KEYSIGHT

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Understanding Battery Cell Key Parameters and the Challenges to Measure Them

For engineers who are selecting and applying cells
when developing battery-powered electronic products and systems

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May I introduce myself?   Bob Zollo

- Solution Architect for Battery Testing, Keysight Technologies
- Create battery testing solutions roadmap
  by researching customer and industry trends
- 40 years: Keysight, Agilent, HP (one company, 3 names)
  - R&D and Marketing
  - Power supplies, electronic loads, power analysers,
    data acquisition equipment, and test systems
  - Managed battery test systems business
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KEYSIGHT

Global Leader in Test

Cell/Battery Test Systems
Charger Test Systems
Grid Compliance Test
Lidar, Radar, In-Vehicle Network Test
Vehicle Cybersecurity Test

Agenda

- Basic Definitions
- Key Parameters and Challenges for Measurement
  - OCV
  - Self-Discharge
  - ACIR
  - DCIR
  - Capacity
- Summary

Cylindrical Cells

Pouch Cells

Prismatic Cells

Image: Courtesy of Flash Batteries

A Few Basic Definitions

SoC – State of Charge

The amount of charge stored in the cell.

- 100% SoC = fully charged to its rated capacity.
- 50% SoC = charged to 50% of rated capacity.
- 0% SoC = fully discharged.

C - rate

- The current required to fully charge or fully discharge a cell in 1 hour.
- A cell rated at 25 Ah has a C-rate of 25 A and therefore 1 C = 25 A.
- Thus it reaches a capacity of 25 Ah when it is charged at 1C or 25 A for 1 hour.

SoH – State of Health

This is a concept vs a defined measurement. Typically, SoH is considered to be

- (Max Available Capacity) / (Rated Capacity) because Max Available Capacity drops as cell wears out
  -or-
- Internal resistance (IR) greater than some arbitrary threshold, like IR > 0.5 Ω because resistance rises as the cell wears out
  -or-
- Some combo of the above

Key Cell Parameters and Why They are Important

	Key Cell Parameter	Why important? What does it tell you?
1	**Open Circuit Voltage (OCV)**	• Most fundamental measurement. Assesses current status of the cell. Acts as a proxy for SoC; if you know the OCV, you can approximate the SoC.
2	**Self Discharge**	• How quickly the stored energy leaks away when the cell sits unused. • Knowing self discharge help you determine how long a car can stay parked or how long a defibrillator can be stored before needing maintenance.
3	**AC Internal Resistance (ACIR)**	• Internal resistance of the cell. Used to determine SoH. • Knowing R tells you the cell behavior under varying current.
4	**DC Internal Resistance (DCIR)**	• Internal resistance of the cell • Primarily used to determine cell behavior under high current pulsed loads

5	**Capacity**	• How much electric charge can be stored in the cell.
		• Important input to a Battery Management System (BMS)
		• Knowing capacity allows you to determine the
		    • SoC, SoH
		    • remaining runtime
		    • when does cell need to be charged
		    • when to stop recharging the cell

Let’s begin by looking at OCV …

(1) Open Circuit Voltage (OCV)

More difficult to measure than one might think

Chemistry	Min Voltage (V)	Max Voltage (V)
LFP ($LiFePO_4$)	2.0 – 2.5	3.55 – 3.65
NMC ($LiNiMnCoO_2$)	2.5 – 3.0	4.2 – 4.3
LCO ($LiCoO_2$)	3.0	4.2
LMO ($LiMn_2O_4$)	3.0	4.2
NCA ($LiNiCoAlO_2$)	2.5 – 3.0	4.2 – 4.3
LTO ($Li_4Ti_5O_{12}$ + NMC/LMO)	1.5	2.7 – 2.8

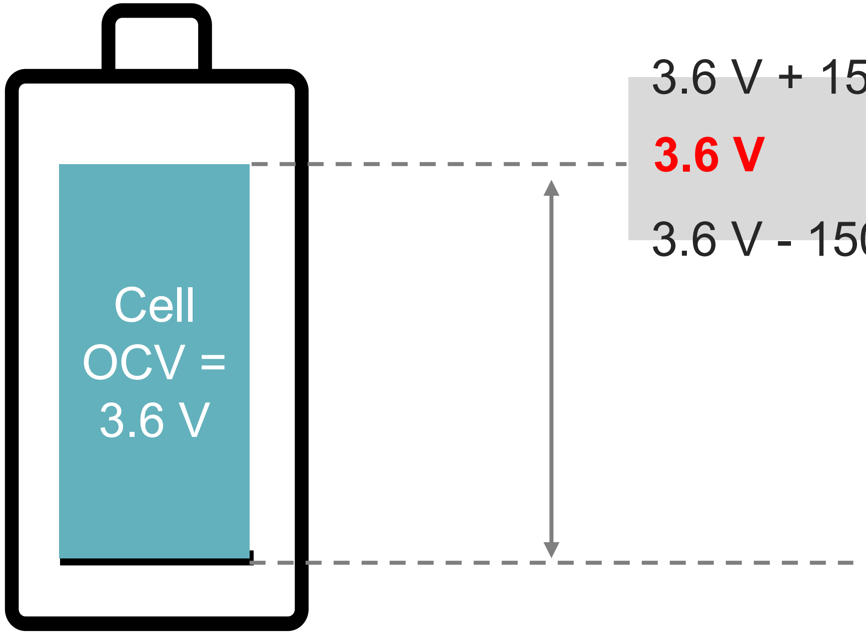
Approach

- Use a standard DMM to measure cell OCV
- Cell OCV will be between 1.5 V and 4.3 V across chemistries
- Therefore, you will need to use the 10 V range
- But you must consider DMM Error →

	World's Best DMM ***Found in Calibration Lab*** **8.5 Digits**	**High Performance DMM** ***Common in R&D*** **6.5 Digits**
Specification	0.00041% of reading + 0.000005% of 10 V range	0.003% of reading + 0.0004% of 10 V range
Error on 3.6V cell voltage when measured on 10V range	0.00041% of 3.6 V = 14.8 µV 0.000005% of 10 V = 0.5 µV Total error = ± 15.3 µV (BEST CASE)	0.003% of 3.6 V = 108 µV 0.0004% of 10 V = 40 µV Total error = ± 148 µV

DMM Error When Making OCV Measurements

- Cell OCV is 3.60000 V
- High quality **DMM error** = ± 150 µV on a 3.6 V measurement.



3.6 V + 150 µV = 3.600150 V

3.6 V

3.6 V - 150 µV = 3.599850V

± 150 µV error band
0.004% error
on the OCV measurement

- The 3.60000 V cell will measure anywhere from 3.599850 V to 3.500150 V, which is 0.004% error.
- Thus, this high quality DMM is quite adequate for making great OCV measurements.

(2) Self-Discharge

As a quality criterion

- Li-ion cells have self-discharge of 1 to 2% SoC per month
- Influences on self-discharge

Influences on Self-Discharge as expected by design

- Temperature
- State-of-charge
- Electrode material quality

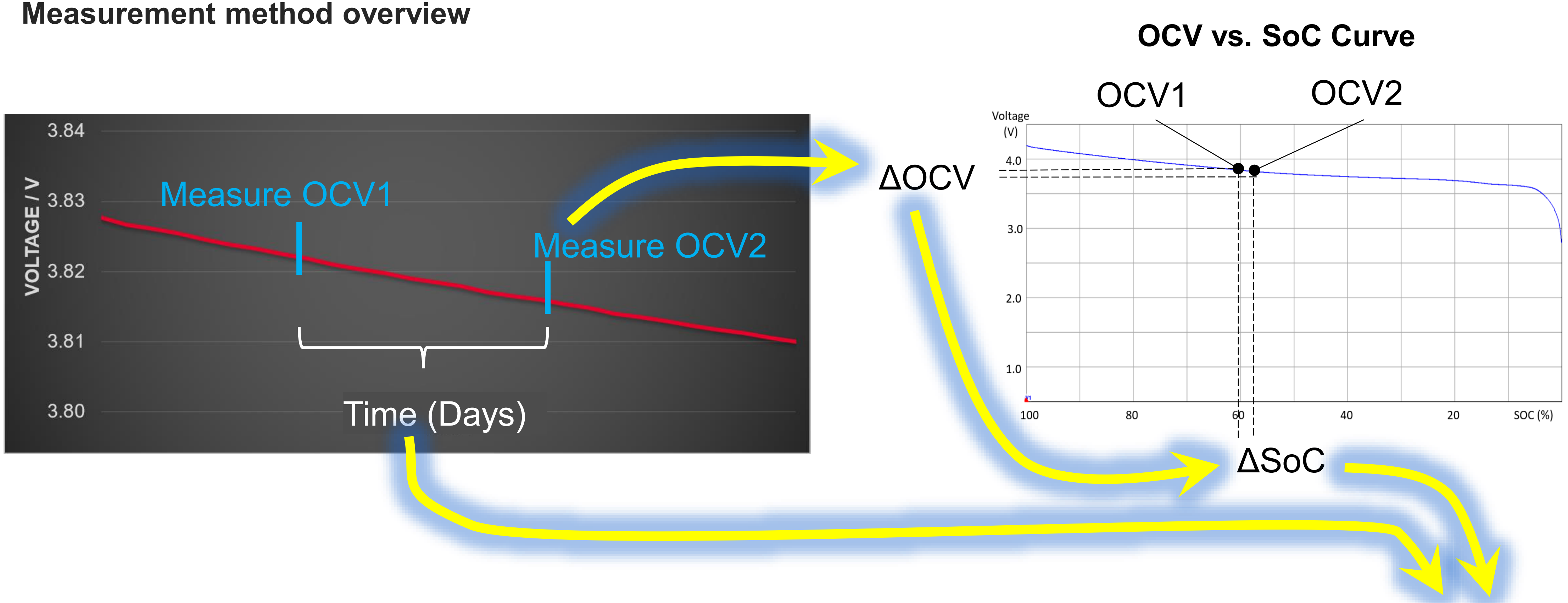
Increased Self-Discharge caused by defects during manufacturing, cycling, handling

- Electrode material quality
- Separator defects
- Formation of dendrites
- Damage from heating

Normal Self-Discharge level → Excessive self-discharge means quality issues

Measuring Self-Discharge using Traditional ΔOCV Method

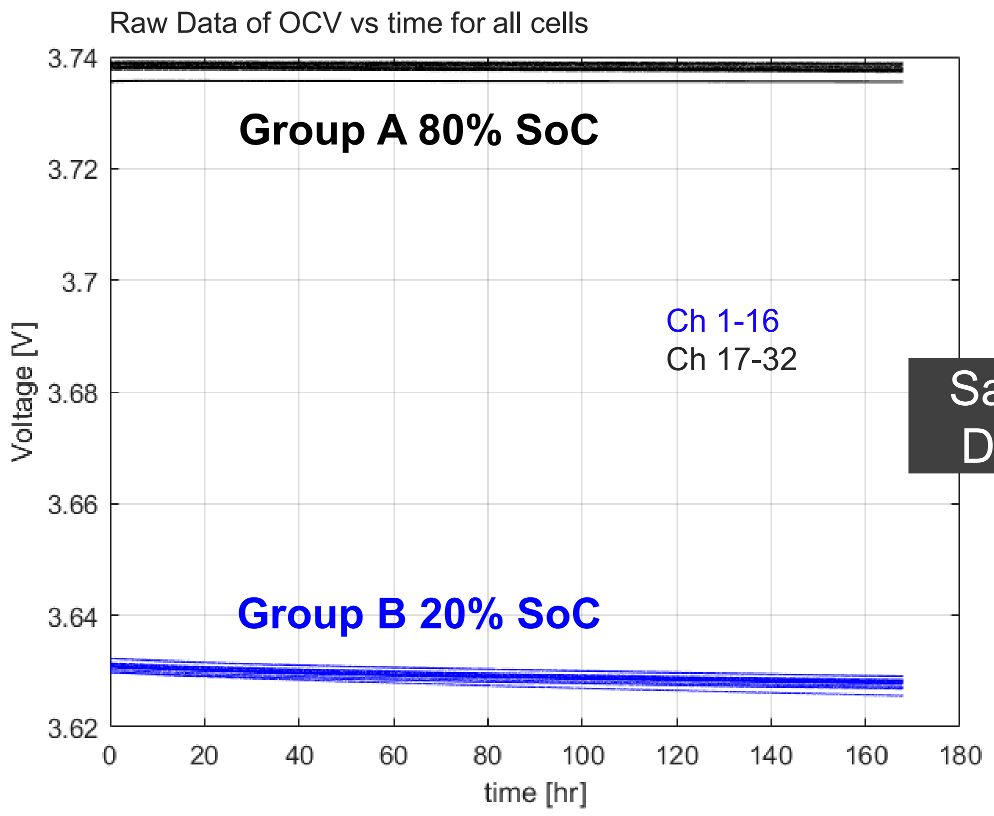
Measurement method overview

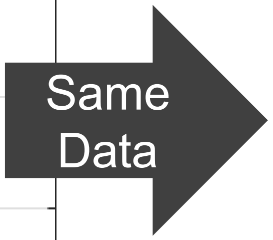


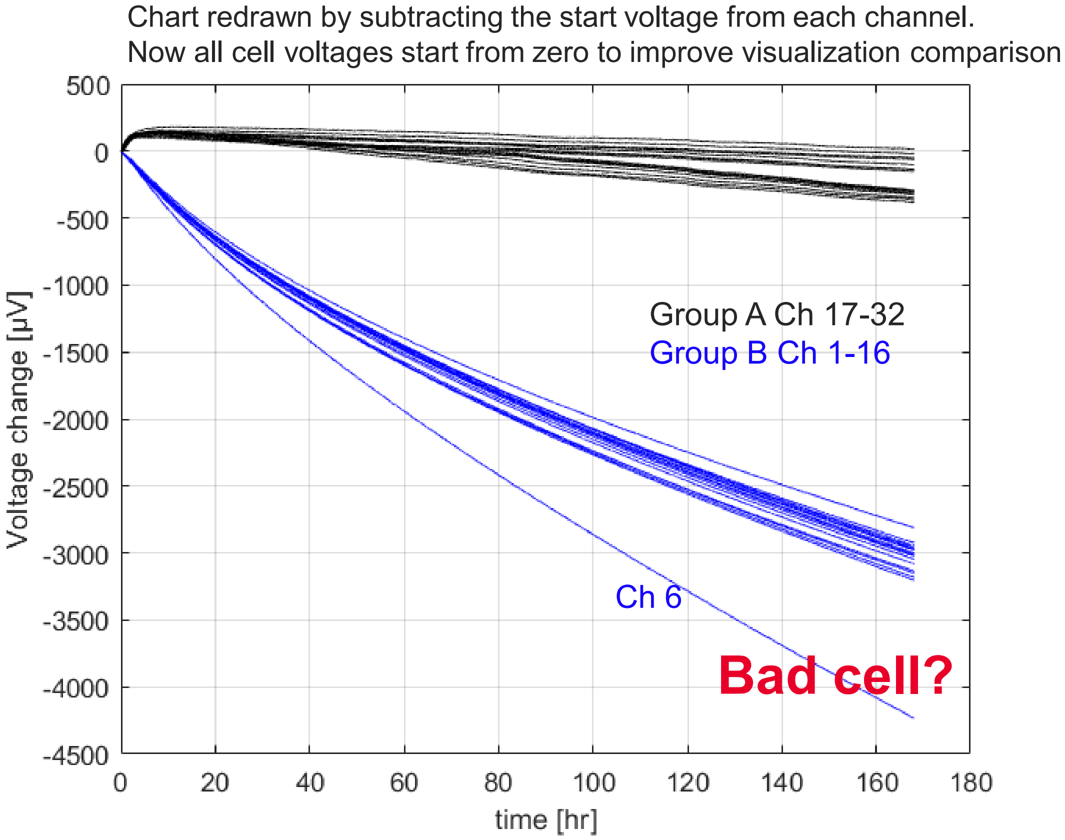
- Measure OCV_1
- Wait days — Typical 3 to 5 days
- Measure OCV_2
- $\Delta OCV = OCV_1 - OCV_2$ — Typ: 5 mV
- Determine ΔSoC from OCV vs SoC curve
- Self-Discharge Current = (ΔSoC x Capacity) / Time

Example Data for ΔOCV on 2 Cell Groups (A and B) for a 30 Ah Cell

Measured over 7 days







Challenges When Making Traditional ΔOCV Measurements

- Because the discharge is slow, you must wait several days between V1 and V2 for the voltage to change significantly enough be able to accurately and repeatably measure the change in voltage.
- Typical ΔOCV measurement → Time = 3 to 5 days → Results in ~5 mV of change in OCV.
- But, these factors need to be considered:

Cell Relaxation

- Cell relaxation occurs following a change in SoC caused by charging or discharging
- OCV can change by 10's of mV during first few hours of relaxation
- Measuring ΔOCV before the cell is relaxed will give incorrect ΔOCV results, causing cells to be incorrectly graded.

Cell OCV Temperature Sensitivity

- Cell OCV is a function of temperature
- Temperature impact can be up to 400 μV for 1°C change
- If Lab or Factory temperature is ± 2 °C, this can cause ~1.5 mV of OCV change and give incorrect ΔOCV results, causing cells to be incorrectly graded.

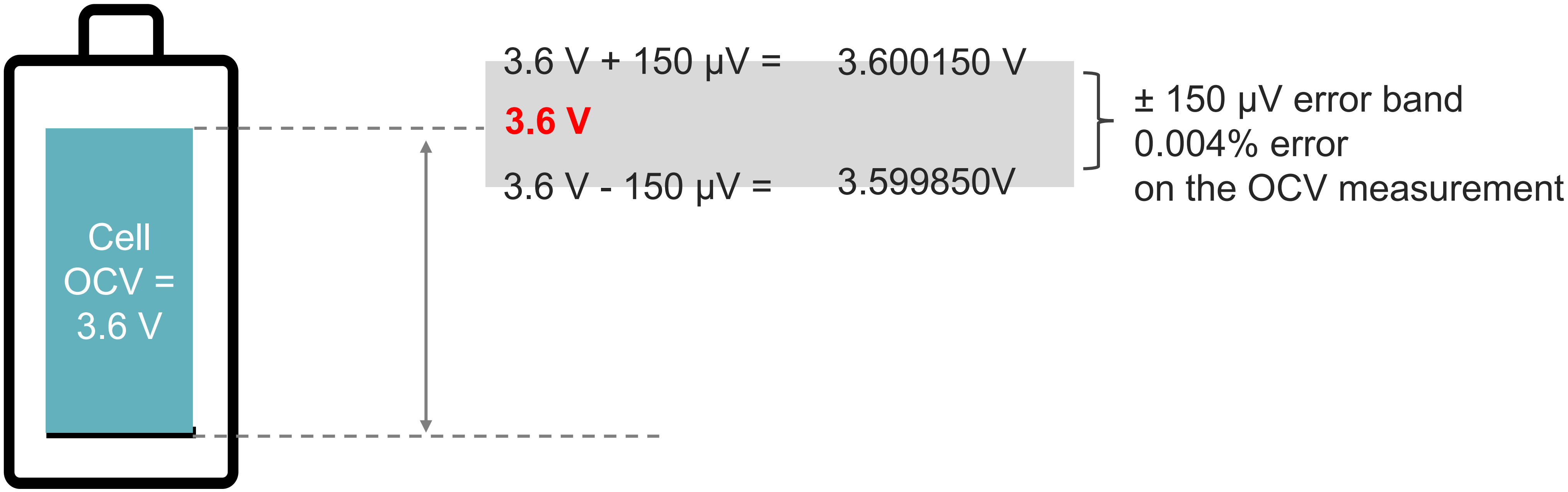
DMM Error

- We touched on this earlier
- Let's see how DMM error can effect ΔOCV measurements …

Let's review from earlier: DMM Error When Making OCV Measurements

When making a simple OCV measurement with a DMM

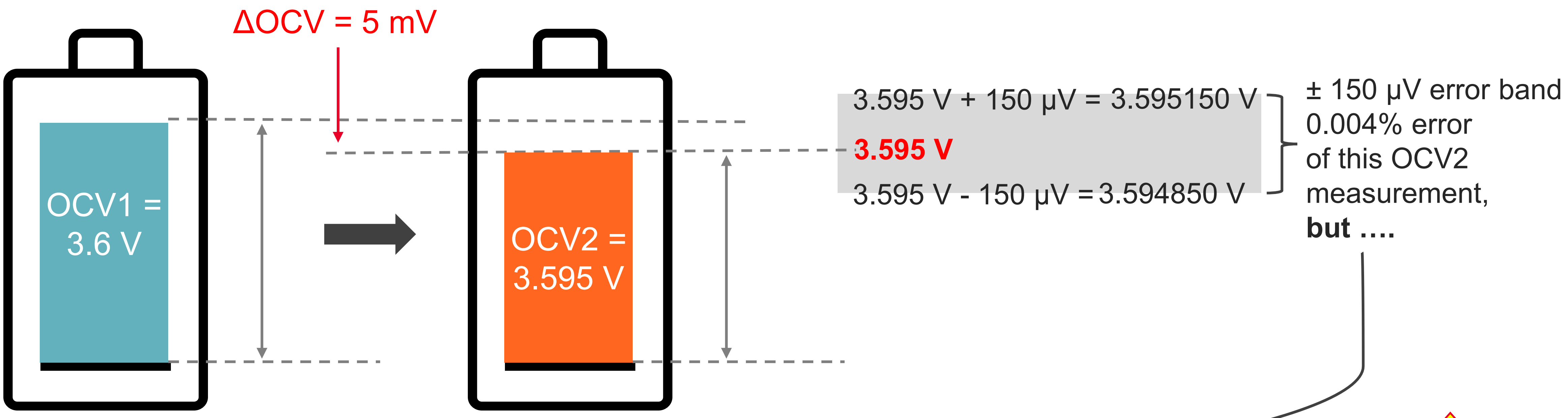
- Cell OCV is 3.60000 V
- High quality **DMM error** = ± 150 µV on a 3.6 V measurement.



- The 3.60000 V cell will measure anywhere from 3.599850 V to 3.500150 V, which is 0.004% error.
- Thus, this high quality DMM is quite adequate for making great OCV measurements.

DMM Error When Making ΔOCV Measurements

- Cell started at OCV1 = 3.60000 V, but has aged and dropped by 5 mV to OCV2 = 3.59500 V.
- High quality DMM error = ± 150 µV on each measurement of OCV.
- Therefore, OCV2 of 3.59500 V will measure anywhere from 3.594850 V to 3.595150 V.



- ΔOCV requires 2 measurements: OCV1, OCV2
  with error of 150 µV from OCV1 **+** 150 µV from OCV2,
  giving a total error of 300 µV on the 5 mV ΔOCV, or an **error of 6% on the ΔOCV of 5 mV**.

That's very different from 0.004%!

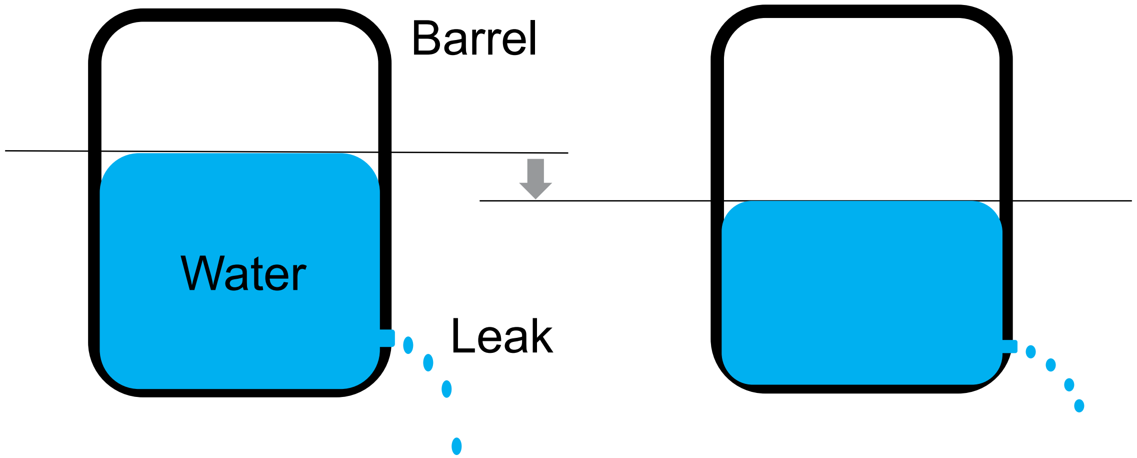
Innovative Measurement of Self-Discharge: Faster, More Accurate Results vs ΔOCV with Long Aging

The Direct Self-Discharge Potentiostatic Method

Analogy: Self-discharge is like a water leak

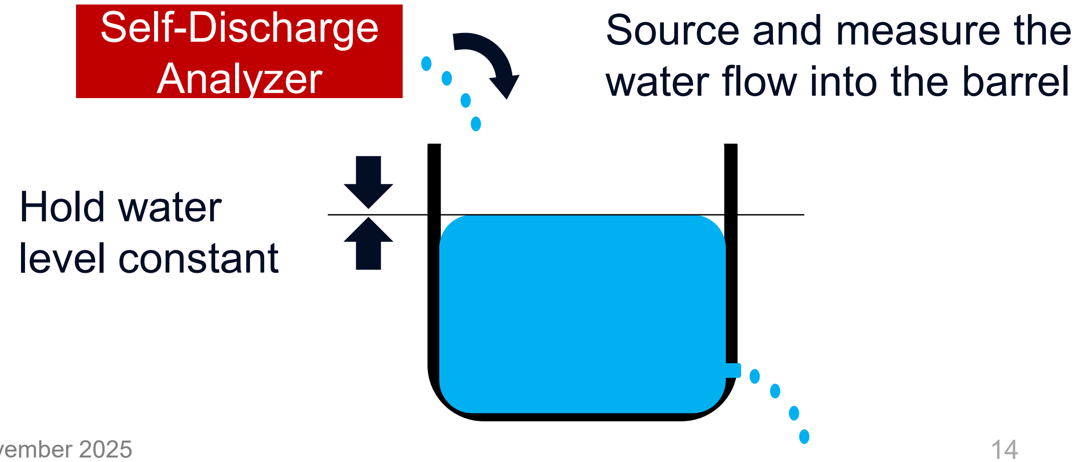
- Loss of water due to leakage
- Leak is small leak
- Must wait a long time for water level to change
- Change in water level = Δ OCV

Traditional ΔOCV method



Self-Discharge Analyzer using Potentiostatic Method

- Keep cell voltage constant during measurement period
- Current that flows = self-discharge current



Potentiostatic Self-Discharge Measurement

- Accurate to µA's with nA resolution
- Suitable for any cell capacity, chemistry, or form factor (prismatic, cylindrical or pouch)
- Detection of **good vs bad cell in as fast as < 1 hour**
- Saves
  - **Huge inventory carrying costs** in production
  - No need to store millions of cells for up to many days
  - **Lower risk from fire** caused by long storage of faulty cells with excessive self discharge
- **Faster process feedback** has benefits
  - Shorter R&D cycles
  - Reduced scrap rates in Manufacturing

(3) ACIR and (4) DCIR

ACIR – AC Internal Resistance R (in Ω)

- Standard test
- Performs a single frequency measurement at 1 kHz
- Easy measurement – low frequency means no measurement challenges
- Fast – just one frequency to be sourced and measured
- Commonly available from instruments focused on battery test: battery analyzers, voltmeters
- Gives an indication of cell resistance to compare across cells, but **does not provide much insight into cell**

DCIR – DC Internal Resistance R (in Ω)

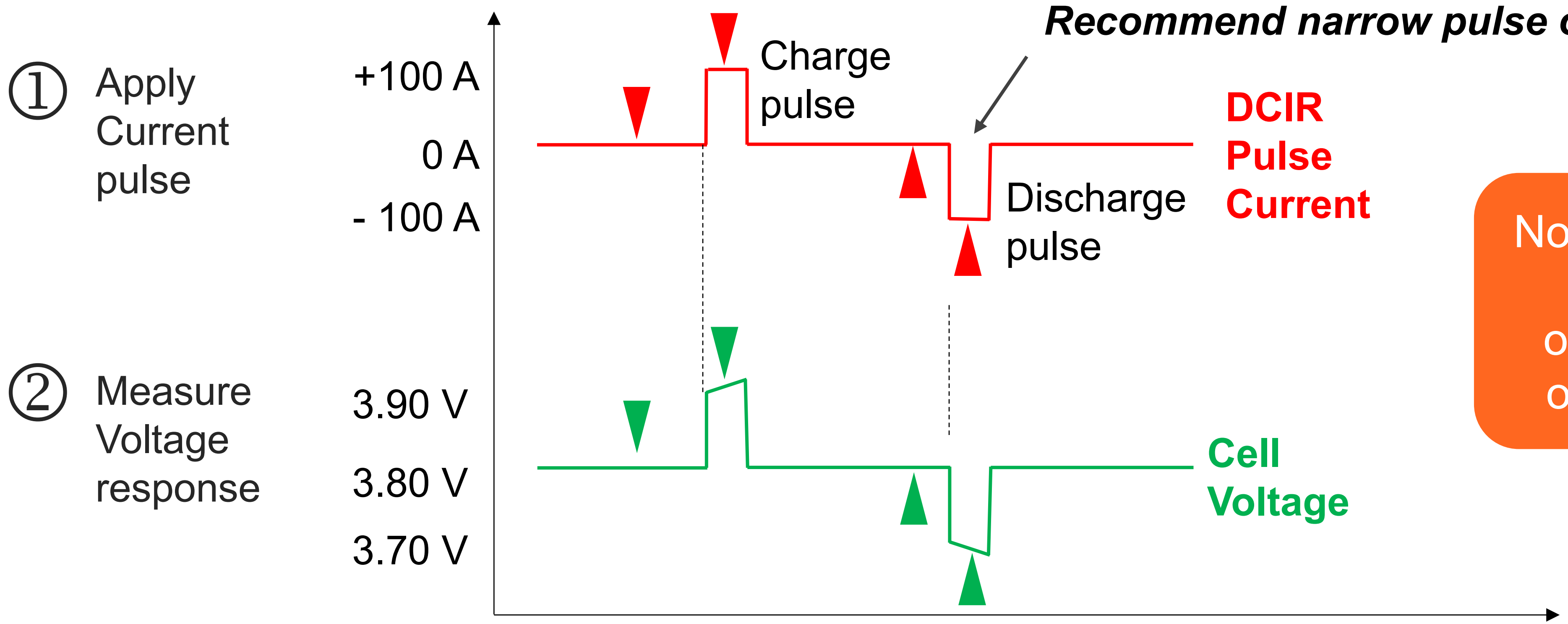
- Non-standard test, so test definition is variable (see next slide)
- Performs measurement of DC resistance only
- Uses high DC current, typically 2C to 10C
- Speed ranges from 100's of ms to minutes
- Expensive due to high current and high speed measurement requirements
- Tells more about the **real behavior of the cell in response to a current pulse**

DCIR using a Charge then Discharge Pulse

Using + and – pulse means SoC remains unchanged

DCIR method:
1. **Apply current pulse**
2. **Measure voltage response**

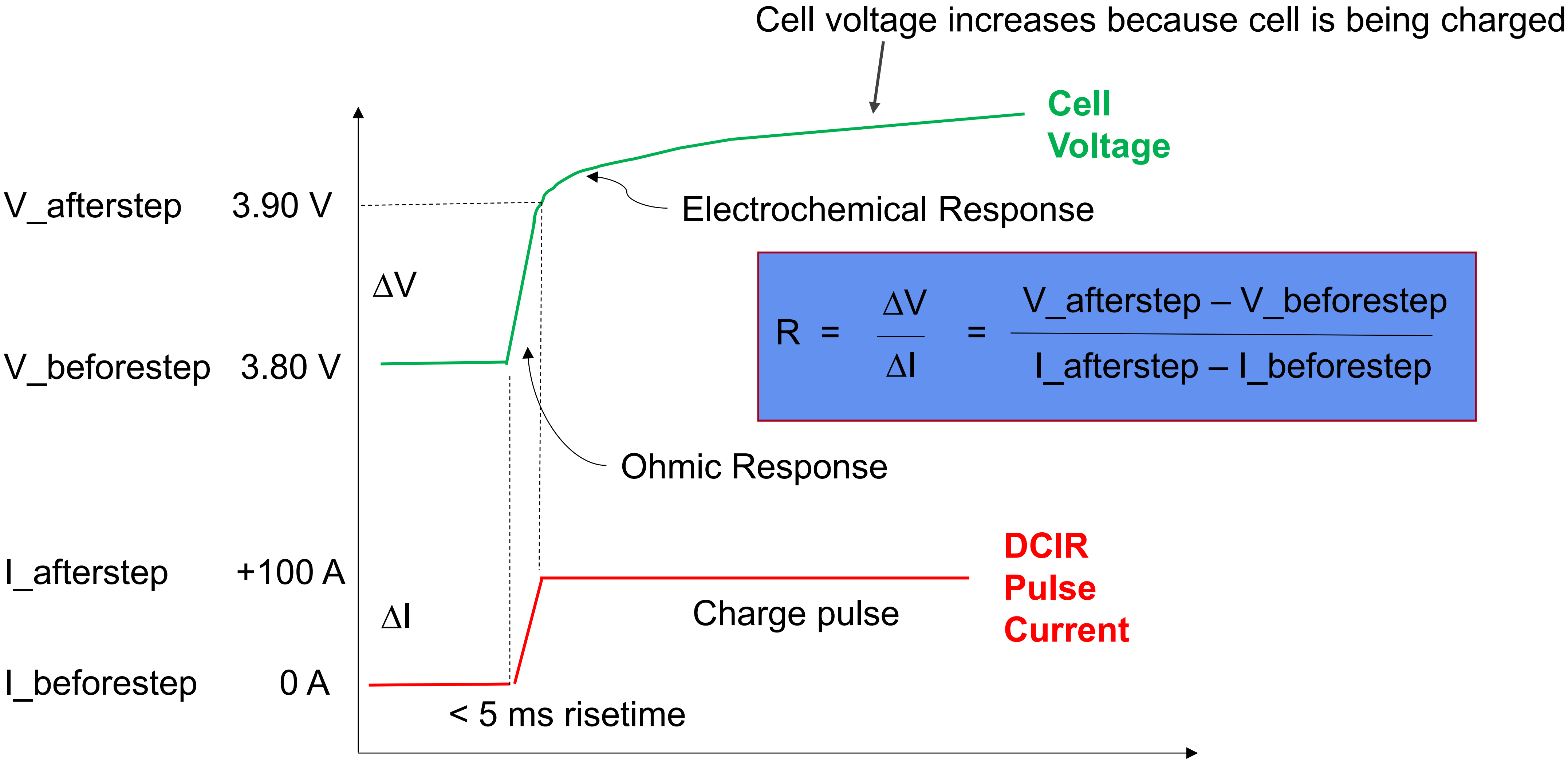
$$R = \frac{\Delta V}{\Delta I} = \frac{V\_afterstep - V\_beforestep}{I\_afterstep - I\_beforestep}$$



No standard method for timing of measurements or for pulse width

DCIR using a +100 Ampere Charge Pulse

Use charge pulse when SoC is low



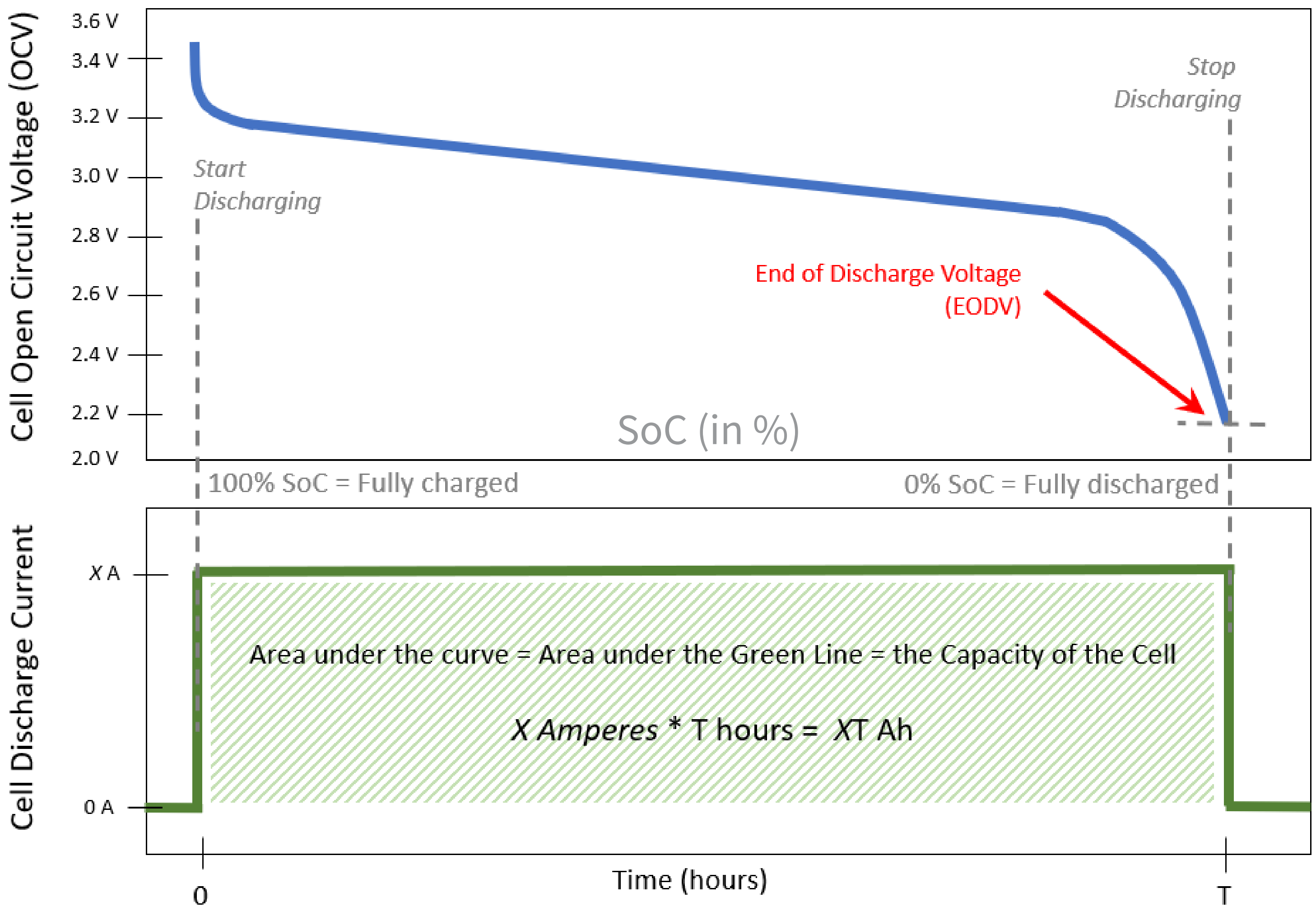
(5) Capacity

- Capacity is the measurement of charge stored in a cell.
- Capacity is measured in ampere-hours (Ah) = product of amperes times hours.
- A typical 18650 lithium-ion cell will store around 3 Ah or 3000 mAh of charge.

- 1 Ah means that you can draw 1 A from the cell for 1 hour. *Recall: C-rate = 1 C = 1 A for 1Ah cell.*
- Likewise, 1 Ah also means you can draw 2 A for 0.5 hours or 0.25 A for 4 hours.
- Ah capacity is actually a measure of stored coulombs = stored charge.
  - 1 A = 1 couloumb / second
  - 1 Ah = 1 A * 1 hour = 1 coloumb / second * 1 hour = 3600 coulombs stored in the cell

Graphical View of Capacity Measurement

Using Constant Current Discharge



Factors Affecting the Accuracy of the Capacity Measurement

Requires Ammeter, Voltmeter, and Clock

- Capacity is based on measurement of time, voltage, and current.
- Measuring time can be done with extreme accuracy using clock in computer or in ammeter, so the error in time measurement is not likely to seriously negatively impact the capacity measurement.
- Voltage measurement accuracy is important, as the ability to measure EoDV is what stops the clock. Poor voltage measurement will cause the integration to run too long or too short, resulting in capacity error. However, most DMMs can measure EoDV accurately enough to have negilble impact on capacity measurement because they will stop the clock precisely when EoDV is accurately detected.
- Current measurement accuracy is the dominant factor in determining the error in the Ah capacity measurement.

Capacity – Example Calculation of Error

Part 1: Determining the specification

- Typical ammeter specification (when measuring high currents)
  - **Current** measurement accuracy of 0.05% of reading + 3 mA
  - **Timebase** accuracy of 0.01%.

- Gain term of the capacity measurement error =
  Sum of current measurement gain accuracy of 0.05% + time base accuracy of 0.01% = 0.06%

- Offset term of the capacity measurement error =
  Measurement has 3 mA of offset error for each measurement.
  The measurement is 1 hour, so here is 3 mAh of error for every hour of measurement.

- Result is **capacity** measurement accuracy of 0.06% of reading + 3 mAh / hour

Capacity – Example Calculation of Error

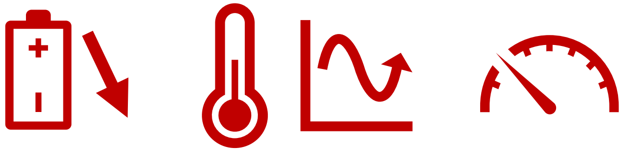
Part 2 – Applying the specification

<u>Capacity</u> measurement accuracy = 0.06% of reading + 3 mAh / hour

- Device = Cell with 1C rate of 10 A and expected capacity of 10 Ah
- To measure, draw 1C = 10 A for 1 hour because it should take 1 hour for the cell to reach its EoDV, which "stops the clock" on the capacity measurement.
- This would be 10 Ah of capacity
- Capacity error gain term would be 0.06% of 10 Ah, or 6 mAh
- Capacity error offset term would be 3 mAh / hour for 1 hour = 3 mAh
- Total capacity error when measured at 10 A current draw for 1 hour is 6 mAh + 3 mAh = 9 mAh of error on 10 Ah or 0.09% error on 10 Ah.

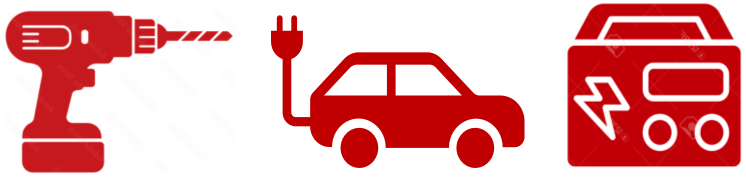
Summary

5 key parameters provide insight
to SoC, SoH, cell status/condition



While these are simple measurements,
there are challenges with accuracy,
methods, and interpretation of results

By understanding the measurements and challenges,
engineers can evaluate, select, and apply cells
into battery-powered devices and energy-storage systems
(HEMS, BESS) to achieve safety and maximum run-time.



Questions?

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I invite you to read my technical articles about many topics in cell testing, cell manufacturing, power instrumentation at https://www.electronicdesign.com/home/contact/21809010/bob-zollo

Test Goals along the Life Cycle: Design, Manufacture, Select/Use

Materials → **Cell** → **Pack** → **EV**

Cell Designer

"Did my cell design achieve its goals?"
"Did I select the right materials?"
"Did I process them correctly?"

To answer these questions:
Perform cell design **validation**

Good cell design

Cell Mfg

"Did I make a good cell?"

To answer this question:
Control the **manufacturing process**

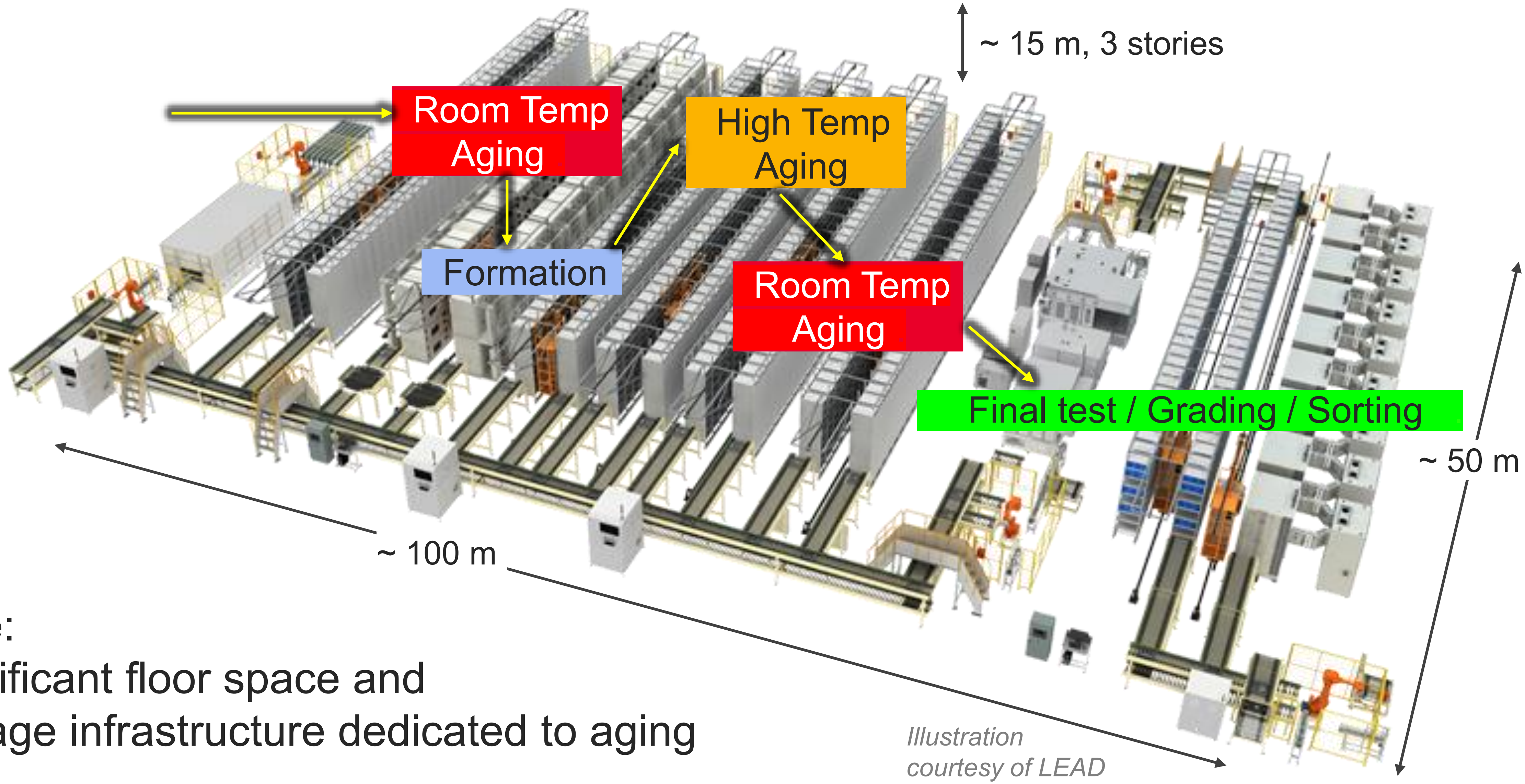
Good cell

User = Battery Maker

"Did I select the right cell for my application?"
To answer: Perform cell **evaluation**

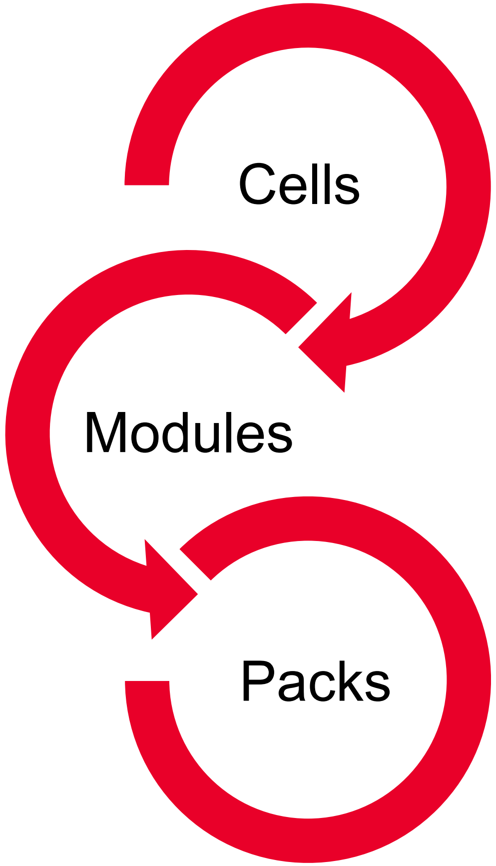
"Does my battery pack achieve its goals?"
To answer: Perform pack design **validation**

Gigafactory Cell Manufacturing Line



Note:
Significant floor space and storage infrastructure dedicated to aging

R&D: Testing Cells vs Testing Modules/Packs



Cell testing is device testing

- Characterize the cell behavior vs temperature, current, etc
- Determine parameters:
  Capacity, Open Circuit Voltage, Internal Resistance, Self-Discharge
- Measure cycle life (long test)

Pack testing is system testing

- Do not retest cell performance
- Verify pack functionality as a system
- Stimulus / Response Test including BMS, CAN, Safety, etc
- Verify system operation under expected environment