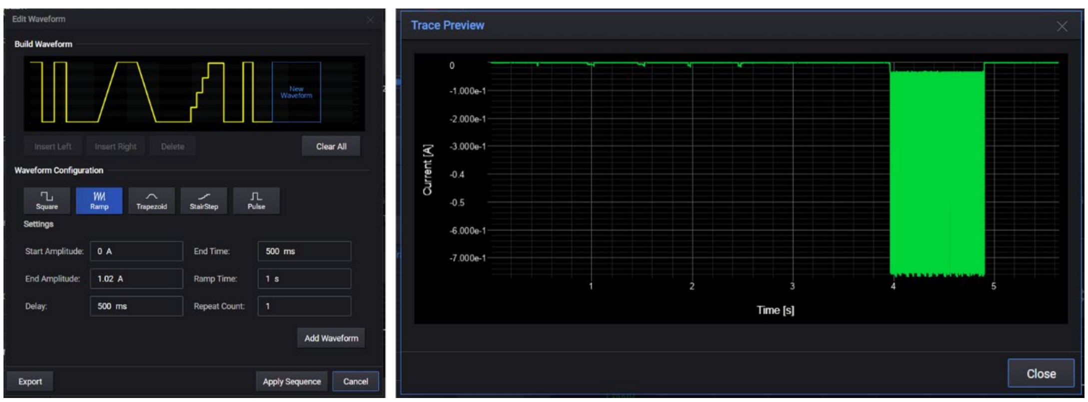


Figure 6. A dynamic load profile was created using the waveform editor (left), and an imported arbitrary consumption load profile as measured on a real device (right).

Users can select the appropriate two-quadrant power supply / electronic load hardware according to their battery power level, specify the cut-off conditions, and easily create the desired battery models in a few hours, depending on the desired discharge rate. The end of the modeling is controlled by setting the cut-off condition on the open circuit voltage (VOC) or the battery load voltage (VL). Users can decide to stop the modeling after a given amount of capacity has been extracted from the battery, allowing for more control. Models can be created under controlled temperature environments, and temperature can be precisely monitored and measured by integrating a data logger into the same environment.

Device and user safety are critical when performing such tests. To identify and prevent issues such as overheating, leakage, or short circuits, the system includes overtemperature protection. This feature enables users to define a temperature range, reducing the risk of fires or explosions.

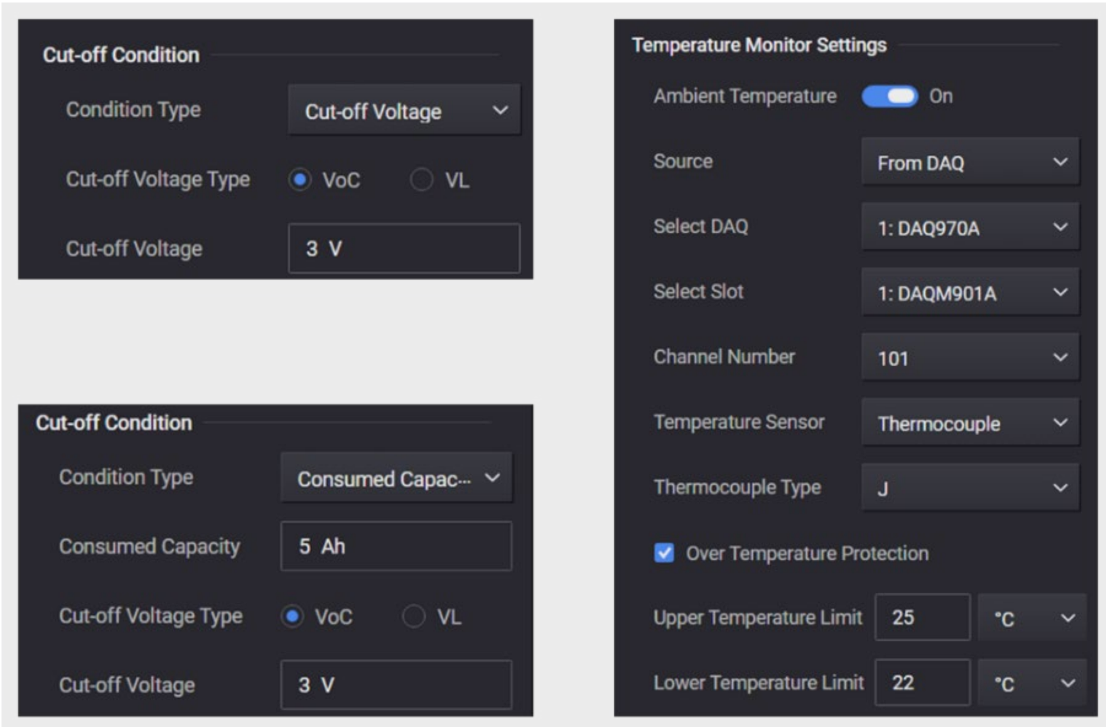


Figure 7. Cut-off condition configuration options, temperature monitoring settings, and protection features.

During the modeling process, the user can monitor the load voltage, discharge current profile, and battery model, including open-circuit voltage and internal resistance in real-time, and continuously save all the data. Once the cut-off condition has been reached, the user can visualize the model, analyze the results, assess the extracted capacity, export it as a CSV file, or use the model on a battery emulator in place of the battery.

Example: Modeling a High-Power LFP Polymer Cell: 3.2V Nominal 20Ah

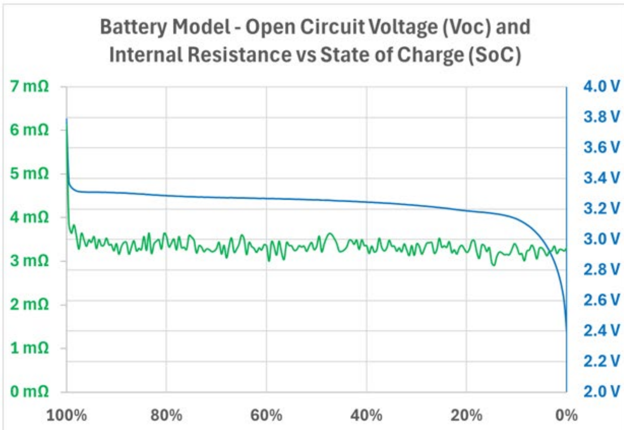
The following example tests a high-power LFP polymer cell, using the specifications provided in the manufacturer's datasheet shown below:

Item	Specifications	Remark
Nominal Capacity	20000mAh±5%	0.2C_5A discharge，25℃
Nominal Voltage	3.2V	Average Voltage at 0.2C_5A discharge
Standard Charge Current	0.2 C_5A	Working temperature：0~45℃
Max Charge Current	1C_5A	Working temperature：0~45℃
Charge cut-off Voltage	3.8V	CC/CV
Standard Discharge Current	2.0C_5A	Working temperature：-10~60℃
Discharge cut-off Voltage	2.4V	
Cell Voltage	3.2-3.4 V	When leave factory
Impedance	≤4mΩ	AC 1KHz after 50% charge,25℃

Figure 8. Battery specification from the manufacturer's datasheet.

To validate the nominal capacity, the manufacturer suggests charging the battery to 3.8 V, laying the battery to rest for 30 minutes, and then discharging at 0.2 C to a cut-off voltage of 2.4 V.

Figure 9. Battery modeling test with discharge current of 0.2C = 4A, current pulse width 12.5 ms, rest time = 1s and cut-off voltage Voc = 2.4 V



Battery Model Table		
Actual Battery Capacity (Ah): 20.0005		
Elapsed Time:00.05:03:36:377		
State of Charge(%)	Open Circuit Voltage(V)	Internal Resistance(Ω)
100.00	3.79	0.00614
99.50	3.38	0.00387
99.00	3.34	0.00365
98.50	3.33	0.00384
98.00	3.32	0.00360
97.50	3.32	0.00329
97.00	3.31	0.00365
96.50	3.31	0.00351
96.00	3.31	0.00335
95.50	3.31	0.00350

Figure 10. Exported battery model: open circuit voltage (VOC) and internal resistance (Ri) versus State of Charge (SoC).

The Keysight N7972A (40 V, 50 A, 2 kW) two-quadrant power analyzer and its software operated in profiler and discharge mode with parameters defined by the manufacturer, as shown in Figure 9. The test ran for 5 hours and 3 minutes, delivering an extracted battery capacity of exactly 20.0005 Ah, consistent with the datasheet specification.

Battery Capacity Validation

Capacity testing is an important step that measures how much electrical charge a battery can provide under specific conditions, such as temperature, power load, and discharge rate. This process is essential for validating whether a battery performs according to its manufacturer's rated capacity, typically expressed in Ampere-Hours (Ah) or Milliampere-Hours (mAh).

Purpose of Capacity Validation

Performance verification

The primary goal is to verify that a battery meets its advertised specifications. This ensures that when deployed in real-world applications — ranging from smartphones and electric vehicles to aerospace and grid storage — the battery performs reliably and efficiently.

Quality control

Capacity testing is a standard part of manufacturing quality assurance to catch underperforming cells before they reach consumers. Any deviation from expected performance could indicate material defects, incorrect assembly, or degradation.

Application suitability

Different devices and environments place unique demands on batteries. Capacity testing under various temperatures and load conditions helps confirm that the battery can deliver consistent performance in specific use cases, such as cold-weather operation for outdoor sensors or high-drain usage in power tools.

Validating battery capacity is relatively straightforward with Keysight solutions. Once you have selected the appropriate two-quadrant power supply model and electrically connected it to your battery via a four-wire connection, as shown in Figure 2, you can use the software charge / discharge feature to automate the process and obtain the desired result.

You can specify a constant discharge current or create / import a dynamic load profile to validate the battery capacity under real-life conditions. The battery discharges to the designated cut-off voltage and records the resulting depleted capacity. This enables users to compare the measured capacity with datasheet specifications or expected values. The software allows capacity validation when charging and discharging. You can measure the capacity of the battery with the charging feature. Discharging will measure the capacity released by the battery.

Experiment – Battery Charging

In this experiment, the battery is set to charge with a constant current of 1C = 20A, followed by the CV phase with a voltage limit of 3.8 V. Both voltage and current can be used as a stop condition. In this case, the CV phase is maintained, and the stop condition is set to a current level of 0.05C (1 A).

Figure 11. Capacity stored in the battery while charging a fully discharged battery in constant current mode with a current of 1C = 20A, from 2.4 V to 3.8 V, and then CV mode with a current stopping limit of 0.05C = 1A. Stored capacity 19.9 Ah.

The overall test ran for approximately 2 hours and 20 minutes, and 19.9 Ah was stored. During the constant current phase, which lasted about 53 minutes, 17.65 Ah was stored in the battery. During the constant voltage phase, which lasted 1 hour and 27 minutes, only 2.25 Ah was stored.

Battery Cycling

Battery cycling testing is to evaluate a battery's performance, durability, and degradation behavior over repeated charge and discharge cycles. These tests simulate real-world use conditions to assess how capacity, efficiency, and internal resistance evolve over time. Cycling tests are critical for predicting battery lifespan, validating performance claims, ensuring safety, and optimizing battery management systems. They provide essential data for applications ranging from consumer electronics to electric vehicles and grid storage. These tests help manufacturers and users make informed decisions about battery reliability and longevity.

Experiment – Battery Cycling Tests

The manufacturer recommends using the test method as specified in Table 2 for the battery cycler test.

Item		Test Methods	Performance
4.3	Cycle Life	Constant current $1C_5A$ charge to 3.8V, then constant voltage charge to current declines to $0.05C_5A$, stay 5min， constant current$1C_5A$ discharge to 2.4V， stay 5min. Repeat above steps till continuously discharging time less than 36min.	⩾500times

Figure 12. Manufacturer cycle test method and settings recommendation.

Keysight battery test software offers advanced capabilities that enable users to sequence and combine various steps within a cycle, which can be composed of charging, discharging, and resting, and arranged in any order. The user can decide to charge and discharge with constant, arbitrary, or dynamic current profiles, simulating any real-world situation. Setting up this test is relatively straightforward. In this case, the test begins with a fully charged battery.

A single cycle includes four steps:

1. Discharge in CC mode at 1C (20 A) until the cell reaches 2.4 V.
2. Rest for 5 minutes.
3. Charge in CC mode at 1C (20 A) up to 3.8 V, stopping when current tapers to 1 A.
4. Rest for 5 minutes.

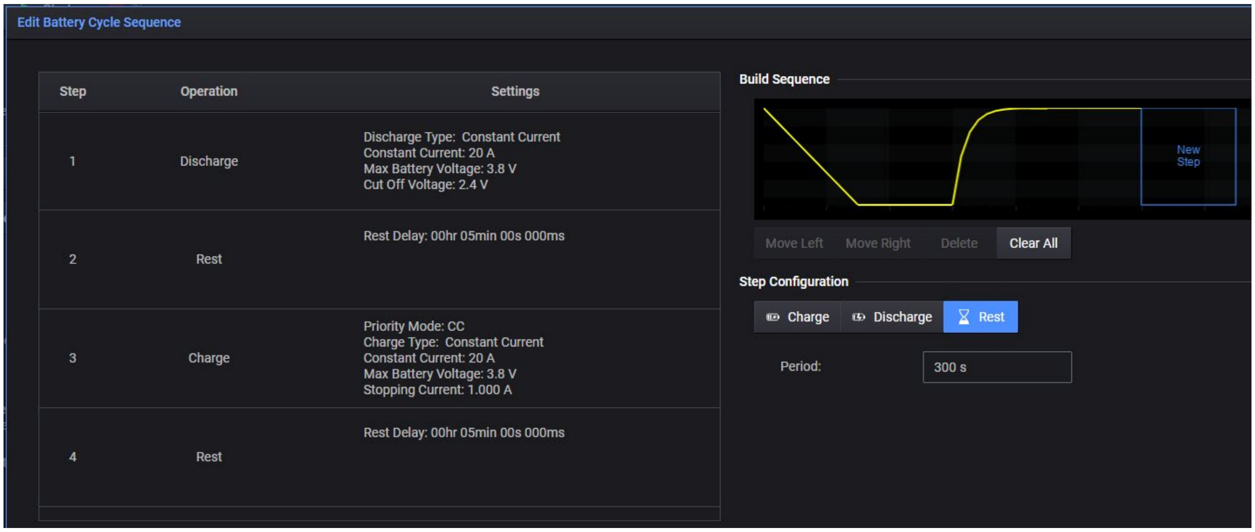


Figure 13. Cycler sequence editor, integrating charge, discharge, and rest steps.

The cycler solution supports up to 1,000 cycles, and these tests are lengthy and time-consuming. The test uses 10 cycles, with voltage, current, and capacity continuously logged and saved for each cycle, as shown in Figure 13. A summary table, including accurate capacity measurements and timing for each step and cycle, is automatically generated and saved for the user for later processing and analysis. This facilitates the monitoring of capacity variations and losses over multiple cycles and extended periods.

Figure 14. Cycler with battery voltage, current, and capacity graph (top), and a cycle capacity table (bottom).

Steps	Cycle 1 Capacity (Ah)	Cycle 2 Capacity (Ah)	Cycle 3 Capacity (Ah)	Cycle 4 Capacity (Ah)	Cycle 5 Capacity (Ah)	Cycle 6 Capacity (Ah)	Cycle 7 Capacity (Ah)	Cycle 8 Capacity (Ah)	Cycle 9 Capacity (Ah)	Cycle 10 Capacity (Ah)
Discharge	-19.529	-19.291	-19.175	-19.119	-19.086	-19.075	-19.058	-19.030	-18.953	-18.930
Rest	-0.006	-0.010	-0.004	-0.001	-0.007	-0.010	-0.003	-0.008	-0.009	-0.008
Charge	19.217	19.172	19.108	19.077	19.061	19.058	19.041	18.992	18.930	18.921
Rest	0.000	0.000	0.000	0.001	0.001	0.000	0.000	0.000	0.001	0.001

Figure 15. Cycler capacity measurement table for each step and cycle.

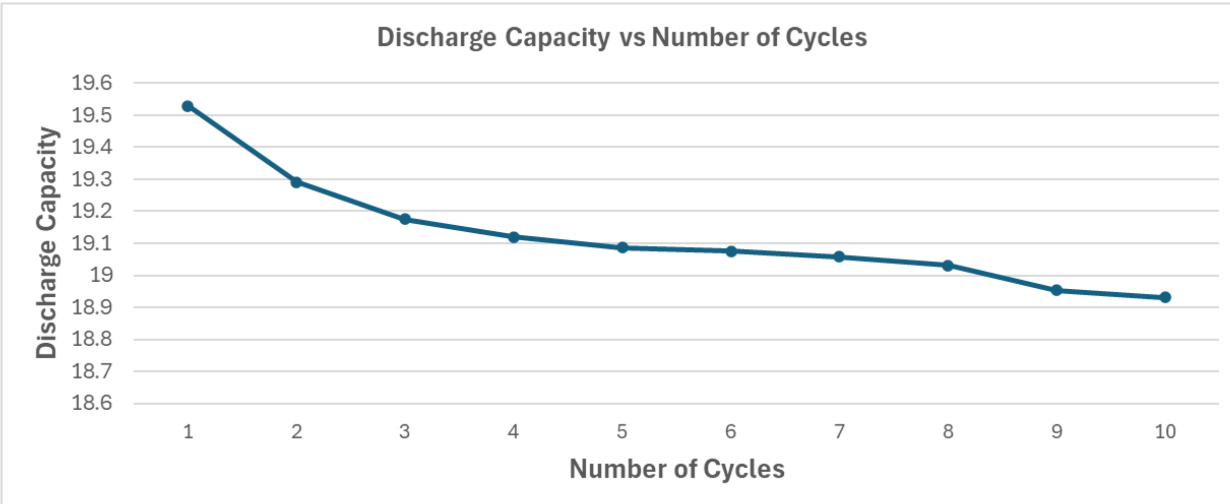


Figure 16. Cycler capacity measurements graph.

The test ran continuously for more than 24 hours and stopped after the 10th cycle. Data analysis and plotting, shown in Figure 15, reveal a gradual capacity decline with each cycle. In the first cycle, the battery discharged 19.529 Ah (Figure 13), whereas in the 10th cycle, it delivered only 18.93 Ah. This reduction corresponds to a capacity loss of 0.598 Ah, or roughly 3%. Capacity results and reference capacity tables obtained from a golden battery sample can be stored and later used as benchmarks to evaluate the State of Health (SoH) of any battery of the same model or batch.

Conclusion

Battery testing is fundamental to ensuring that modern energy storage solutions meet the performance, safety, and reliability standards required in today's applications, from consumer electronics to electric vehicles and large-scale storage systems. As batteries continue to evolve in chemistry, design, and capacity, the complexity of accurately testing and modeling them increases. This demands precise, versatile, and safe test equipment capable of handling diverse conditions while delivering repeatable and trustworthy results.

The Keysight portfolio of two-quadrant power supplies, combined with advanced software tools, provides engineers with the flexibility to perform a wide range of battery evaluations including modeling, capacity validation, and long-term cycling under real-world conditions. By enabling detailed analysis of critical parameters such as open circuit voltage, internal resistance, and cycle degradation, Keysight solutions help predict battery performance and optimize design for longevity and safety.

Ultimately, reliable battery testing not only accelerates innovation but also reduces risk and improves product quality across industries. With accurate measurement tools and robust methodologies, engineers can confidently validate new battery technologies, support sustainable energy applications, and meet the growing demands of the electrified world.