Deep Battery Diagnostics

Assuring Minimum Operational Reserve Energy (MORE)

By Isidor Buchmann, Founder, CEO

www.cadex.com www.batteryuniversity.com Info@cadex.com Isidor.Buchmann@cadex.com

Avoiding Innovation Blind Spots . . .

Electrification is advancing without mature battery diagnostics.

The user asks: *“Will my battery die quietly or quit with a bang?”*

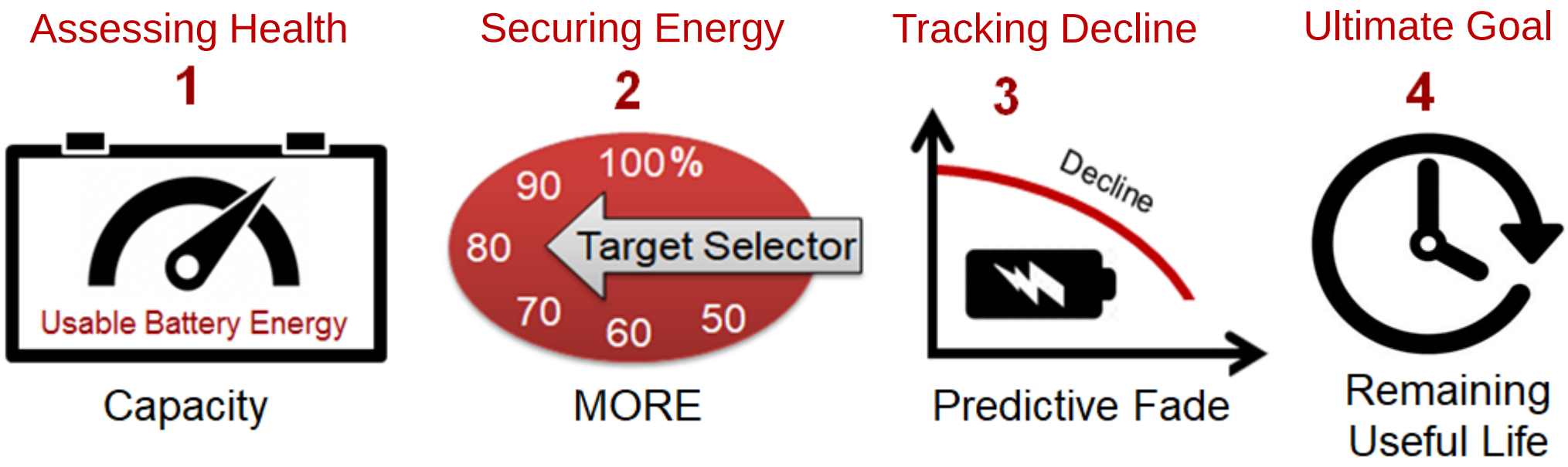
Lessons Learned

Railway tracks laid in the mid-1800s across the continent were too frail and required replacement with double the ties.

Commercial jets in the 1950s developed cracks at rivet points after 9,000 flying hours.

Introducing “Deep Battery Diagnostics”

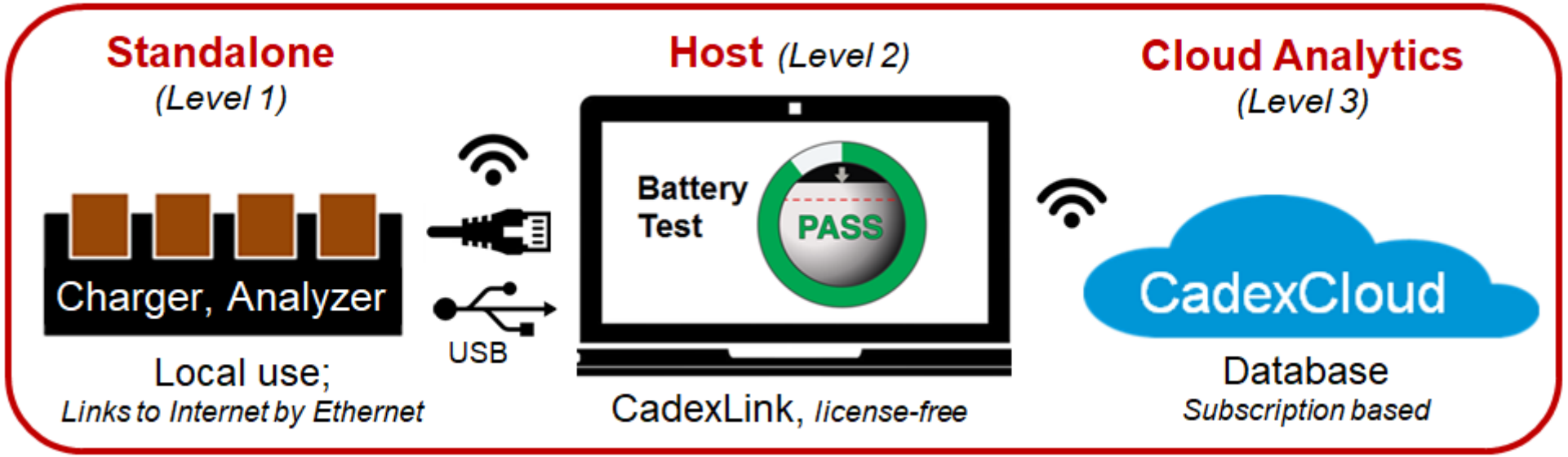
- Four-step approach assures *Minimum Operational Reserve Energy (MORE)*
- The ultimate goal is attaining *Remaining Useful Life (RUL)* of batteries



MORE utilizes each battery fully and calls for replacement before failure

Plug-and-Play

Modern battery chargers work in standalone mode; connect to a host to view battery state-of-health; and provide cloud analytics.



The lone charger is turning into a powerful battery supervisory system by plug-and-play

Simplicity

User

Level 1

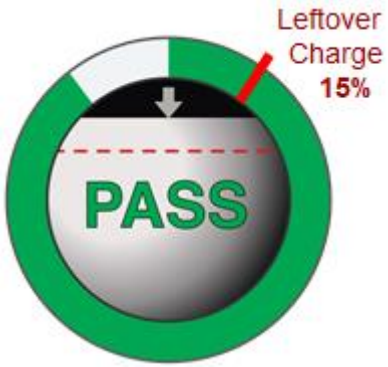
In standalone mode, a modern charger validates energy requirements for a mission by illuminating the green *SoH Light* when *capacity is* met. *A*mber requests calibration or battery replacement. Pass/fail default is 80%.

SoH Light

Supervisor

Level 2

Connecting the USC to a PC reveals battery status by Fishbowl icon. Of importance is Leftover Charge that should be 10–20% on a weak battery. Adjustment is by the Target Selector. Cloud Analytics is optional.



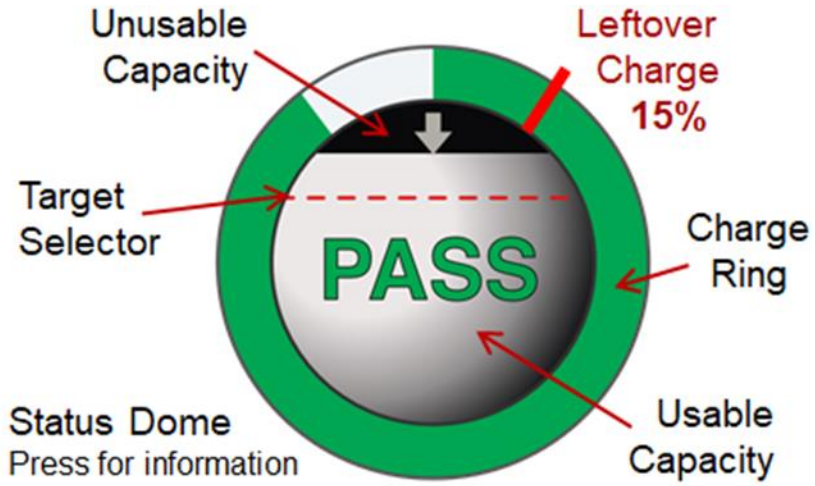
Fishbowl

Level 3

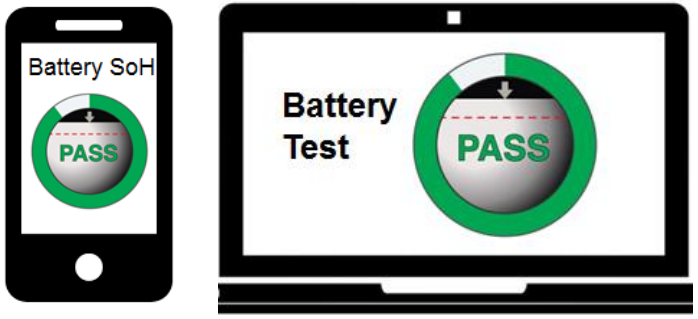
Cloud Analytics offers trend analysis of battery fleets based on Leftover Charge, Energy Used and Remaining Useful Life.

Viewing battery State-of-Health by Fishbowl

- Leftover Charge is marked in %.
- The outer ring reveals state-of-charge that moves clock-wise with charge and counter-clockwise on discharge.
- The hanging black ceiling tracks capacity that slowly drops towards the Target Selector redline as the battery ages.
- Touching the Status Dome displays battery data.



Fishbowl Icon



Status reveals battery condition in brief

Ready to go *Calibrate* *Anomaly* *Low capacity*

The Fishbowl makes battery state-of-health transparent

Battery Information

State-of-function definition:

- **Capacity** in a smart battery is measured by *Full Charge Capacity* representing “digital capacity”
- **Max Error** prompts calibration on cycle count
- **Cell Balance Delta** records high/low voltage

Battery Information

State-of-function		Battery Summary	
SoC	75%	Manufacturer	Medica
Capacity (FCC)	85%	Battery Model	Bat-ABCD
Target Selector	80%	Serial Number	B1234567
Temperature	22°C	Mfg. Date	20180224
Cycle Count	100	Chemistry	Li-ion
Max Error	5	**Specifications** (nominal)	
Cell Balance Δ	100mV	Battery V	14.40V
State	Pass	Rating	6800mAh
Date	YY-MM-DD	Charge	4000nAh

Historic Battery Report

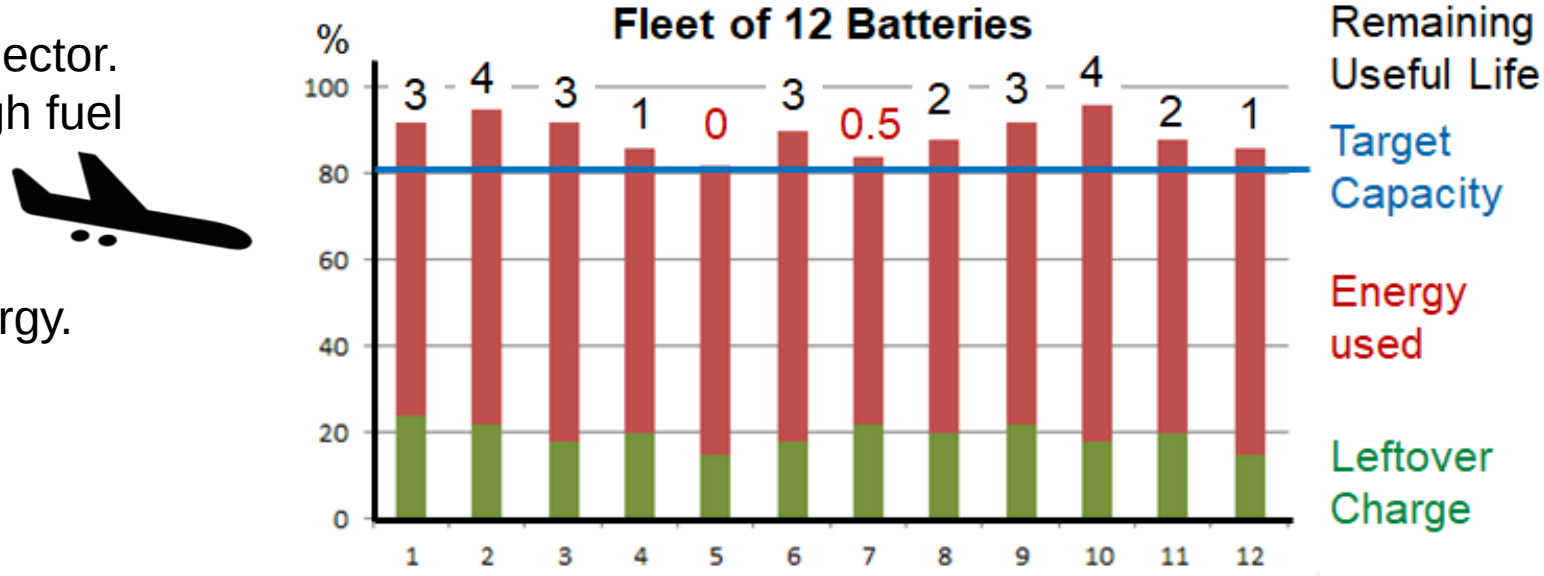
- Inserting a smart battery stores battery status in the CadexCloud.
- Tables can be customized

Reports

Date, time	Battery SN	Program	Capacity (FCC)	Leftover Charge	Site	Remaining Useful Life
2024-02-10	USCA00027	Charge	85%	15%	Ambulance	2
2024-02-10		Charge	88%	25%	Urgent care	1
2024-02-09		Charge	93%	12%	Clinic	4
2024-02-08		Airship	82%	14%	Dialysis	3
2024-02-07		Calibration	78%	12%	Nursing	2

How to set the Target Selector

- Leftover Charge is set by the Target Selector. An analogy is an aircraft carrying enough fuel for landing.
- If Leftover Charger is low, set the target capacity higher to increase reserve energy.
- If consistently high, lower the setting to keep batteries in service longer.



Cloud Analytics with Level 3

Target Selector serves as Gatekeeper

85-90%: **Critical mission** – F*ewer batteries pass*
80%: **Default setting** – A*verage setting*
60-70%: **Relaxed duty** – *Batteries serve longer*

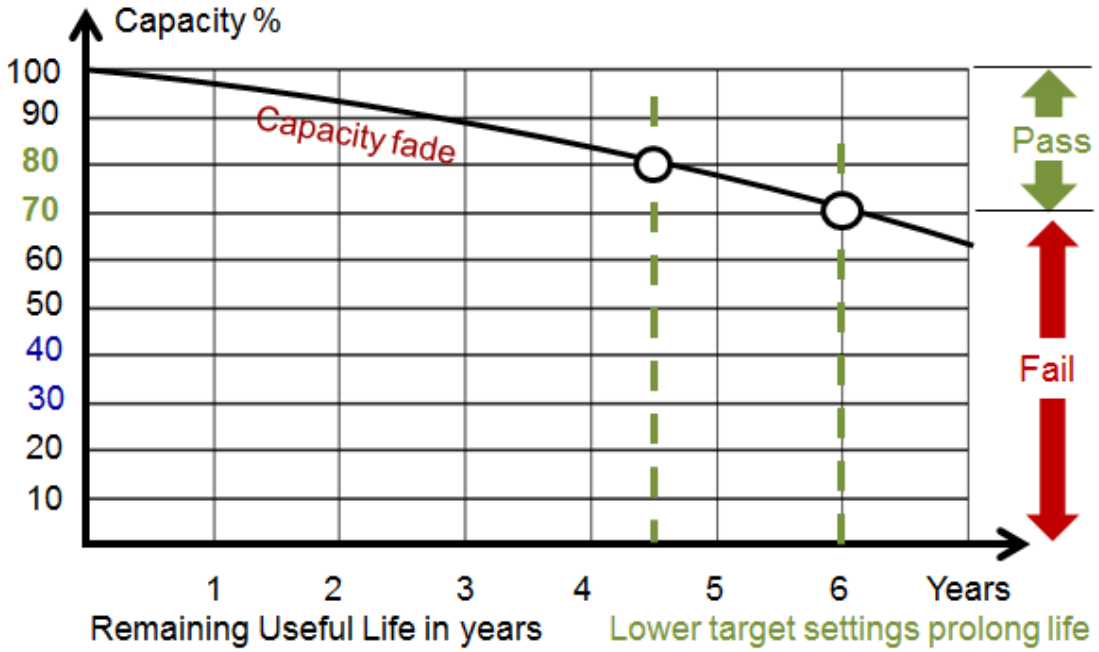
Target Selector sets the 'sweet spot' between high reliability and long battery life

How to Attain the Remaining Useful Life

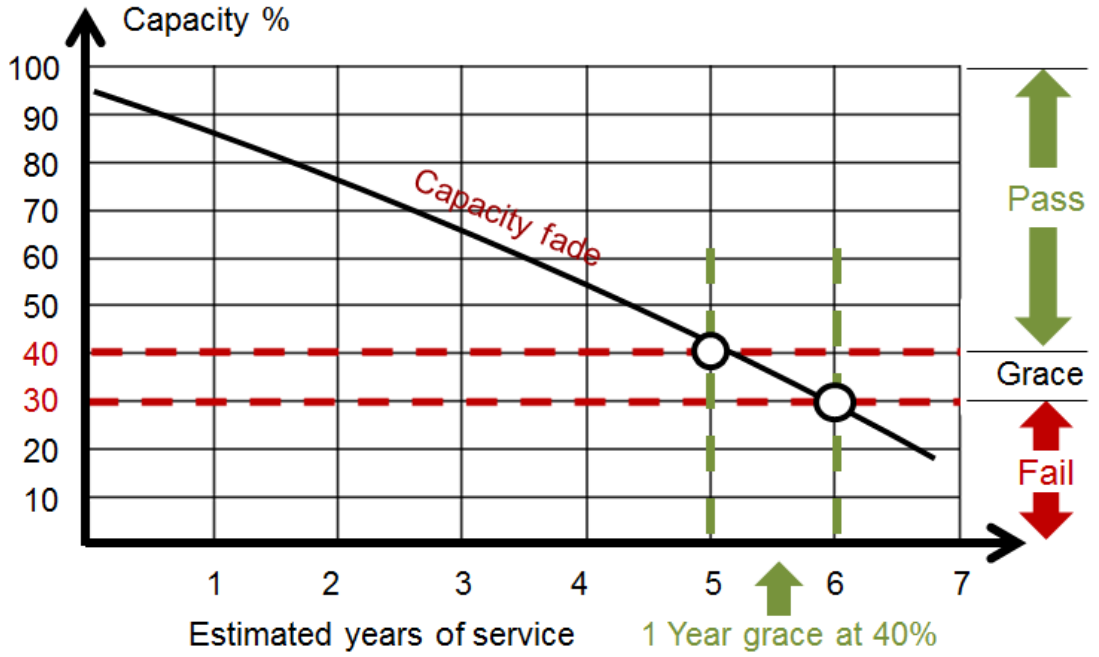
Portable Battery: A 80% target typically delivers 4.5 years of service; 70% provides 6 years

Starter Battery: A 40% capacity threshold gives grace, good to next service

Portable Battery



Starter Battery



Battery capacity is the leading health indicator

Service for Portable, Mobility, Automotive and Stationary Batteries

Supervisor Charger
Modern chargers work in standalone mode and connect to WebApp.

C7000 Series Battery Analyzer
checks batteries by a full cycle.

C8000 Battery Test System is for lab use

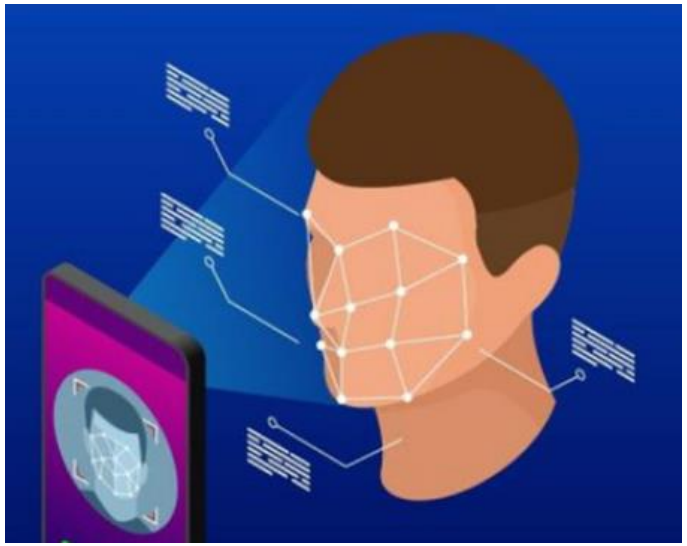
Spectro Modular

CA-12 Battery tester

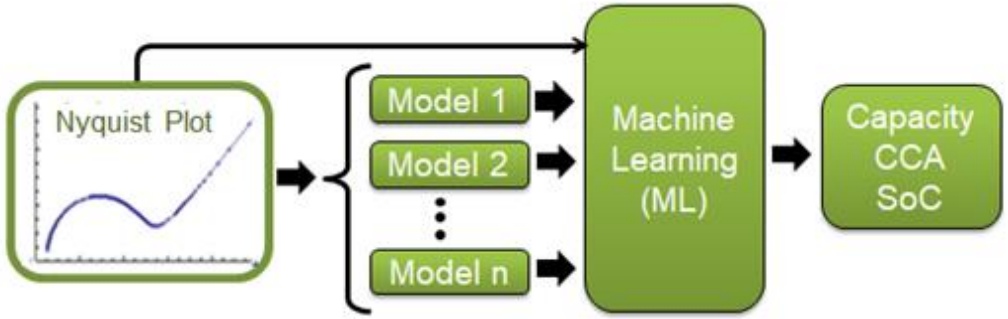
Spectro™ assesses battery state-of-health non-invasively by electrochemical impedance spectroscopy (EIS).

What's the Advantage of EIS?

- Multi-model EIS, known as Spectro™, takes the electrochemical evidence of a battery and compares the data with a matrix. The technology resembles face recognition using AI.
- The test lasts 30 seconds, longer with large batteries.
- Scanning frequency is 2,000Hz to 4Hz; 0.1Hz for large batteries.



Spectro resembles face recognition



Complex EIS modeling assesses capacity and CCA

Scanned data goes through filtering and magnitude extraction. Modeling uses a matrix that is made up of same-type batteries but different SoH.

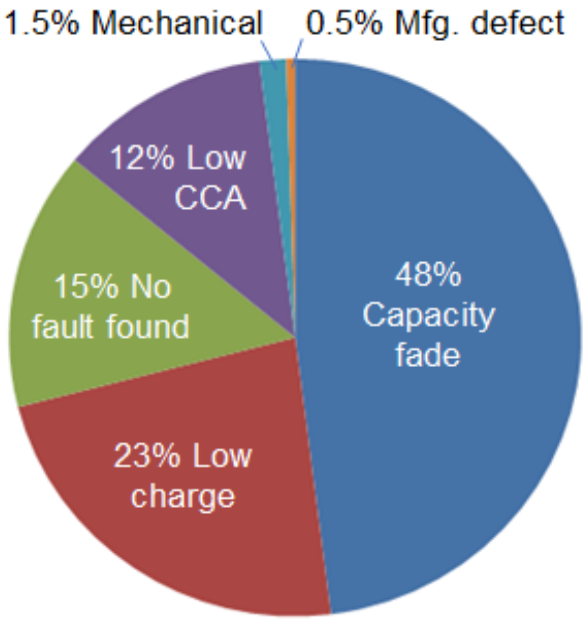
Data fusion correlates the values to derive capacity, CCA, SoC and other readings.

U.S. patent 7,072,871, U.S. patent 6,778,913

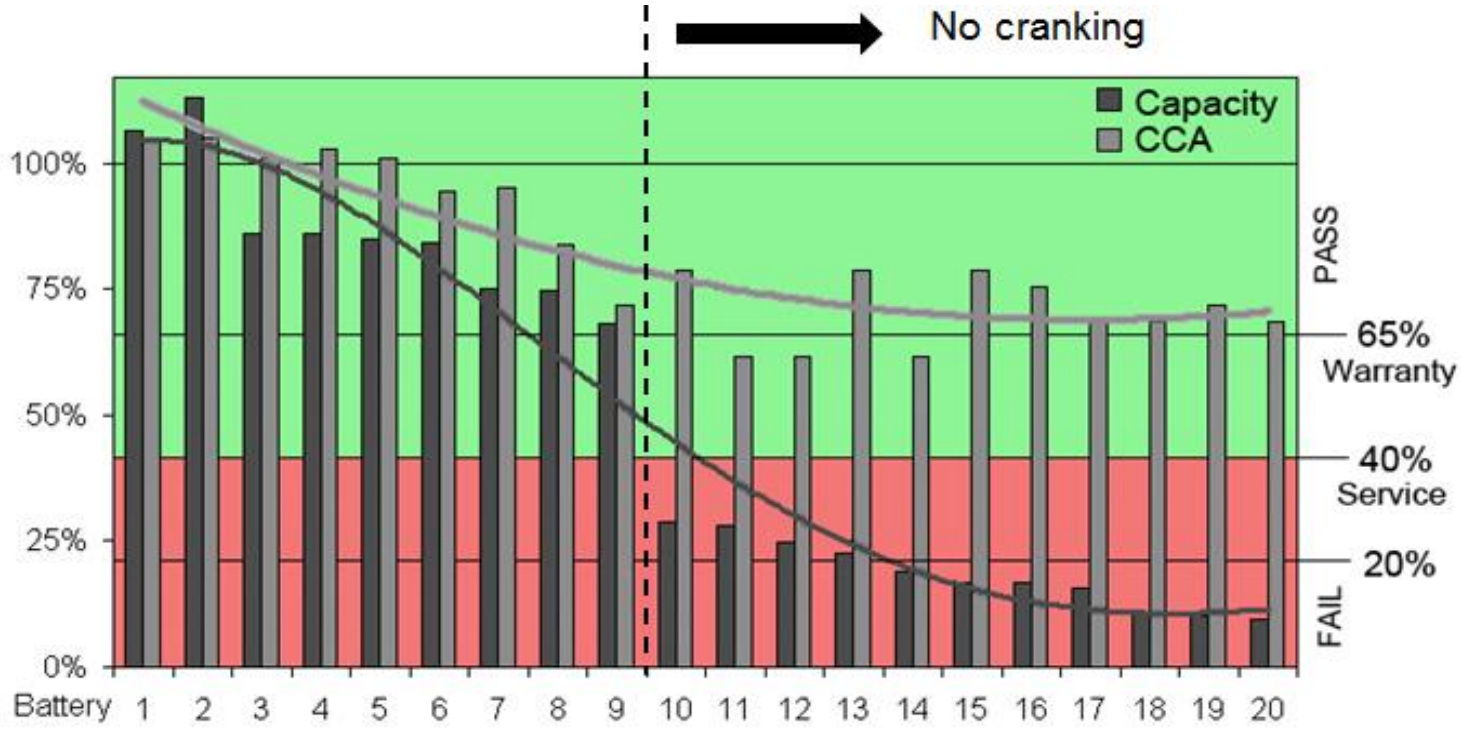
Scientists predict that the future of battery diagnostics lies in EIS

What causes Starter Batteries to Fail?

- CCA stays high while capacity drops without apparent loss of cranking power.
- We set the pass/fail capacity at 40%. Motor still cranks below 30%.



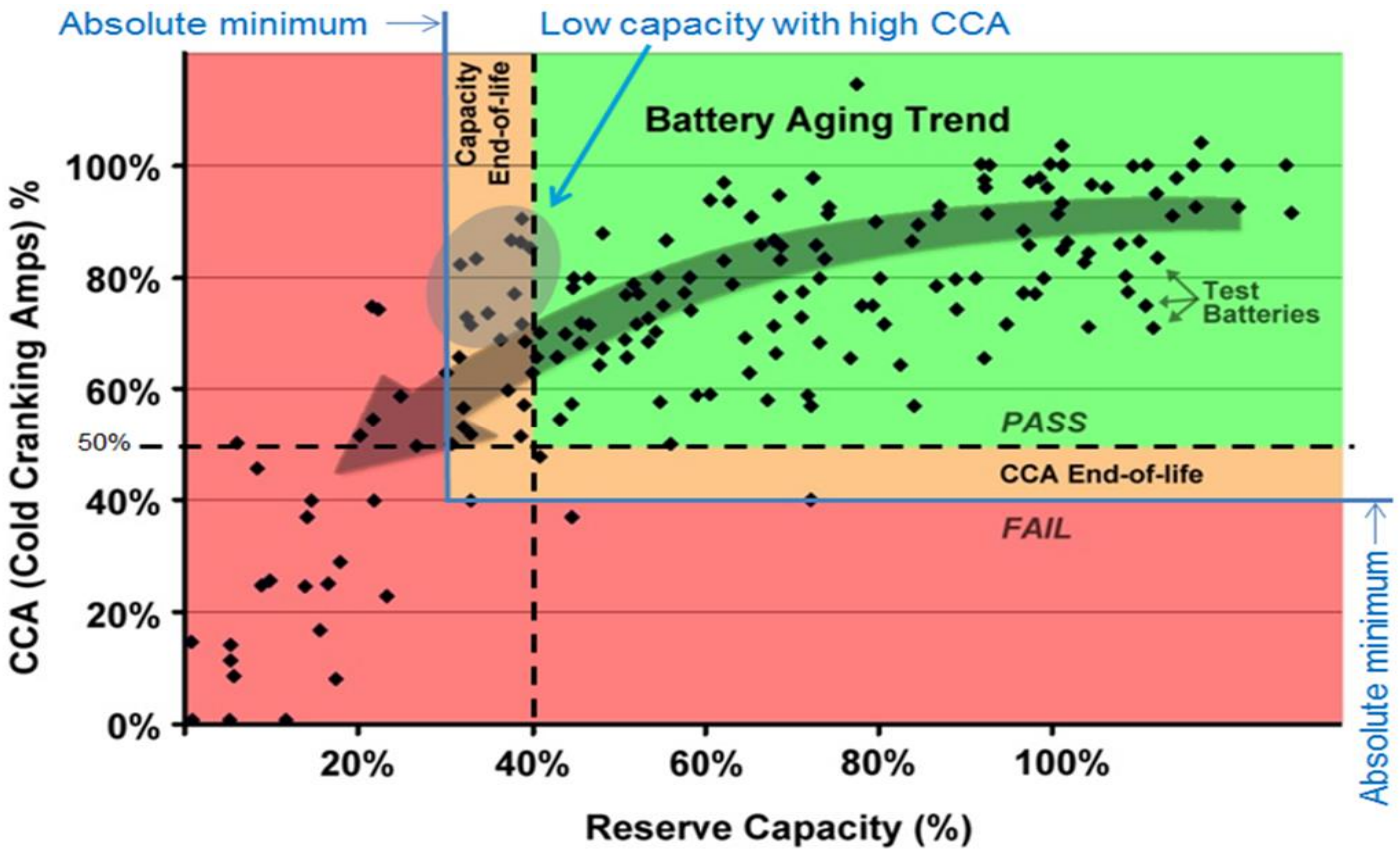
Source: Johnson Controls Power Solutions; AABC Europe 2017, Mainz, Germany



CCA stays strong while the capacity drops, unknown to the driver

CCA measurement with a load test alone is incomplete

Capacity is the Leading Health Indicator



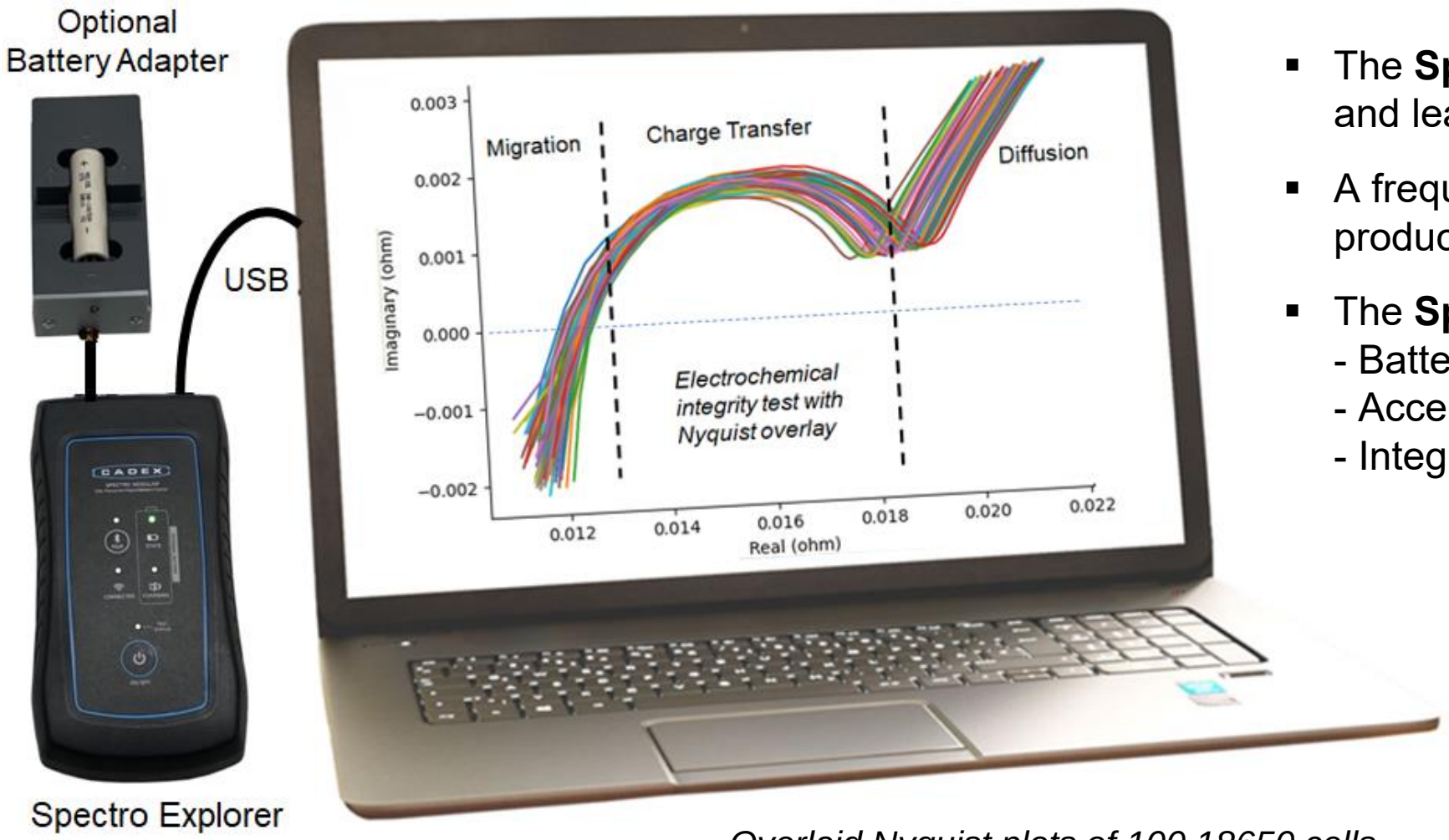
Spectro Modular

Non-invasive EIS assesses the capacity and CCA of lead acid and Li-ion up to 300Ah.

- A German car maker checked capacity and CCA of 175 AGM batteries
- Batteries age by capacity fade

A CCA reading is not enough. Capacity to CCA correlation is 55%

Testing E-bike Batteries with the Spectro Explorer



- The **Spectro Explorer** tests Li-ion and lead acid batteries from 3−48V.
- A frequency scan from 2,000−4Hz produces the Nyquist plot shown.
- The **Spectro Explorer** serves:
  - Battery manufacturing for QA
  - Acceptance testing in supply chain
  - Integrity checking for after-service

Overlaid Nyquist plots of 100 18650 cells.

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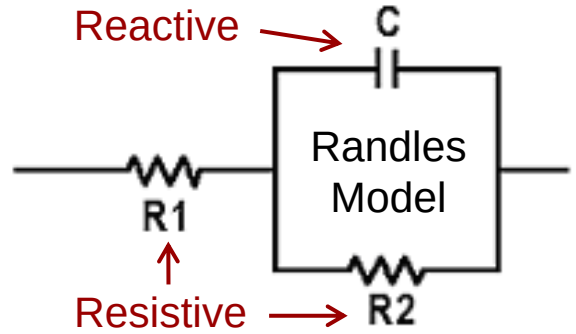
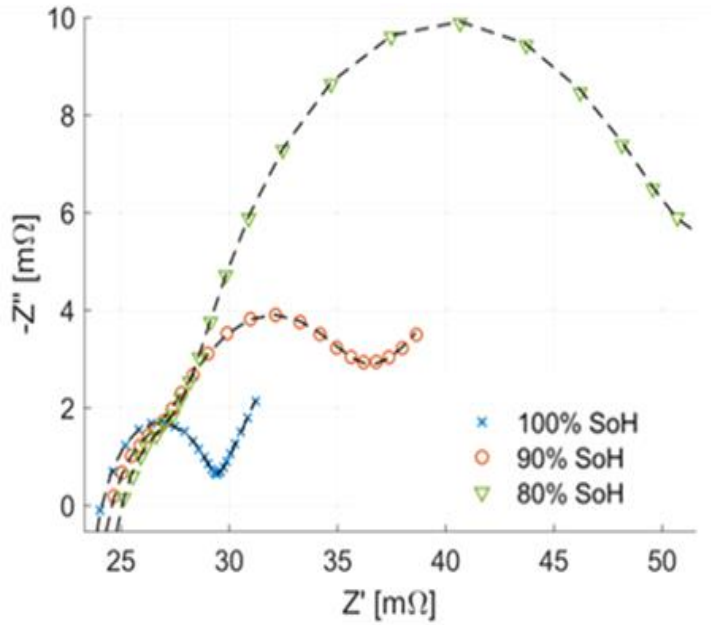
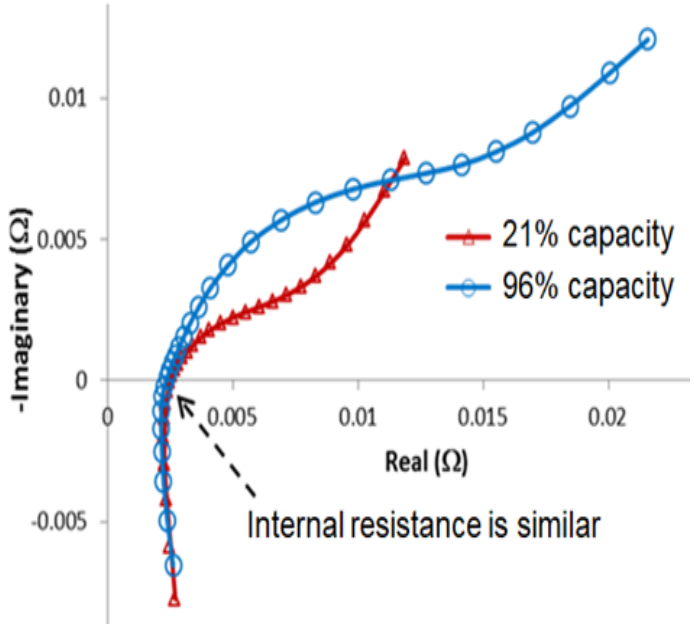
What is a Nyquist Plot?

A Nyquist plot places ***resistive reading*** *(Real Z)* on the horizontal axis and ***reactive readings*** on the vertical axis.

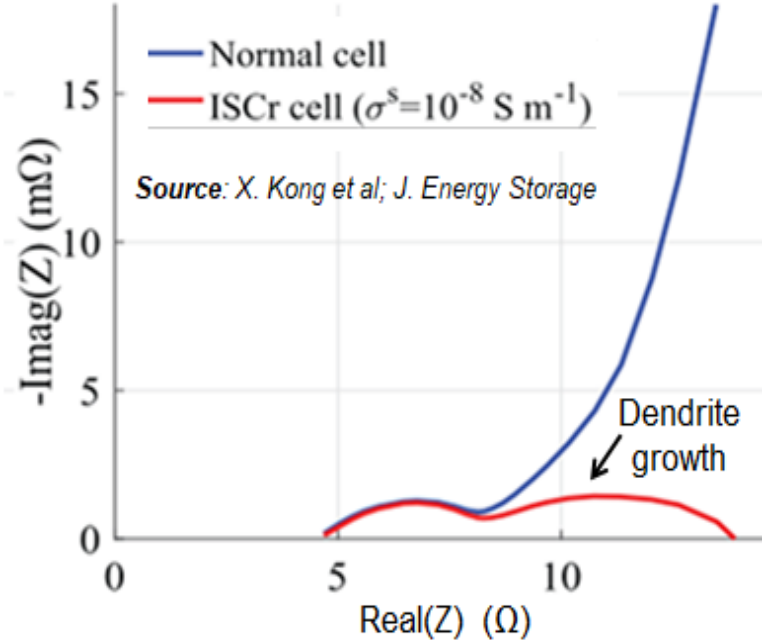




Li-ion with diverse capacities

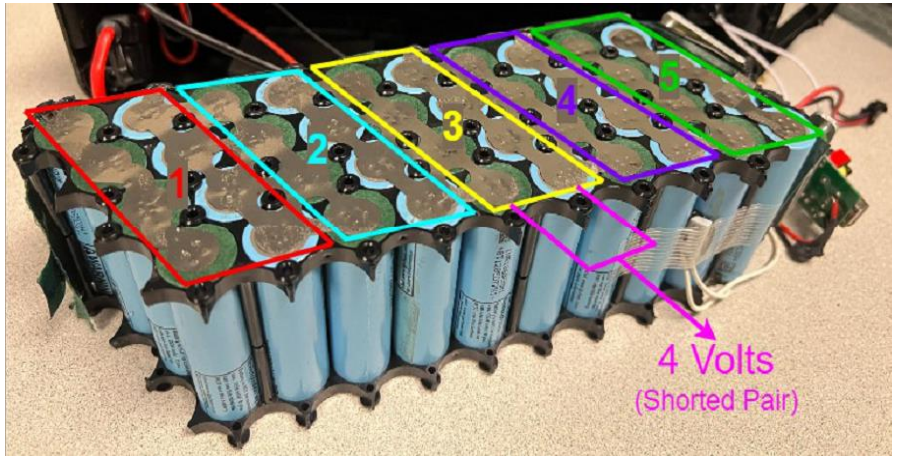


Li-ion in red has an anomaly

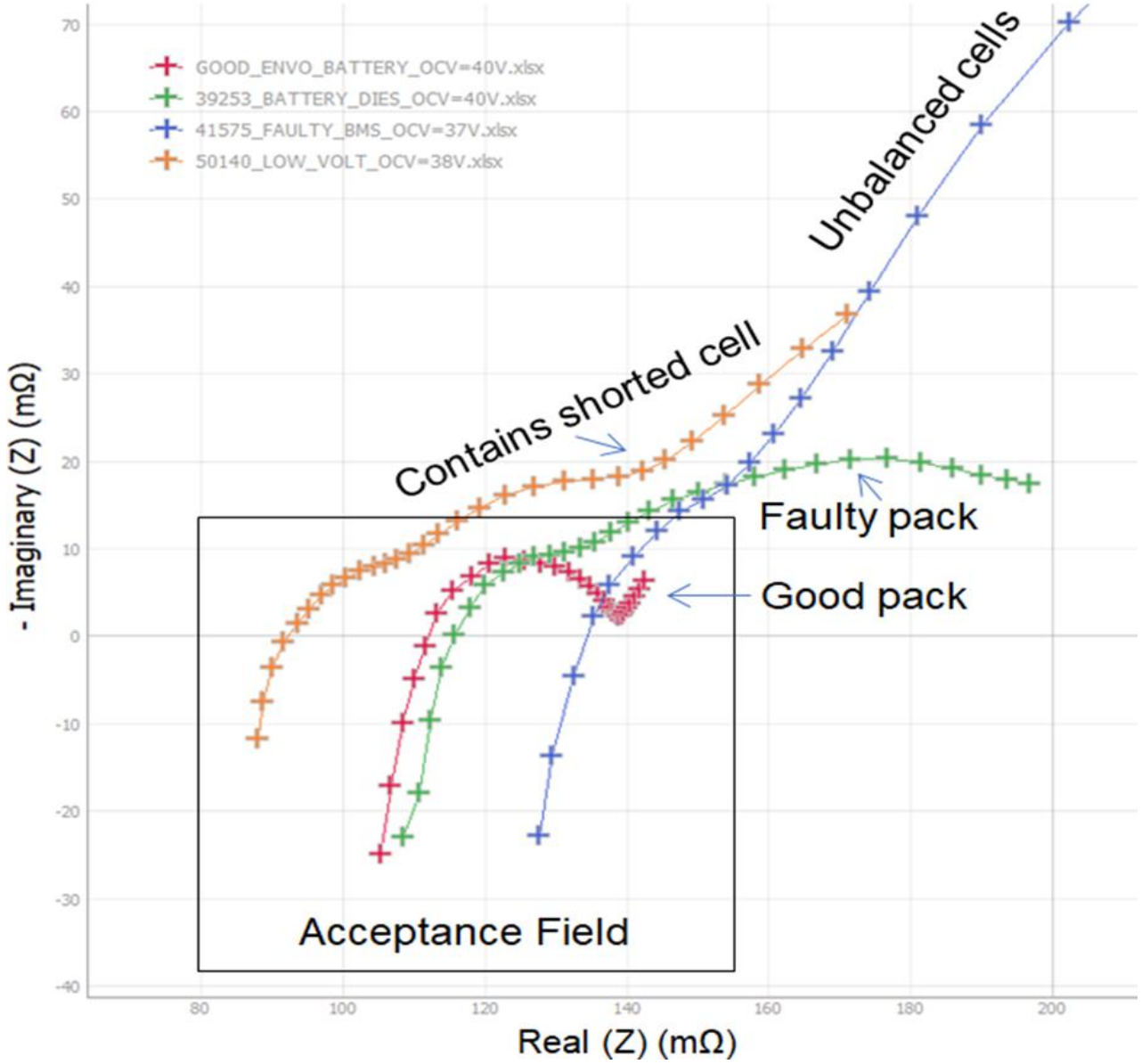


Cell in red has dendrite

Nyquist test on E-bike Battery



40V pack has 4 cells in parallel and 10 pairs in series



- Acceptance Field serves as pass/fail criteria.
- Works for Li-ion and lead acid battery systems.

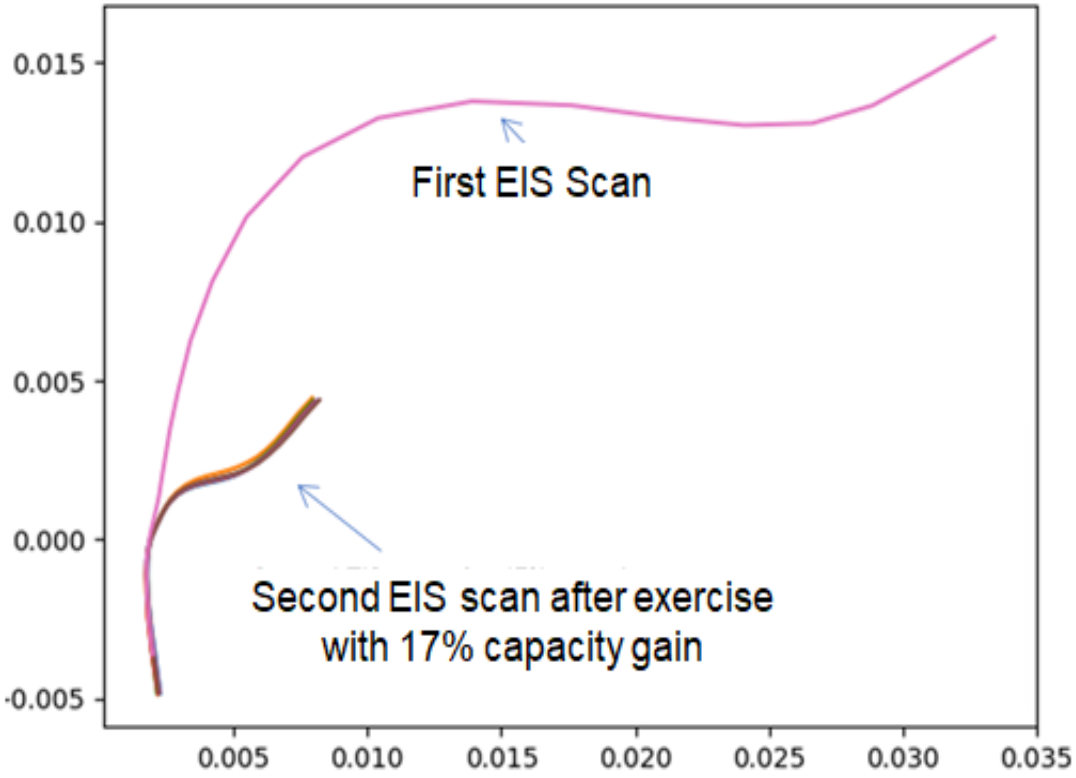
EIS detects Sulfation of Lead Acid Battery

- Lead acid batteries stored for six months and longer develop sulfation that reduces performance.
- Soft sulfation is reversible by exercise.
- If left unattended, hard sulfation becomes permanent.

What is Sulfation?
Sulfation is a build-up of lead sulfate crystals in lead-acid batteries that leads to failure when stored under-charged.

New battery *Sulfated plates* *After de-sulfation*

***Source**: BatteryMINDer*

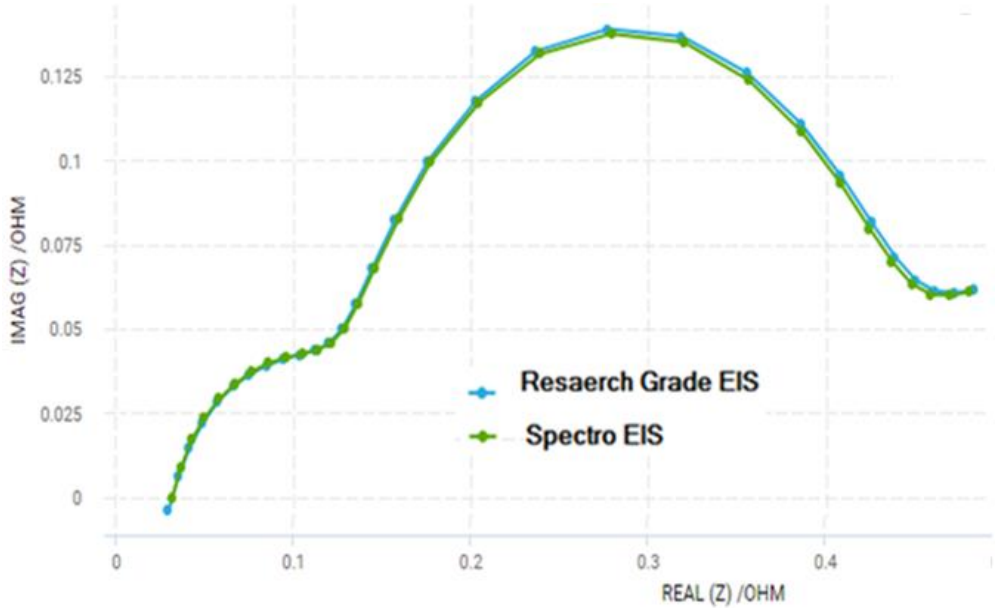


Exercise improved capacity from 75% to 92%

Turning the Spectro Explorer into a Household Name

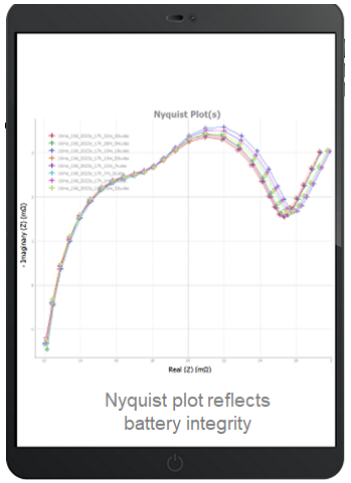
BioLogic SP-50

- 12V max (nominal)
- Laboratory device
- Laboratory cost



Nyquist plot is compared with a research grade instrument and the Spectro Modular

Cadex turns lab-grade technologies into cost-effective instruments for field use.



Nyquist plot reflects battery integrity

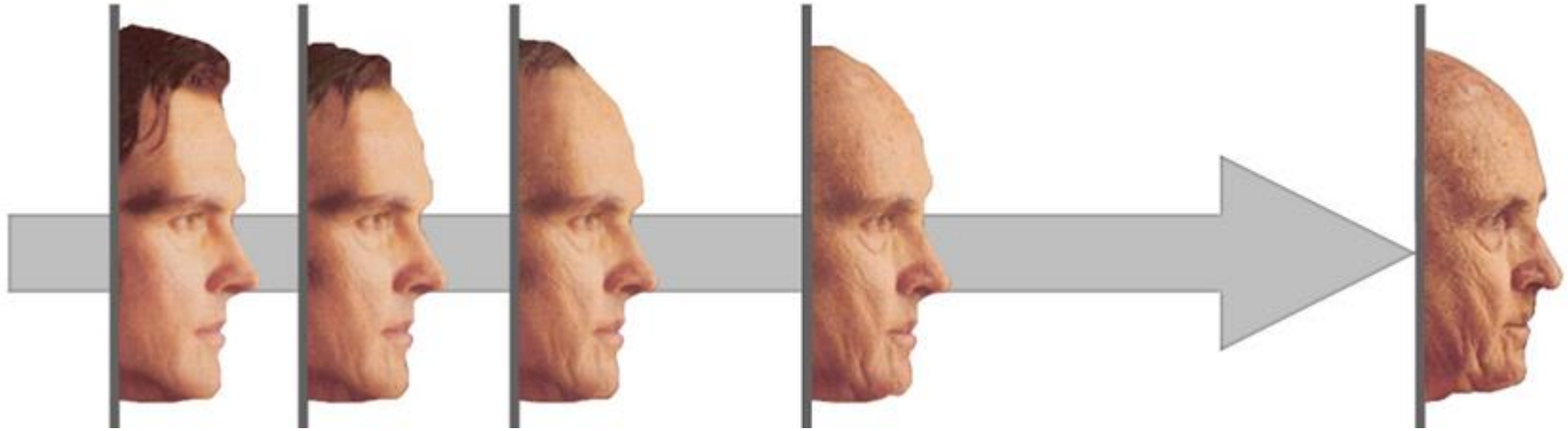
Spectro Explorer

- 3-48V (nominal)
- Easy to use with PC
- Rugged and low cost

Part Two

The Importance of Battery Diagnostics

- Batteries are often installed and forgotten.
- Batteries are the weakest link in a system with need to replace.
- Battery users should know the *Minimum Operational Reserve Energy (MORE)*
- Without diagnostics, batteries are often replaced too soon, but most stay too long.



Design engineers forget that a battery ages too

Healthcare is highly regulated *(except in batteries)*

A US FDA survey says:
"Up to 50% of issues in hospitals are battery related."

Battery management emerged as a top 10 medical-device challenge.

A two-day FDA Battery Seminar reveals:

1. *Deficiency in quality assurance in batteries by device manufacturers.*
2. *Lack of understanding in battery system integration.*
3. *Not knowing the end of battery life.*

A Biomed Tech speaks up:

- Batteries are the most abused components in hospitals.
- Staff care little about batteries and only does the bare minimum.
- Recommendations for battery maintenance are vague, hidden inside service manuals.

Info@cadex.com Isidor.Buchmann@cadex.com

A DOE official said . . .

“Every year roughly one million usable lithium-ion batteries are being sent for recycling with most having a capacity of up to 80%.”

***Citation by**: Dr. Imre Gyuk, DOE Energy Storage Research Program*

HAZMAT

Diagnostic Battery Management utilizes each battery fully and calls for replacement before failure.

Diagnostic Battery Management also applies to Defense

Battery disposal in Afghanistan.

In 2016, over 373,000 from a total of 400,000 vehicle batteries were replaced at a cost of over $80M.

Source: U.S. Army photo by Chip Herrell, AMSAA

Technology is available to assess the condition of a battery and apply corrective service

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Reliability-Centered Maintenance (RCM)

- RCM was introduced in the1960's to improve air safety.
- First applied on the Boeing 747, RCM reduced maintenance 60-fold over the Douglas DC-8 in pre-RCM days.
- Nuclear plants, defense and railways also adopted RCM.

Batteries for critical uses need RCM to utilize each battery fully and replace before failure.

Global authorities are working on battery diagnostics norms.

The Airbus 330 needs maintenance after 200-400 take-offs and landings.

Jet engine needs a major overhaul after 50,000 flying hours.

System Management Bus (SMBus)

- SMBus was developed by Intel and Duracell in 1994.
- The early SMBus battery only showed state-of-charge.
- Modern SMBus provides “digital capacity” in Full Charge Capacity (FCC).

SMBus battery

Standards

Level 1 supported a single chemistry (no longer used).

Level 2 controls charge. The battery becomes the host; charger is the slave.

Level 3 accommodates SMBus and regular batteries in a hybrid system.

Level 3 is preferred. The hybrid charger takes over when SMBus fails.

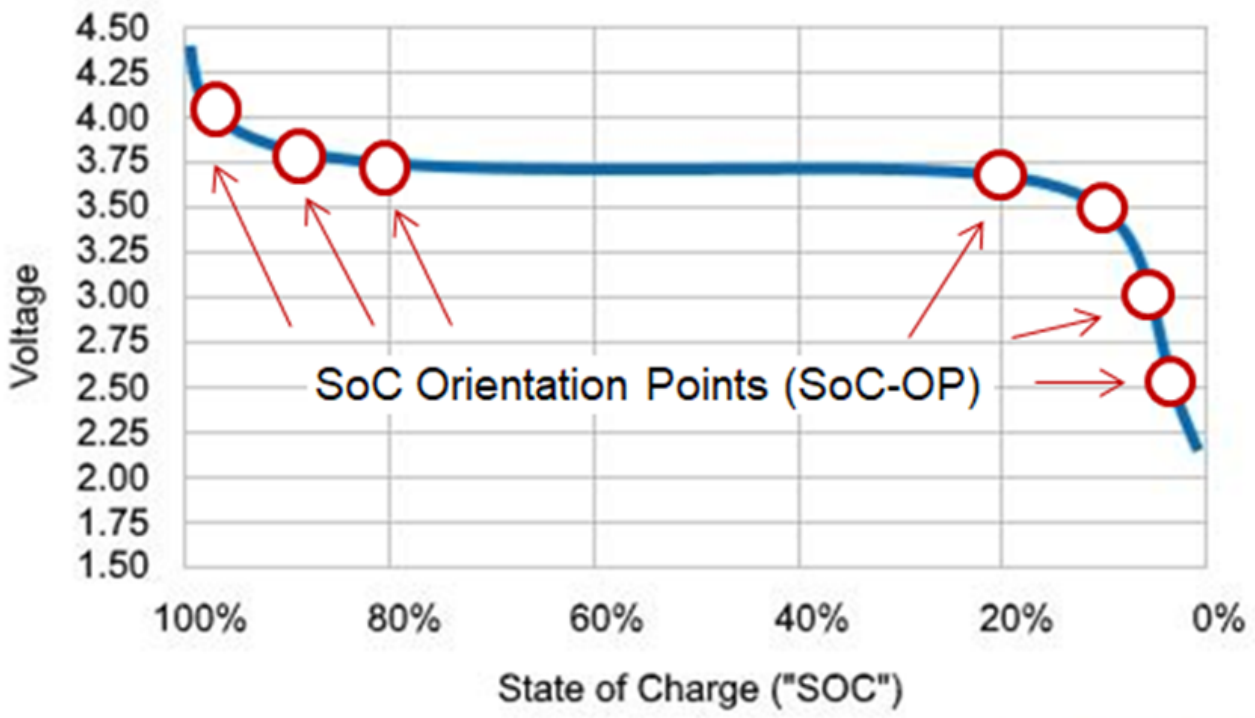
Protections

- Most BMS include protection circuits to limit voltage-peaks on charge and discharge.
- BMS also includes current control and temperature cut-off.

Self-calibration

Smart batteries need calibration that is seldom done – hence self-calibration. Here is how it works:

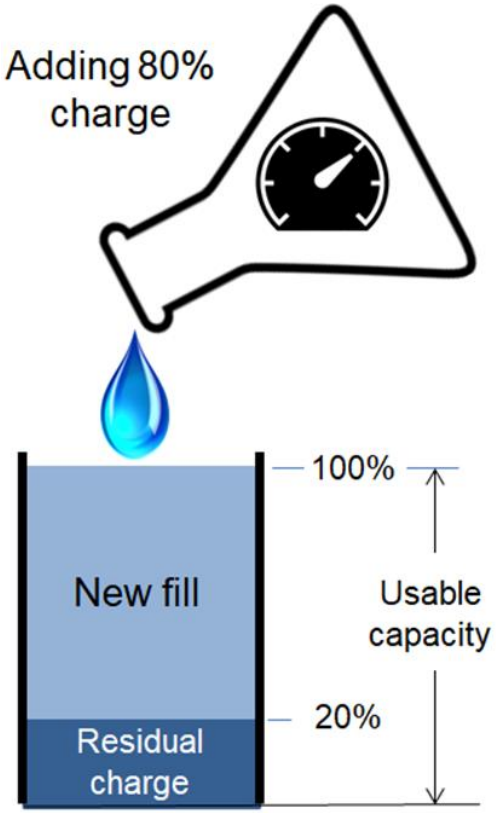
1. The voltage is measured after the battery has rested to establish residual charge.
2. With SoC known, charge (or discharge) is measured by coulomb counting*
3. Usable capacity is the sum of residual charge plus new charge.



SoC Orientation Points serve as navigation beacons

Self-calibration seeks "SoC Orientation Points" at relaxation stages.

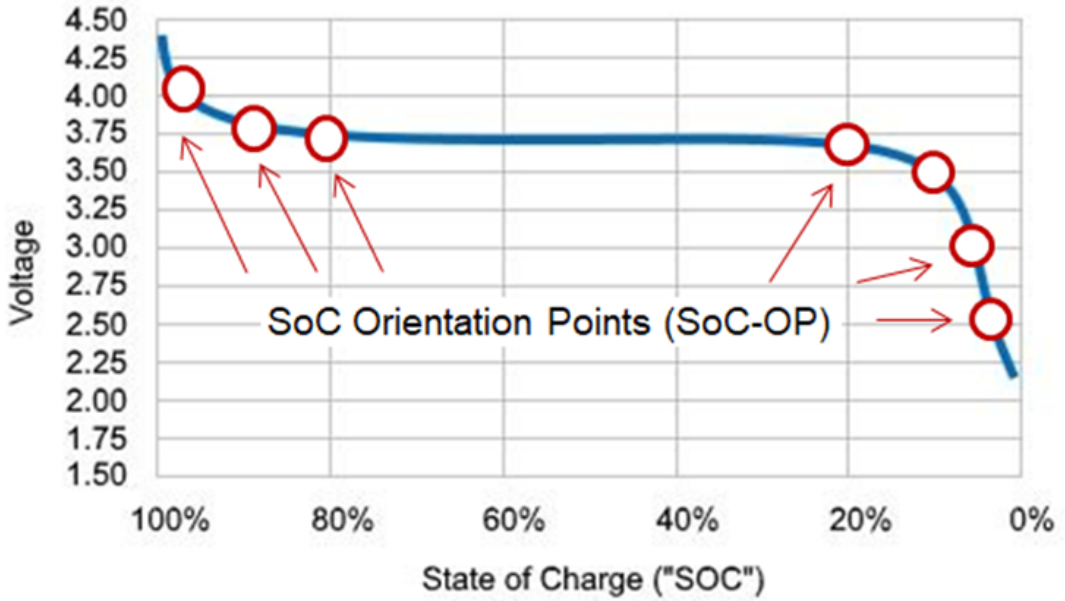
Adding or removing coulombs is compared against available SoC.



* One coulomb is 1A in 1 second

How to calibrate your EV without Tools

1. Discharge the battery by driving the extra mile to set the low SoC-OP.
2. Allow the battery to rest for 4−6 hours without load to stabilize voltage.
3. Charge and add a 2 to 4-hour of rest at full charge before use.



Calibration of SMBus and EV batteries is similar

How accurate is self-calibration?

Two-third of smart batteries tested at the Cadex labs were within 5% of measured capacity and FCC.

Thank you. Questions?

Social Networking™
in Battery Care

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