Welcome

Connecting batteries in parallel
Unexpected effects and solutions

Battery Power Conference
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Overview

- Why parallel batteries
- Paralleling at the factory vs. in the field
- Factory: cells in parallel vs. strings in parallel
- Field: negative effects of paralleling batteries
- A few techniques to overcome those effects

Reasons to parallel strings

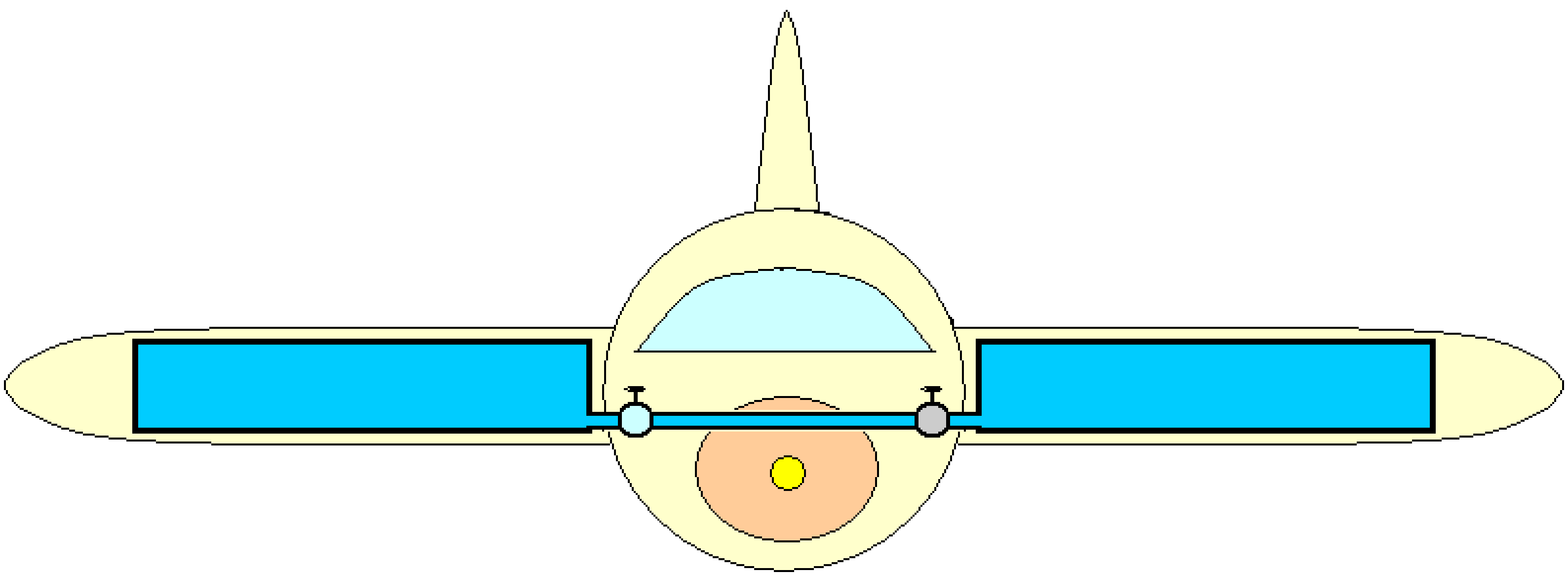
At the factory:

- To get desired capacity

In the field:

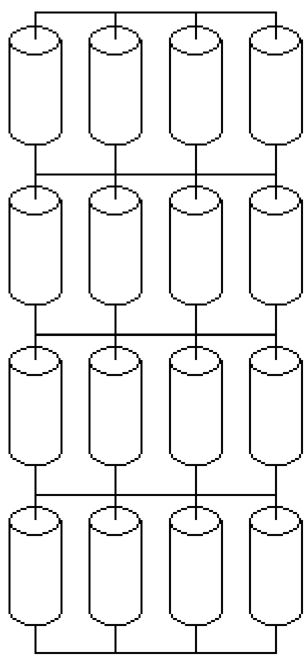
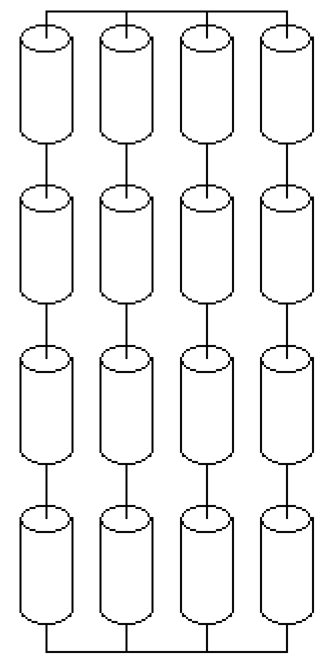
- For flexibility
- To maximize charge
- For redundancy
- For serviceability

The fuel tank analogy
One tank at a time



Bad analogy to batteries in parallel

Cell in parallel vs. strings in parallel

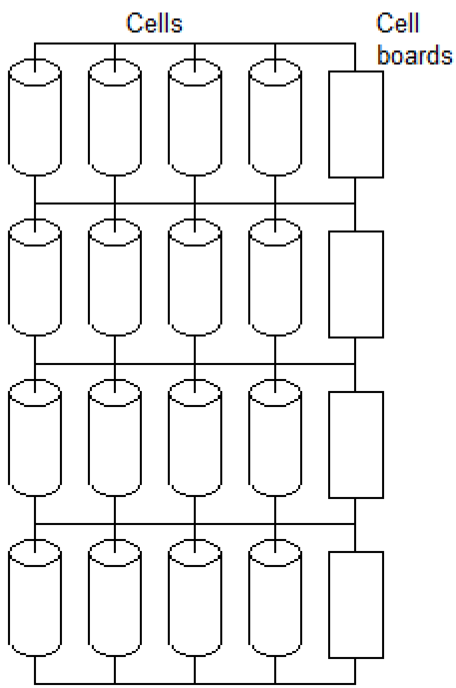
Cells in parallel	Strings in parallel
Cellis in parallel, then sets in series (lattice network) 	Cells in series, then strings in parallel 

Cell in parallel vs. strings in parallel

BMS cell boards or tap points

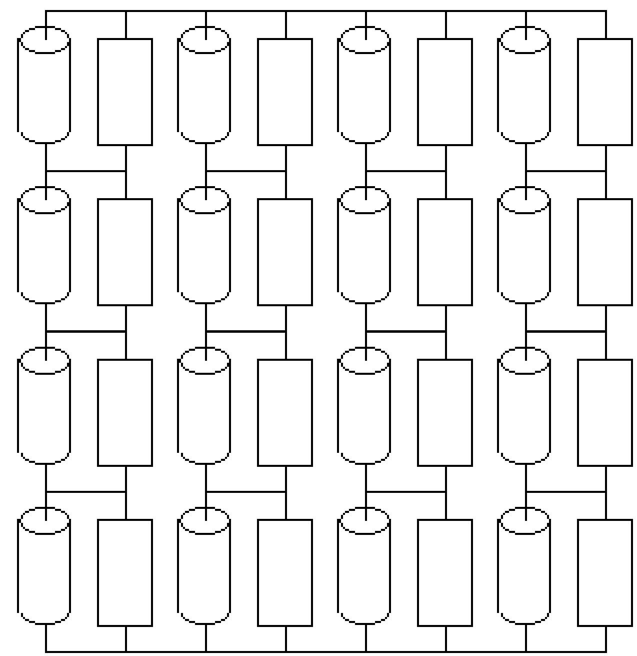
Cells in parallel

4 cell boards, or 5 tap points



Strings in parallel

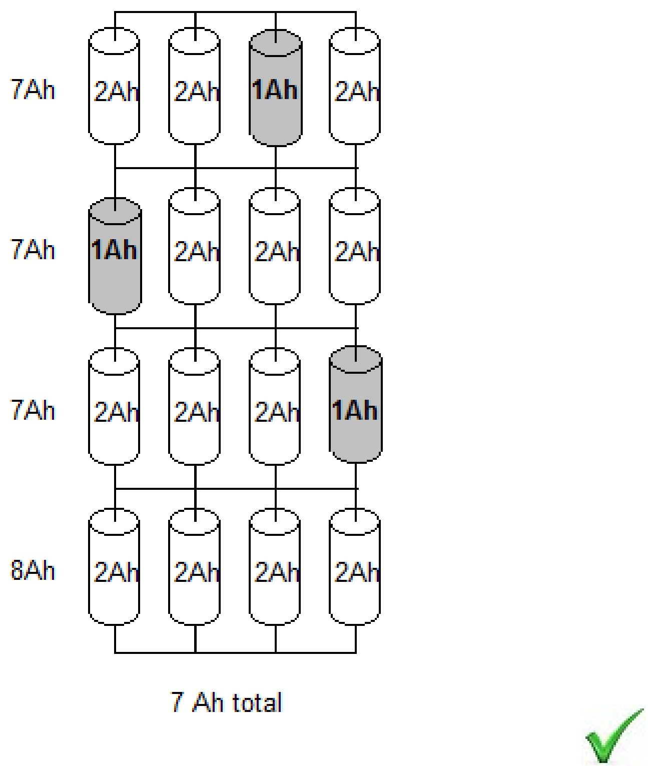
16 cell boards, or 14 tap points



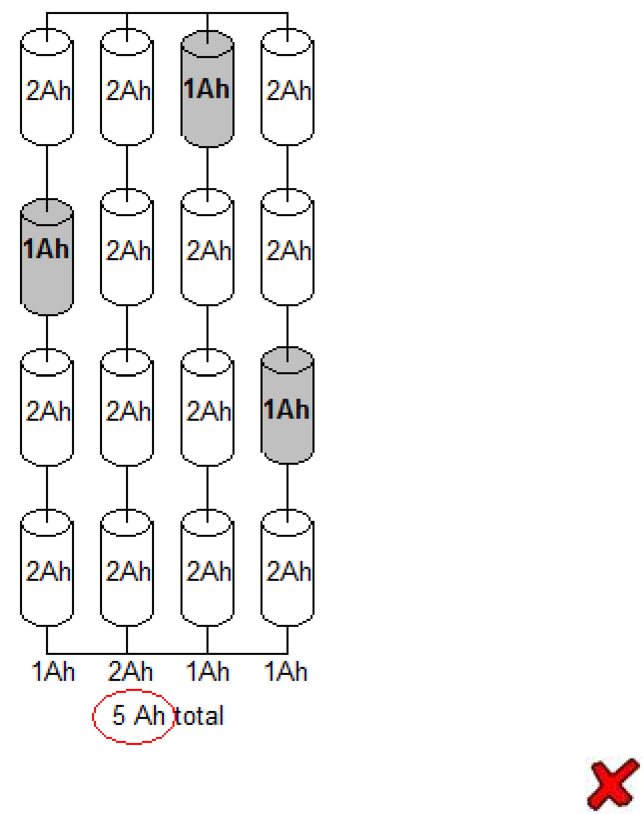
Cell in parallel vs. strings in parallel

Capacity loss

Cells in parallel



Strings in parallel

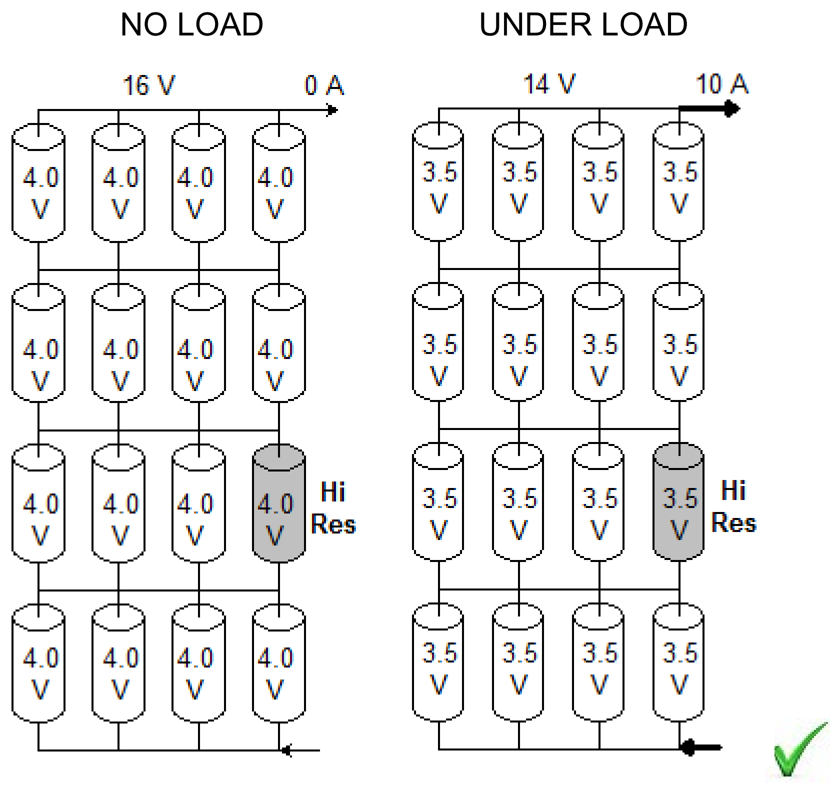


Cell in parallel vs. strings in parallel

Bad cell limitation

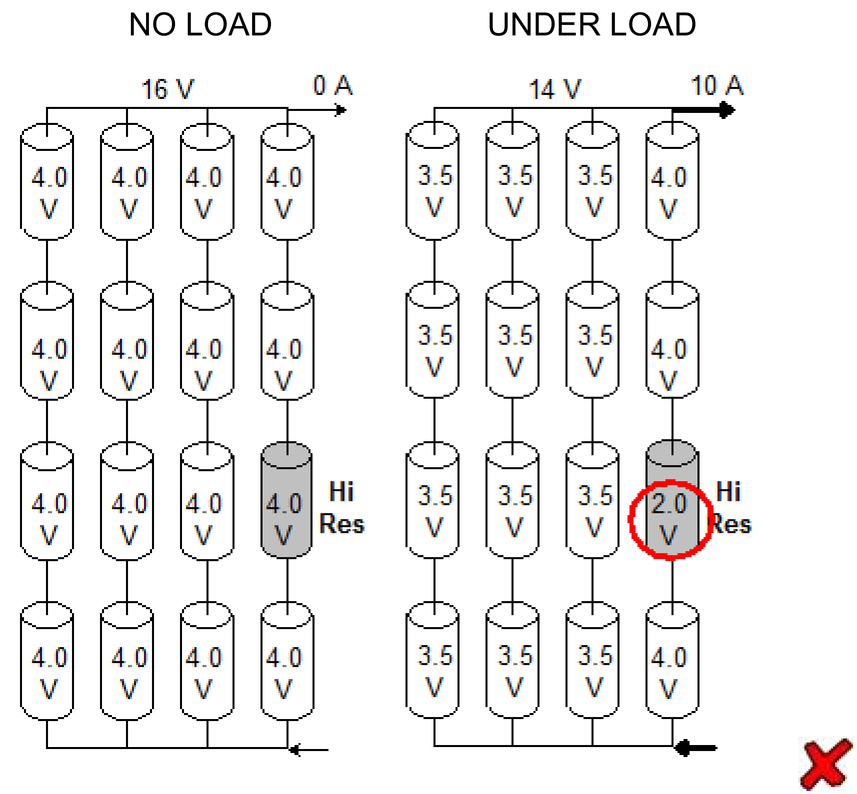
Cells in parallel

Bad cell reduces capacity



Strings in parallel

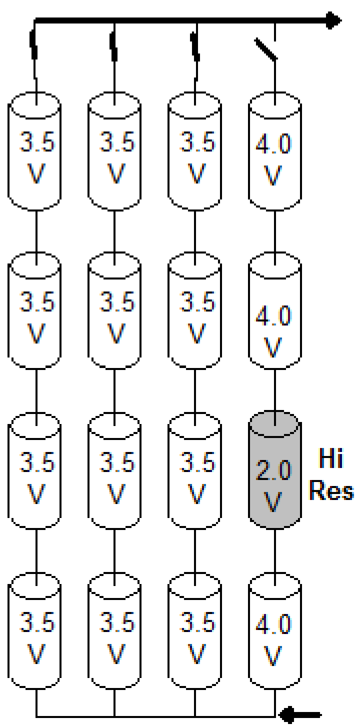
Bad cell shuts down battery

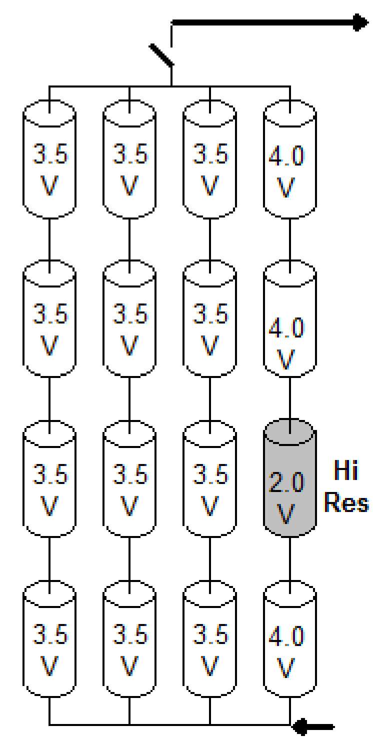


Cell in parallel vs. strings in parallel

Redundancy

One switch per string	String directly in parallel
Bad string can be isolated	Bad cell shuts down battery

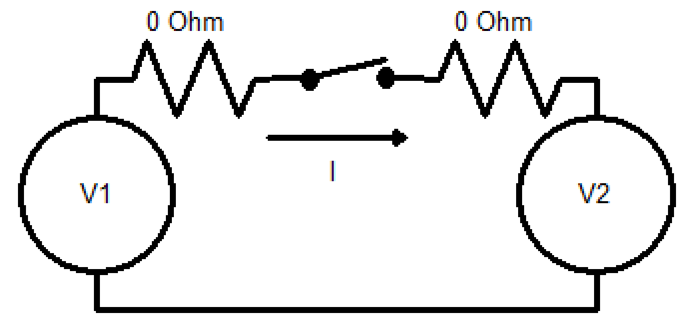




Initial connection (in field)

Batteries as voltage sources

- Batteries are voltage sources:
  - Series: easy
  - Parallel: problematic
- If ideal voltage sources...

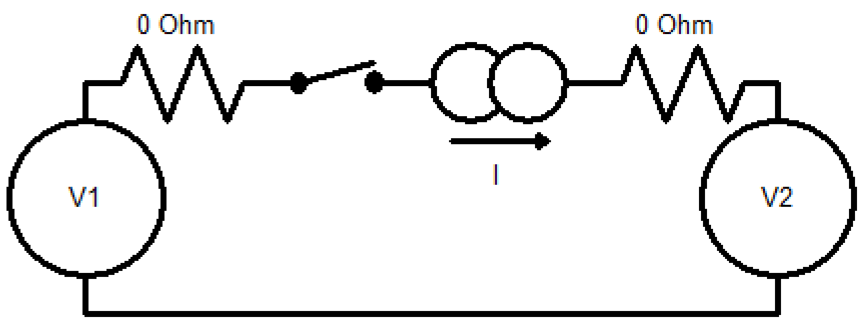


$$\frac{V1 - V2}{0\ \Omega} = \infty A$$

- Parallel ideal voltage sources = infinite current

Initial connection (in field)
Way to parallel voltage sources

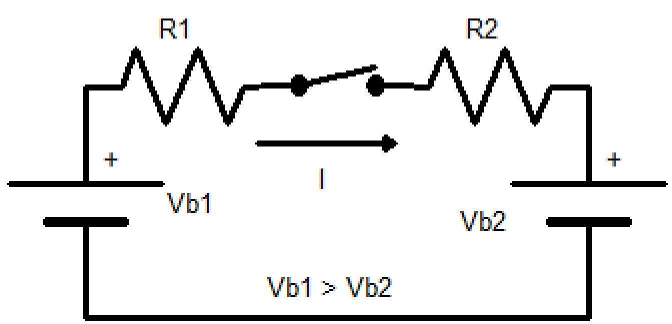
- Ideally, voltage sources are connected through current sources



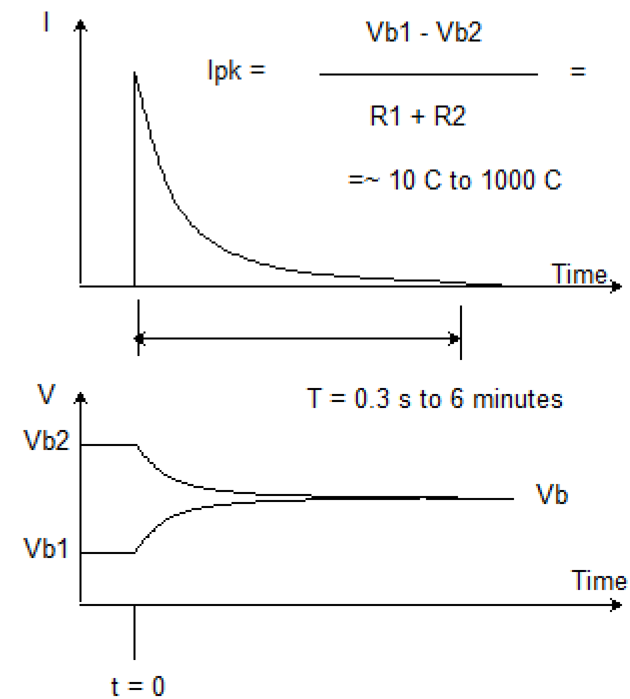
- Or, at least, through resistors
- Never directly

Initial connection (in field)
Real world batteries

- Resistance is non-0
- Voltage changes with SOC



$$i(t) = \frac{Vb1 - Vb2}{R1 + R2}$$



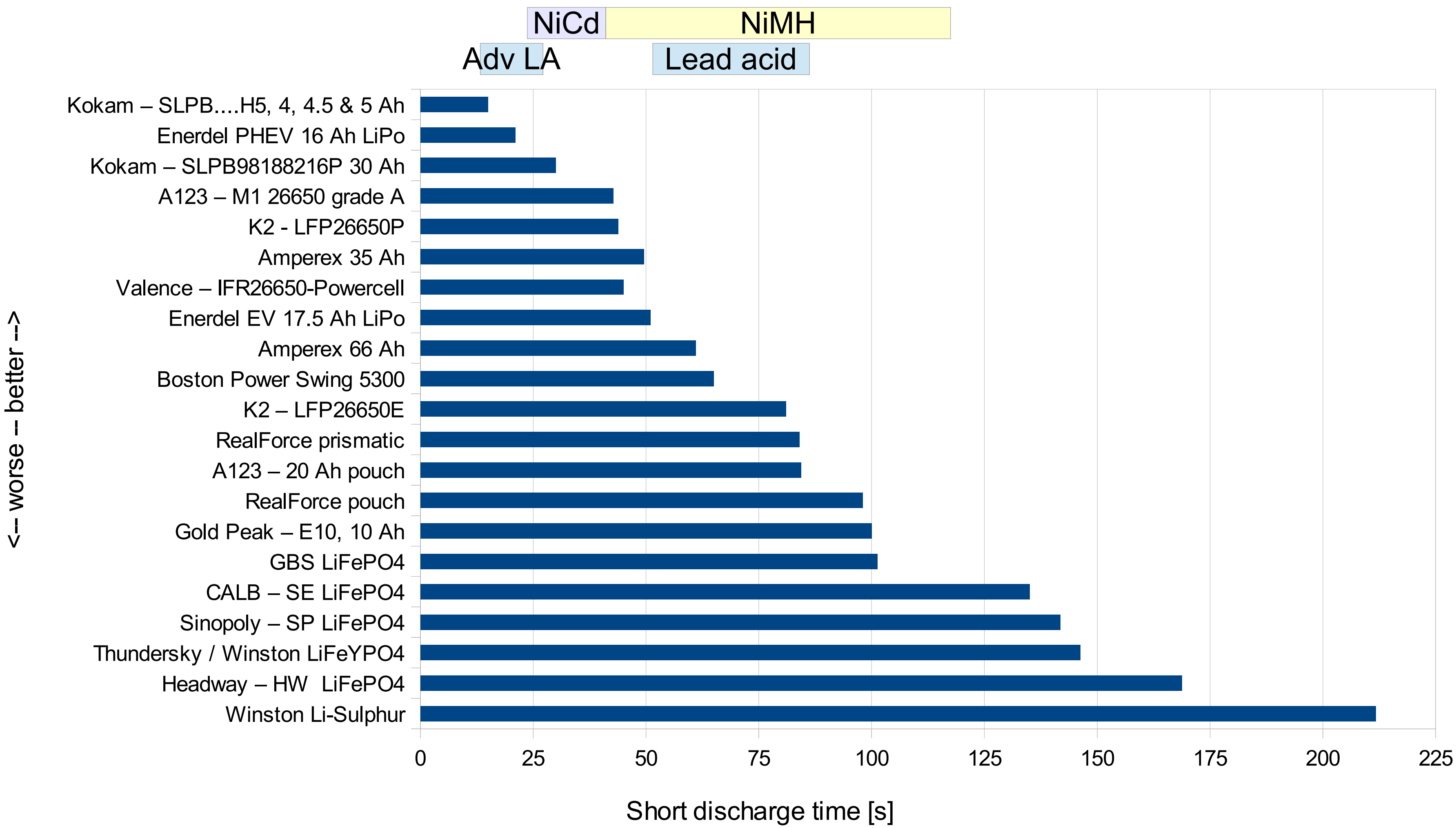
Initial connection (in field)
Damage from inrush current

- Damage to interconnects
- Damage to cells? Possible if:
  - High dV/dSOC (standard Li-ion)
  - Low Rseries

Short discharge time
Definition

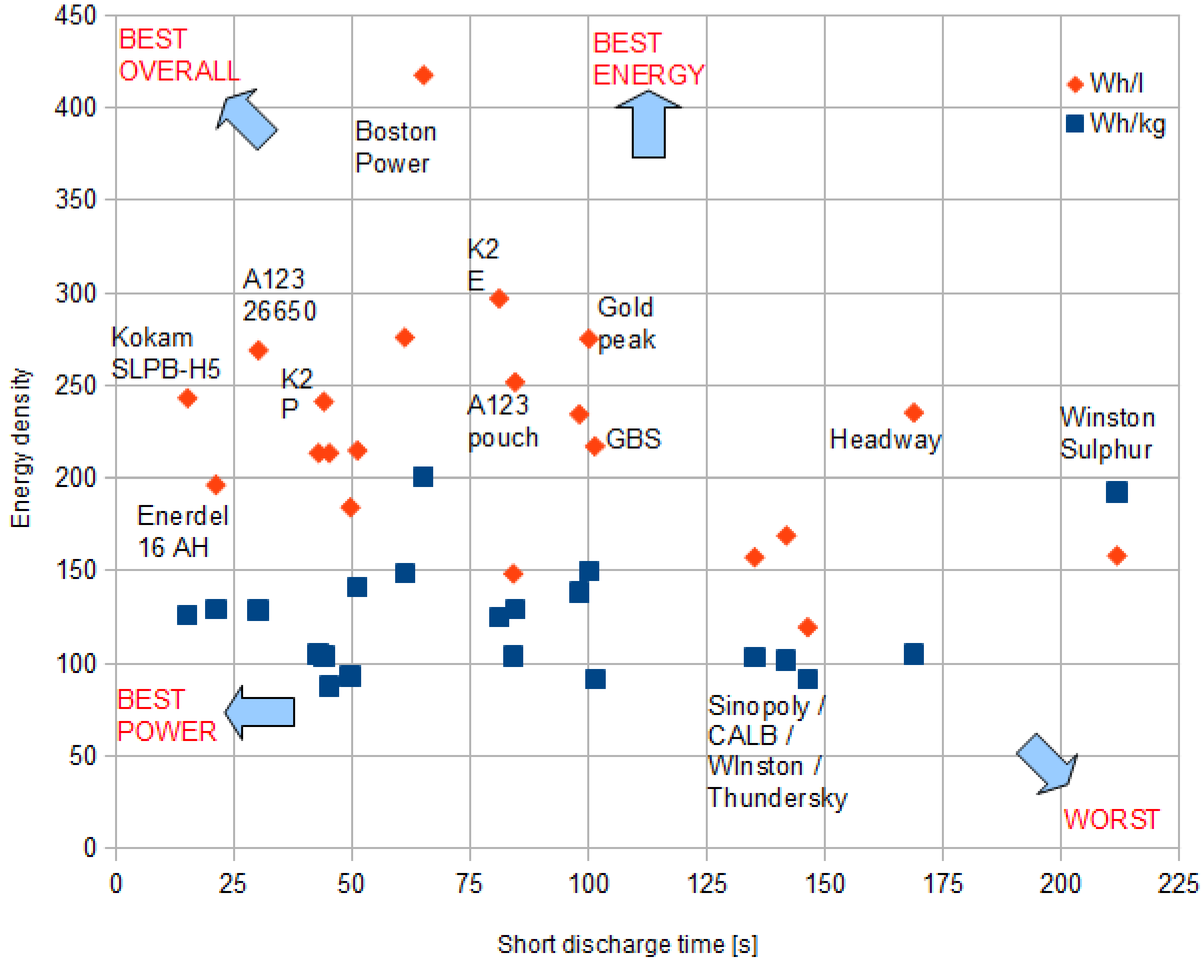
- Theoretical discharge time across a short circuit
- Constant, characteristic of each cell technology, regardless of capacity or voltage
- Easy calculation of resistance
  - $R = T_{ShortDisch} * Voltage / Capacity$
- Easy calculation of efficiency
  - $E_{heat} = E_{out} * T_{ShortDisch} / T_{ActualDisch}$
- Ranges from ~20 s to ~200

Short discharge time
for various cell families



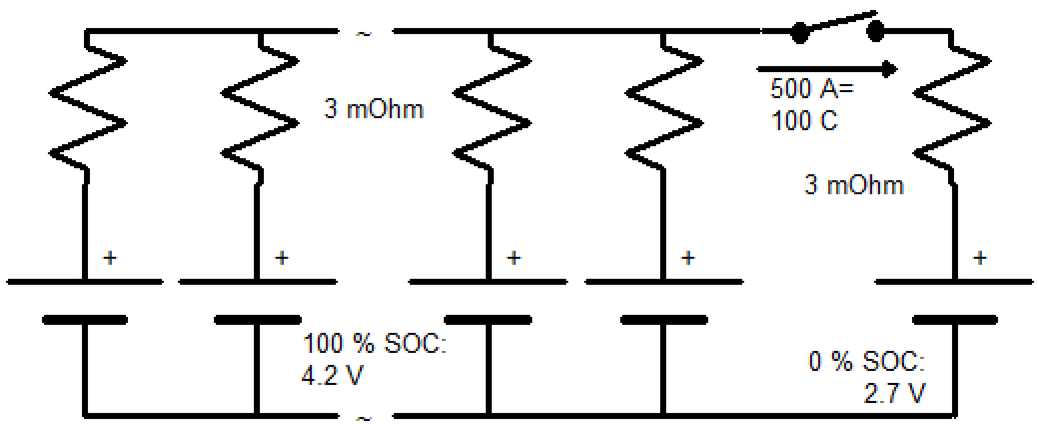
Short discharge time

Short discharge time vs energy density



Initial connection (in field)
Worst case

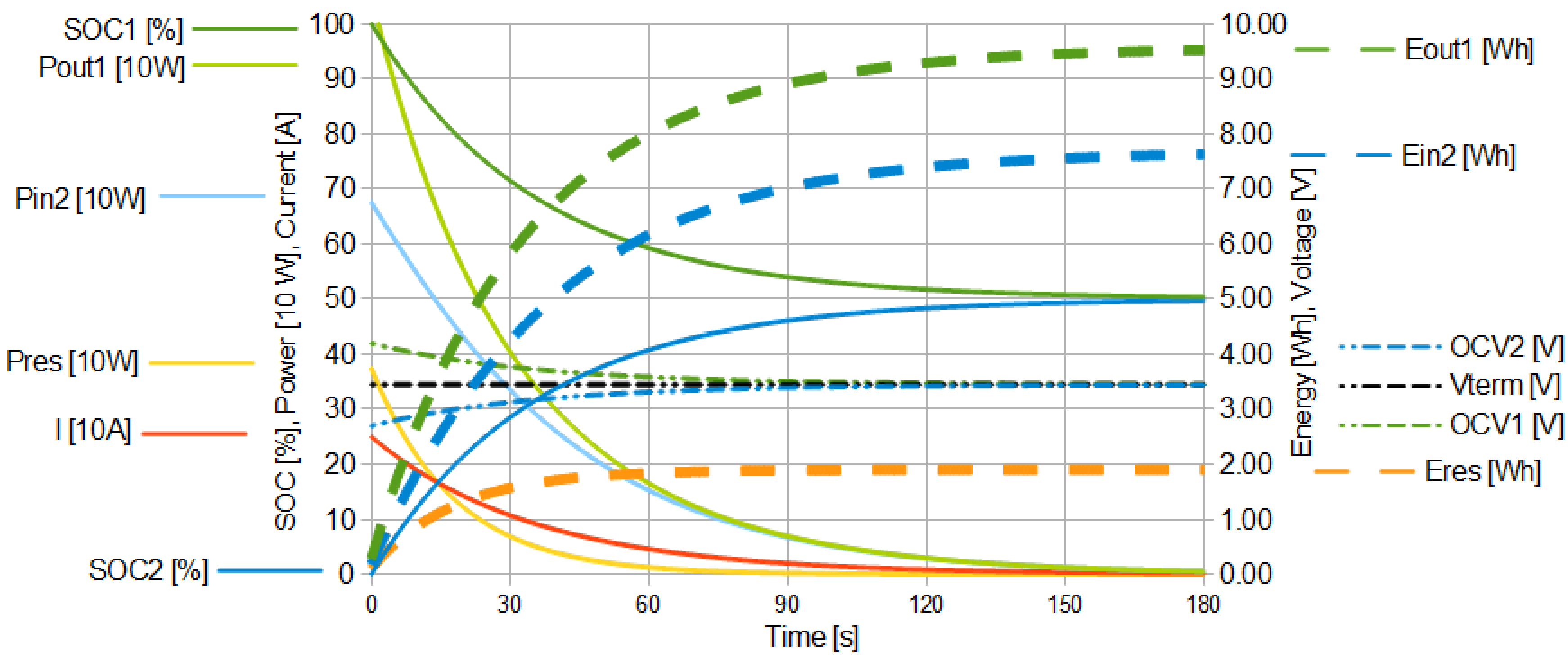
- KOKAM SLPB....H5 cells (LiPo, 5 Ah, 3 mΩ)
  - Lowest resistance, high dV/dSOC
- N-1 cells 100 % SOC + 1 cell 0 % SOC



- (4.2 V – 2.7 V) / 3 mΩ = 500 A = 100 C
  - In general 10 ~ 100 C

Initial connection (in field)
2 cells

- KOKAM SLPB....H5 cells (LiPo, 5 Ah, 3 mΩ)
- 1 cell 100 % SOC + 1 cell 0 % SOC2



Initial connection (in field)

Energy and charge loss

Charge loss	Energy loss
No charge is lost: Just as many electrons flow out of the most charged battery as flow into the least charged one. However, BMS may lose SOC count: the BMS may be off, or the current could exceed the BMS's range	A bit of energy is lost: The current through the connecting resistance produces heat. The energy loss is: • ~12 % for std Li-ion • ~8 % for LiFePO4 • Less for delta SOC < 100 % • Independent of resistance

Paralleling batteries

Factory vs. field

- Paralleling at the factory: OK
  - Cells all have same SOC
- Paralleling in the field: not ideal
  - Possible damage with low resistance cells
  - BMS's SOC value may become invalid
  - Energy loss ~10 % @ ΔSOC = 100 %
  - Charge loss is 0

Paralleling techniques (in field)
To minimize inrush

- Wait for equal voltages
- Charge lowest battery
- Discharge highest battery
- Transfer energy between batteries

Paralleling techniques (in field)
SOC evaluation

- Each battery requires its own BMS (& SOC)

- SOC after connection:
    - If high inrush, BMS estimates SOC from OCV
    - If low inrush, BMS knows SOC

- Master BMS computes SOC and capacity of entire pack from individual battery SOCs

Conclusions
At the factory

- Paralleling at the factory is OK
  - Parallel cells directly (not strings)

Conclusions

In the field

- Paralleling in the field can be a problem
  - Avoid if possible
  - But, if you must:
    - Use 1 BMS & 1 switch / string
    - Prevent high inrush at connection: first...
      - Wait for equal voltages, or
      - Charge low battery, or
      - Discharge high battery, or
      - Transfer energy between them
    - Calc pack SOC from each battery's SOC

Thank you

Questions?