Battery Management Deep Dive

Impedance Track configuration considerations for different applications

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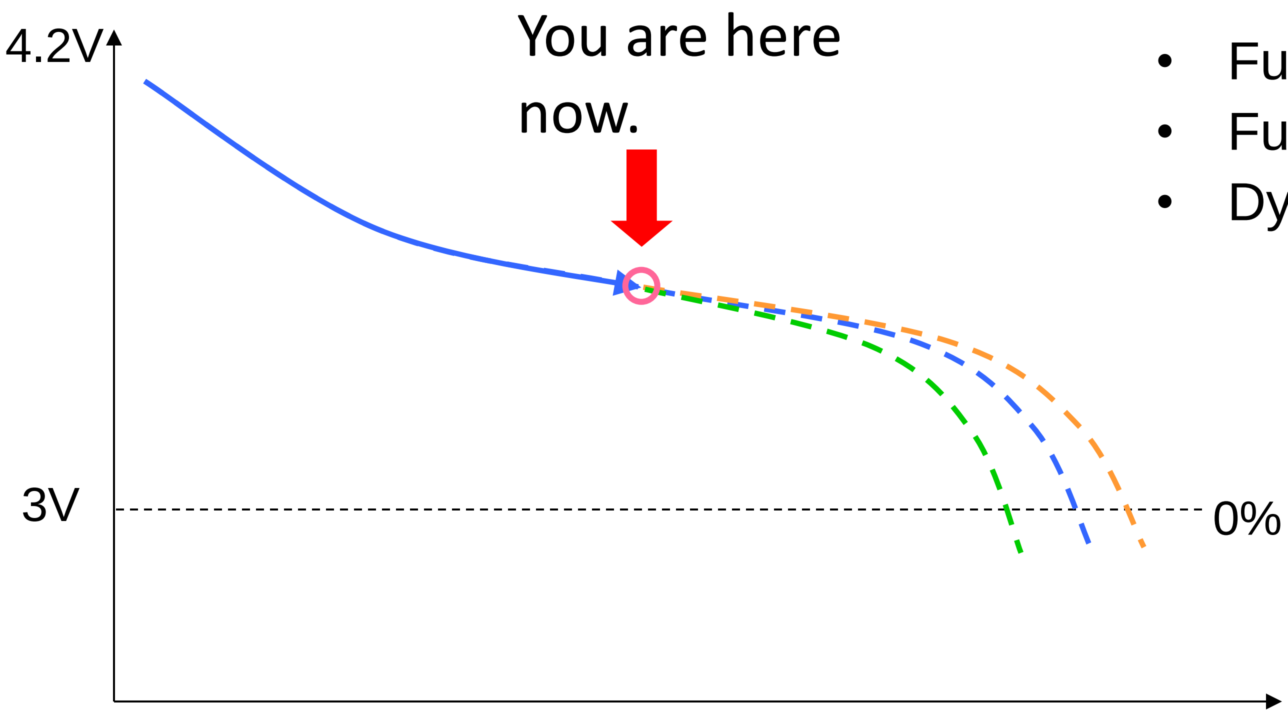
How can a gauge predict the future?

Which route is the battery taking?

- Future load?
- Future temperature?
- Dynamic load?



Abstract

- Batteries are used in a wide range of applications and usage conditions.
- The default configurations of a fuel gauge may not be ideal for maximum accuracy in many cases.
- There are also a number of options to adjust how the gauge will make its predictions.
- We will cover a number of configuration options which are typically modified, as well as a handful of specific use-cases.

Agenda

- Concept and Terminology Review
- IT Memory Configuration and Key Parameters
- Typical Implementation Challenges and Resolutions
  - Low temperature performance
  - Transient and thermal modeling
  - Dynamic loads
- Gauge options

Fuel Gauging – Impedance Track™

Cell Voltage Measurement

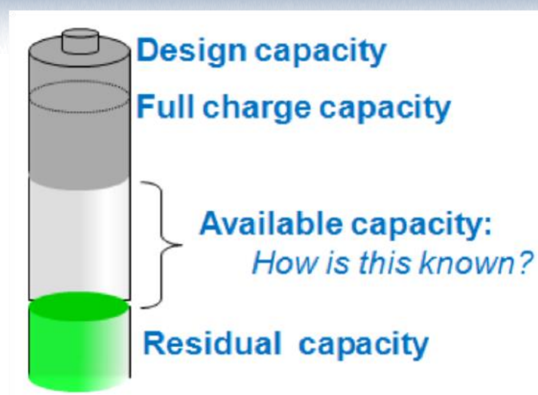
- Measures cell voltage
- Advantage: Simple
- Not accurate over load conditions

Coulomb Counting

- Measures and integrates current over time
- Affected by cell impedance
- Affected by cell self discharge
- Standby current
- Cell Aging
- Must have *full to empty* learning cycles
- Must develop cell models that will vary with cell maker
- Can count the charge leaving the battery, but won't know remaining charge without complex models
- Models will become less accurate with age

Impedance Track™

- **Directly measures effect of discharge rate, temp, age and other factors by learning cell impedance**
- **Calculates effect on remaining capacity and full charge capacity**
- **No learning cycles needed**
- **No host algorithms or calculations**



What is Impedance Track?

1. Chemistry table in Data Flash:

   $OCV = f\ (dod)$

   $dod = g\ (OCV)$

10,000 foot View

2. Impedance learning during discharge:

   $$R = \frac{OCV - V}{I}$$

3. Update Max Chemical Capacity for each cell

   Qmax = PassedCharge / (SOC1 – SOC2)

4. Run periodic simulation to predict Remaining and Full Capacity

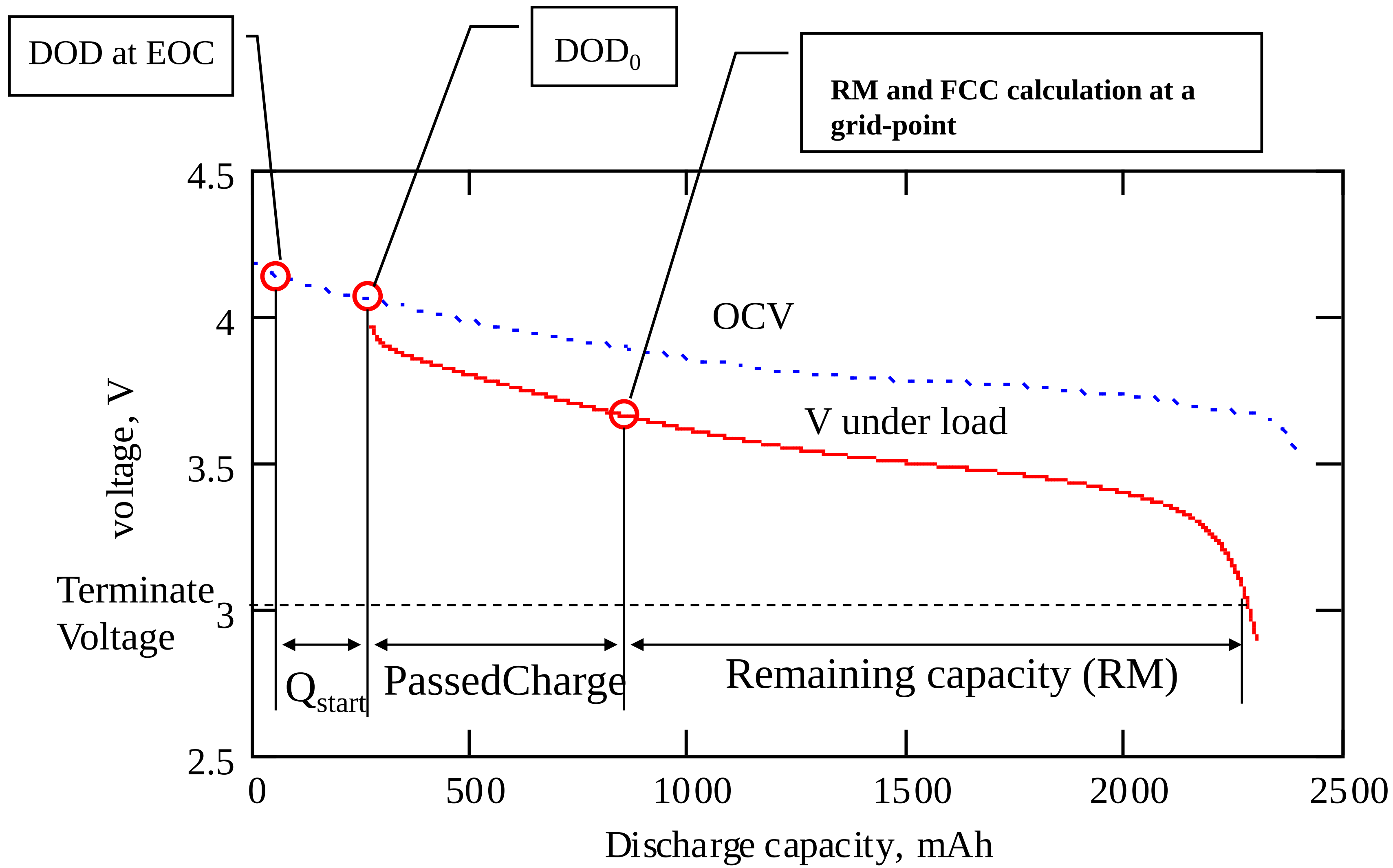
Definitions (part 1)

- OCV – open circuit voltage
  - relaxed or predicted voltage with no load
- DOD – depth of discharge
  - 0% is charged to the brim, 100% is completely empty of energy
  - Does not depend on load or temperature or system characteristics
- RM – Remaining Capacity in mAh
  - Usable capacity of the battery from current DOD to empty
- FCC – Full Charge Capacity in mAh
  - Usable capacity of the battery from full to empty
- SOC – state of charge, 0% - 100%
  - Full and empty points depend on the system
  - Can change with load and temperature
  - SOC = RM / FCC

Key IT parameter configuration

- Load Mode/Select Configuration
- Current Thresholds
- Charge Termination Detection

Simulation to find RemCap and FCC



Definitions (part 2)

- DOD0
  - last DOD point measured directly by the gauge
- DODatEOC
  - DOD at End of Charge representing SOC = 100% for a particular system
- Qstart
  - capacity between DODatEOC and DOD0
- Qpass
  - accumulated passed charge since last DOD0 update
- Terminate Voltage
  - voltage at which the system can no longer operate; target for SOC = 0%
- Taper Current
  - Current level at which charger shuts off

Load Mode/Select Configuration

- All about what current or power to use when the gauge runs a simulation to predict FCC and SOC

- What's a simulation?
  - Do While V > Vtermination
    - DOD = DOD + 4%
    - Lookup OCV and resistance
    - Adjust resistance for predicted cell temperature
    - Calculate current based on LOAD MODE
    - V = OCV – IR
    - Exit loop when V = Vtermination

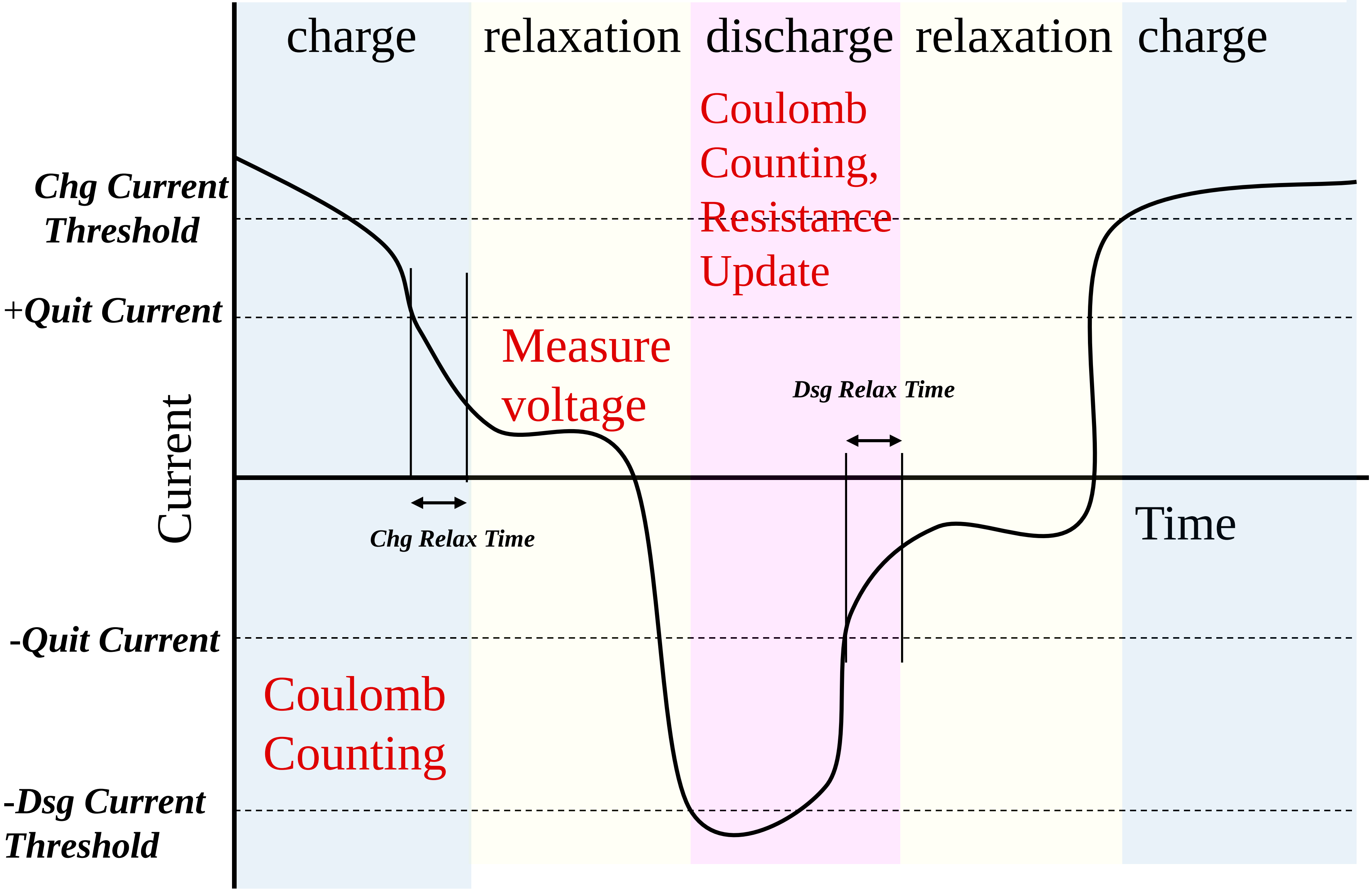
Load Mode/Select Configuration

- When does the simulation run?
  - Initialization at reset, battery insertion, or POR (power on reset)
  - Start of charge
  - Charge Taper Termination
  - Start of discharge
  - Every grid update during discharge.
    - The grid points here are the 15 Ra grid points of the resistance table.
  - Every Relax Rem Cap Update Time (usually 1 hour) after OCV in relax mode
  - Qmax update
  - Every time there's a big change in temperature
  - Every 30 seconds (if Fast Resistance Scaling is running near empty)

Load Mode/Select Configuration

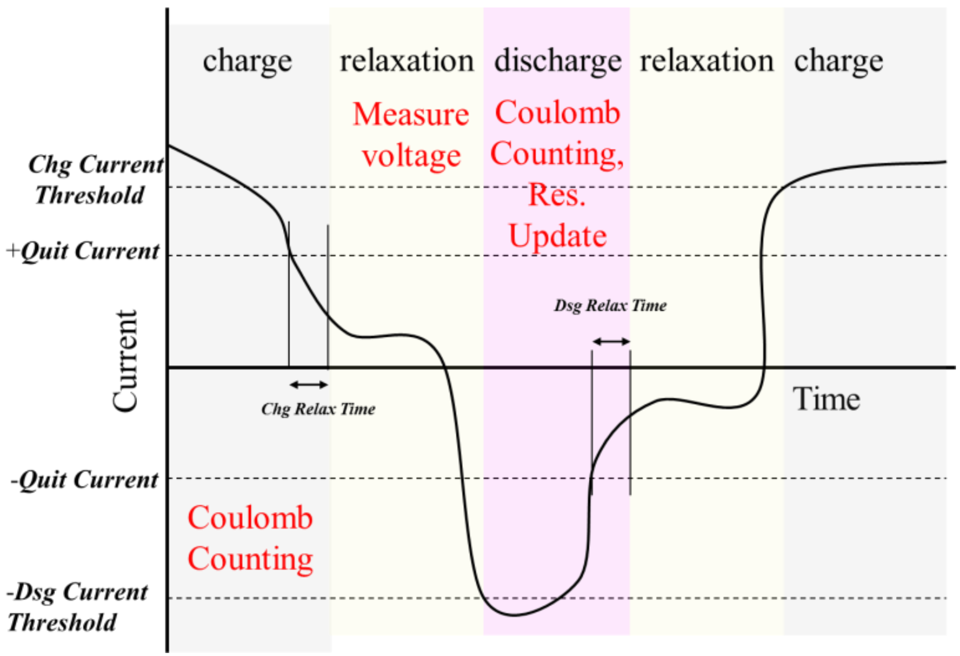
- What are the LOAD SELECT choices?
  - IF ***Load Mode = 0: (Constant Current)***
    - **0 = *Avg I Last Run***
    - **1 = Present average discharge current (average over entire discharge)**
    - **2 = Current**
    - **3 = AverageCurrent**
    - **4 = DesignCapacity/5**
    - **5 = AtRate (mA)**
    - **6 = *User-Rate-mA***
  - IF ***Load Mode = 1: (Constant Power)***
    - **0 = *Avg P Last Run***
    - **1 = Present average discharge power**
    - **2 = Current x Voltage**
    - **3 = AverageCurrent x Average Voltage (average over entire discharge)**
    - **4 = DesignEnergy/5**
    - **5 = AtRate (10mW)**
    - **6 = *User-Rate-mW***

Current Direction Thresholds and Delays

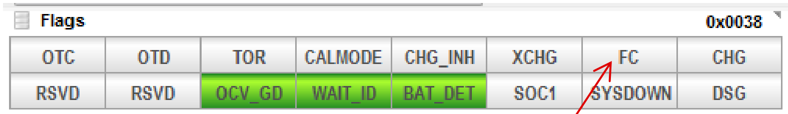


Choosing your thresholds

- Defaults may work for you, but…
- ***DF:Quit Current:*** recommend using < C/20
- ***DF:Chg / Dsg Current Thresholds***
  - Ensure ***Taper Current*** > ***Chg Current Threshold*** > ***Quit Current***
  - Ensure ***Dsg Current Threshold*** > ***Quit Current***



Charge termination



- Best way to synch charger termination with gauge 100% is to stop charging when gauge *FC* bit is set
- If open-loop charging, ensure that:
  - DF:***TaperCurrent*** > actual charger termination condition
- Note: SOC = 100% does NOT always mean the battery is full and the gauge detected full charge.
- Recommend using DF:***FC Set %*** = -1 to synch FC bit with algorithm charge termination conditions.

Typical implementation challenges and resolution

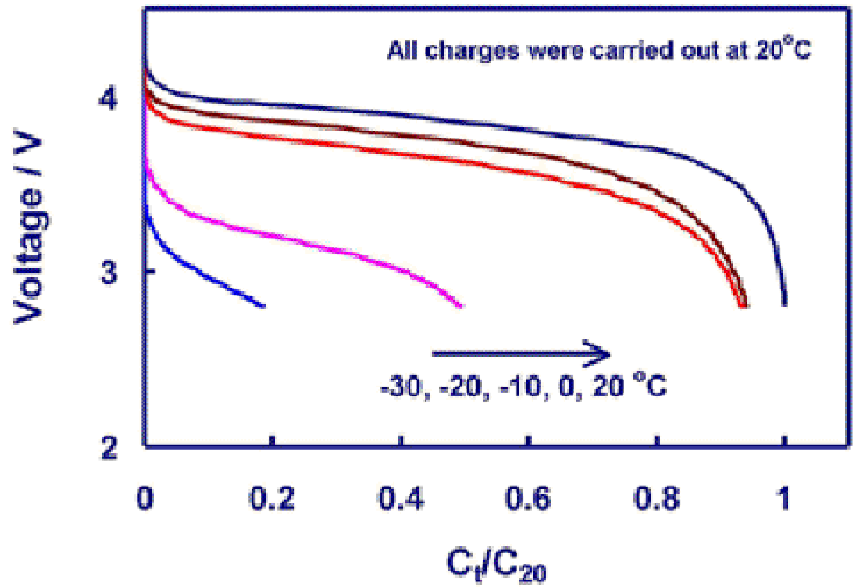
- Low temperature performance
- Dynamic loads
- No relaxation applications
- Backup batteries
- PCB effects
- Long standby applications

Challenge: low temperature performance

- Temperature is important for
  - Capacity estimation
  - Safety
  - Charging control

Ensure gauge is measuring cell temperature, not your PCB!

- Temperature impacts model parameters
  - Resistance
  - Capacitance
  - OCV
  - Max capacity

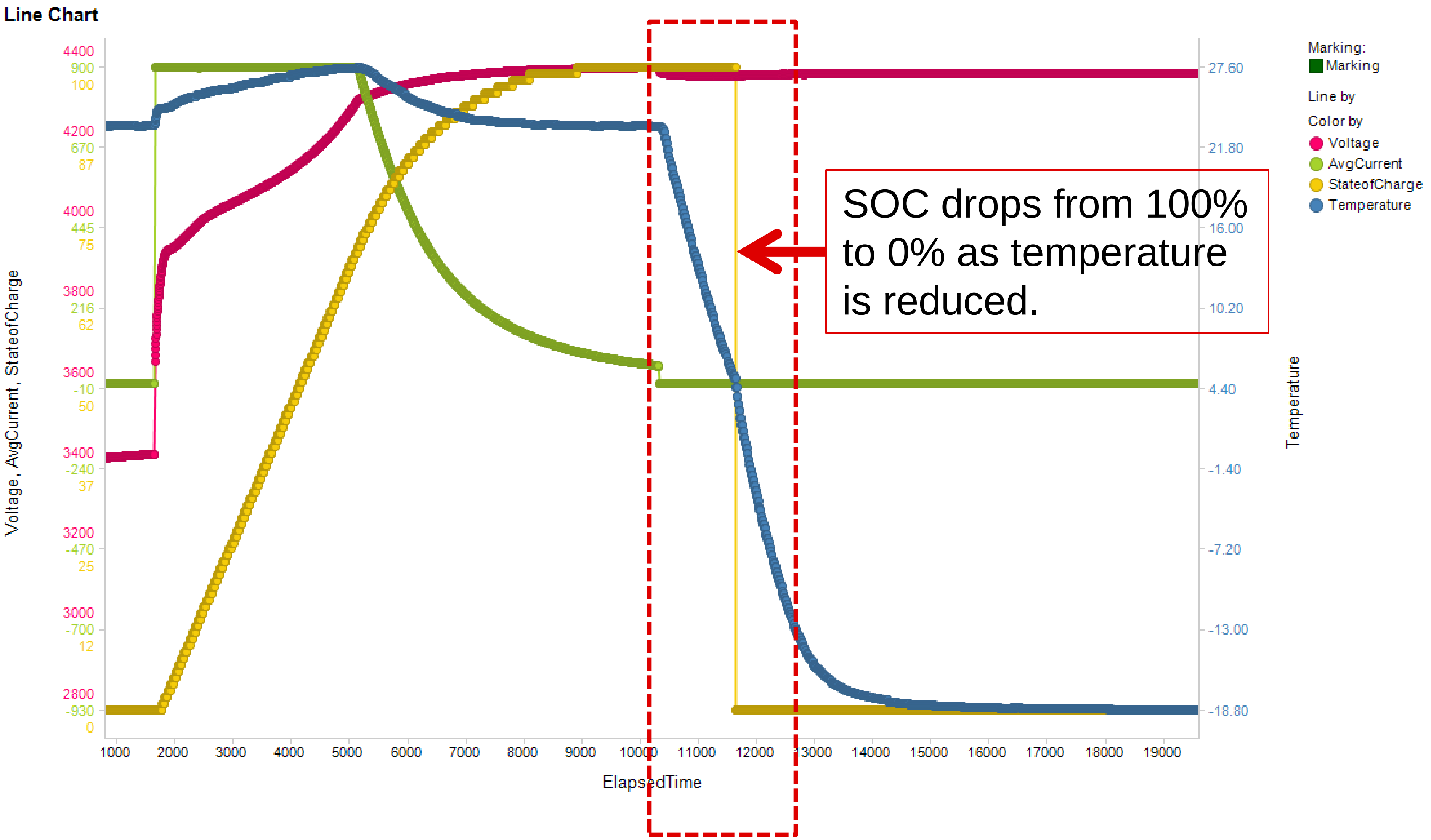


Impedance Track Temperature

- Fixed tables in Chem ID for:
  - How open circuit voltage depends on temperature
    - "OCV tables"
  - How resistance depends on temperature
    - "Rb tables"

- Dynamic table for Impedance Tracking – "Ra Table"
  - Typically normalized resistance at 25°C
  - Update must be made at various temperatures, so temperature model must be correct
  - For example, every time the Ra table is updated at 41°C, it must use the Rb tables to normalize and store the resistance at 25°C.

Low temperature issue



SOC drop at low temp

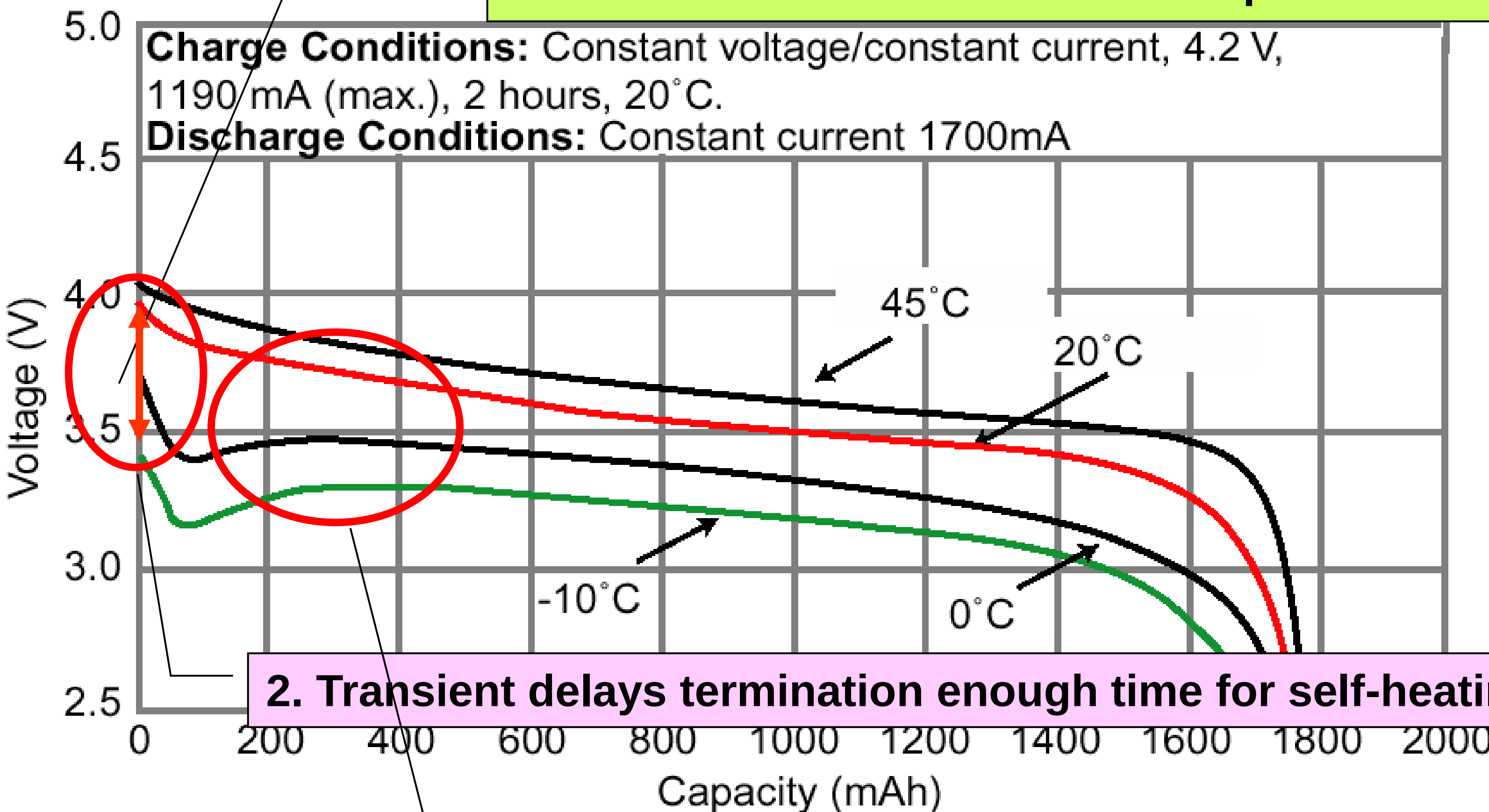
- For low temperature issues, these are the steps to follow.
  - 1) Ensure you are accurately measuring the battery temperature.
    - Thermistor placement (or IC placement if using internal temp sense) should be on or near the battery cell.
    - Check gauge's temperature reading against an external probe if necessary.
  - 2) Ensure you have the correct chemID selected.
    - Use http://www.ti.com/tool/GPCCHEM to find or confirm a match.
  - 3) Ensure you have optimized Qmax and Ra.
    - Either perform a learning cycle or use http://www.ti.com/tool/GPCRA
  - 4) Optimize low temp parameters (for flash gauges only)
    - Use http://www.ti.com/tool/GPCRB
      - Tweaks chemID for low temp performance: "Rb tweak"
      - Calculates thermal modeling parameters *(T Rise and T Time Constant)*

Adjusting transient and thermal models

- Symptom
  - Gauge may jump from 100% to 0% when temperature drops
- Cause
  - IT algorithm is predicting instant drop below Terminate Voltage due to high resistance at low temp
  - Actual drop will be less due to transient effect and then temperature will increase during a discharge
- Resolution
  - Increase transient modeling (***ResRelax Time***)
    - Start with at least 500; try 800 or more
  - Adjust thermal modeling (***T Rise*** up; ***T Time Constant*** down)
    - NOTE: multi-cell gauges have dynamic thermal modeling

Need for transient modeling

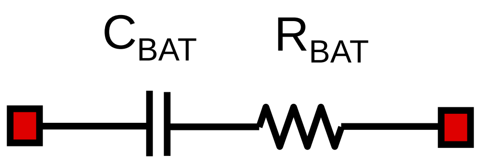
1. Resistance increases at low temperature

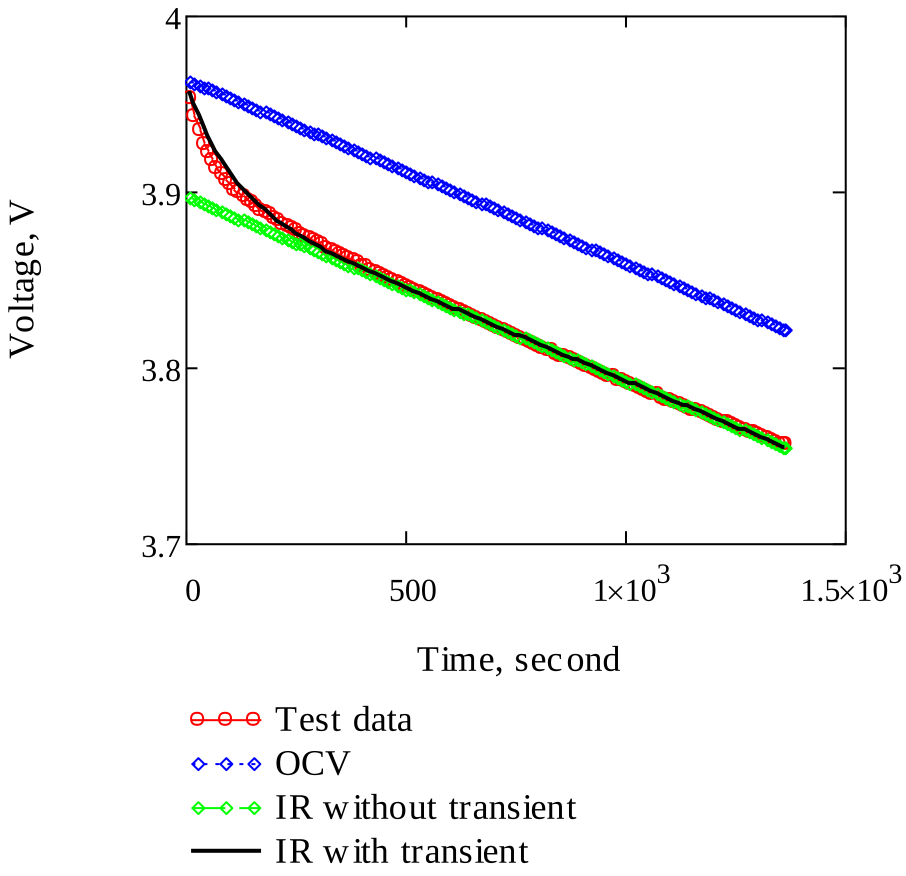


2. Transient delays termination enough time for self-heating

3. Self-heating allows to keep cell voltage above termination

Transient modeling

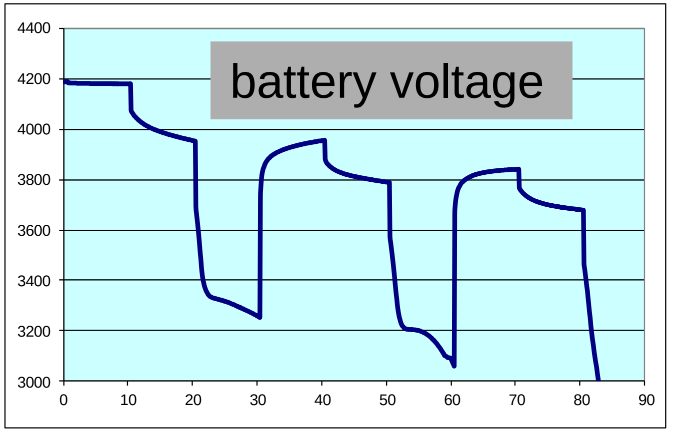




- Voltage without transient modeling (red line) goes too low initially
- With transient modeling, voltage coincides with test data

"*ResRelax Time*" is the gauge parameter which represents this time constant.

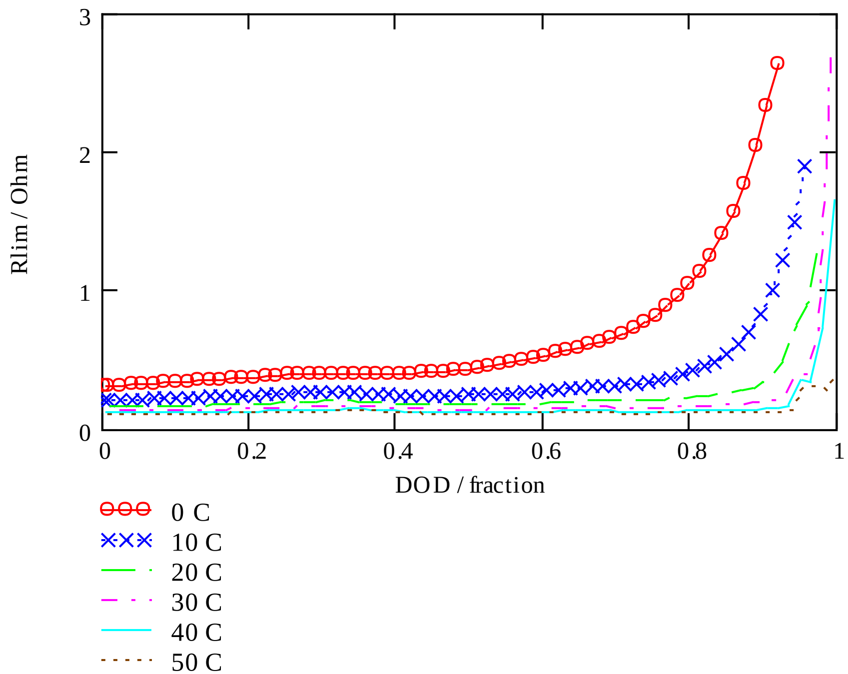
Challenge: dynamic load

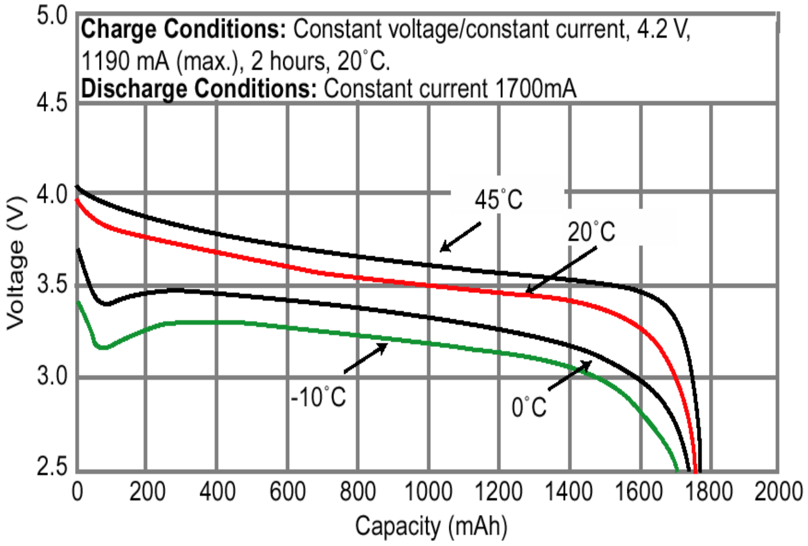


- Symptom
  - Gauge jumps to 0% when load current suddenly increases.
- Cause
  - Either:
    - Voltage dropped below Terminate Voltage with heavier current.
    - Gauge updated prediction with new heavier load and expects "empty" will be reached imminently.
- Resolution:
  - Do NOT increase Terminate Voltage as further guardband!
  - If possible, lower Terminate Voltage. Trust IT!
  - Change Load Select to another option.
  - Use Imax/TurboMode to intelligently throttle system current.

Review – battery impedance at temperature

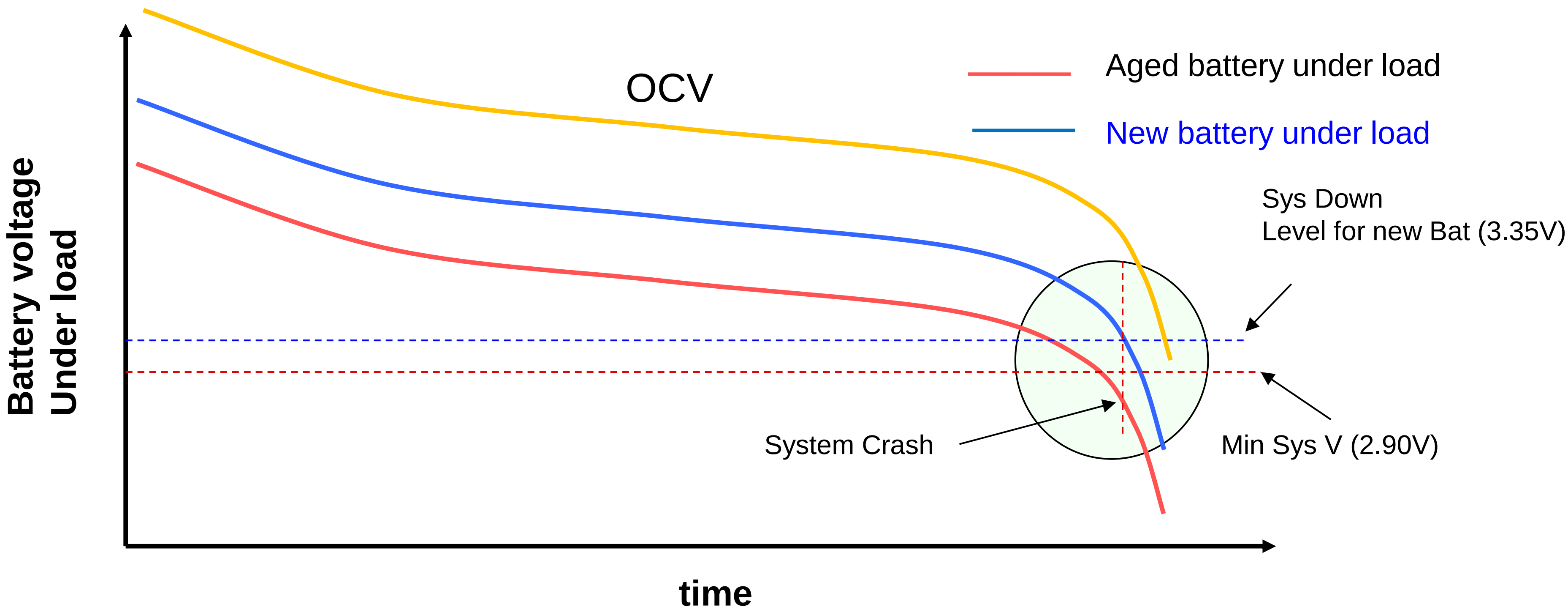
- **Impedance is strongly dependent on temperature**
- **Both value and profile shape depend on temperature**
- **Impedance decreases about 1.5 times per 10 C increase**





Review – battery impedance with aging

- **Impedance increases with usage**
- **Impedance doubles after approximately 100 cycles**



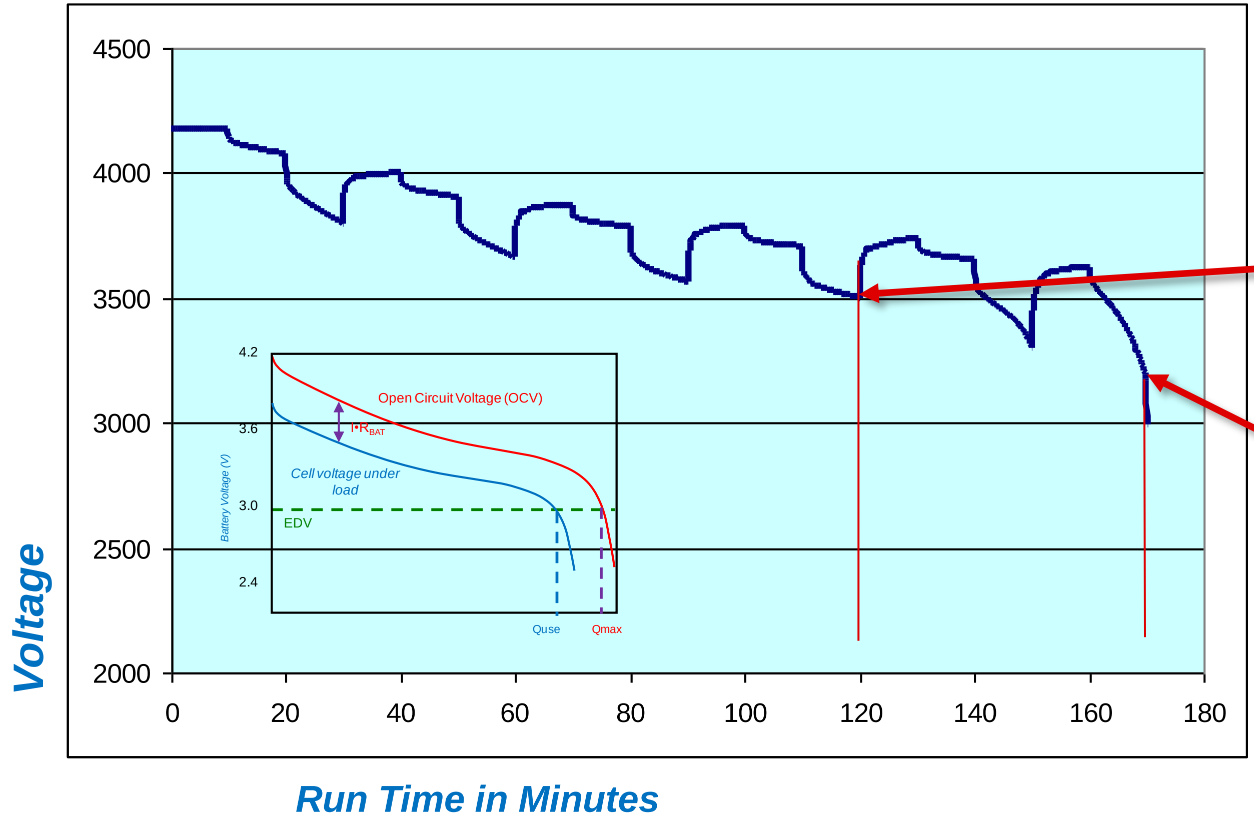
Run Time Comparison Example

Impedance Track^{TM} 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 3.6V in order to cover worst case reserve capacity**
  - ***3.5V 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 battery w/ variable load mix



Conditions:

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

OCV
Shutdown @ 3.5V
120 minutes run time

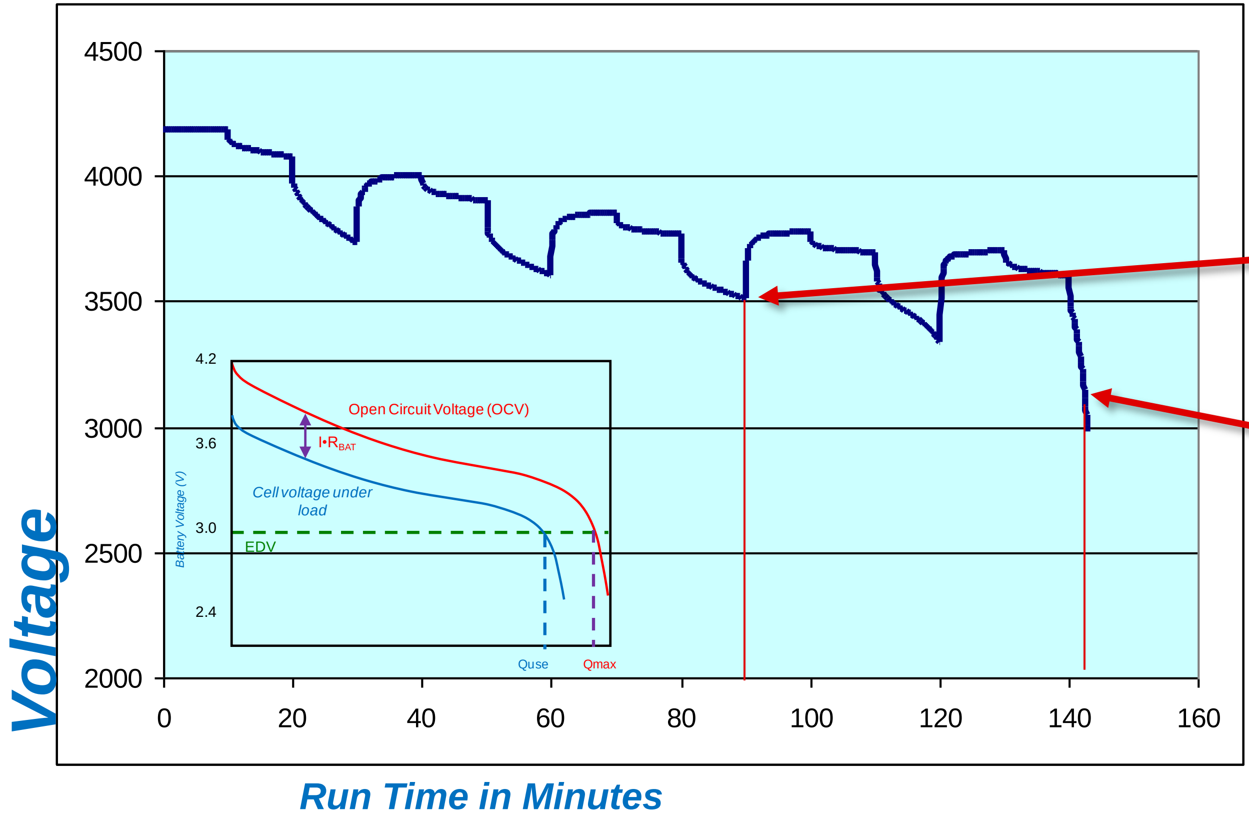
Impedance Track™ Gauge Shutdown @ 3.295V
168 minutes run time

Extended runtime with TI Gauge: +40%

TI Information – Selective Disclosure. Battery Management Deep Dive 2015

Fuel Gauging

OCV vs. IT Use Case Exp – OLD battery w/ variable load mix



Conditions

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

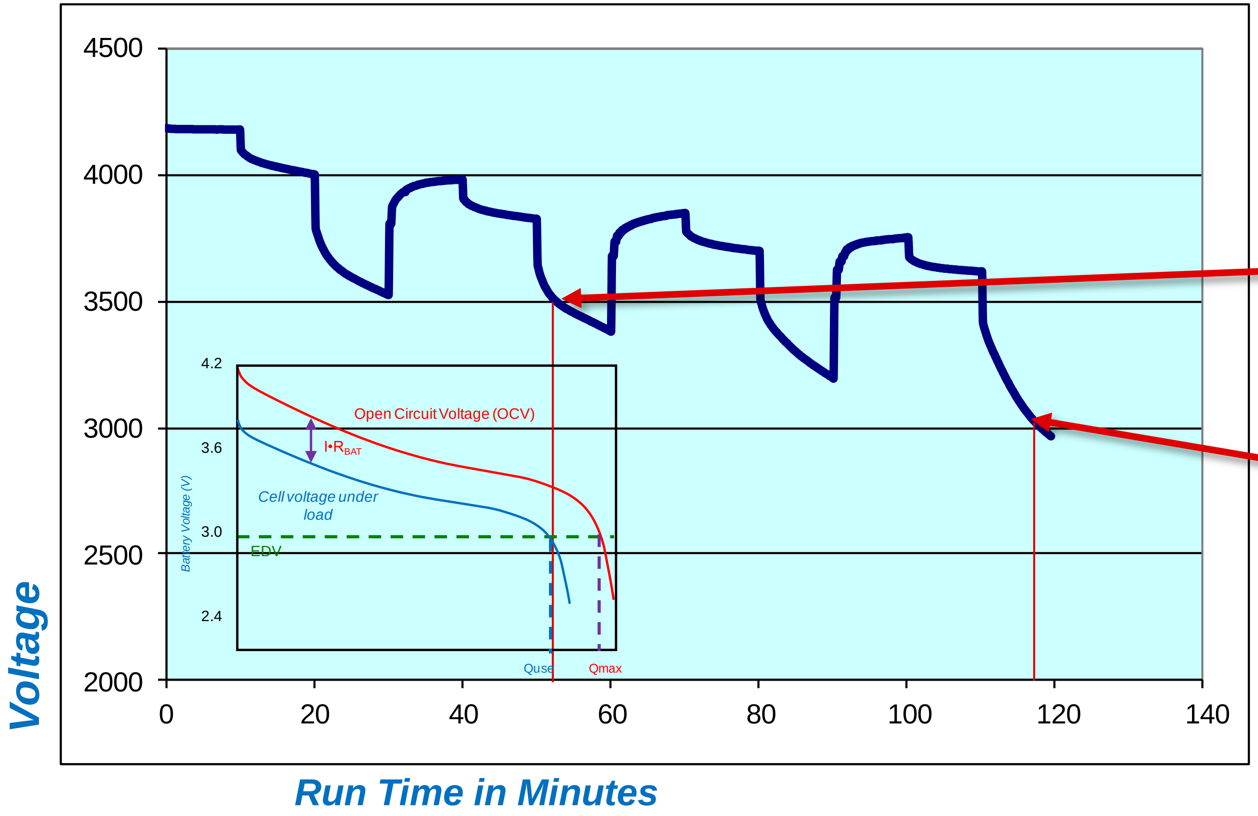
OCV
Shutdown @ 3.5V
90 minutes run time

Impedance Track™ Gauge Shutdown @ 3.144V
142 minutes run time

Extended runtime with TI Gauge: +58%

Fuel Gauging

OCV vs. IT Use Case Exp – NEW battery COLD w/ variable load mix



Conditions *Batty*

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

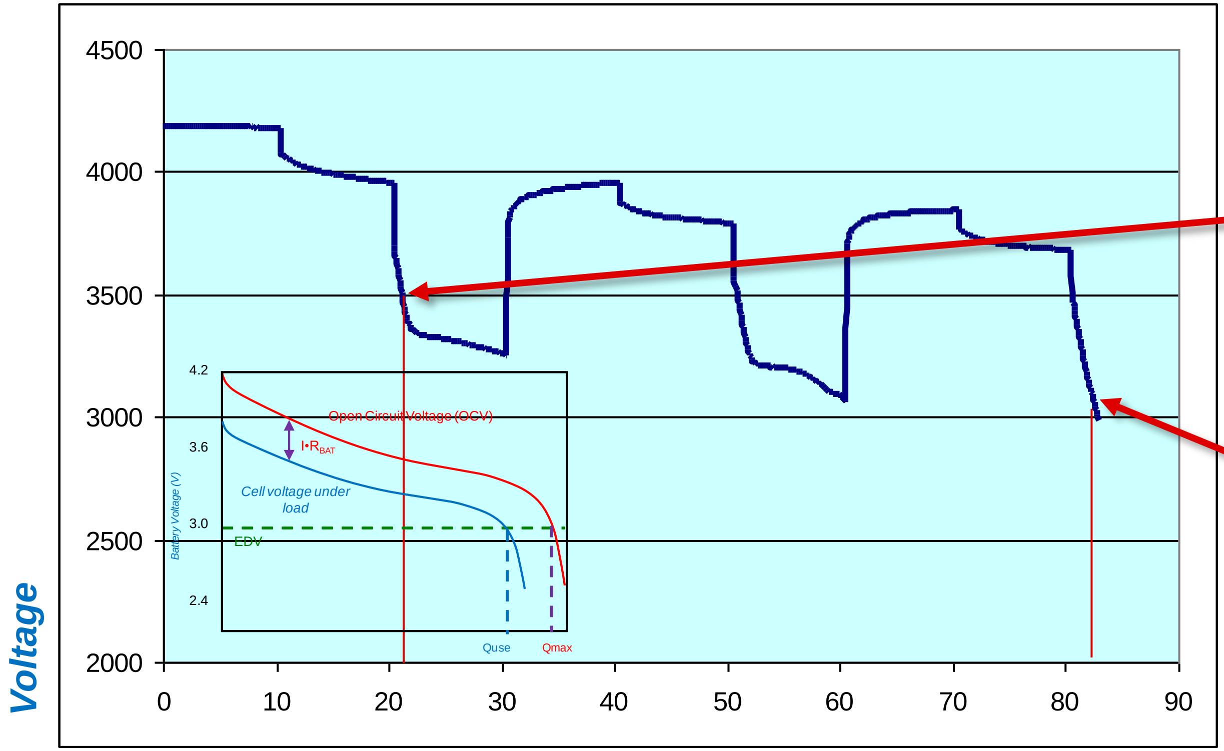
OCV
Shutdown @ 3.5V
53 minutes run time

Impedance Track™ Gauge
Shutdown @ 3.020V
117 minutes run time

Extended runtime 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 @ 3.5V
21 minutes run time

Gauge shutdown at 3.061 volts:
82 minutes run time

Extended runtime with TI Gauge: +290%

Load Mode/Select Configuration

- What are the LOAD SELECT choices?

  - IF ***Load Mode = 0: (Constant Current)***
    - **0 = *Avg I Last Run***
    - **1 = Present average discharge current (average over entire discharge)**
    - **2 = Current**
    - **3 = AverageCurrent**
    - **4 = DesignCapacity/5**
    - **5 = AtRate (mA)**
    - **6 = *User-Rate-mA***

  - IF ***Load Mode = 1: (Constant Power)***
    - **0 = *Avg P Last Run***
    - **1 = Present average discharge power**
    - **2 = Current x Voltage**
    - **3 = AverageCurrent x Average Voltage (average over entire discharge)**
    - **4 = DesignEnergy/5**
    - **5 = AtRate (10mW)**
    - **6 = *User-Rate-mW***

"Constant Power" applies to systems with switching DC/DC converters. P=I*V, so current increases as voltage decreases if converter uses a fixed power delivery.

Load Select options:

- ***Load Mode = 1: (Constant Power)***
  - 0 = *Avg P Last Run*
  - 1 = Present average discharge power
  - 2 = Current x Voltage
  - 3 = AverageCurrent x Average Voltage (average over entire discharge)
  - 4 = DesignEnergy/5
  - 5 = AtRate (10mW)
  - 6 = *User-Rate-mW*

Load Select = 0

- Uses **"*Avg P Last Run*"** for all simulated predictions.
- "*Avg P Last Run*" is stored in Data Memory and is typically updated after every discharge (>500s).
- Initialize "*Avg P Last Run*" to a typical or max system load in your golden file.

Load Select options:

- ***Load Mode = 1: (Constant Power)***
  - **0 = *Avg P Last Run***
  - **1 = Present average discharge power**
  - **2 = Current x Voltage**
  - **3 = AverageCurrent x Average Voltage (average over entire discharge)**
  - **4 = DesignEnergy/5**
  - **5 = AtRate (10mW)**
  - **6 = *User-Rate-mW***

Load Select = 1

- Uses **running average from entire discharge** for simulations.
  - Only after discharge has lasted at least 500s.
  - Uses "*Avg P Last Run*" for simulation at start of discharge or during charge and relaxation.
- New running average will be updated in "*Avg P Last Run*" after discharge stops.
- Initialize "*Avg P Last Run*" to a typical or max system load in your golden file.

Load Select options:

- ***Load Mode = 1: (Constant Power)***
  - 0 = ***Avg P Last Run***
  - **1 = Present average discharge power**
  - **2 = Current x Voltage**
  - **3 = AverageCurrent x Voltage (running average over 14s)**
  - **4 = DesignEnergy/5**
  - **5 = AtRate (10mW)**
  - **6 = *User-Rate-mW***

Load Select = 2

- Whenever a simulation is run during discharge, it will use the **present current * voltage** as the assumed load.
  - Uses "*Avg P Last Run*" for simulation at start of discharge or during charge and relaxation.
- New running average will be updated in "*Avg P Last Run*" after discharge stops.
- Initialize "*Avg P Last Run*" to a typical or max system load in your golden file.

Load Select options:

- ***Load Mode = 1: (Constant Power)***
  - 0 = ***Avg P Last Run***
  - **1 = Present average discharge power**
  - **2 = Current x Voltage**
  - **3 = AverageCurrent x Voltage (running average over 14s)**
  - **4 = DesignEnergy/5**
  - **5 = AtRate (10mW)**
  - **6 = *User-Rate-mW***

Load Select = 3

- Whenever a simulation is run during discharge, it will use a **14 second running average** load.
  - Uses "*Avg P Last Run*" for simulation at start of discharge or during charge and relaxation.
- New running average will be updated in "*Avg P Last Run*" after discharge stops.
- Initialize "*Avg P Last Run*" to a typical or max system load in your golden file.

Load Select options:

- ***Load Mode = 1: (Constant Power)***
  - **0 = *Avg P Last Run***
  - **1 = Present average discharge power**
  - **2 = Current x Voltage**
  - **3 = AverageCurrent x Voltage (running average over 14s)**
  - **4 = DesignEnergy/5**
  - **5 = AtRate (10mW)**
  - **6 = *User-Rate-mW***

Load Select = 4

- All simulations will use a C/5 rate.

Load Select **options:**

- ***Load Mode = 1: (Constant Power)***
  - **0 = *Avg P Last Run***
  - **1 = Present average discharge power**
  - **2 = Current x Voltage**
  - **3 = AverageCurrent x Voltage (running average over 14s)**
  - **4 = DesignEnergy/5**
  - **5 = AtRate (10mW)**
  - **6 = *User-Rate-mW***

Load Select = 5

- All simulations will use whatever value has been written by the host to the *AtRate( )* register.
- Allows the system to dynamically dictate how the gauge should make predictions.

Load Select **options:**

- ***Load Mode = 1: (Constant Power)***
  - **0 = *Avg P Last Run***
  - **1 = Present average discharge power**
  - **2 = Current x Voltage**
  - **3 = AverageCurrent x Voltage (running average over 14s)**
  - **4 = DesignEnergy/5**
  - **5 = AtRate (10mW)**
  - **6 = *User-Rate-mW***

Load Select = 6

- All simulations will use the value stored in Data Memory parameter "User-Rate-mW".
- Some customers set User Rate = maximum expected load.
  - This makes gauge assume the worst case load at all times, so it will not be surprised if a heavy load appears.
  - Downside: gauge will reach 0% while there is still capacity available for light loads.
    - *Another alternative is to use IMAX( ) or TurboMode feature.*

Reference: common sources of error

- Wrong or skipped calibration
- ChemID or modeling parameters not correct for actual cell in use
- Golden file not optimized: skipped or bad learning cycle leads to wrong initial Qmax and resistance values
- Temperature error: make sure thermistor is actually attached to the cell during test
  - It needs to know the cell temperature, not the ambient temp.
  - Cells typically self-heat during discharge.
- Gauge not allowed to accurately measure starting capacity
  - Ex. Attach unrelaxed cell so gauge uses wrong starting voltage to calculate initial SOC
  - Ex. Charge or load is present when gauge is initialized or cell is attached
- Thermal modeling:
  - Bare cell at low temp will not heat up much
  - Typical system will be enclosed and have more self-heating
  - Does your gauge handle either situation or does it need configuration of thermal modeling parameters?
  - Symptom: large temperature changes during test may result in inaccuracies and/or capacity jumps unless gauge is configured to handle it
- Selecting wrong LoadMode (constant current or power) and LoadSelect for application
- Avg I/P Last Run in dataflash not initialized to expected rate to be used in test
- Overcharging or undercharging cell by charging at high or low temperatures (compensated in newer FW)
- Overcharging by tapering to a lower current than gauge is configured to use for full charge detection
- Using old firmware version: TI is always continuously improving the IT algorithm to better handle corner cases or odd usage conditions!