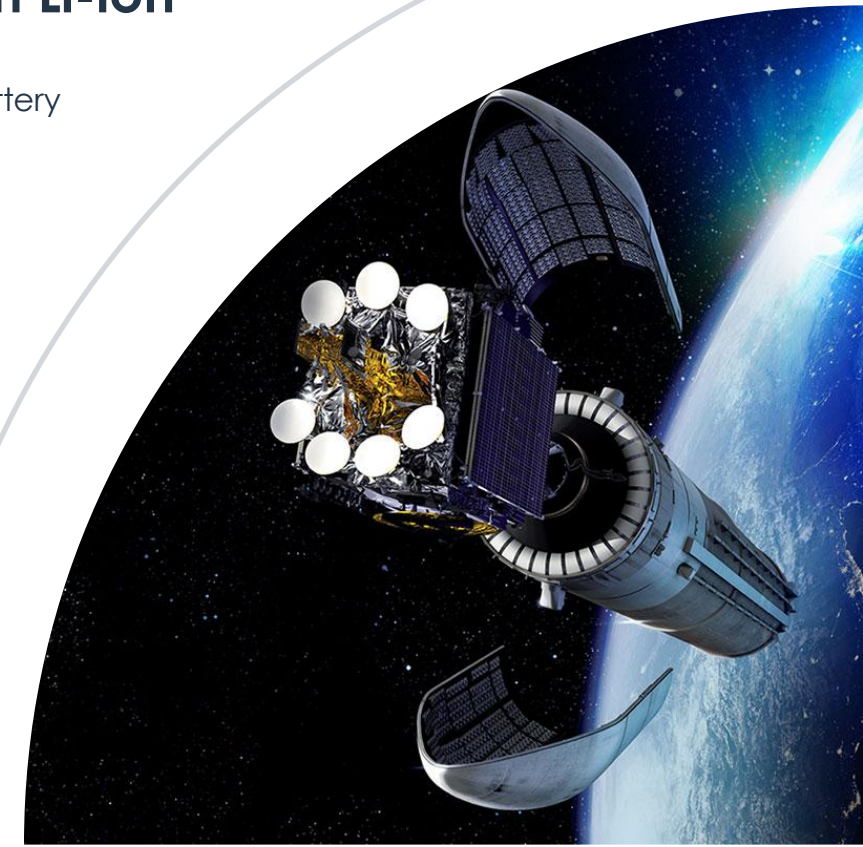
New approach for controlling a cell soft short failure in a Li-ion spacecraft battery

Eloi Klein

ThalesAlenia Space
a Thales / Leonardo company

Thales Alenia Space experience with Li-ion

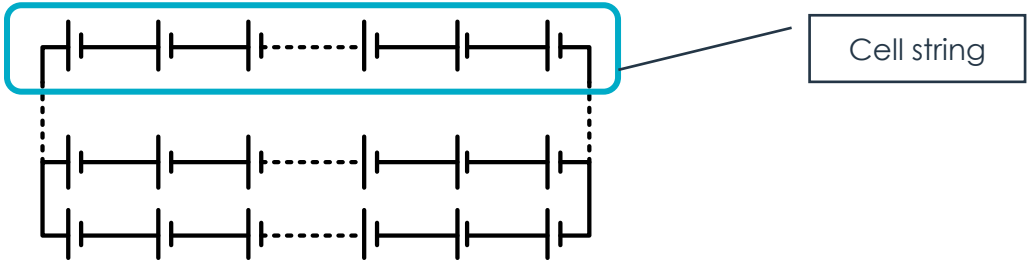
- Since 2005, more than 120 spacecraft featuring Li-ion battery have been launched with Thales Alenia Space as prime contractor.
- Energy storage capability ranges from 0.7 to 25 kWh per spacecraft.
- 10 different cell types are used, with a nominal energy ranging from 5 Wh to 700 Wh per cell.
- Batteries are made from 6 to 24 cells in series, and from 1 to 224 cells in parallel.



Series parallel or parallel series connection

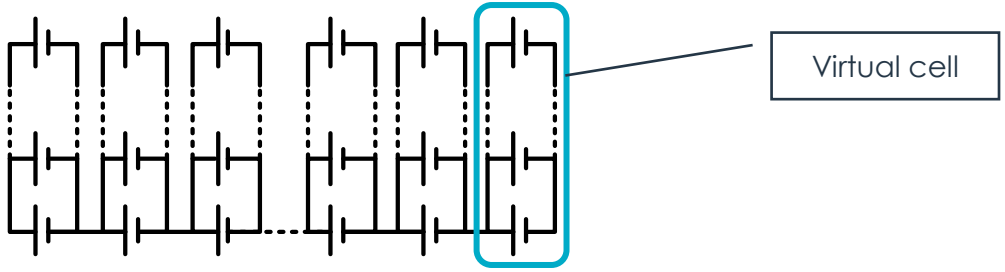
- Series parallel connection (related to cells or batteries):

arrangement of cells or batteries wherein in series connected cells or batteries are connected in parallel



- Parallel series connection (related to cells or batteries):

arrangement of cells or batteries wherein parallel connected cells or batteries are connected in series



From IEC 60050 « International Electrotechnical Vocabulary »

Cell soft short-circuit

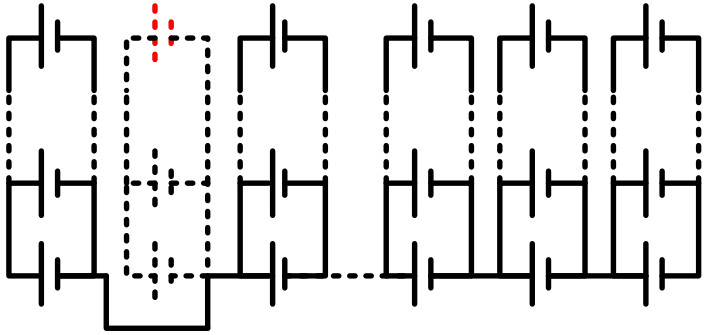
- A soft short-circuit at cell level can be defined as a short-circuit which does not induce cell thermal runaway. It is equivalent to a high self discharge.

- It is considered as a failure if the short-circuit current is beyond the balancing capability of the Battery Management System (if balancing function is included).

- Could be due to:
  - External causes (conductive part shorting cell terminals, BMS failure)
  - Internal causes(contact between electrodes, due to misalignment or through the separator).

- Other failures type (open circuit, premature aging of one cell vs. the others…) can be prevented by careful battery design, manufacturing and testing.

P-S configuration

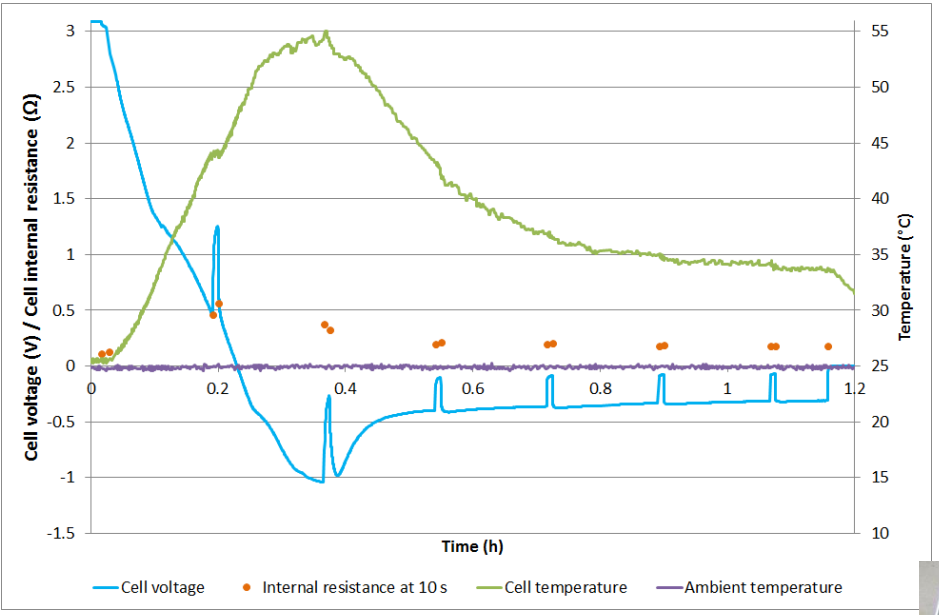


- The battery and cell design has to guarantee that a cell failure does not propagate to the adjacent virtual cells.

- The worst case consequence of a cell failure has to be the replacement of the failed virtual cell by a low and stable resistance, in order to maintain battery continuity.

- An expensive solution is to implement one bypass switch on every virtual cell. Another option is to let the virtual cell overdischarging up to the point where it is self short-circuited.

Cell over-discharge



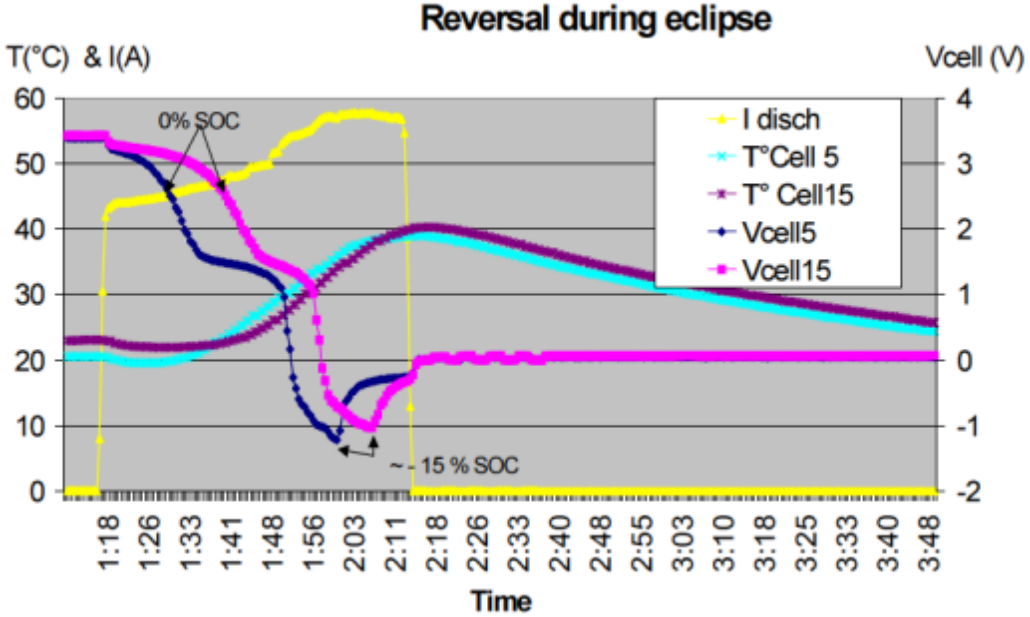
Overdischarge of a 18650 COTS cell (LG MJ1).
Discharge at 0.5C, with 30 s / 0.1C steps every 10 minutes

- Cell overdischarge leads to voltage reversal, which leads to copper plating on the positive electrode. The cell behaves as a stable resistor, with a low resistance value (usually within the same order of magnitude than the typical DC resistance of a healthy cell).
- If the conditions can be controlled, in terms of reversal current and heat dissipation, a bypass switch is not needed.

Positive electrode and separator showing copper deposit

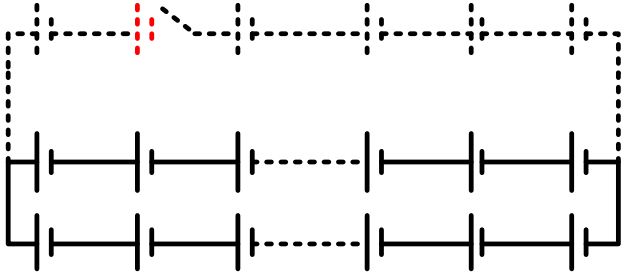
Cell soft short-circuit in P-S configuration

- This self-healing mechanism was successfully tested in orbit by Thales Alenia Space in 2010, on a GEO satellite with two 3P20S batteries (Saft VES140S). This followed a ground test campaign performed by Saft and ESA.
- Balancing shunt switched ON on two virtual cells during the eclipse season.



From « LITHIUM-ION CELL PASSIVATION IN FLIGHT CONDITIONS »
G.Bouhours[1], E.Klein[1], C.Rebuffel[1], C.Wallstein[1], R.Asplanato[1], Y.Borthomieu[2]
[1]: Thales Alenia Space [2]SAFT
European Space Power Conference 2011

s-p configuration

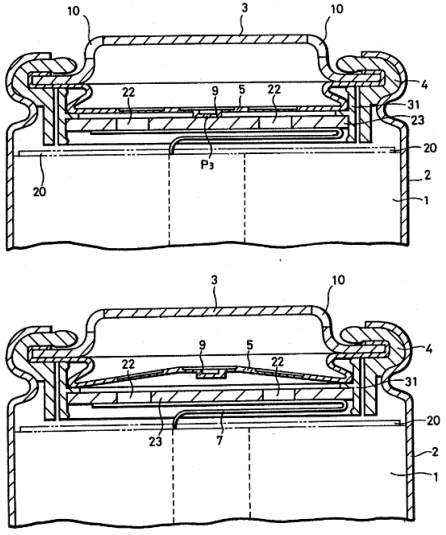


- The worst case consequence of a cell failure has to be an open circuit of one string.
- Battery voltage is not affected by a cell failure, which enables a simple Battery Management System.
- A practical solution is to trigger the cell internal Current Interrupt Device, which is standard in most Li-ion cells.

Cell Current Interrupt Device

- Opens when internal pressure is high, due to:
  - Overcharge above electrolyte oxidation potential (typically 4.8 V or higher)
  - High temperature

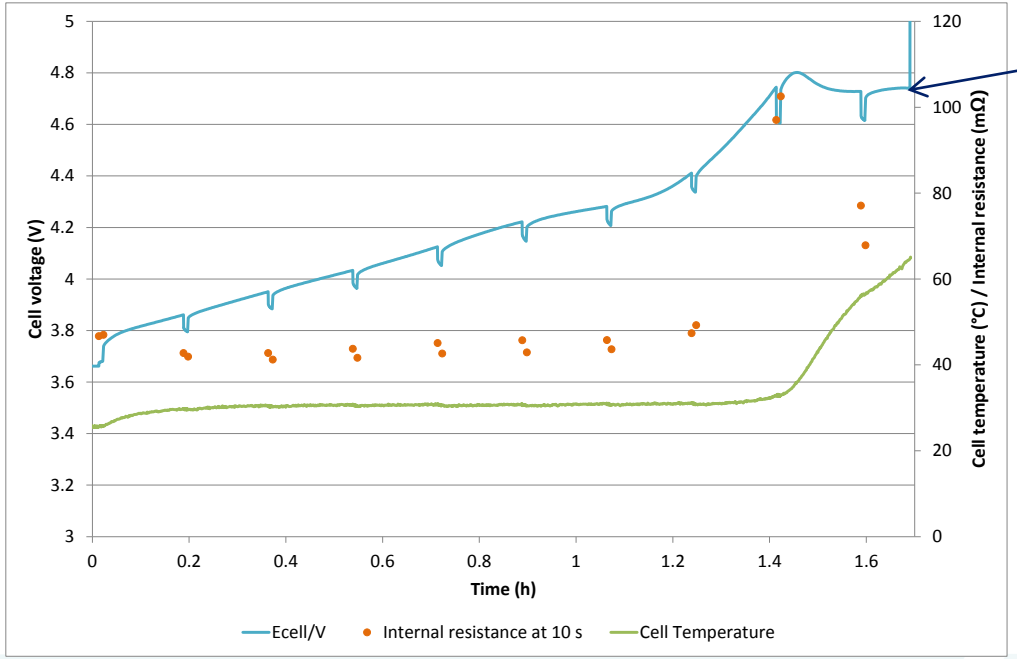
- Activation depends on:
  - Active materials and electrolyte composition
  - Cell potential
  - Overcharge current
  - Rupture disc strength
  - Cell previous history
  - Cell internal free volume



From Patent US 5418082 A

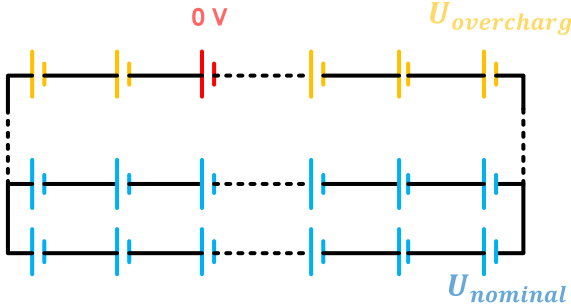
Cell overcharge

- Overcharge of a COTS 18650 cell (LG MJ1) at C/2 with 30 s / 0.1C steps every 10 minutes.
- Up to 4.7 V, no increase of heat dissipation, no increase of cell resistance.



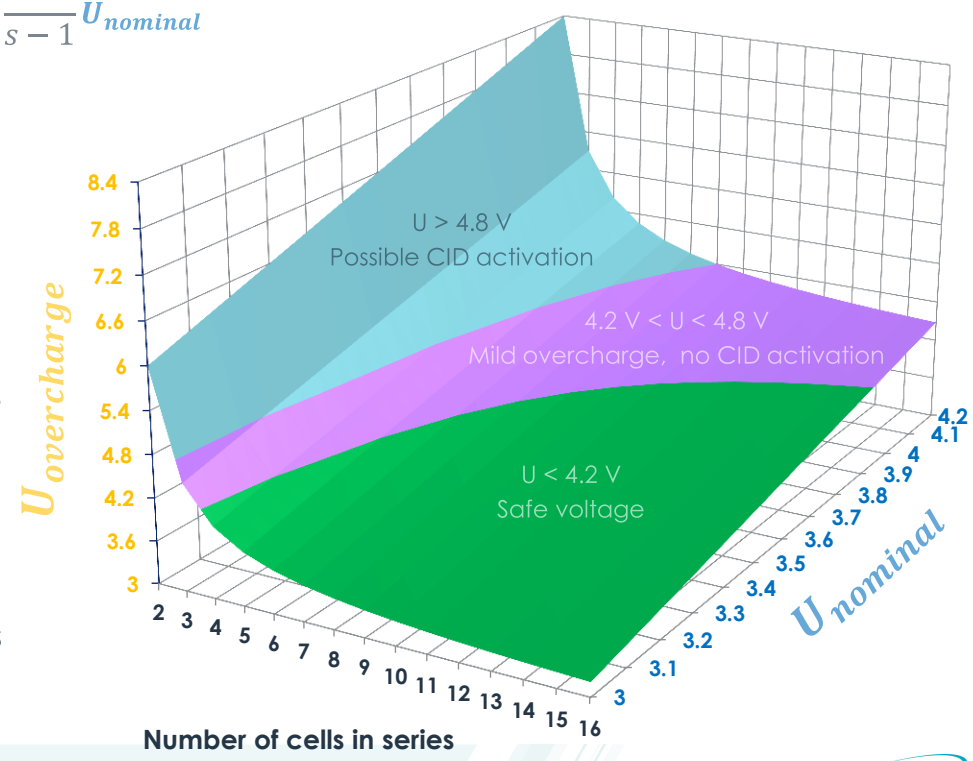
CID activation
at ~120% SOC
(SOC 100% at 4.2 V)

Cell soft short-circuit in s-p configuration



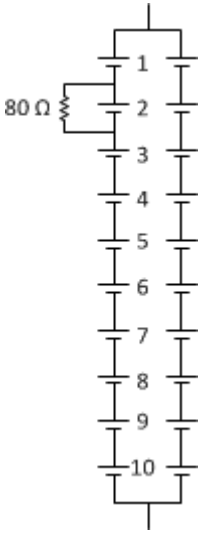
$$U_{overcharge} = \frac{s}{s-1} U_{nominal}$$

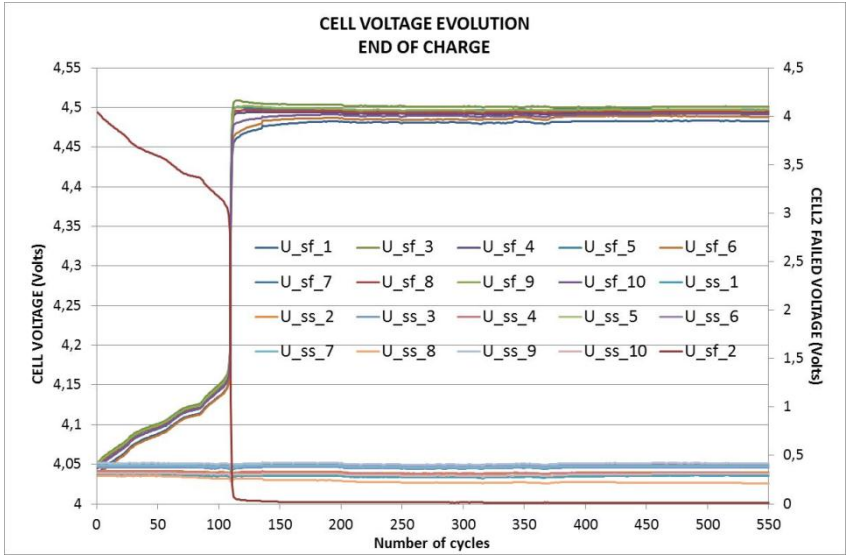
- When a cell fails in soft short, the voltage of other cells increase to compensate the failed cell voltage drop, resulting in an overcharge.
- Most Li-ion cells need to be overcharged at more than 4.8 V for the CID to open.
- This will never occur if the number of cells in series is higher than 8.

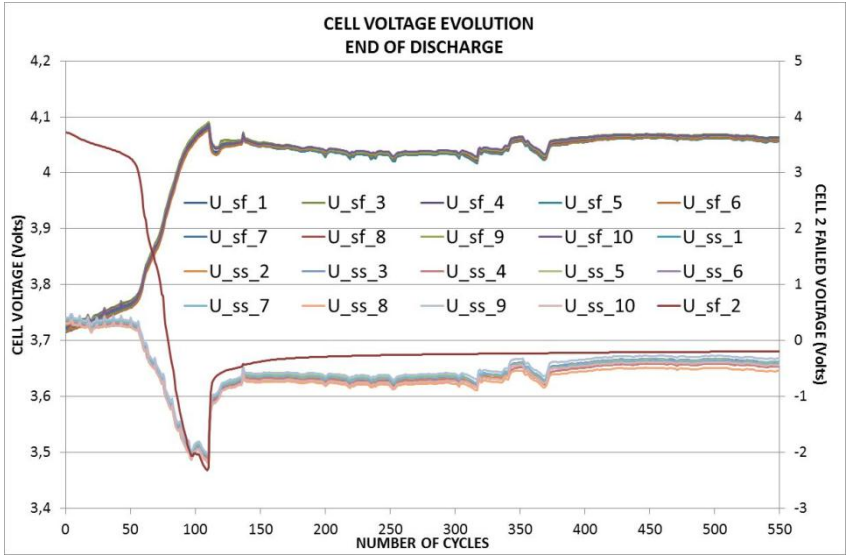


Cell soft short-circuit in s-p configuration

- ESA and Saft performed a simulation of a cell soft short on a 10s2p battery, using Saft VES16 cells (4.5 Ah). The battery was cycled in LEO representative conditions (30 minutes C/2 discharge)







From "EFFECT OF AN INDUCED CELL SOFT-SHORT AT A VES16 BATTERY MODULE"
Maria Nestoridi[1] , Olivier Mourra[1] , Edouard Mosset[2] , Stéphane Lefeuvre[2] , Stéphane Remy[2]
[1] : ESA/ESTEC, [2] : Saft
presented at the 10th European Space Power Conference 2014 (ESA conference proceedings SP-719)
Reproduced with permission

Cell soft short-circuit in s-p configuration

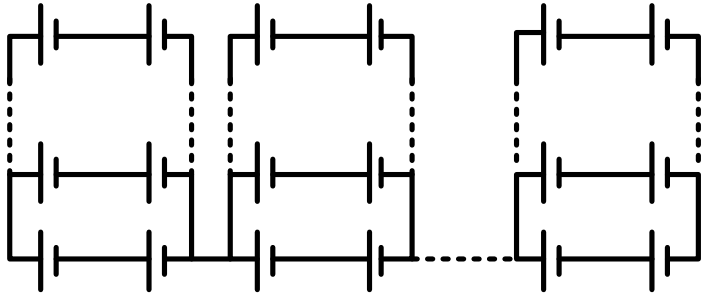
- Saft and ESA showed that the VES16 cell is able to be safely charged from 4.05V to 4.5 V, for more than 400 cycles.

- This may not be the case for other types of cells, for which charging at such a high voltage is strictly forbidden.

- The long term consequence of such repeated but mild overcharge could be benign (ending up with the activation of one CID), or catastrophic (thermal runaway, with risks of propagation to other overcharged cells). It is anyway strongly dependent on the cell characteristics, and requires long term testing in test chambers suitable for abuse testing.

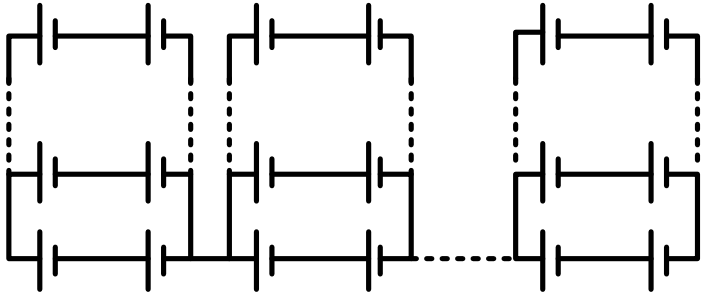
- It could be preferable to modify the battery architecture so that the overcharge of the cells is more straightforward, resulting in an efficient passivation of the soft short failure.

A combined architecture: series-parallel-series



- Limiting the number of cells in series to two or three guarantees that in case of a cell soft short, the remaining cells will maximize their chance to activate the CID.
- The number of overcharged cells is lower. The risk of thermal runaway and propagation is reduced.
- As presented by Augeard et al. (IEEE Transactions on Components, Packaging, and Manufacturing Technology, July 2016), such a configuration mitigates the risk of electrical arcing in case of battery external short circuit. The voltage across the CID stays below arc ignition voltage (19 V), until the last cell opens.

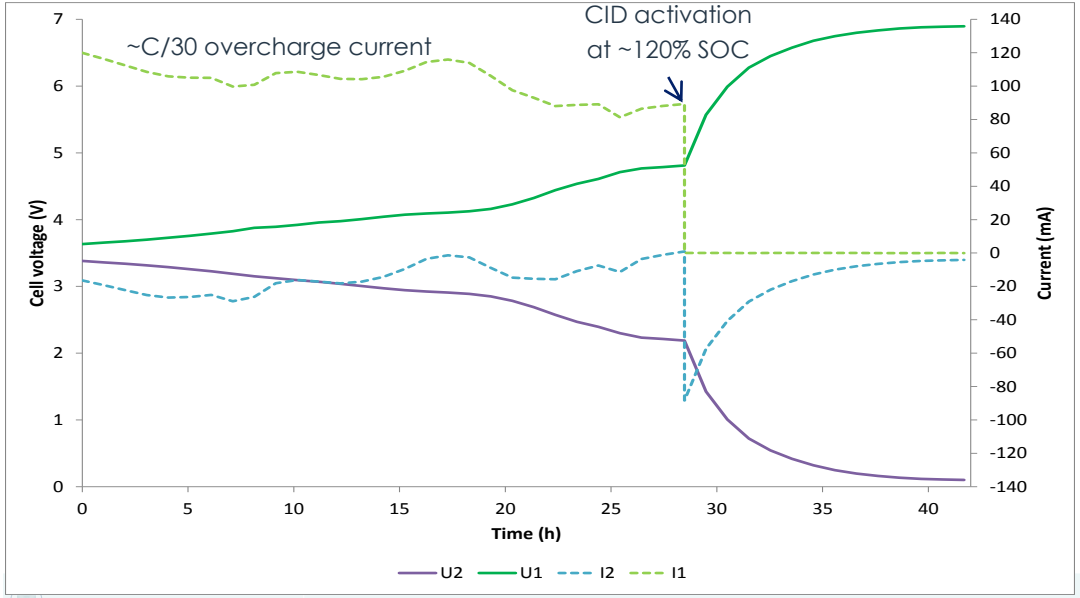
A combined architecture: series-parallel-series



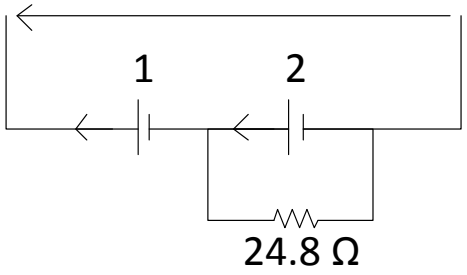
- As for a pure series parallel battery, such a battery has to be sized considering a max DoD compatible with the loss of some sub-strings.
- The sub-pack where the failure occurs will be less charged than the other sub-packs, by a ratio of less than 50%/(p-1). If p is high (more than 10 strings in //), the impact is negligible.

Cell soft short-circuit in 2s configuration - Overcharge at low current

- CID activation requires a relatively high overcharge current (≥C/10). But In case of soft short occurring when the battery is not active (during storage for instance), the overcharge current can be very low.
- In this case, two LG MJ1 cells were connected in series, and then connected to a 7 V source. One resistor was then connected to cell #2 to induce a soft short.

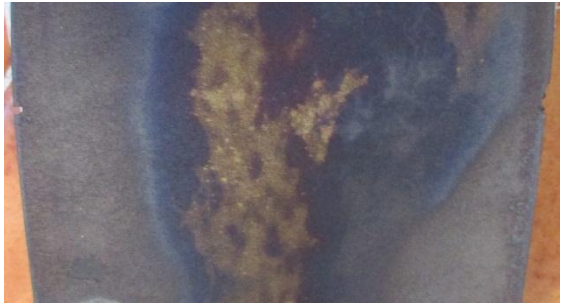


7 V voltage source



Cell soft short-circuit in 2s configuration - Overcharge at low current

- The same experiment was conducted on another type of 18650 COTS cell (2200 mAh).
- The CID did not activate, but the DC resistance of the overcharged cell became very high (several ohms), which efficiently and safely limits the current in the string.
- Cell internal pressure was high, causing electrolye leak at the gasket after a few days.
- Significant Li deposit was found on the negative electrode.



- Since the results depend strongly on the cell characteristics (CID mechanical design, internal free volume, electrolyte composition…), each cell type should be tested.

Conclusion

- In a series parallel battery, a soft short of one cell results in overcharging the other cells from the same string.
- Depending on several factors (including the size of the string), the overcharge can or cannot activate the cell CID.
- Each cell type may behave differently, and requires testing.
- Limiting the size of the string to two or three cells in series maximizes the chance to have a clean activation of the CID, or at least a large increase of cell resistance. This results in a passivation of the failure, and prevents efficiently any further safety concerns.