Texas Instruments

TI POWER

TI *Live!* BATTERY MANAGEMENT SYSTEMS SEMINAR

ERIC VOS

BATTERY GAUGING FUNDAMENTALS

Agenda

- What is a gauge, and what can it do?
- Battery basics
- Gauging algorithm types
- Gauging challenges

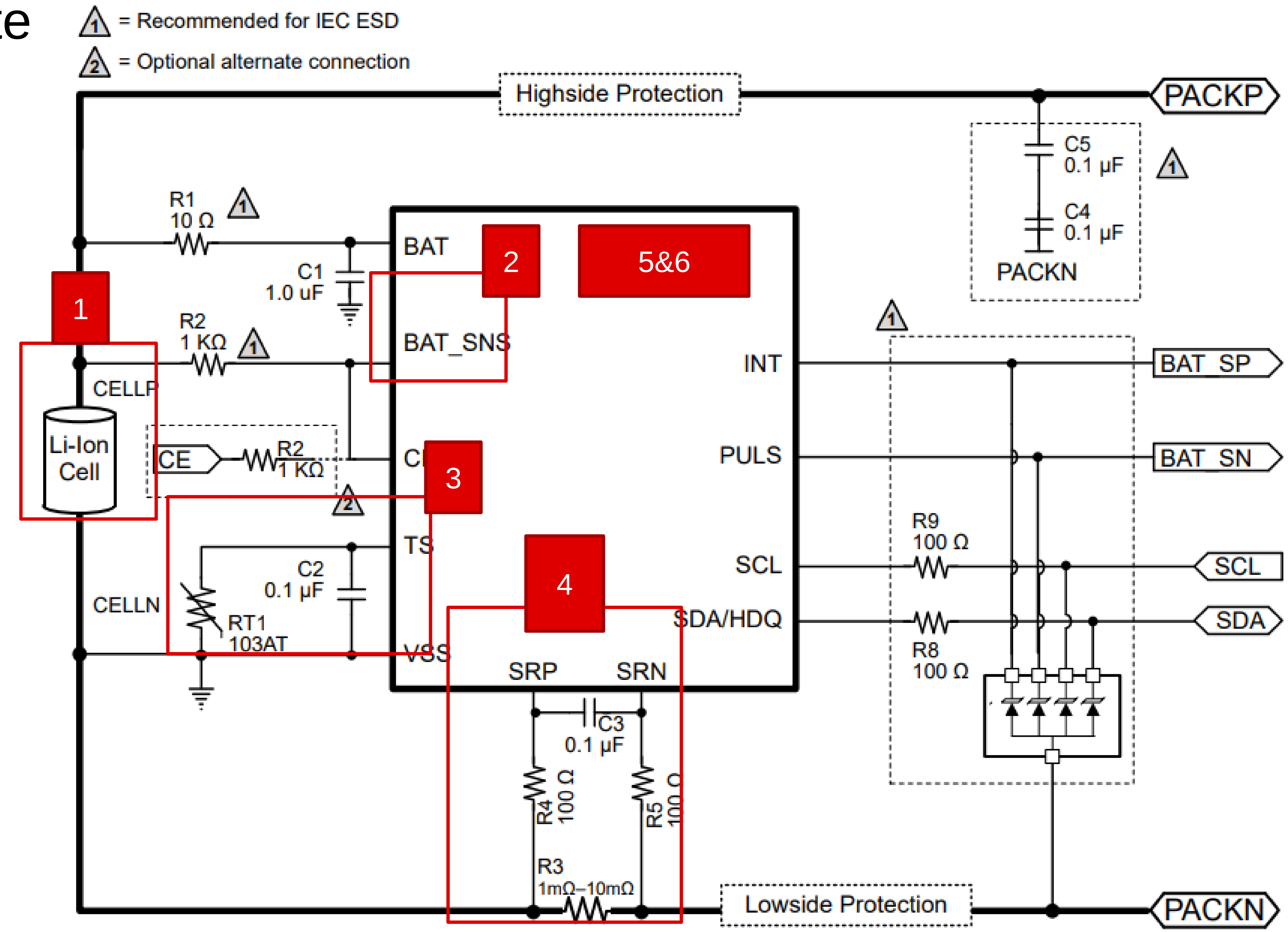
What is a gauge, and what can it do?

What is a gauge?

Custom microcontroller with an accurate analog-to-digital converter (ADC) and coulomb counter!

Gauges need:

1. Battery
2. Voltage measurement
   - Ideal at least 1-mV accurate
3. Temperature measurement
   - Battery temperature
4. Current measurement
   - Integrating ADC
   - Accumulating passed charge
   - Current measurements
5. CPU/RAM
6. Non-volatile memory
   - Flash or EEPROM and/or ROM



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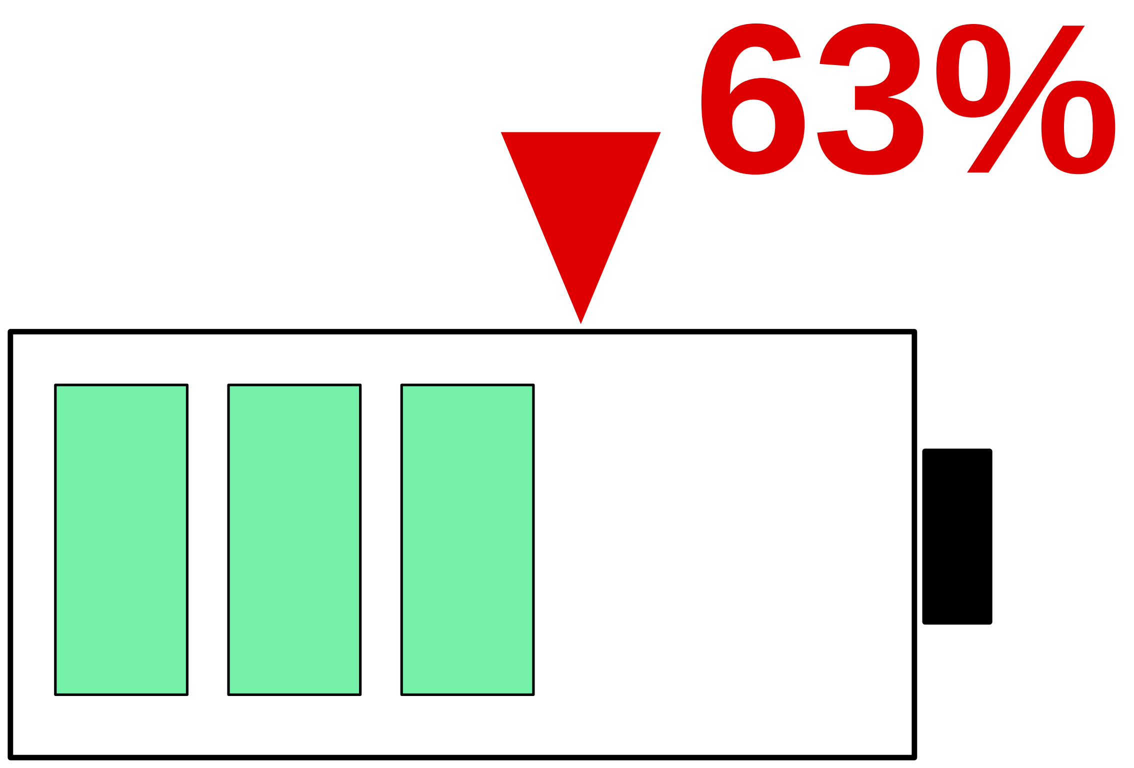
What can a gauge do?

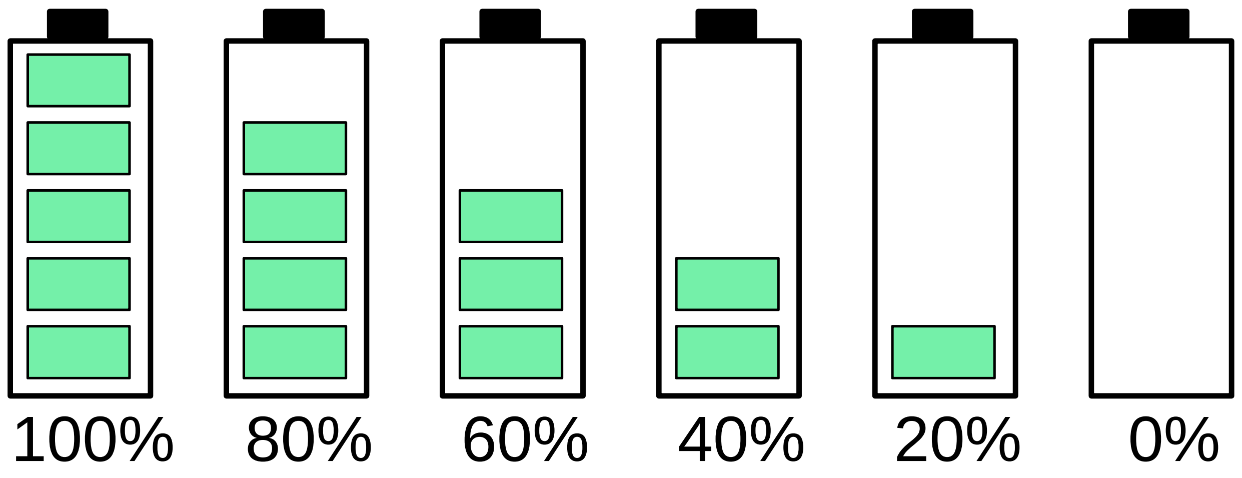
- Predict the future:
  - Capacity (% or mAh or mWh)
  - Run-time predictions (in minutes)
  - What-if predictions
  - Charge time predictions



Run time 6:27

2701 mWh

730 mAh



What can a gauge do?

- Predict the future
- Enhance safety:
  - Controls protection functions inside the battery pack

What can a gauge do?

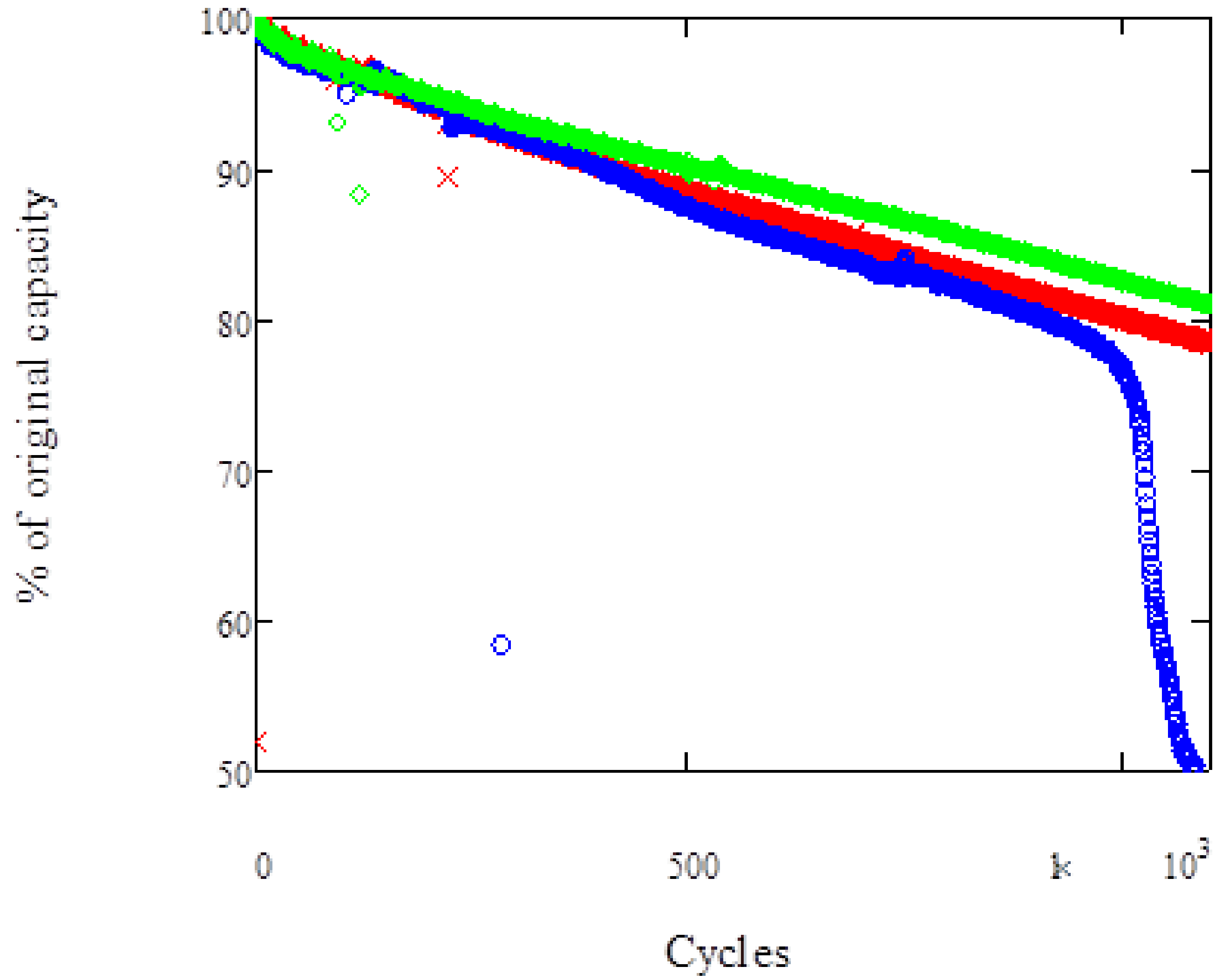
- Predict the future
- Enhance safety
- Be a “black box:”
  - Record usage conditions
  - Assist with warranty analysis and troubleshooting
  - Assist with supplier quality improvement

What can a gauge do?

- Predict the future
- Enhance safety
- Be a “black box”
- Extend run-time:
  - Confidently use all available battery capacity with no surprises
  - No unused capacity due to over-cautious shutdown conditions
  - (see appendix for example)

What can a gauge do?

- Predict the future
- Enhance safety
- Be a “black box”
- Extend run-time
- Extend battery lifetime:
  - Gets more cycles from a battery
  - Uses dynamic learning and battery modeling to control healthy, safe, and fast charging



What else can a gauge do?

- Authentication:
  - Ensure only safe/authorized packs are used
- State of health:
  - Objectively tell user when a battery is at end of life
- Traceability:
  - Store serial numbers, production information and more inside gauge’s flash memory

- Instrumentation in system:
  - Highly accurate voltage, current and temperature measurements
  - Useful for system characterization and production tests
- Assist with power management:
  - Recommend maximum current that won’t crash battery
  - Allow host to remain in low-power state and wait for interrupts

Battery basics (LI-ion)

Healthy battery habits

- **Most stable in 50% charged state** – ideally between 80%-20%.
- High voltages accelerate corrosion and electrolyte decomposing. **Charging should be limited to maximal voltage** specified by manufacturer (4.1 V – 4.45 V).
- Short deep discharge is **not detrimental**, but **long storage in discharge state** results in dissolution of protective layer and resulting **capacity loss**.
- **High temperature is main battery degrader**. Provide appropriate **cooling** and place battery far from heat-generating circuits. Take battery **out of equipment** if long-term AC powered to prevent pack exposure to high temperatures.

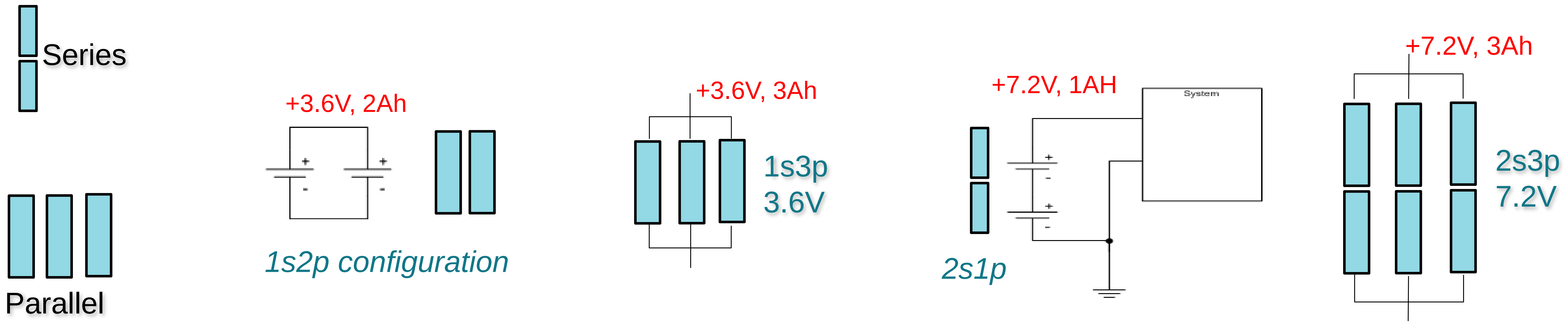
Healthy battery habits

- Use battery **soon after manufacturing**. Discharge capacity degrades even if not used.
- Storage at **low temperatures** increases **shelf life**.
- If used in stand-by application, charger should terminate charging and not resume until state of charge **drops below ~95%.** Trickle charging is **not recommended**.
- Unnecessary charging or discharging should be avoided. Unlike NiCd and NiMh, there is **no benefit** from **“exercising”** the battery.

Battery configuration

- XsYp:
  - "X" number of cells in series:
    - Voltage of pack is "X"*Vcell
  - "Y" number of cells in parallel:
    - Capacity of pack is "Y"*Capacity cell

Pack configurations (example: 3.6-V, 1-Ah per single battery)

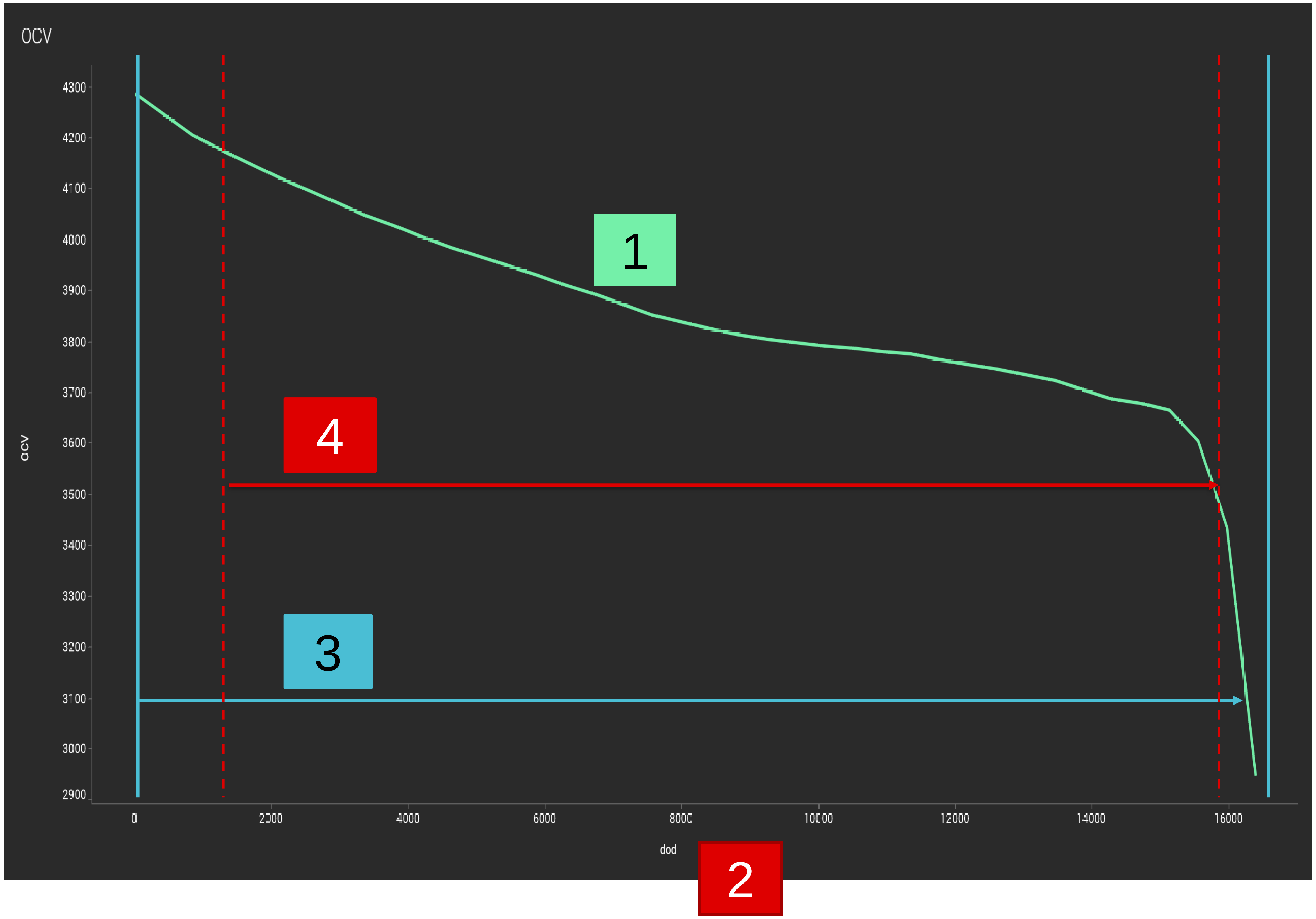


Battery terms

- “C-rate” or “Hour rate” expresses current relative to nominal battery capacity.
- If nominal capacity is 3300 mAh:
  - A discharge rate of “1C” means use a current of 3300 mA.
    - In theory, it would take 1 hour to discharge at this rate, but it typically takes less time.
  - A charge rate of “C/2” means use a current of 1650 mA.
    - This is also considered a “2-hour rate.”

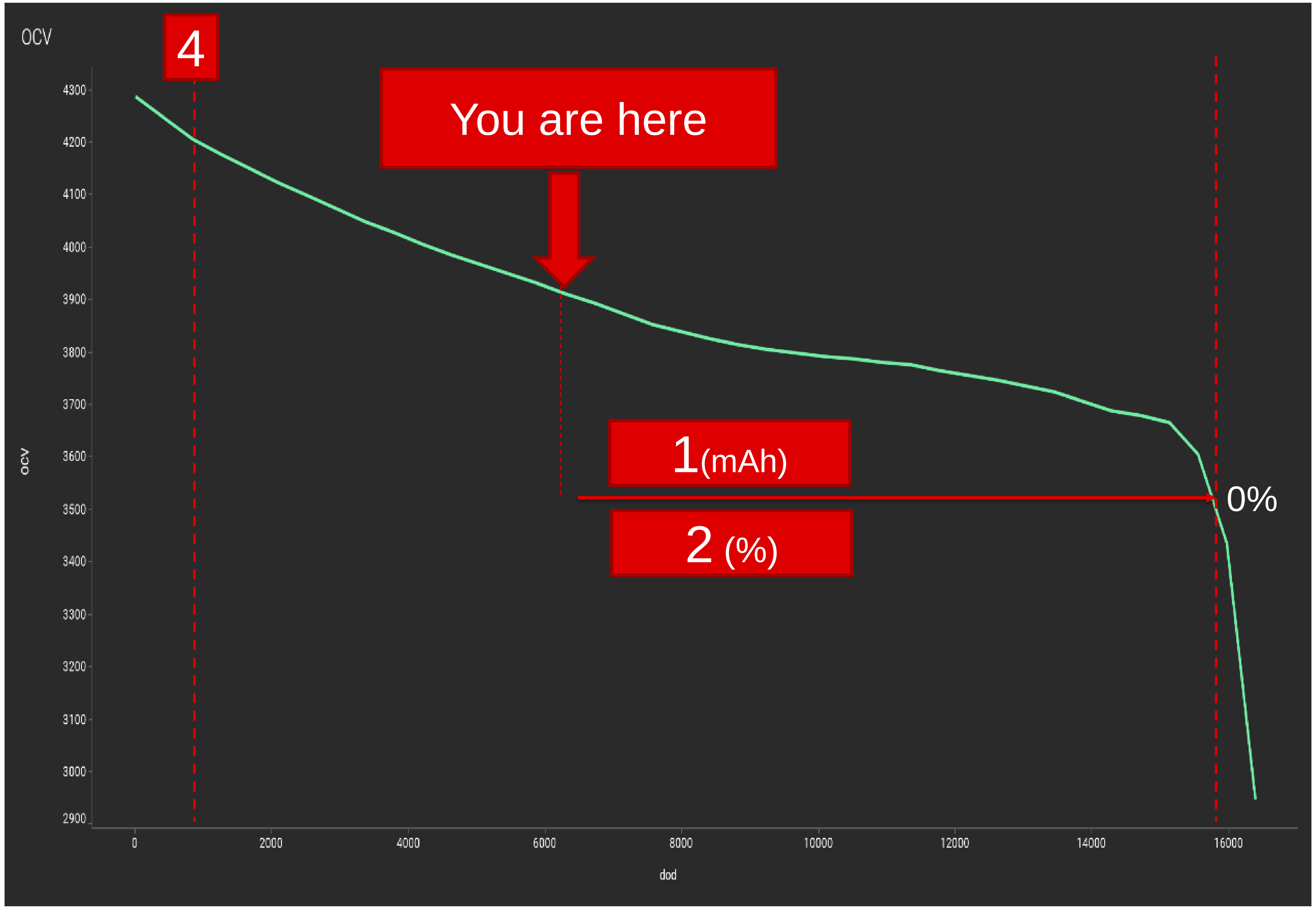
Battery terms

1. **Open circuit voltage** (OCV):
   - Unloaded battery voltage
2. **Depth of discharge** (DOD):
   - Internal factor to give the gauge more resolution (2^{14})
   - 0 = 100% state of charge
   - 16384 = 0% state of charge
3. **Qmax**:
   - Maximum battery capacity under no load
   - Never achievable in real application
4. **Full charge capacity** (FCC):
   - Usable capacity
   - Not charged to battery max
   - Not discharged to min cell V
   - FCC = [Qmax - IR(load) – application]



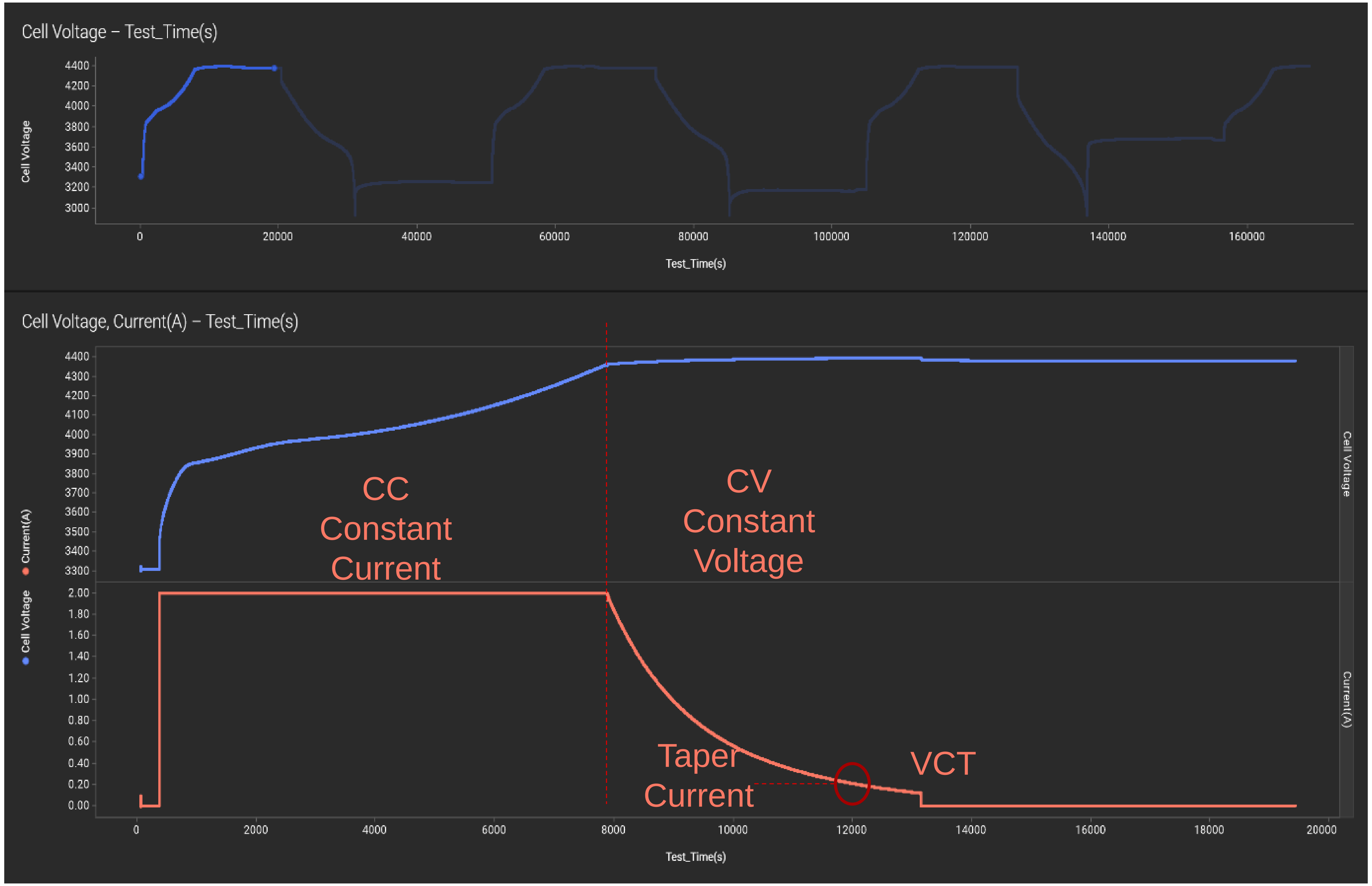
Battery terms

1. **Remaining capacity** (RemCap):
   - Capacity until 0%
2. **State of charge** (SOC):
   - 100% - 0%
   - Based in application range.
   - = RemCap / FCC
3. **State of health** (SOH):
   - 100% - 0%
   - Degradation of battery
4. **DOD@EndOfCharge** (DOD@EOC):
   - 100% - 0%
   - Degradation of battery



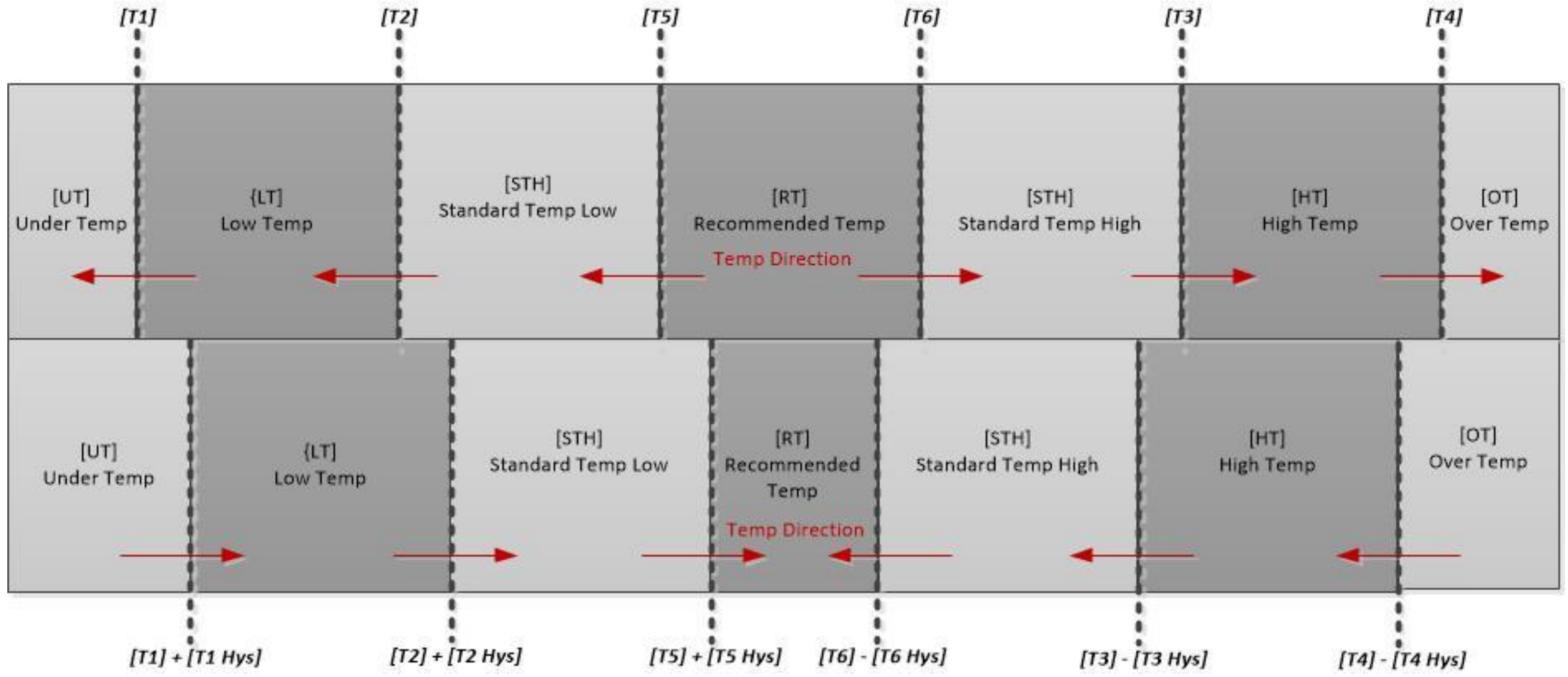
Battery charging

- **Constant current** (CC):
  - –Current stable at adapter power
  - –Often C/2 but increasing in recent years
- **Constant voltage** (CV):
  - –Voltage stable at charge voltage
  - –Current reduces until taper current
  - –Taper often C/20
- **Valid charge termination** (VCT):
  - –Current below taper for window of time
  - –Sync point, gauge knows it is 100%



Battery charging (JEITA)

- What it is:
  - Gauge charge algorithm based on temperature.
  - Helps reduce additional degradation by charging the battery safely.
  - Uses gauge measured battery information to determine charge voltage and currents.
- Can be used to control SMB-compliant chargers (see BCAST).

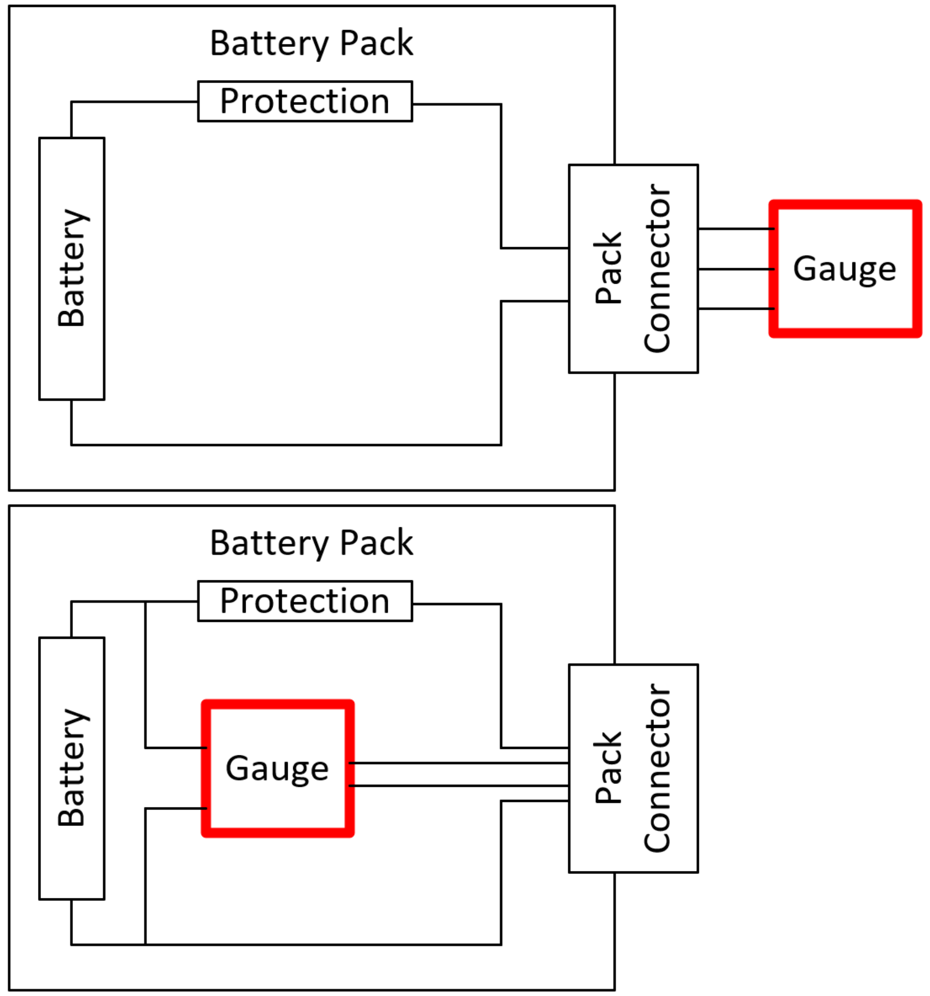


Name	Value	Unit
Temperature Ranges		
T1 Temp	0	°C
T2 Temp	12	°C
T5 Temp	20	°C
T6 Temp	25	°C
T3 Temp	30	°C
T4 Temp	55	°C
Hysteresis Temp	1	°C
Low Temp Charging		
Voltage	4000	mV
Current Low	132	mA
Current Med	352	mA
Current High	264	mA
Standard Temp Charging		
Voltage	4200	mV
Current Low	1980	mA
Current Med	4004	mA
Current High	2992	mA
High Temp Charging		
Voltage	4000	mV
Current Low	1012	mA
Current Med	1980	mA
Current High	1496	mA
Rec Temp Charging		
Voltage	4100	mV
Current Low	2508	mA
Current Med	4488	mA
Current High	3520	mA
Pre-Charging		
Current	88	mA
Maintenance Charging		
Current	44	mA
Voltage Range		
Precharge Start Voltage	2500	mV
Charging Voltage Low	2900	mV
Charging Voltage Med	3600	mV
Charging Voltage High	4000	mV
Charging Voltage Hysteresis	0	mV
SoC Range		
Charging SoC Med	50	%
Charging SoC High	75	%
Charging SoC Hysteresis	1	%

Battery gauge location

System side:
Gauge located in battery pack

Pack side:
Gauge located in battery pack



WRONG!

Correct: Battery removable or not!

Pack side = One gauge, one battery pack for the life of the device
System side = Changeable batteries

Gauging algorithm types

How to gauge a battery

1. Battery
2. Voltage measurement
   - Ideal at least 1-mV accurate
3. Temperature measurement
   - Battery temperature
4. Current measurement
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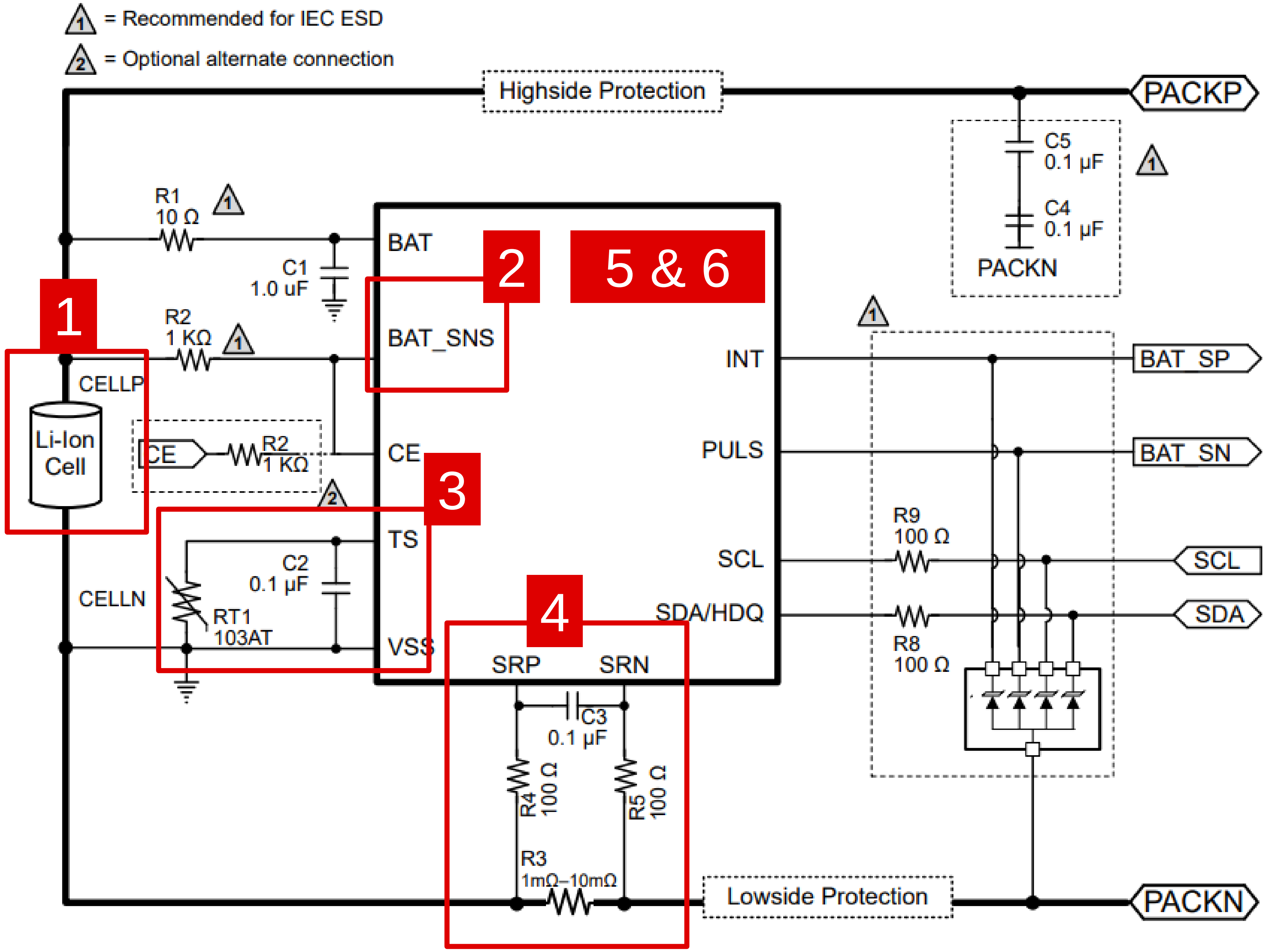
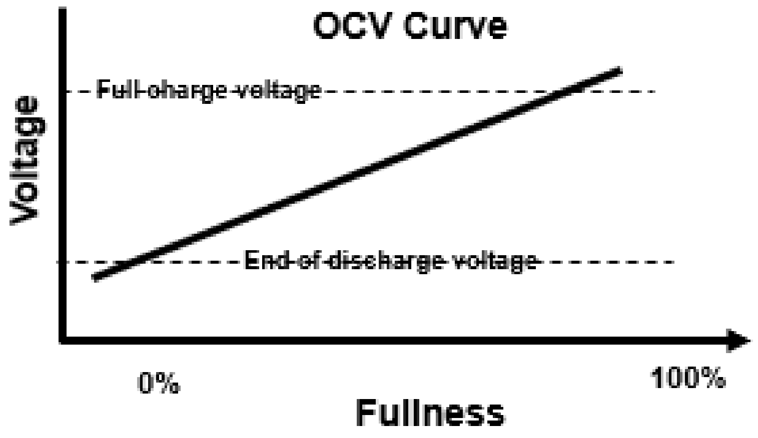
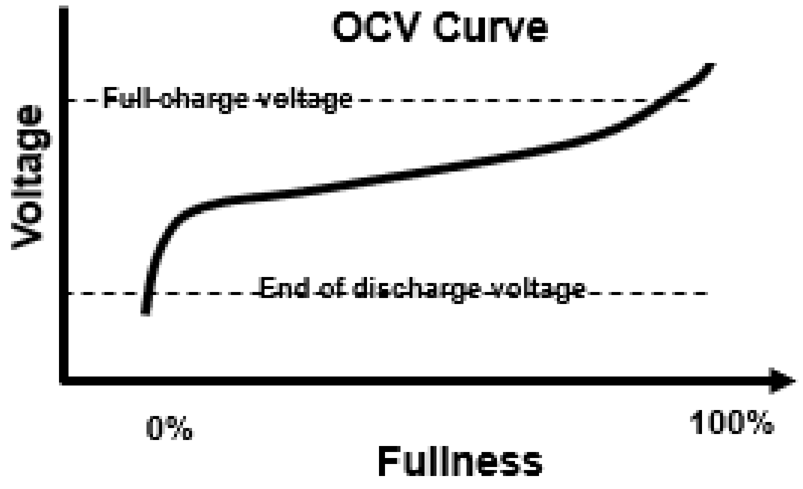


Voltage gauging: Measure voltage and correlate to state of charge



Concept: Easy



Practice: Medium

Challenges:

- Temperature: Changes size of the glass
- Excitement: Drinking or refilling the water makes it hard to measure
- Age: The glass shrinks inside, while the outside remains the same
- Only SOC information

Reality: Hard

How to gauge a battery

1. Battery
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   - Ideal at least 1mV accurate
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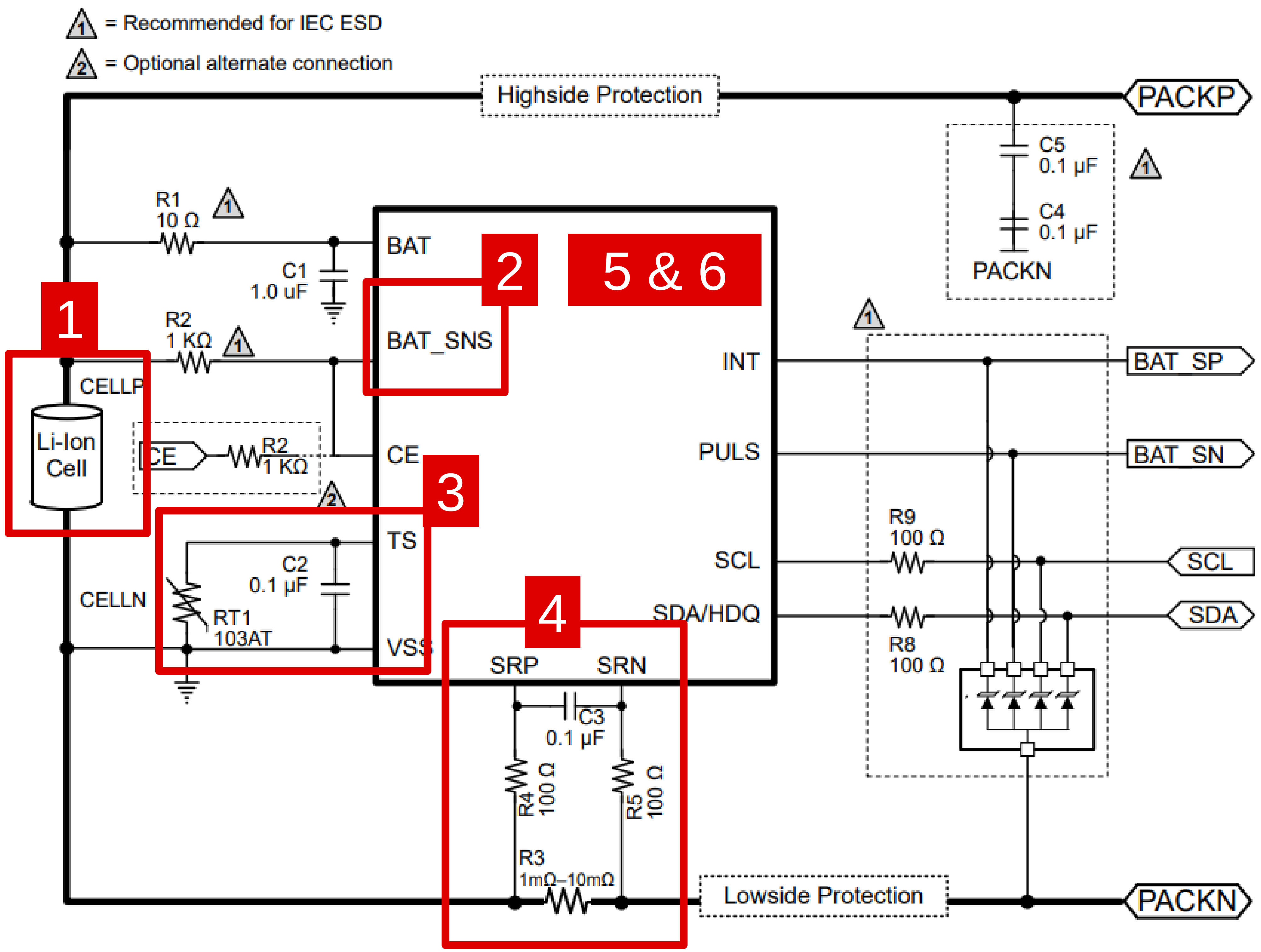
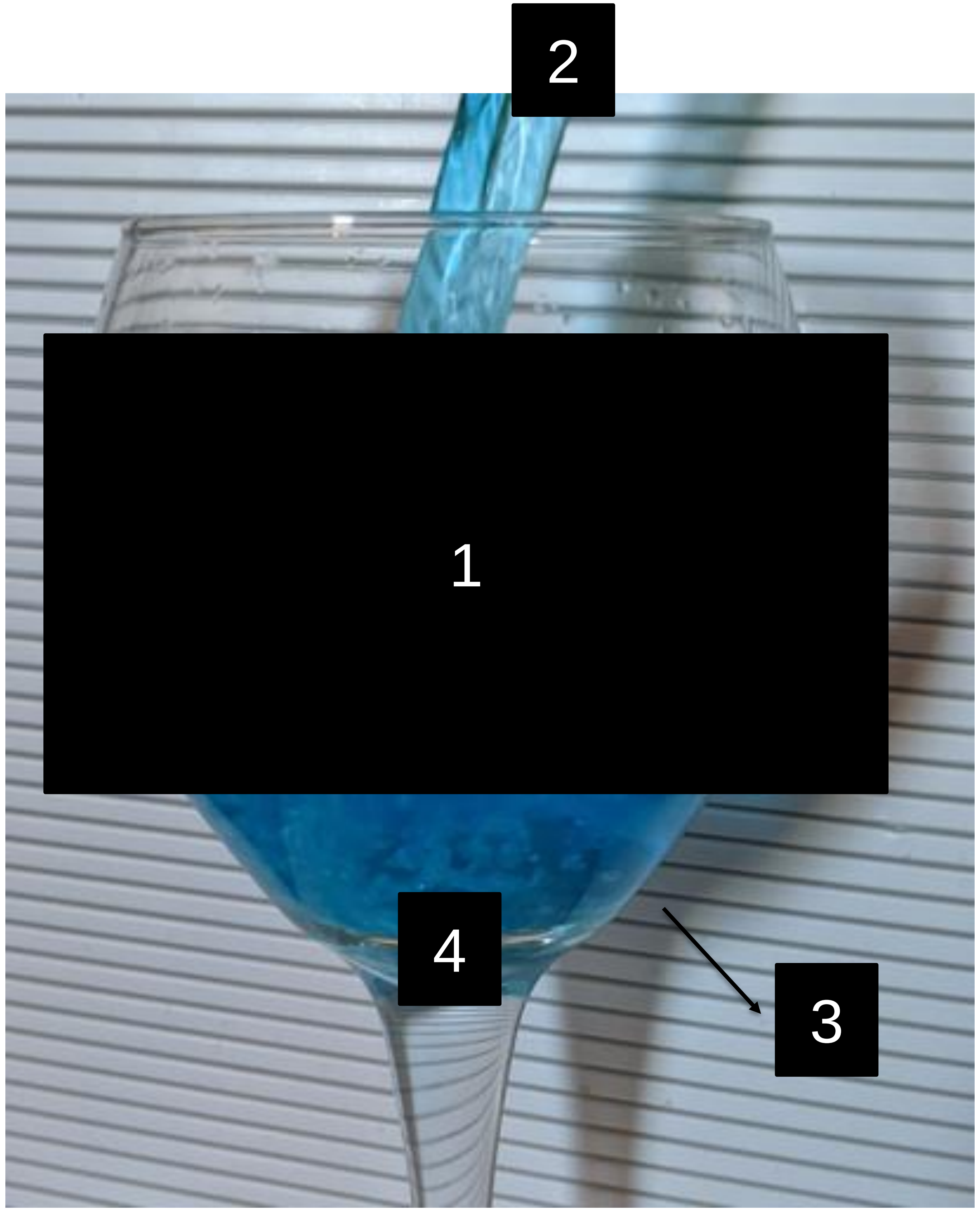


Current gauging

- Count and keep track of charge in and out.
- Challenges:
  - Unknown starting point.
  - Coulomb counting error.
  - Unknown leakage.
  - No idea if glass size changes.



How to gauge a battery

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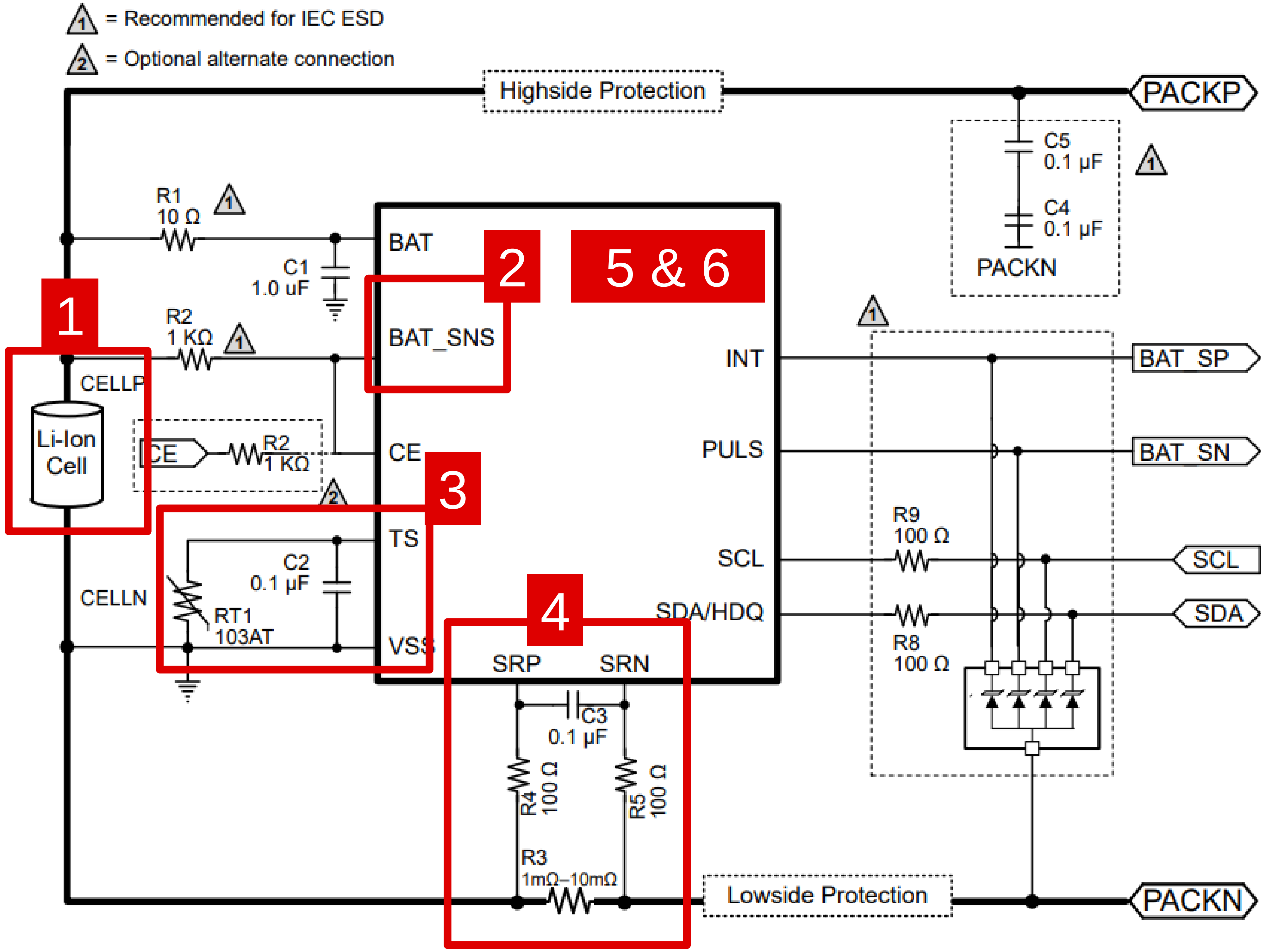


Gauging algorithm types

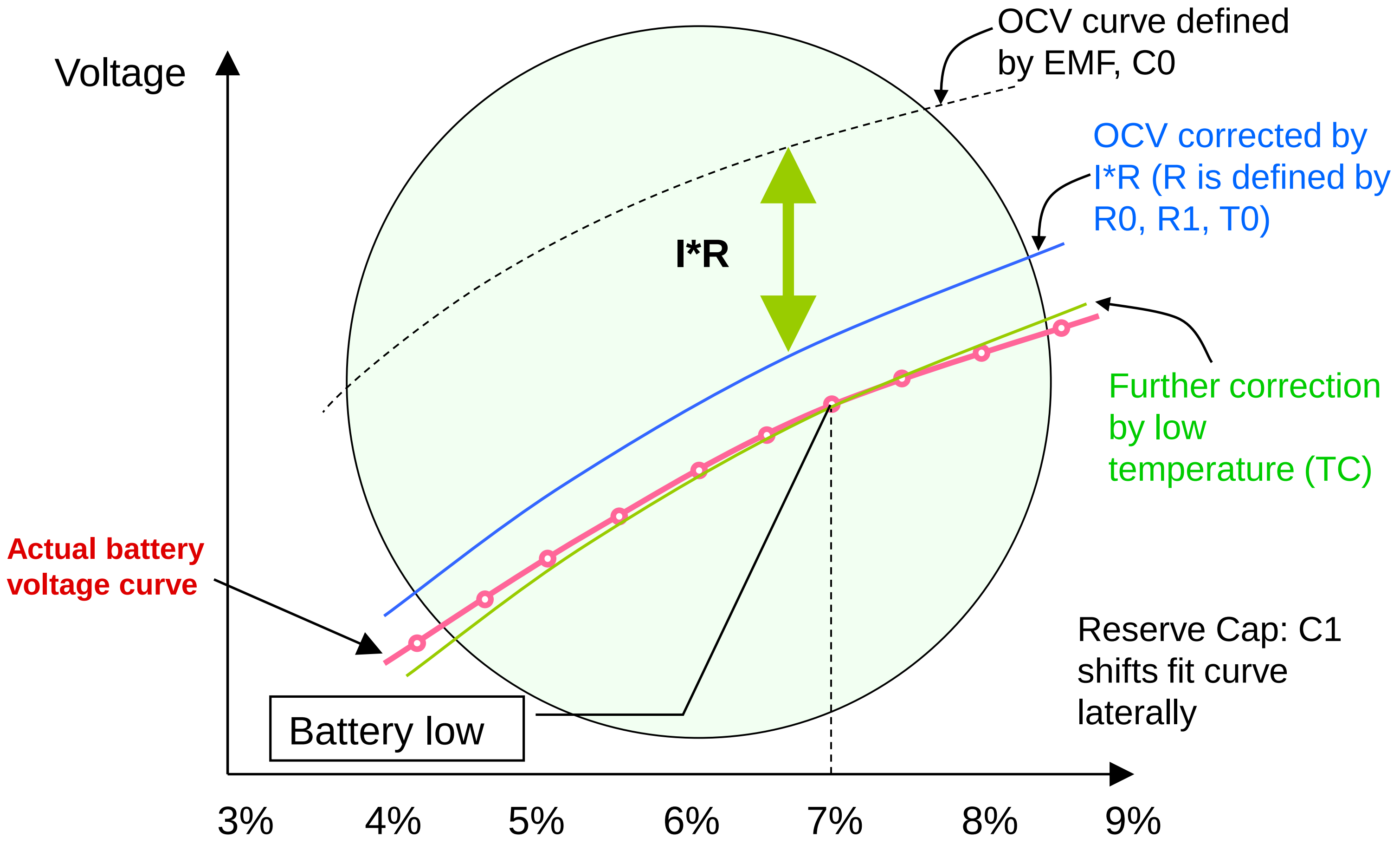
Compensated End of Discharge Voltage (CEDV)

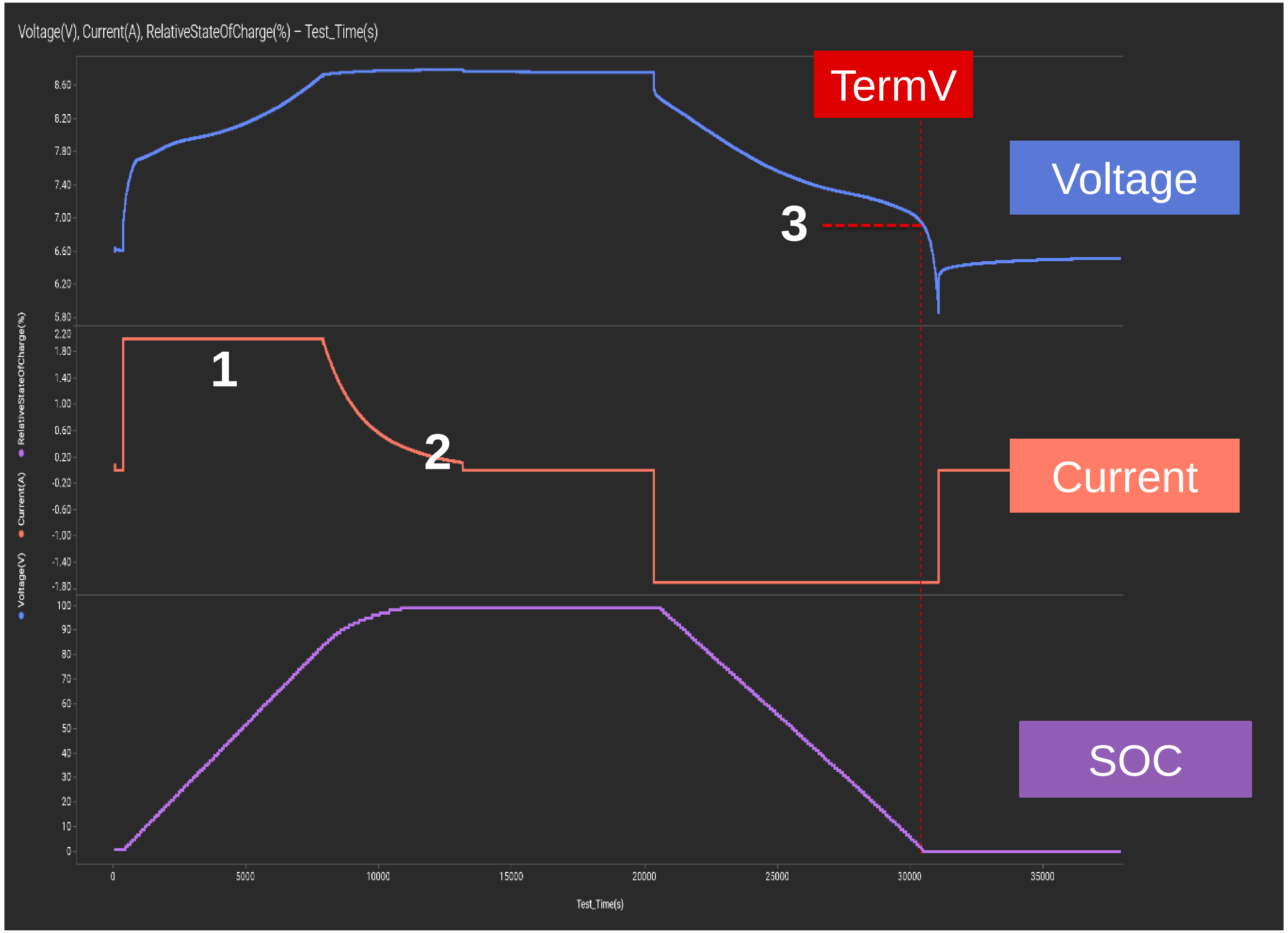
TI gauging method: CEDV

- Compensated End of Discharge Voltage (CEDV)
- Everything done through online tool:
  - https://www.ti.com/tool/GAUGEPARCAL
- Requires 6 discharge cycles:
  - 2x discharge rate (avg application discharge rate and max application discharge rate)
  - 3x temperature (cold, room and hot)
- Expected setup time: Less that 1 week

TI gauging method: CEDV

1. Coulomb counting
2. Sync to 100% at full charge
3. Capacity learning threshold adjusts for:
    - Discharge rate
    - Temperature
    - Age





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Gauging algorithm types

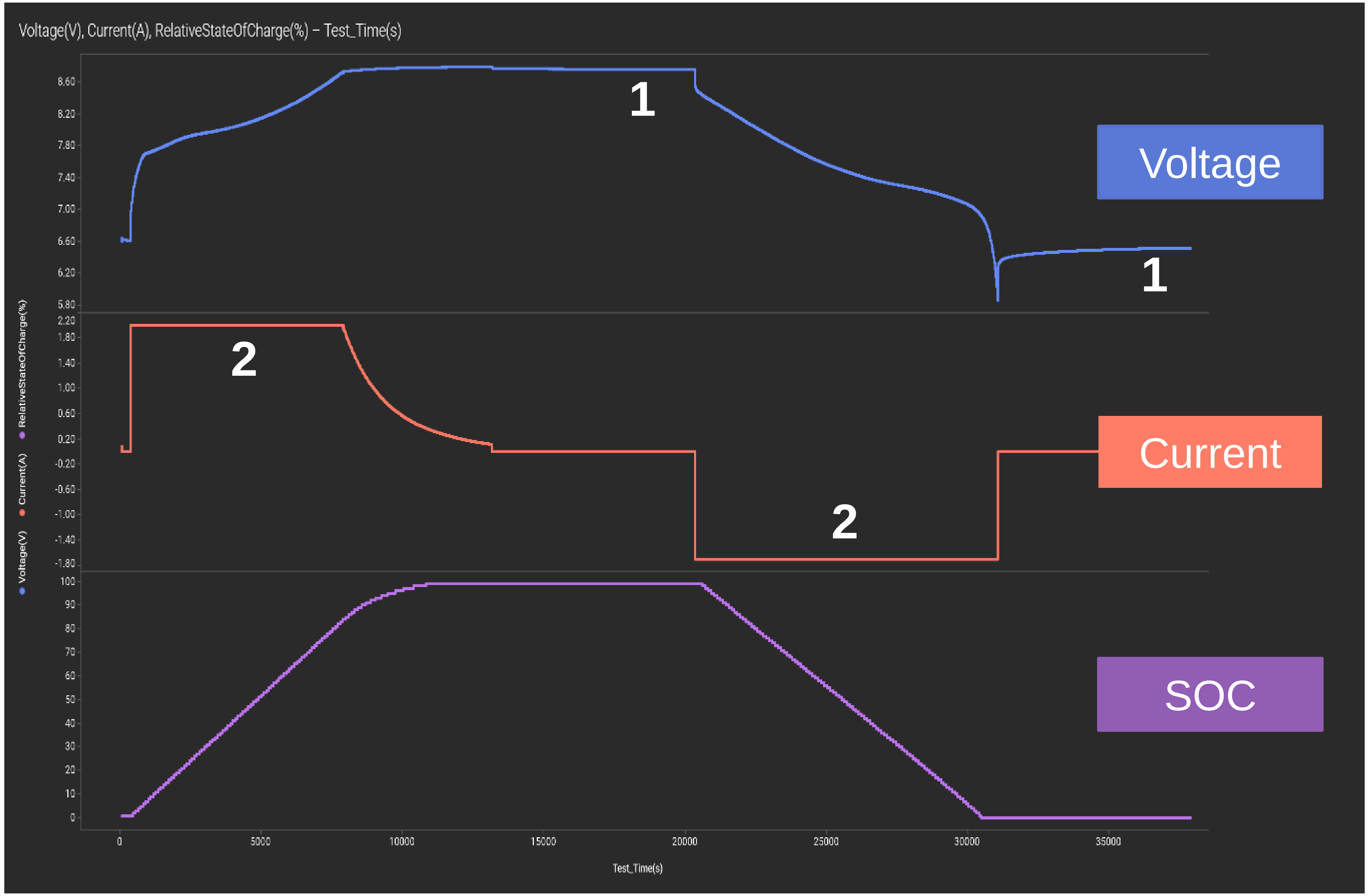
Impedance Track™ technology (IT or ZT)

TI gauging method: Impedance Track technology

- Everything can be done through online tool:
  - https://www.ti.com/tool/GAUGEPARCAL
  - ChemID match, initial golden learning, & cold temp resistance tuning
- Requires 3 discharge cycles:
  - Nominal discharge rate and room temperature
  - Nominal discharge rate and cold temperature
  - Application charging and discharge rate
- Expected setup time: 2 months
  - ChemID: Match (3 days), custom (3-4 weeks)
  - Learn cycle: 1 week
  - Tuning for application: 3 weeks
    - Load select, load mode, charge profile, reserve capacity, thermal model, resistance learning, etc.

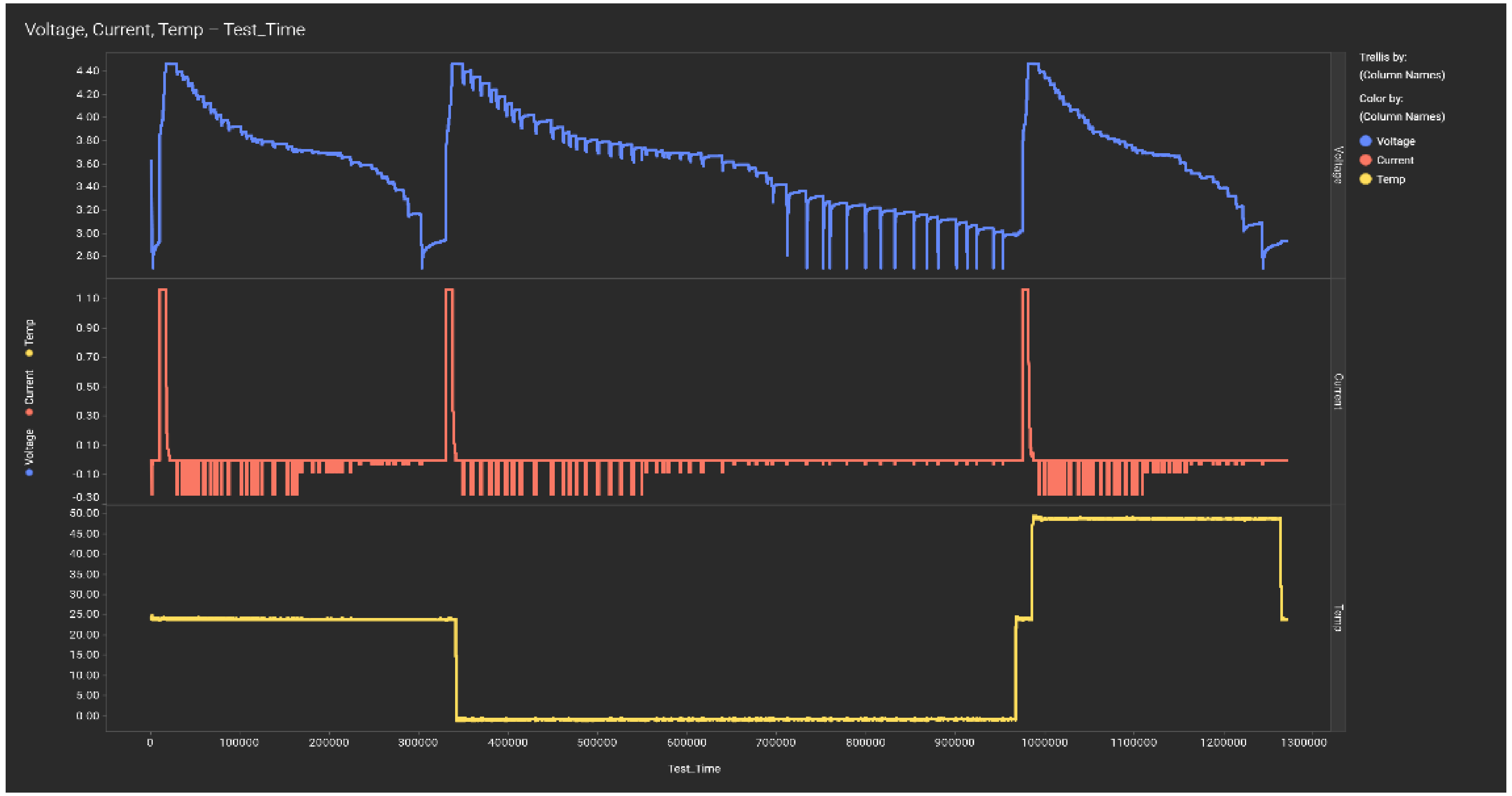
TI gauging method: Impedance Track technology

1. Voltage gauge while battery stable
2. Coulomb counting while active
3. Thermal model prediction:
   - Self-heating
   - Ambient temperature changes
4. Constant capacity simulations:
   - Up to 14 times while discharging
   - Start of chg/dsg
   - OCV readings
   - Charge termination
   - Temperature change
5. Learns the battery over the life of the device

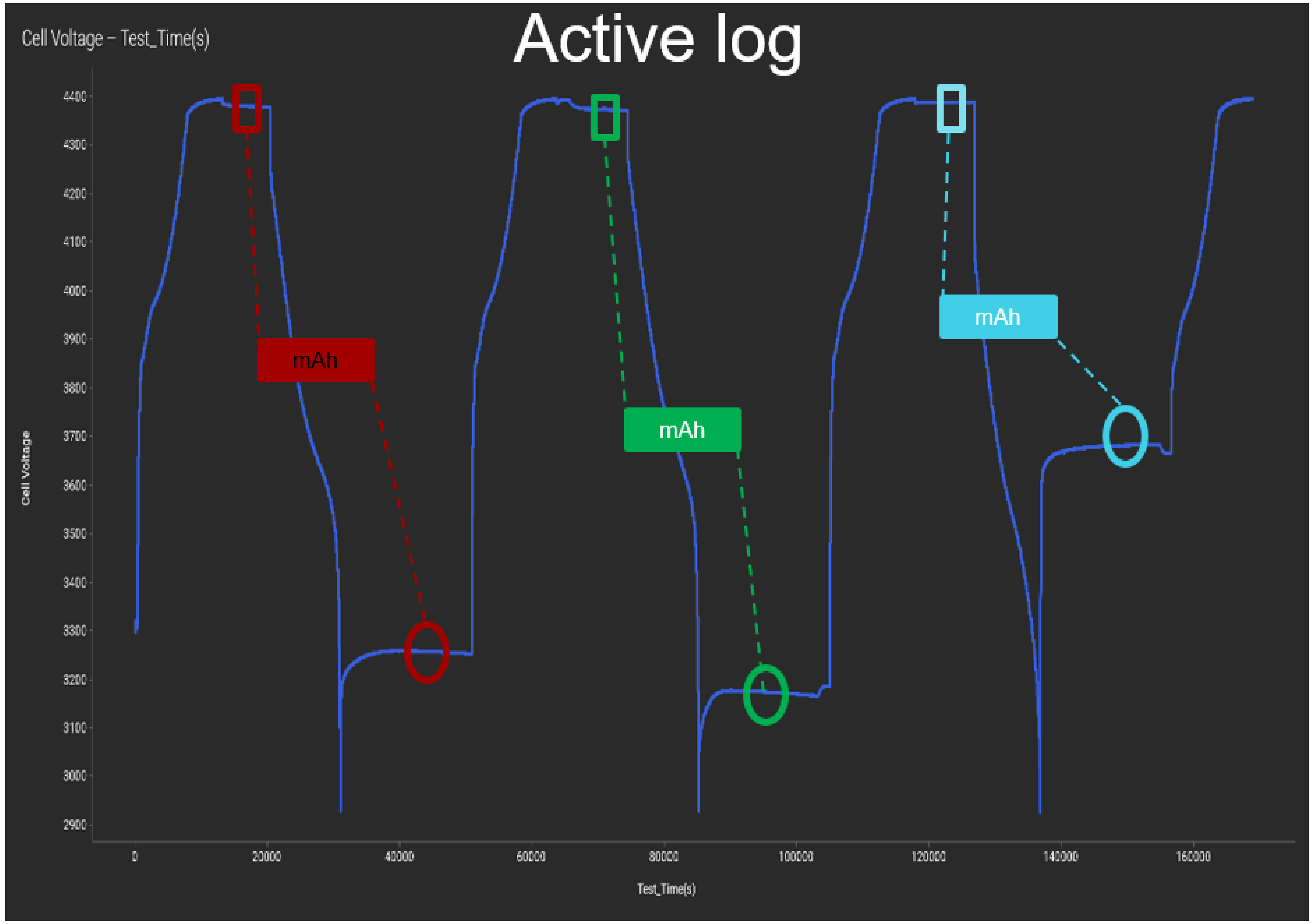


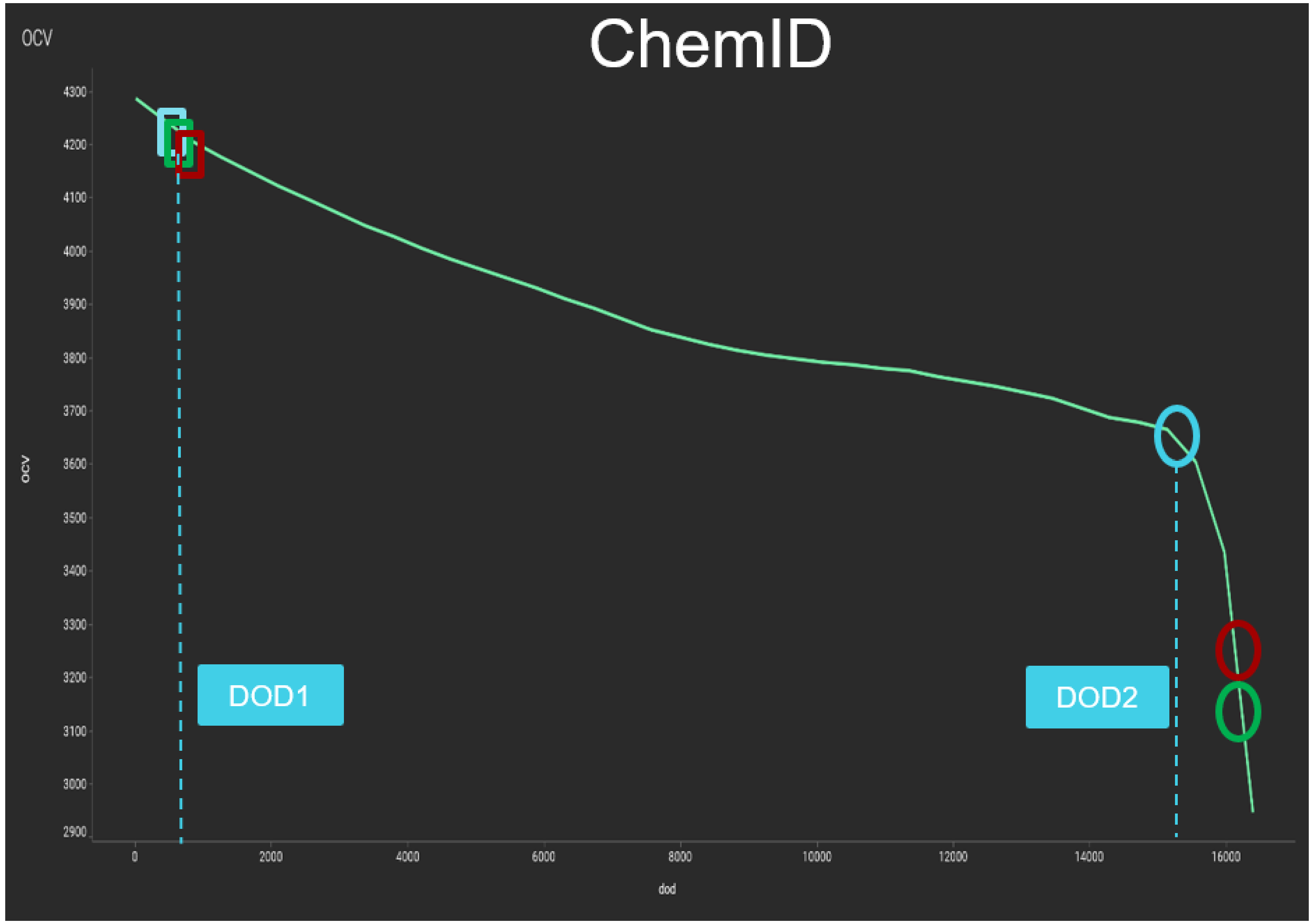
Impedance Track technology: ChemID

- What it is:
  - –Series of proprietary tests to establish the characteristics and behavior of a given battery.
- What it contains:
  - –OCV
  - –Resistance
  - –High frequency resistance
  - –Chemical “flat zone”
- All modeled across temperature



Impedance Track technology: QMax





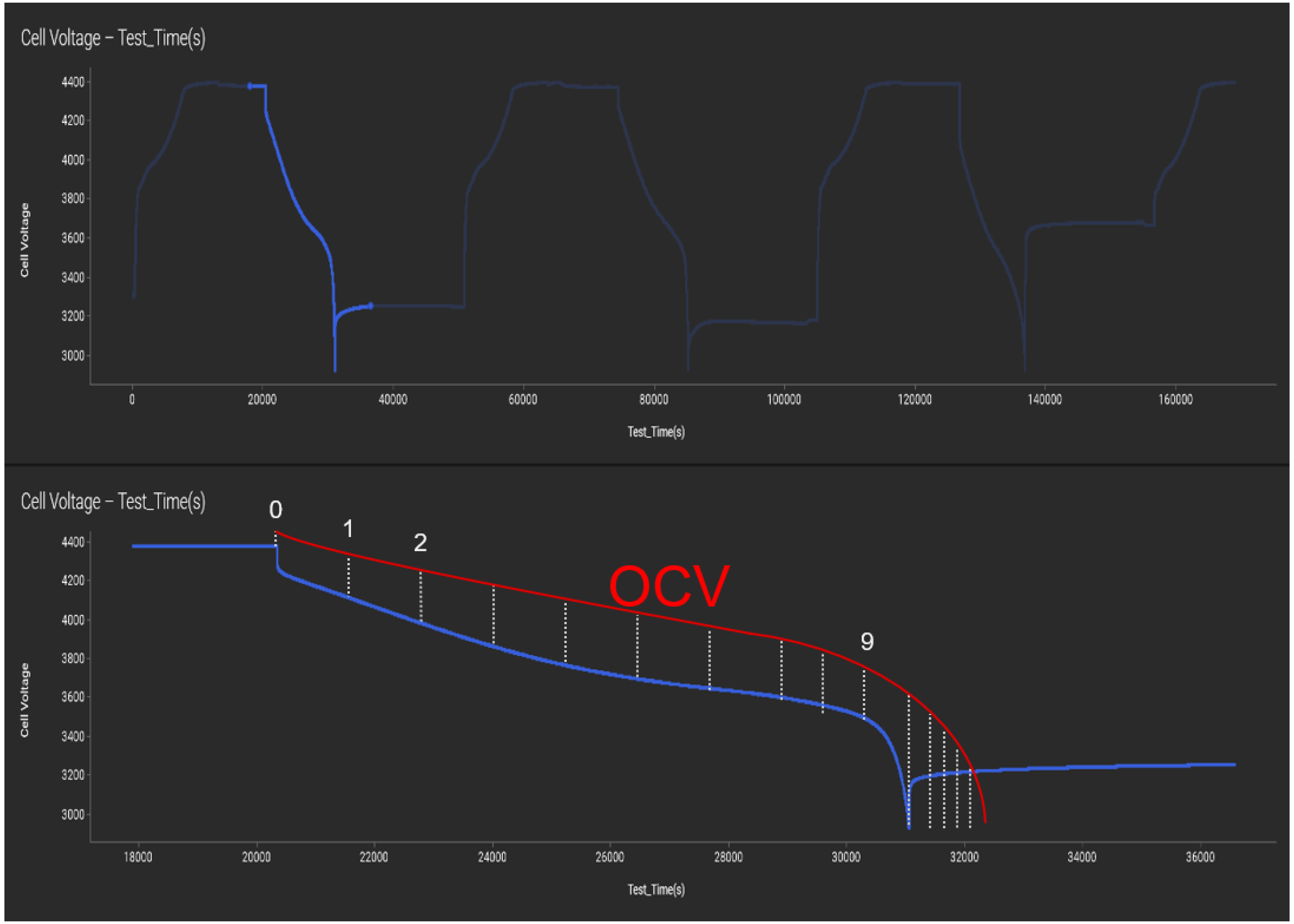
$$\frac{QMax}{16384} = \frac{\Delta Q}{DOD1 - DOD2}$$

Some additional rules:

1. DOD points must be at least [37%] apart, [90%] on first Qmax
2. DOD reading must not be disqualified (flat zone, temperature)
3. Qmax has a max change amount (protection)
4. Qmax has an upper limit (protection)

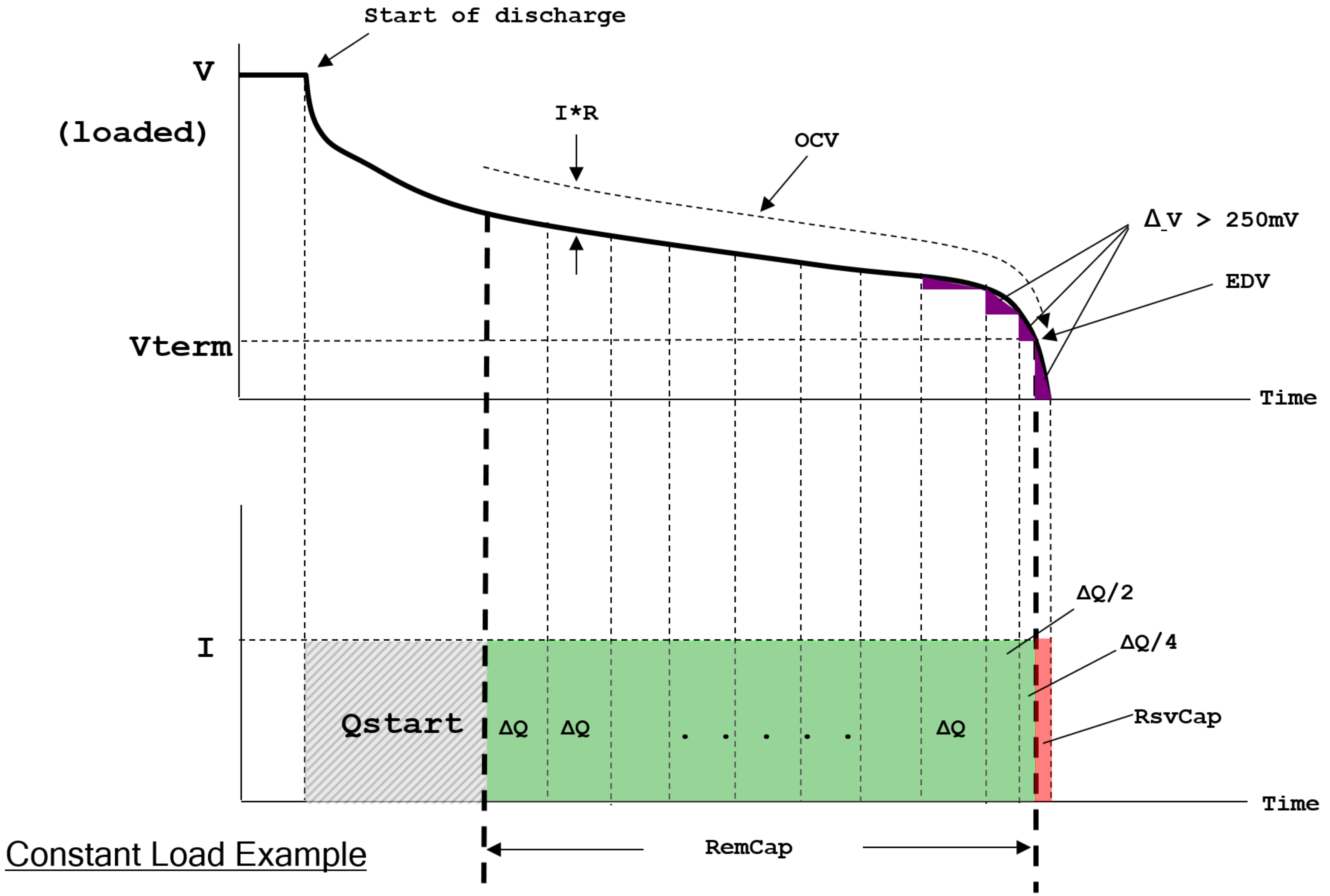
Impedance Track technology: Resistance

1. Resistance update points [Grid Points].
2. 15 grid points over a full discharge.
3. Grids not distributed evenly.
4. Resistance only updated in discharge direction.
5. Must be discharging for an amount of time before resistance update can happen.
6. Resistance updates are heavily filtered.
7. Updates are stored in flash in the Ra & RaX table.
   - Two tables to avoid flash wear out.
8. Simultaneous voltage and current measurement needed.



Impedance Track technology: Simulation

1. Future capacity prediction
2. Simulations are triggered by:
   - Grid points
   - Temp change
   - Start of charge
   - Start of discharge
   - Every hour in relax
   - Valid charge termination
   - OCV reading

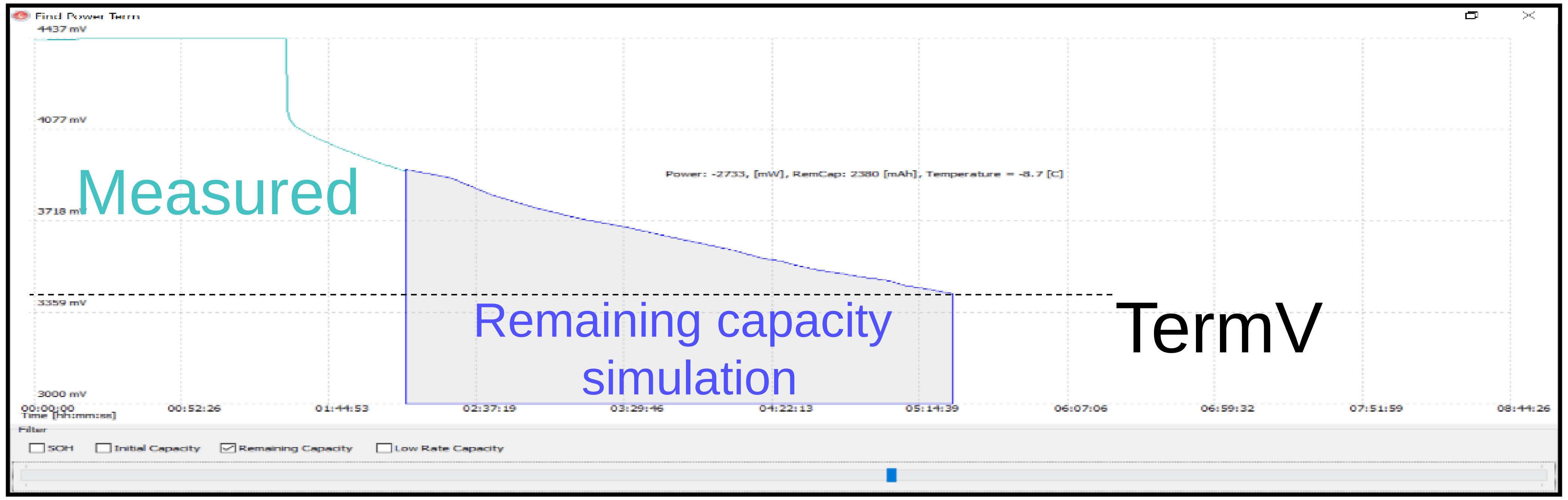


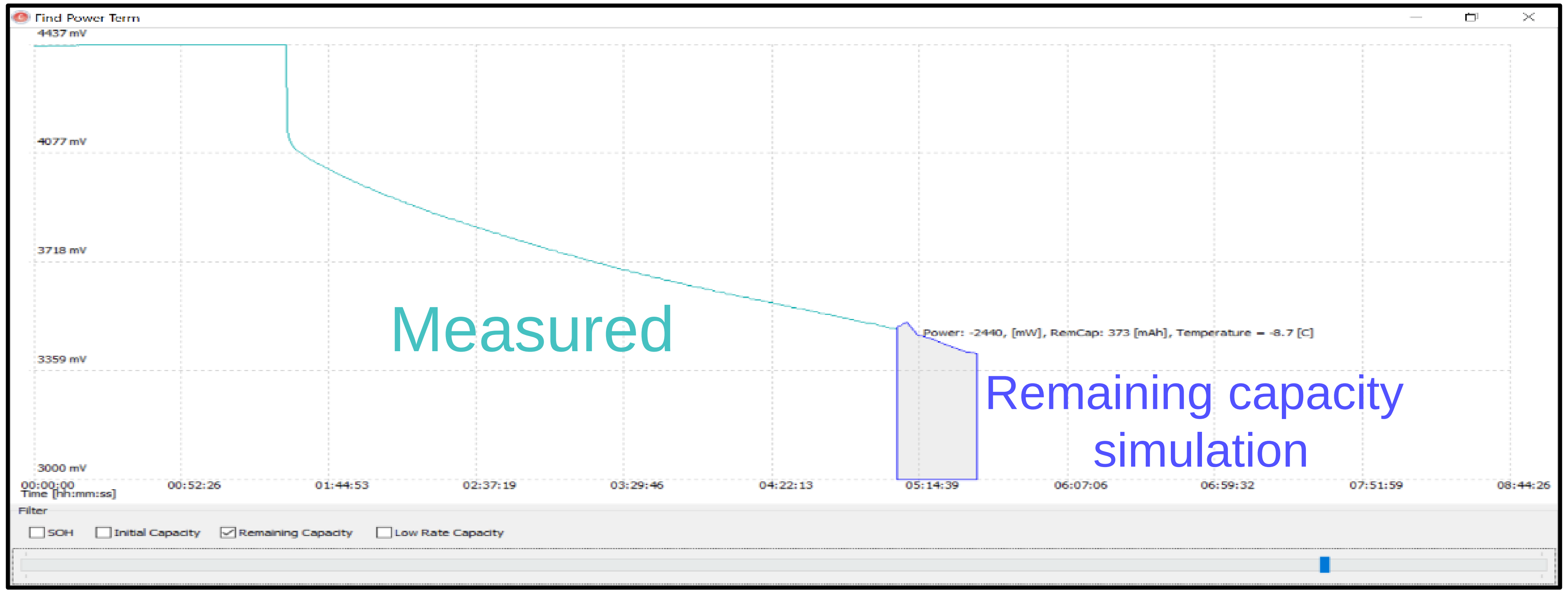
Constant Load Example

Impedance Track technology: Simulation

Example:

1. Temperature = -10°C
2. Constant C/5 discharge

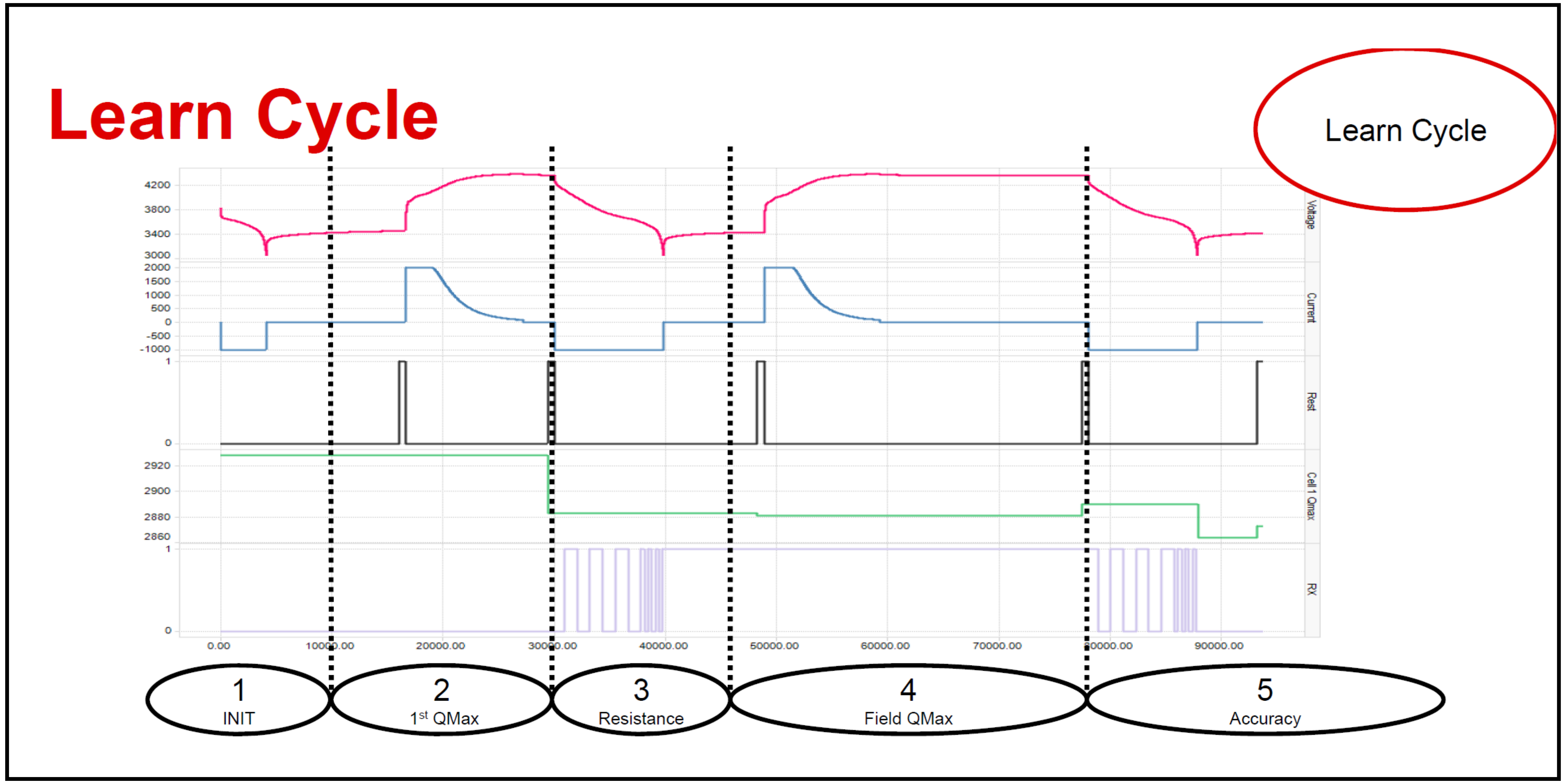




Impedance Track technology: FAQ

Notes:

1. First QMax needs 90% change in DOD.
2. Resistance learning should be done at a C/5 – C/10 rate until min battery voltage.
3. Step 4 should be charged to application max charge voltage to learn reduced VCT point.
4. Learning should be done on multiple packs, then merged, to average cell-to-cell variation.



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Impedance Track technology: Common challenges

1. Extreme cold temperatures (-10°C or lower).
   - **Challenge**: Battery impedance across temperature is non-linear with greater cell-to-cell variation.
   - **Recommendation**: Should be tuned at slightly less extreme temperature (eg. -10°C for -20°C needs).
2. High-rate discharge 1.5C+.
   - **Challenge**: Battery termination could be happening within the “Flat Zone”. Flat zone calculation errors increase due to mV delta per capacity delta.
   - **Recommendation**: Lower termination voltage to increase accuracy.
3. High termination voltage.
   - See #2.

Impedance Track technology: Common challenges

1. Rarely used, battery always “topped” off.
   - **Challenge**: Increase degradation with no resources to learn.
   - **Recommendation**: Force a shallow discharge to allow for learning.
2. No rest periods, constantly cycling.
   - **Challenge**: Gauge build coulomb counter error with no correction spot.
   - **Recommendation**: Utilize specialized gauge features to assist with learning and location reset.
     - FastQMax, Valid Charge Termination, FastOCV…

Gauging algorithm comparison

Algorithm	IT	CEDV
	Impedance Track^{TM} technology	Compensated end-of-discharge voltage+
Accuracy	Typical accuracy ~ 1%	Typical accuracy ~ 5%
Chemistry characterization	• Characterize battery to generate chemID • Estimated time: 2 weeks ~ 6 weeks • Need TI's assistance	• Characterize battery to generate parameters • Estimated time: 1 week • Customers can self-tune the parameters without TI's assistance
State of charge	SOC learning uses current measurement during chg/dsg and voltage correlation during rest	SOC learning uses current during discharge and voltage correlation at the end of discharge
Full charge capacity	FCC learning does NOT require full discharge	FCC learning requires discharge to <7% (Application must be capable of occasionally discharging to <7% ~ once a month)
End equipment profile	• Suitable for end equipment with chg/dsg current and some rests • Suitable for end equipment with extended rest periods and short chg/dsg bursts	• Suitable for end equipment with chg/dsg current and some rests • Suitable for end equipment with continuous chg/dsg current and no rests
Initialization	SOC at power-up uses voltage correlation	SOC at power-up uses voltage correlation
Intel Turbo Mode feature	Supported	Not supported
LiFeP04	Possible	Preferred
Ease of use	Large number of algorithm parameters	Very few algorithm parameters

Resources

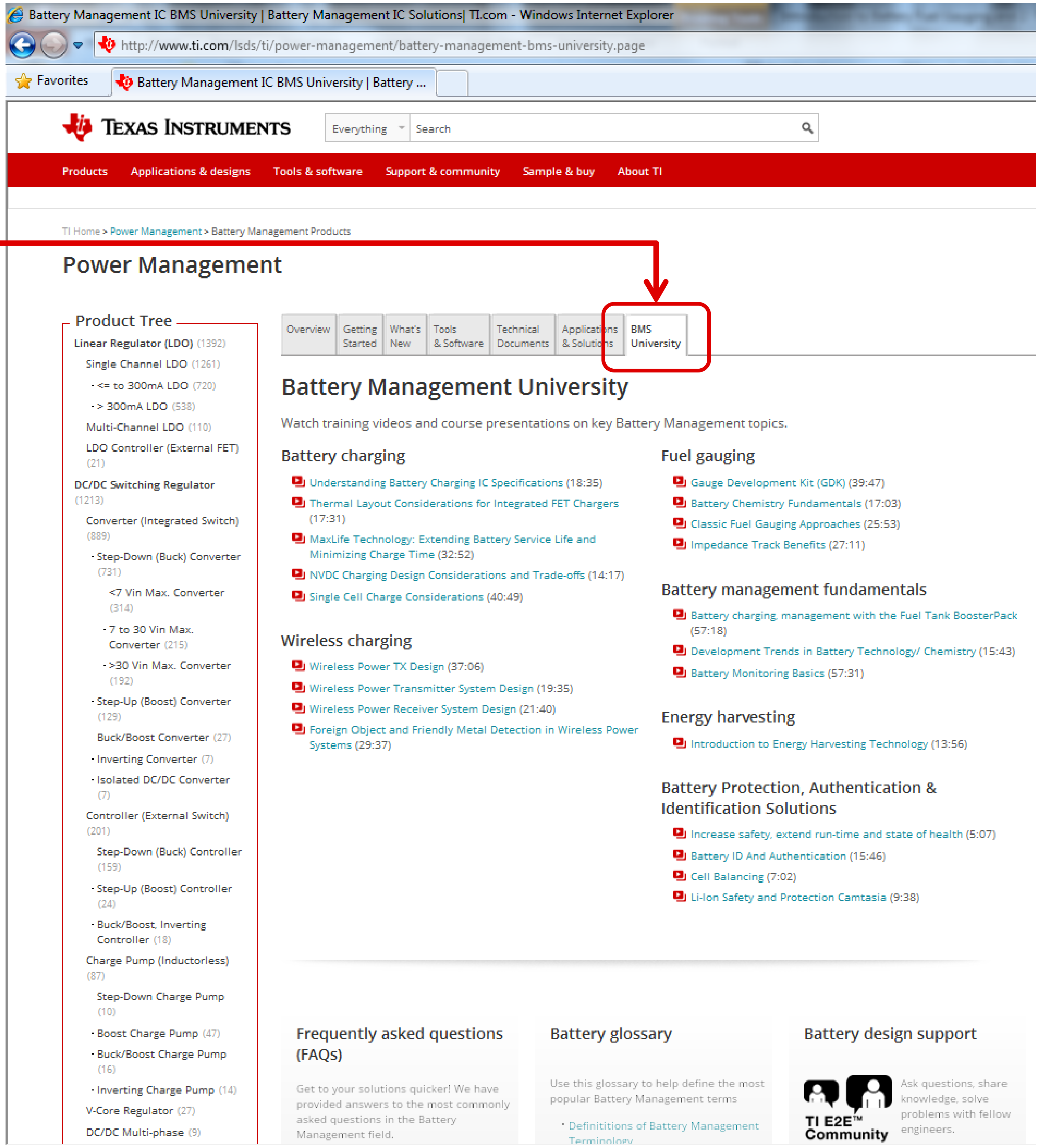
Impedance Track technology advantages

- Combines advantages of voltage correlation and coulomb counting methods.
- Accounts for cell impedance/aging, temperature and variable current loading.
- Doesn’t require full charge-discharge learning cycle for FCC (usable capacity).
- Best accuracy (~1%).
- Dynamically updates the gauge data flash as it fully characterizes the parameters of each cell.
- Parameters learning on-the-fly:
  - Learn impedance during discharge
  - Learn total capacity (Qmax) without full charge or discharge
  - Adapt to spiky loads (delta voltage)
- Host system does not need to perform calculations or gauging algorithm.

BMS University

ti.com/battery

Presentations, videos, documents and more



Battery electronics options

Lowest complexity

Protector

- Simple hardware-based protection to respond to unsafe conditions like over-voltage, under-voltage, over-current, over-temperature, under-temperature, over-current, or short circuit.

Highest flexibility

Monitor

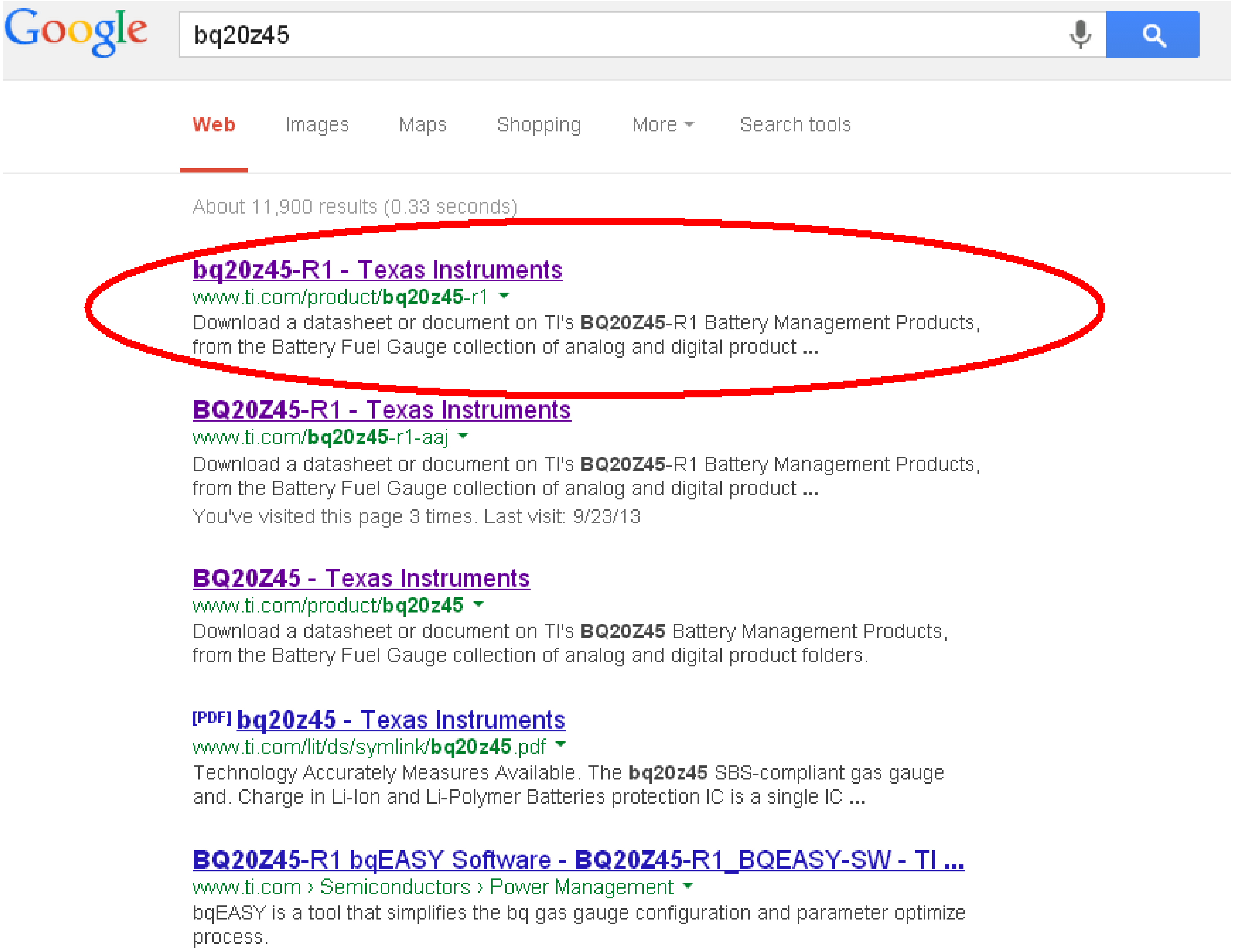
- Measures individual cell voltages
- Measures current (coulomb counting)
- Measures die temperature and external thermistors
- Cell balancing to extend battery run-time and battery life
- Protections with flexible thresholds
- Communicates data and status to MCU or stand-alone gauge

Highest integration

Gauge

- Reports capacity, run-time, state-of-charge
- Enhanced protections
- Black box features to diagnose battery failure
- Extends run-time of battery due to accurately determining how much capacity is remaining
- Extends lifetime by dynamically controlling healthy, safe, fast charging
- Authentication, state-of-health, traceability, etc.

For more information…Google the P/N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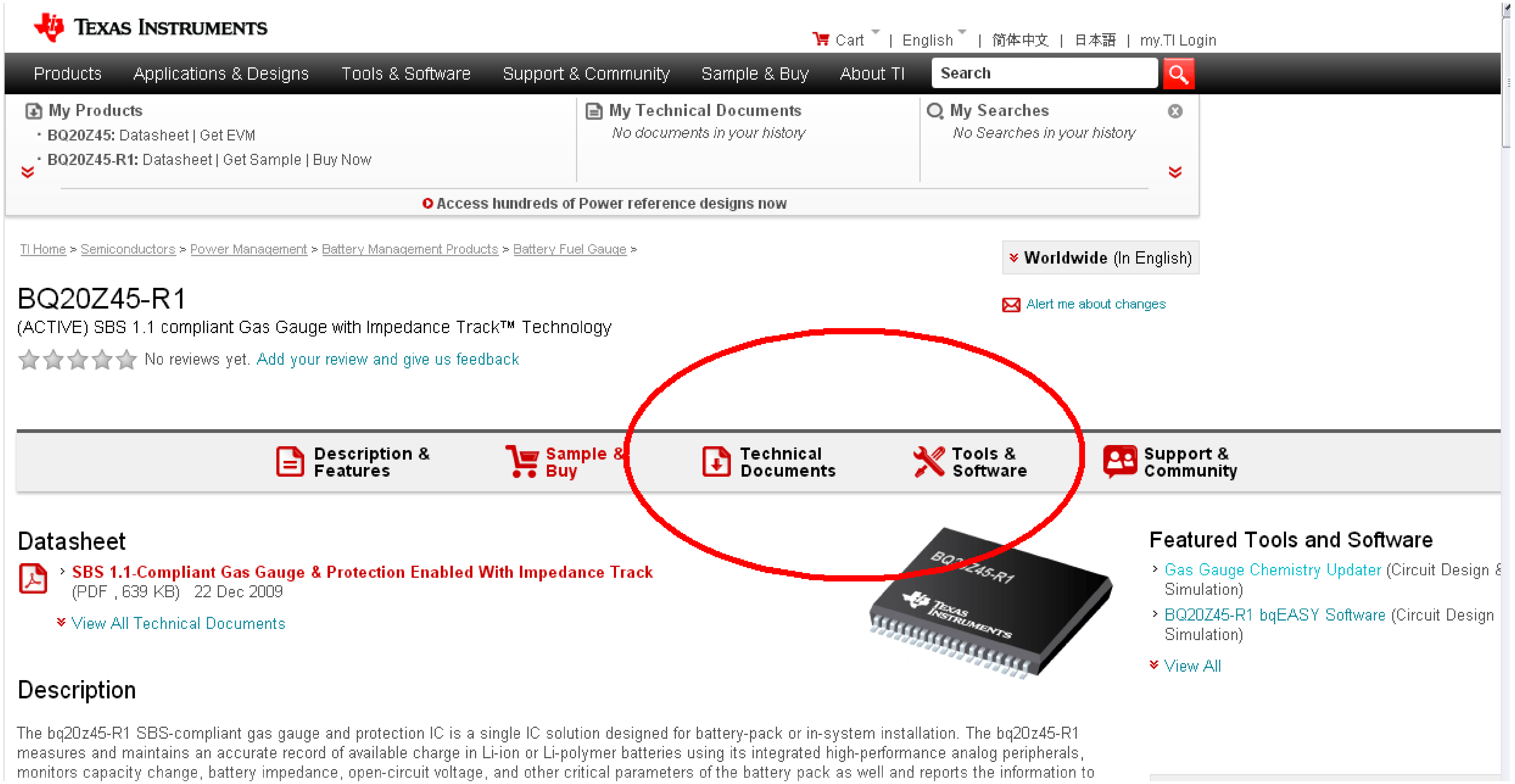
www.ti.com › Semiconductors › Power Management
bqEASY is a tool that simplifies the bq gas gauge configuration and parameter optimize process.

Technical docs, app notes, tools in each product folder



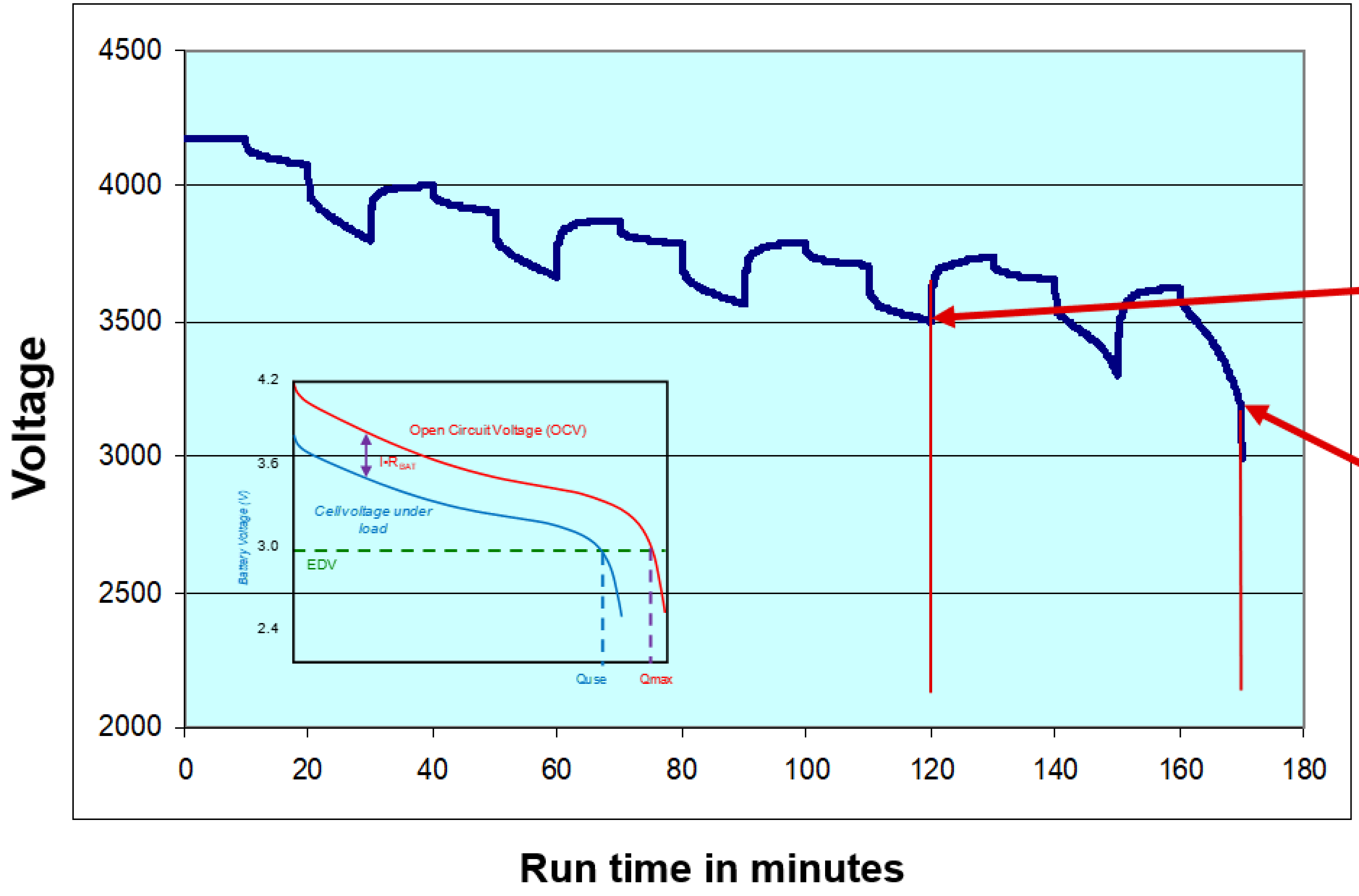
Appendix A

How can you extend run-time with an accurate gauge?

Run-time comparison example: Impedance Track technology gauge shutdown vs. OCV shutdown point

- Systems without accurate gauges simply shutdown at a fixed voltage.
- Smartphone, tablets, portable medical, digital cameras etc… need reserve battery energy for shutdown tasks.
- Many devices shutdown at 3.5 or 3.6 volts in order to cover worst case reserve capacity:
  - 3.5 volt shut down used in this comparison.
  - Gauge will compute remaining capacity and alter shutdown voltage until there is exactly the reserve capacity left under all conditions.
  - 10 mAH reserve capacity is used.
  - Temperature and age of battery are varied.

Fuel gauging: OCV vs. IT use case exp – NEW batterv with variable load mix



Conditions:

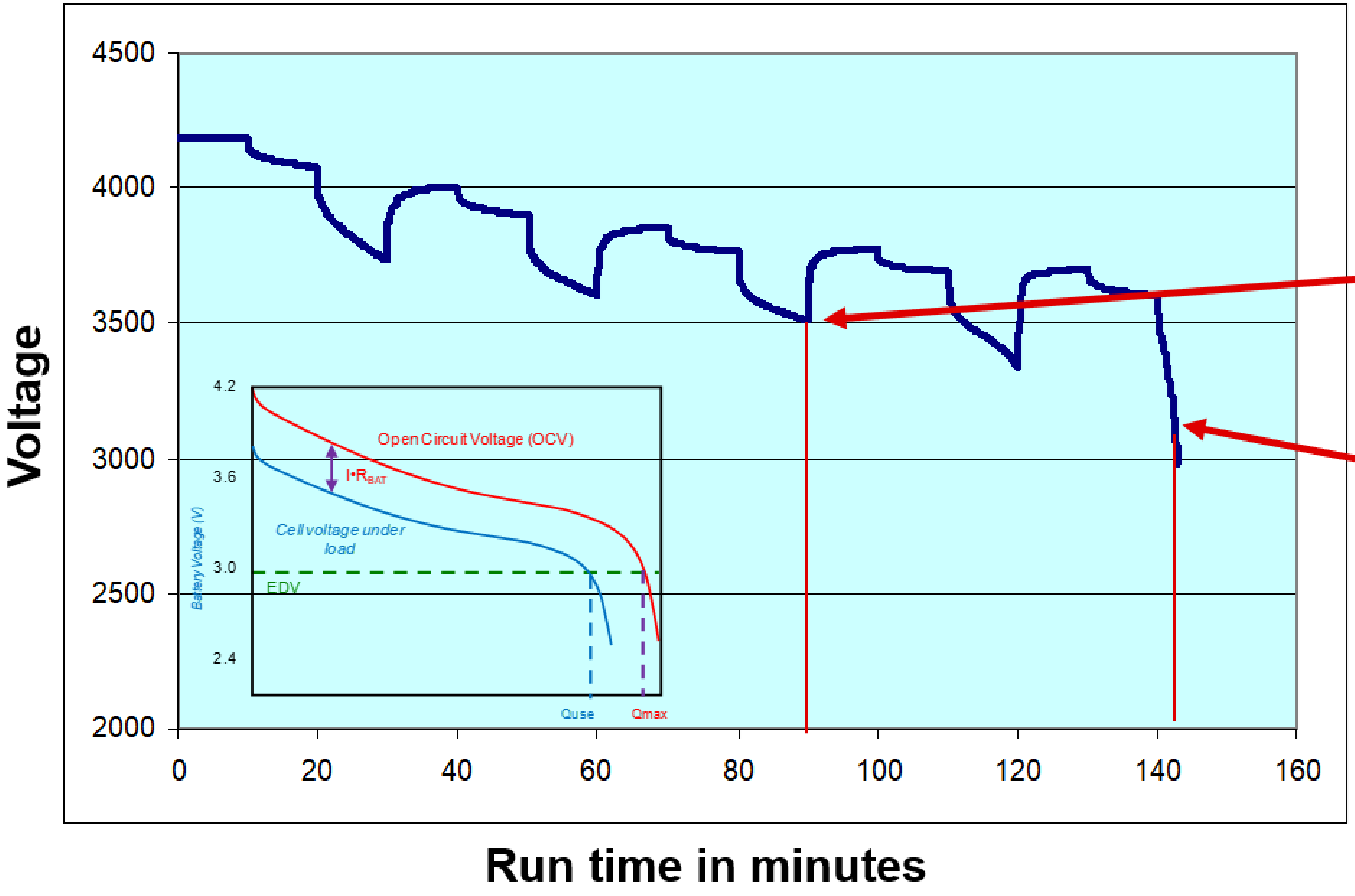
- New battery
- Room temp (25°C)
- 10 mAh reserve capacity for shutdown

OCV
Shutdown @ 3.5V
120 minutes run time

Impedance Track technology gauge shutdown @ 3.295 V
168 minutes run time

Extended run time with TI Gauge: +40%

Fuel gauging: OCV vs. IT use case exp – OLD battery with variable load mix



Conditions:

- Room temp (25°C)
- 10-mAh reserve capacity for shutdown

OCV
Shutdown @ 3.5V
90 minutes run time

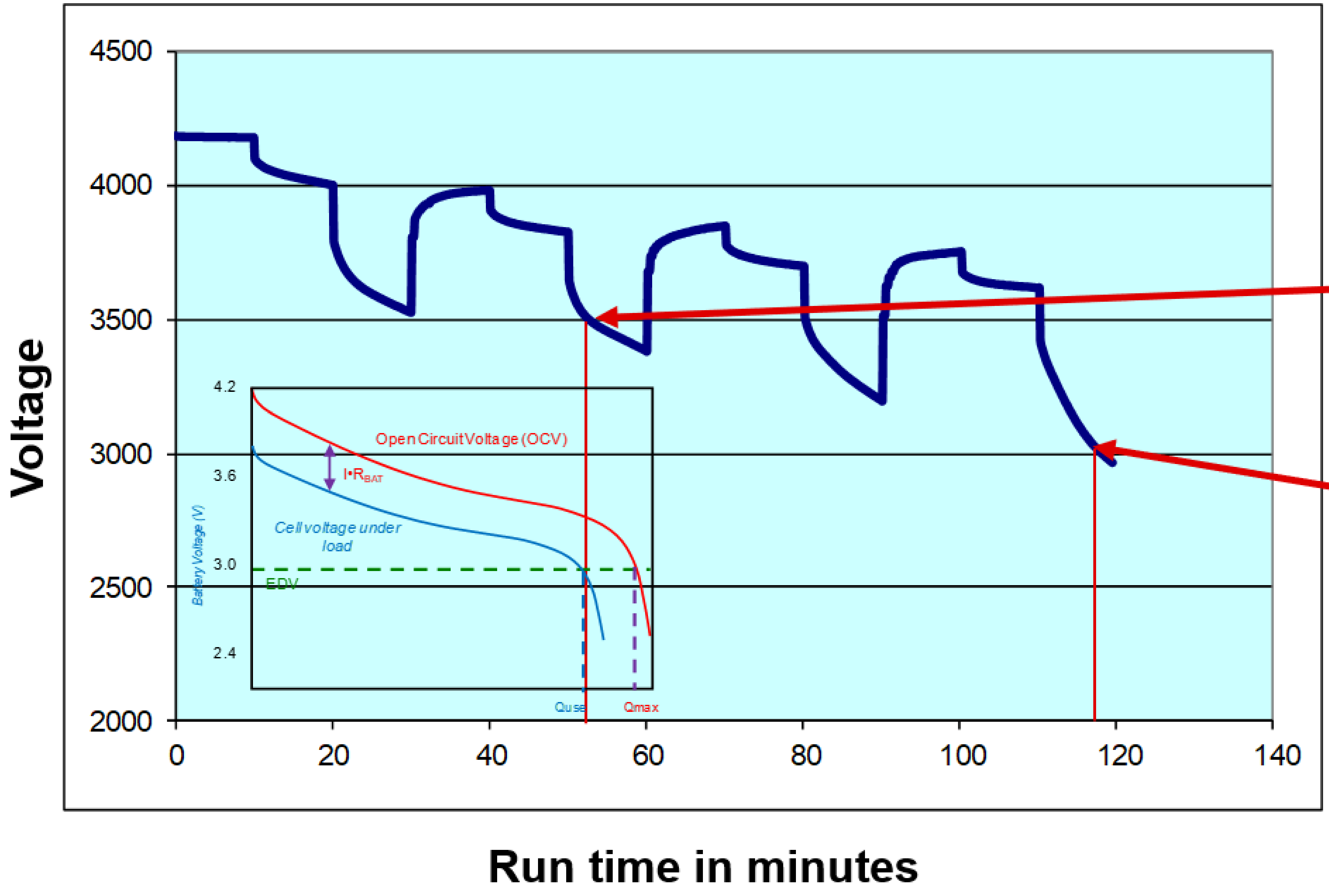
Impedance Track technology
Gauge shutdown @ 3.144V
142 minutes runtime

Extended run time with TI Gauge: +58%

Fuel Gauging: OCV vs. IT use case exp – NEW battery COLD w/ variable load mix

Conditions:

- Cold (0°C)
- 10-mAh reserve capacity for shutdown

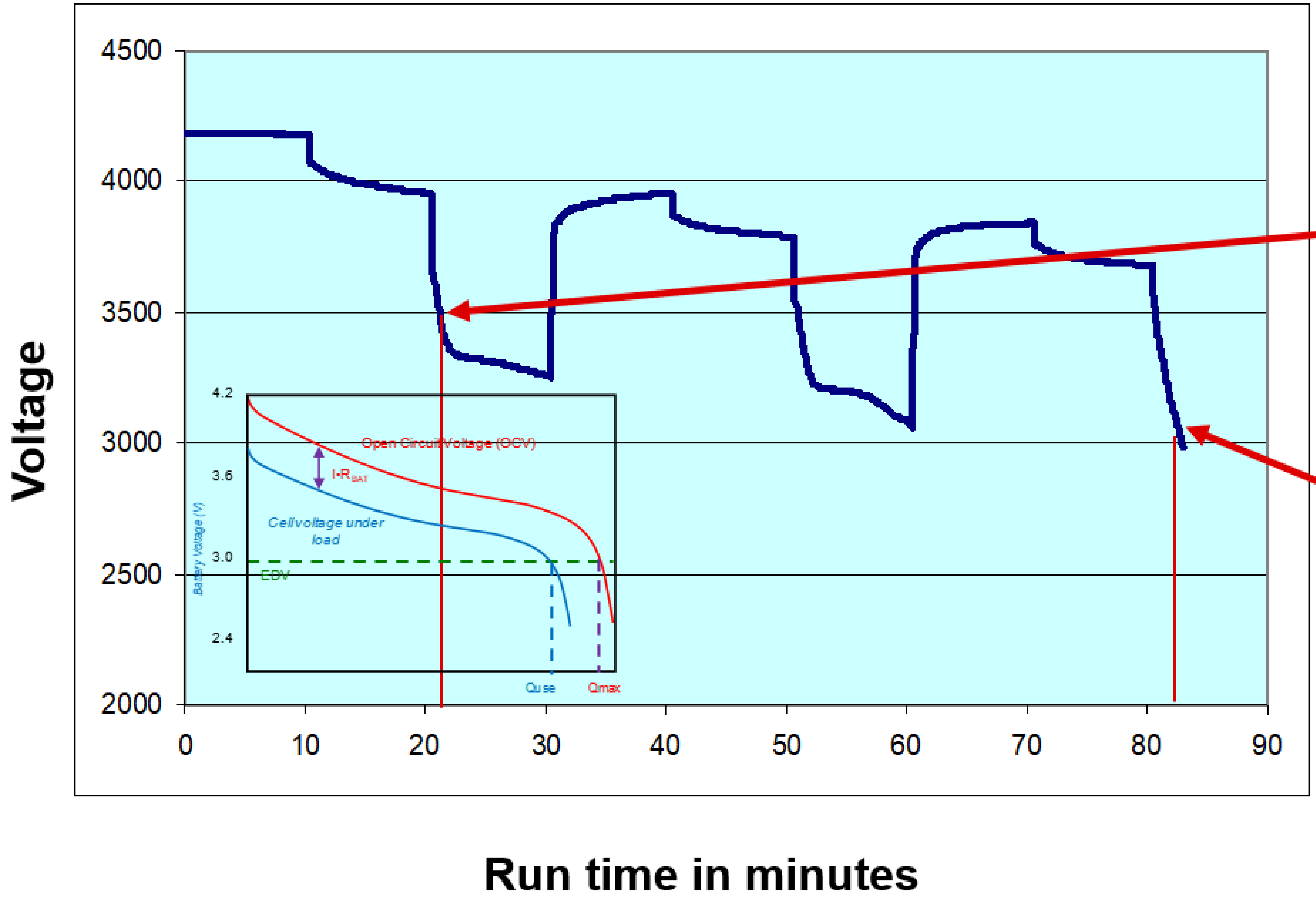


OCV
Shutdown @ 3.5V
53 minutes run time

Impedance Track technology Gauge shutdown @ 3.020V
117 minutes run time

Extended run time with TI Gauge: +121%

Fuel gauging: OCV vs. IT use case exp – OLD battery COLD w/ variable load mix



Conditions (0°C):

- Cold (0°C)
- 10-mAh reserve capacity for shutdown

OCV
Shutdown @ 3.5 V
21 minutes run time

Gauge shutdown at 3.061 volts:
82 minutes run time

Extended run time with TI Gauge: +290%

TEXAS INSTRUMENTS

IMPORTANT NOTICE AND DISCLAIMER