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State-of-Charge, State-of-Health, and What System Designers Really Want to Know About a Battery

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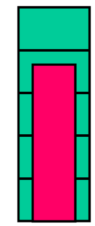
Introduction



- State-of-Charge (SOC), State-of-Health (SOH) are considered important for battery condition monitoring
- But what can we really deduce from these properties of a battery ?
- In future, we will need more reliable information about the availability of energy from a chemical storage device in order to design dependable electrical systems
- **Purpose of this paper:**
  - Review definitions and possible interpretation of Capacity, SOC, SOH
  - Help understanding the behaviour of batteries
  - Lead towards a global common knowledge about measuring power and energy availability from batteries

Present Terms Used In Battery Industry - JCI

- **Nominal Capacity**
  - Determined at a specified temperature and discharge rate on a new fully charged battery (i.e. 50 Ah - 12 V battery @ 20 hour rate, 2.5 A discharged to 10.5 V @ 25 °C)
- **Rated Capacity**
  - The portion of Nominal Capacity available for use in a specific application which is a function of State of Health, Temperature, Discharge/Charge Profile and State of Charge.
- **State of Charge and State of Health**
  - State-of-Charge is a measure of the "deliverable capacity" of the battery with respect to its Nominal or Rated Capacity.
  - State-of-Health is a measure of the remaining full charge capacity of a battery with respect to its Nominal or Rated Capacity for a specific application

Consider the following terms “Charge” and “Capacity”

Charge Q

Charge is a physical quantity, normally measured in Ah, describing the integral of electrical current. You can remove charge from a battery or store charge into a battery. Depending on discharge condition, a battery provides a varying amount of „Usable Charge“, Q_D. Usable Charge is affected by temperature, rate of discharge and state of charge.

Capacity K *)

This term indicates a capability of storing or giving charge.
For a new battery the nominal capacity is K_N .
Capacity is a property of the battery, to be measured by the charge which can be removed under defined load conditions (i.e. 20 Ah at the 20 hour rate of discharge). The capacity of the battery can change with age.

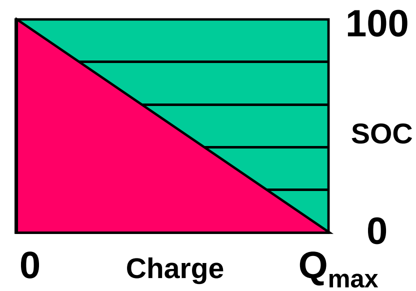
*) Use K instead of C for differentiating from electrical ac-capacitance

Electrochemical definition of State-of-Charge

(as used by most battery manufacturers)

A fully charged battery has SOC = 1
A battery, in which all available active material is discharged, has SOC = 0

$$SOC = 1 - \frac{1}{Q_{\max}} \int I_{eff}\, dt$$



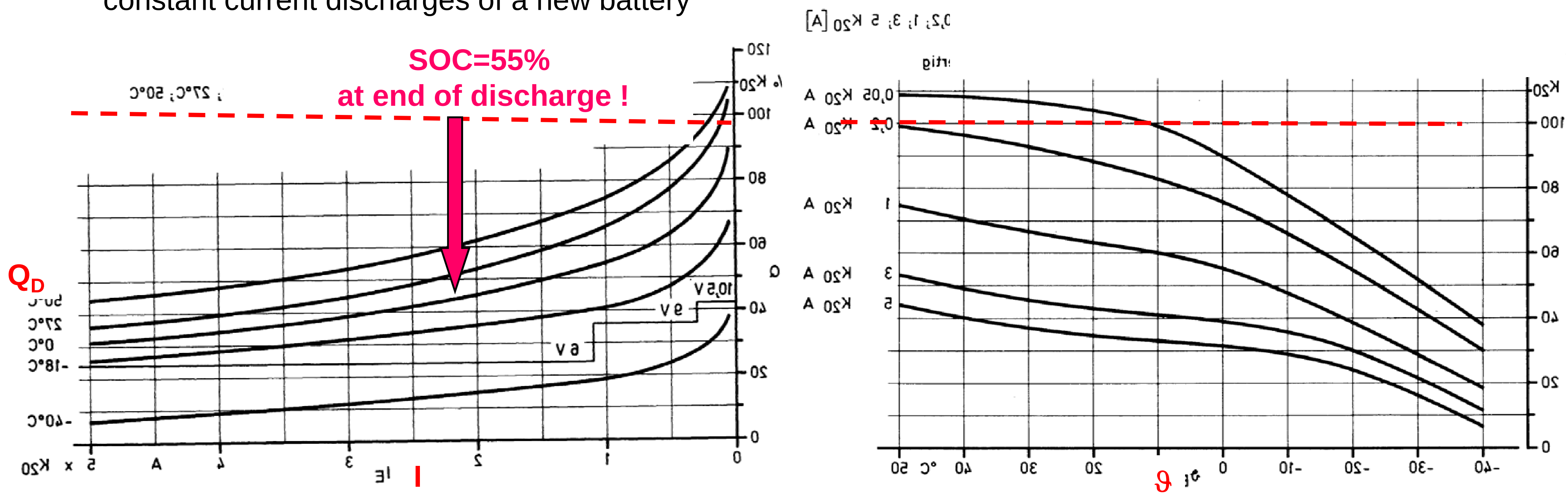
where I_{eff} is the battery current, which effectively discharges the battery (external + self discharge)
Q_{max} is the theoretical maximum charge to be drawn from the battery

SOC indicates the proportion of active material still unused according to Faraday´s law

(For practical reasons, Q_{max} is replaced by nominal capacity K_N or K_{20h};
this implies SOC = 0 for a discharged battery under nominal conditions)

Usable Charge Q_D as function of current I and temperature ϑ

constant current discharges of a new battery

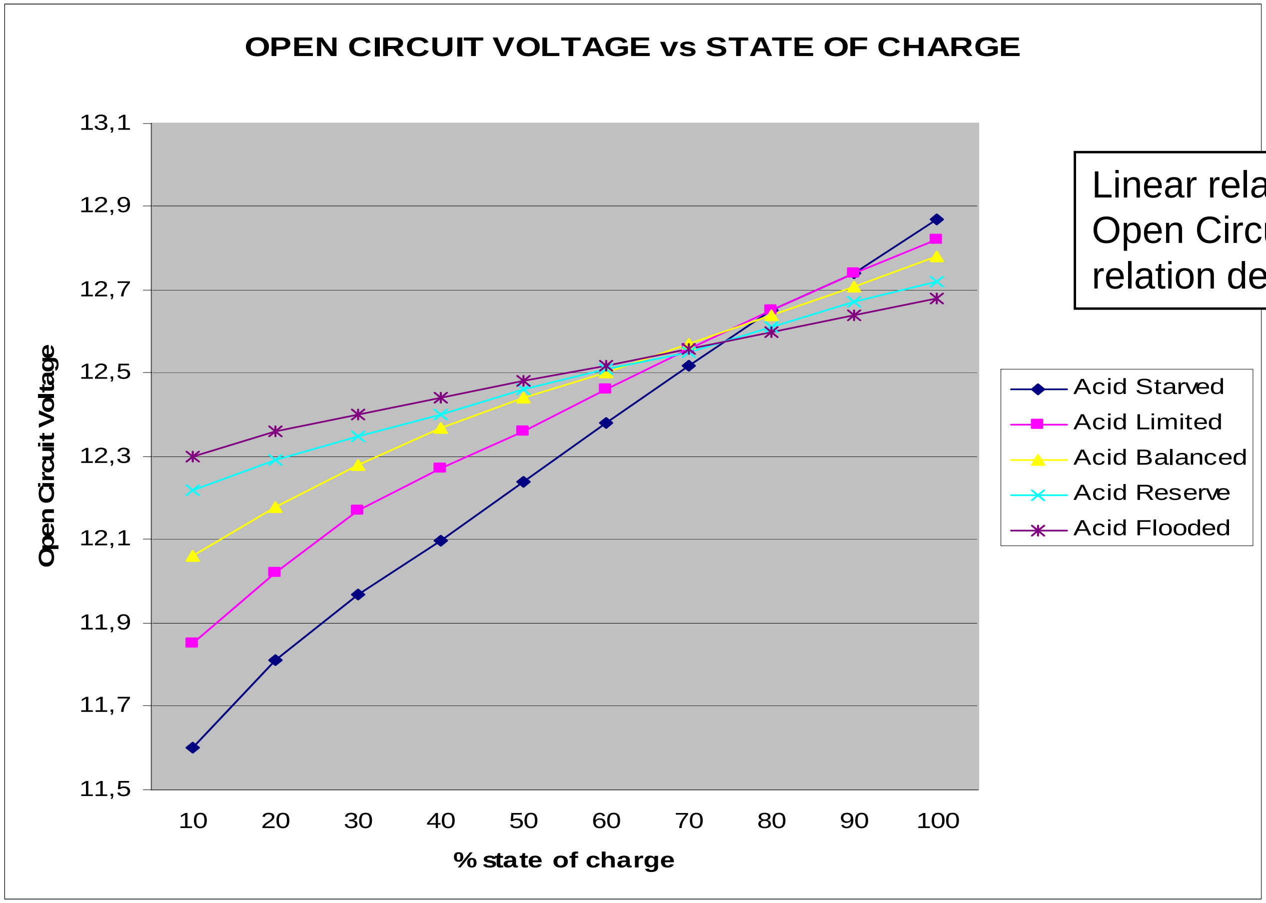


Not all active material can be used for discharge !

(battery reaches a voltage limit before it is empty - diffusion limited)

Thus, SOC by itself does not necessarily give any useful information about the charge which still can be drawn from a battery

Battery Condition Monitoring



Linear relation between SOC and Open Circuit voltage for SOC>30%; relation depends on battery design

Open circuit voltage (after a long resting period) may be used as a measure for SOC, but it is hard to measure !

Battery voltage components

Battery voltage scales linearily with the number of cells: $U_{Bat} = n \cdot U_{Cell}$

$$U_{Cell} = \underbrace{U_0 - \tfrac{1}{C}\int I_{eff}\,dt}_{\text{linear with SOC and with } SOH_K} \underbrace{- U_C}_{\text{depends on load history}} \underbrace{- U_D(I)}_{\text{nonlinear, but little age-dependent}} \underbrace{- (R_A(\vartheta,\ldots) + R_C)\cdot I}_{\text{linear with current; variable, but observable}}$$

I_{eff} is the battery current, which effectively discharges the battery
C describes the average concentration effect of removed charge
U_C is the voltage variation due to local concentration variations (diffusion)
U_D is the voltage drop due to dipoles (chemical activity) on the reactive surface
R_A is the temperature dependent acid resistance (depends also on SOC, condition, age)
R_C is the resistance of the conductors (depends on age)
ϑ is temperature

Not all terms are easy to model, observer necessary

General definition of State-of-Health

SOH: capability of the battery to deliver a given power profile P(t) or current profile I(t)

$$\text{SOH} = f(\vartheta, \text{SOC}, P(t))$$

7 European Lead Battery Conference
20-22 September 2000, Dublin, Eire

VARTA THE BATTERY EXPERTS

"Vehicle Electric Power Systems are Under Change ! Implications on Design, Monitoring and Management of Automotive Batteries" by Eberhard Meissner and Gerolf Richter

SOH in this definition needs the addition "for power profile xxx"; a more precise definition is needed to make it usable

An electrochemical definition of State-of-Health

$$SOH_{ECh} = \frac{Q_{\max}(aged)}{Q_{\max}(new)}$$

new battery: SOH = 1

where

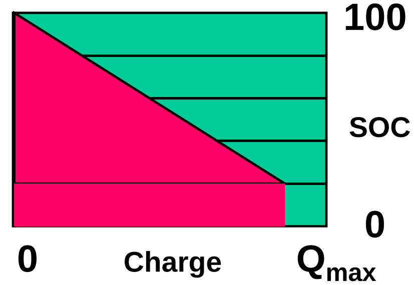
Q_{max} is the theoretical maximum amount of charge which can be drawn from the battery
(in an aged battery some active material is electrically isolated; also the electrolyte density could be reduced and resistances increased)

This definition of SOH indicates, how much reactive material is still electrically active in an aged battery

3 versions of State-of-Charge of aged batteries

Version A:

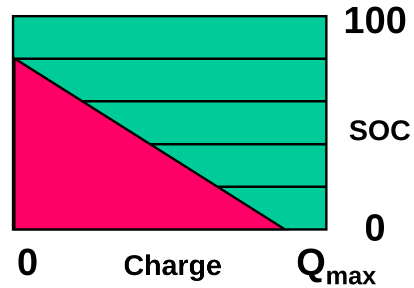
$$SOC_{aged,A} = 1 - \frac{1}{Q_{\max,new}} \int I_{eff}\, dt$$



full: SOC = 1
empty: SOC = $1\text{-}SOH_{ECh}$

Version B:

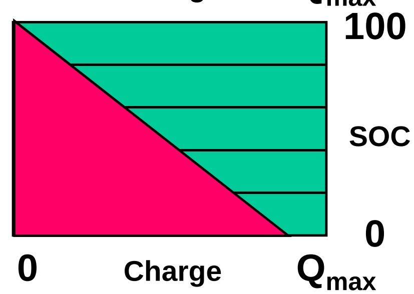
$$SOC_{aged,B} = SOH - \frac{1}{Q_{\max,new}} \int I_{eff}\, dt$$



full: SOC = SOH_{ECh}
empty: SOC = 0

Version C:

$$SOC_{aged,C} = 1 - \frac{1}{Q_{\max,aged}} \int I_{eff}\, dt$$



full: SOC = 1
empty: SOC = 0

No general definition of SOC of aged batteries exists yet !

Proposal for a definition of "State-of-Health with respect to capacity"

(and how to measure it !)

$$SOH_K = \frac{Q_D(I_N, \vartheta_N, aged)}{K_N}$$

new battery: $SOH_K \geq 1$

where

Q_D is the amount of charge which can be discharged before the voltage drops below a certain limit („usable charge")

I_N is the nominal battery current (20h constant current discharge)

ϑ_N is the nominal battery temperature

K_N is the nominal capacity of the battery

SOH_K = usable charge under nominal conditions in relation to nominal capacity

in VARTA´s terms: SOH for nominal discharge conditions

Usable Charge q_D of a fully charged battery

(first approach with little information)

$$q_{D,aged}(I,\vartheta) = \frac{Q_{D,new}(I,\vartheta)}{K_N} \cdot SOH_K$$

where

$Q_{D,new}$ is a table of the amount of charge which can be discharged from a new battery of a given type before the voltage drops below a certain limit (s. charts page 5)

I is the actual battery current

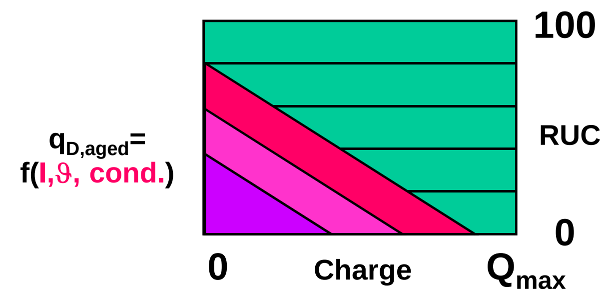
ϑ is the actual battery temperature

K_N is the nominal capacity of the battery

q_D is a (relative) number indicating the usable charge in the battery, based on a measured table $Q_D(I,\vartheta)$ scaled with nominal capacity and one aged-dependent parameter SOH_K

Remaining Usable Charge (RUC) of a partially discharged battery

$$RUC = q_{D,aged}(I, \vartheta, cond.) - \frac{1}{K_N} \int I_{eff} \, dt$$



where

I_{eff} is the battery current, which effectively discharges the battery
K_N is the nominal capacity of the battery

Problem: **Remaining Usable Charge depends on *changing* discharge parameters I and ϑ; diffusion processes and crystal growth effects also play a role („condition“)**

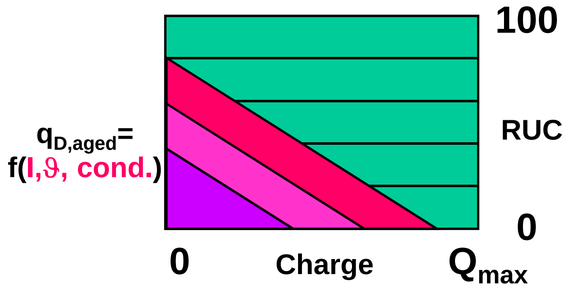
Solution: **modelling & observing of battery condition and adaptation of q_D-table**

RUC multiplied by nominal capacity indicates the remaining usable charge in Ah

Remark: we need at least current, temperature, and nominal capacity for determination of RUC

Relation between RUC and SOC

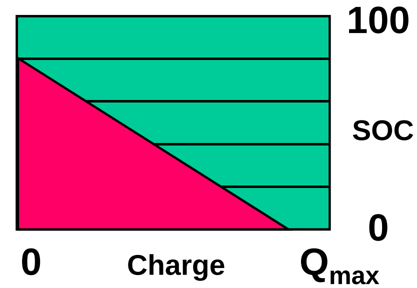
$$RUC = q_{D,new}(I,\vartheta,cond.) \cdot SOH_K - \frac{1}{K_N}\int I_{eff}\,dt$$



For small currents and room temperatures, the usable charge Q_D comes close to Q_{max}; thus $q_{D,new} = 1$.
K_N and $Q_{max,new}$ are close to each other.

For comparison, version B of SOC formulas:

$$SOC_{aged,B} = SOH_{ECh} - \frac{1}{Q_{\max,new}}\int I_{eff}\,dt$$



SOC describes only one single point, while RUC covers a wide operational range

What does a system designer need to know about his energy storage?

Discharge Ability

- How much energy is available in the storage ?
- With what power can I draw this energy from the storage ?
- May I still perform a certain (critical) function relying on the storage ?
- How long can I still continue drawing a certain power ?

Recharge Ability

- How much energy can I still store into the storage ?
- How fast (with what power or current) can I store energy into the storage ?
- What will be my energy losses under different charging conditions ?

SOC, SOH, and RUC do not give direct answers to these questions, but they are the first steps !

Important quantities which influence battery energy and power

- Power = voltage times current and Energy = voltage times charge available
- Voltage = Electrochemical source voltage minus voltage drops
  (resistive, polarisation, diffusion ⇒ battery model and observer)
- Usable charge depends strongly on temperature, current and age (⇒ „RUC“)
- Diffusion status, crystal size and distribution, electrochemical current limits
  (depend on load history ⇒ „Condition Factor“)
- During charging, side reactions (gassing) become highly important
  (depend strongly on voltage and temperature ⇒ charging model)

⇒ **Battery condition monitoring must consider**
voltage drops and aging (use battery model & observer)
besides temperature and current (directly measured),
as well as load history (condition model & observer)

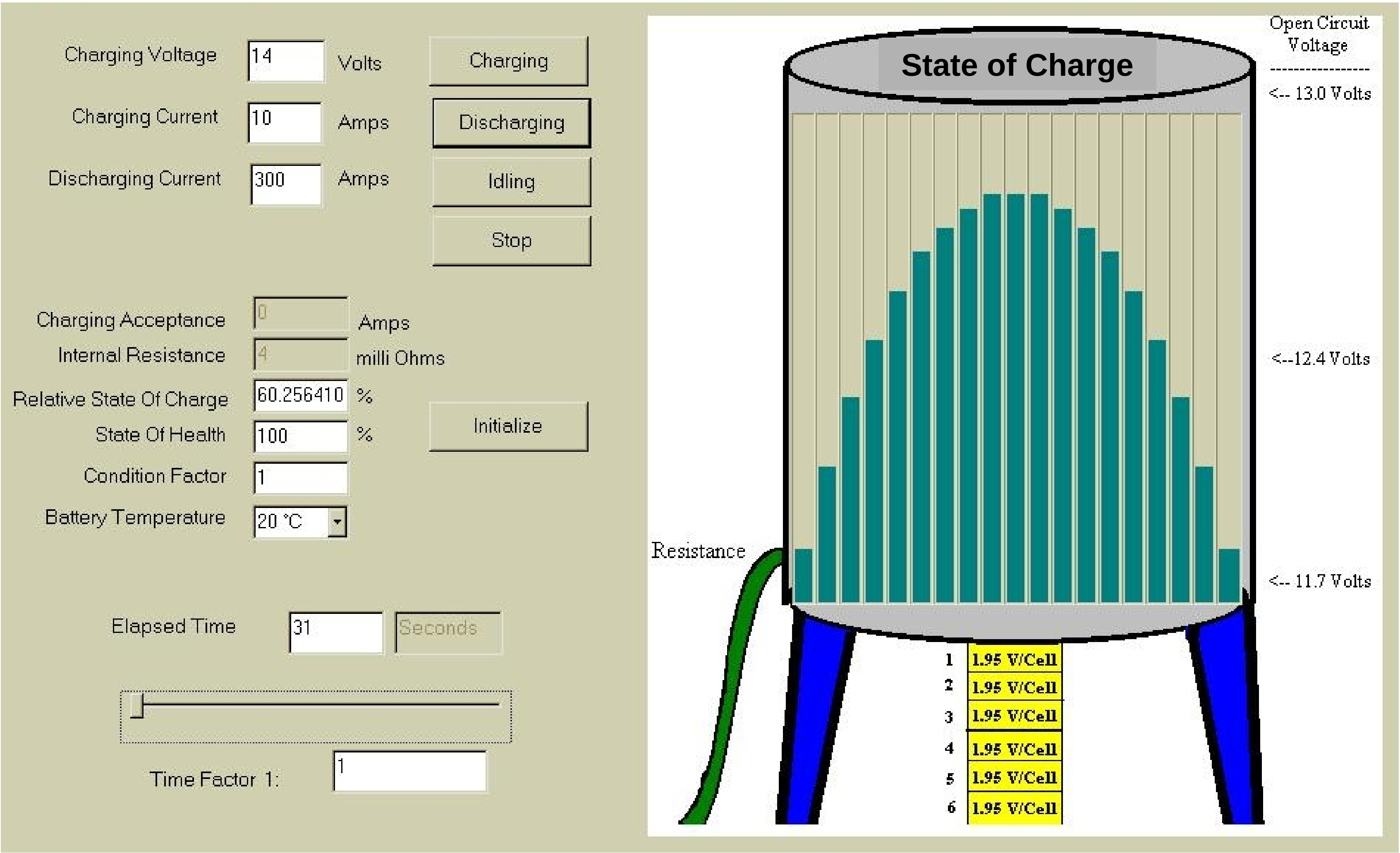
Water tower simulation of a battery

(scales linearily with number of cells)

- The water tower shows: the electrochemically active voltage as water level; the SOC, including age effects, as the water content of the tower (voltage drops due to resistances and polarization are not included).
- Water level in partitions depicts plate cross section and relative voltage with effects of polarization
- Shows dependence on discharge current and temperature
- Visualizes the diffusion effects under rest and charge
- Visualizes the effects of surface recharge and gives example for effect of aging
- Present limits of the simulator: voltage during overcharge / gassing
- Encompasses most of the effects on Deliverable Power and Energy

Visualisation of main features of battery behaviour

Battery Condition Monitoring

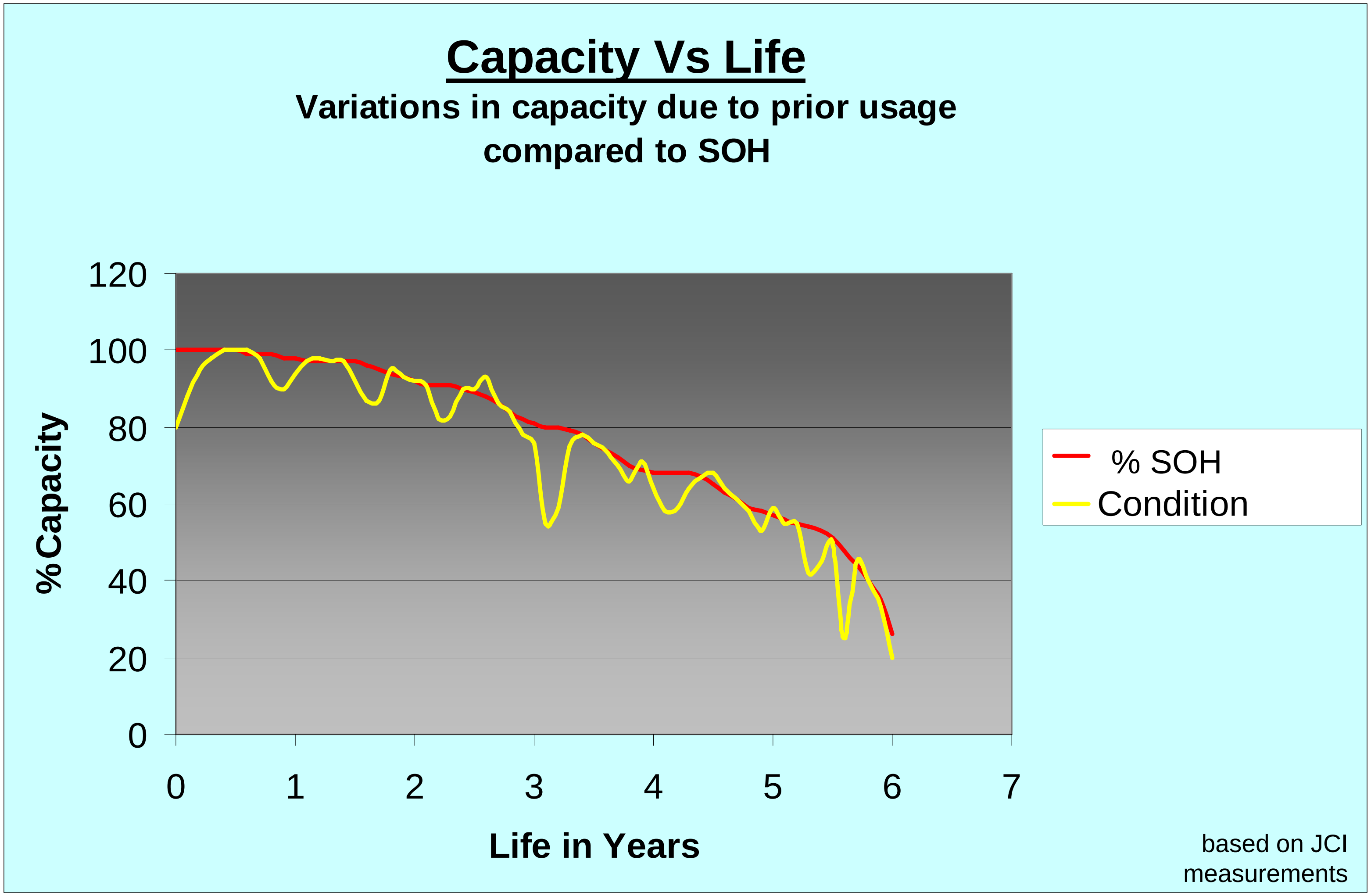


Summary

- SOC definition and its limits of interpretation
- SOH definition proposal
- Concept of usable charge and remaining usable charge (RUC)
- Questions asked by a system designer
- Concept of a battery condition monitoring based on model <u>and</u> observer
- Visualization with the water tower model
- Ongoing work:
  - ⇒ Implementation of a battery observer
  - ⇒ Visualization of battery charging behaviour

Thank you for your attention !

Appendix A :


Capacity Vs Life
Variations in capacity due to prior usage compared to SOH
120
100
80
60
40
20
0
% Capacity
0
1
2
3
4
5
6
7
Life in Years
% SOH
Condition
based on JCI measurements