Journey to a New Regulatory Option

Internal Short Detection/Thermal Runaway Prevention

OICA Submission to IWG for GTR 20, Phase 2
December 2019 – IWG #19, Berlin

Agenda

Part 1 – Roadmap towards a Regulatory Framework

Part 2 – Thermal Runaway and Thermal Propagation Detection on Cell Level

Part 3 – Thermal Runaway and Thermal Propagation Detection for more than one Cell

Overall Conclusions

Part 1 – Roadmap towards a Regulatory Framework

Roadmap Thermal Runaway

1. **Introduce concept that detection is possible – COMPLETE**
   - IWG meeting #15, Beijing (March 2018)
   - EVS1536-613
2. **Describe scientific basis for safe/unsafe zones and analysis methods to support development – COMPLETE**
   - IWG meeting #18, Tokyo (June 2019)
   - EVS18-E1TP-0400
3. **Provide examples of how internal shorts can be detected, including potential alternative method – TODAY**
   - IWG meeting #19 (December 2019)
4. **Describe acceptable risk concepts and levels – How good does detect/prevent need to be?**
   - By mid 2020
5. **Demonstrate successful detection and benefit when detection occurs**
   - Mid 2020
6. **Develop conceptual regulatory framework**
   - Late 2020
7. **Write draft regulatory language**

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KEY MESSAGE:

Under some circumstances, cell internal shorts are detectable. This detection may provide opportunity to take action prior to thermal runaway, thereby completely preventing thermal runaway propagation.

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KEY MESSAGE:

Proven scientific principles can be used to explain thermal runaway behavior, including how it is possible to have an internal short without thermal runaway.

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KEY MESSAGE:

Since thermal runaway is a mechanical/thermal/electrochemical phenomenon, characteristics and behaviors associated with lithium ion battery thermal runaway are detectable, in some cases prior to onset of thermal runaway.

Part 2 - Thermal Runaway and Thermal Propagation Detection on Cell Level

Process description of self-accelerating thermal runaway

- Observational models are already very detailled and consolidated in scientific literature

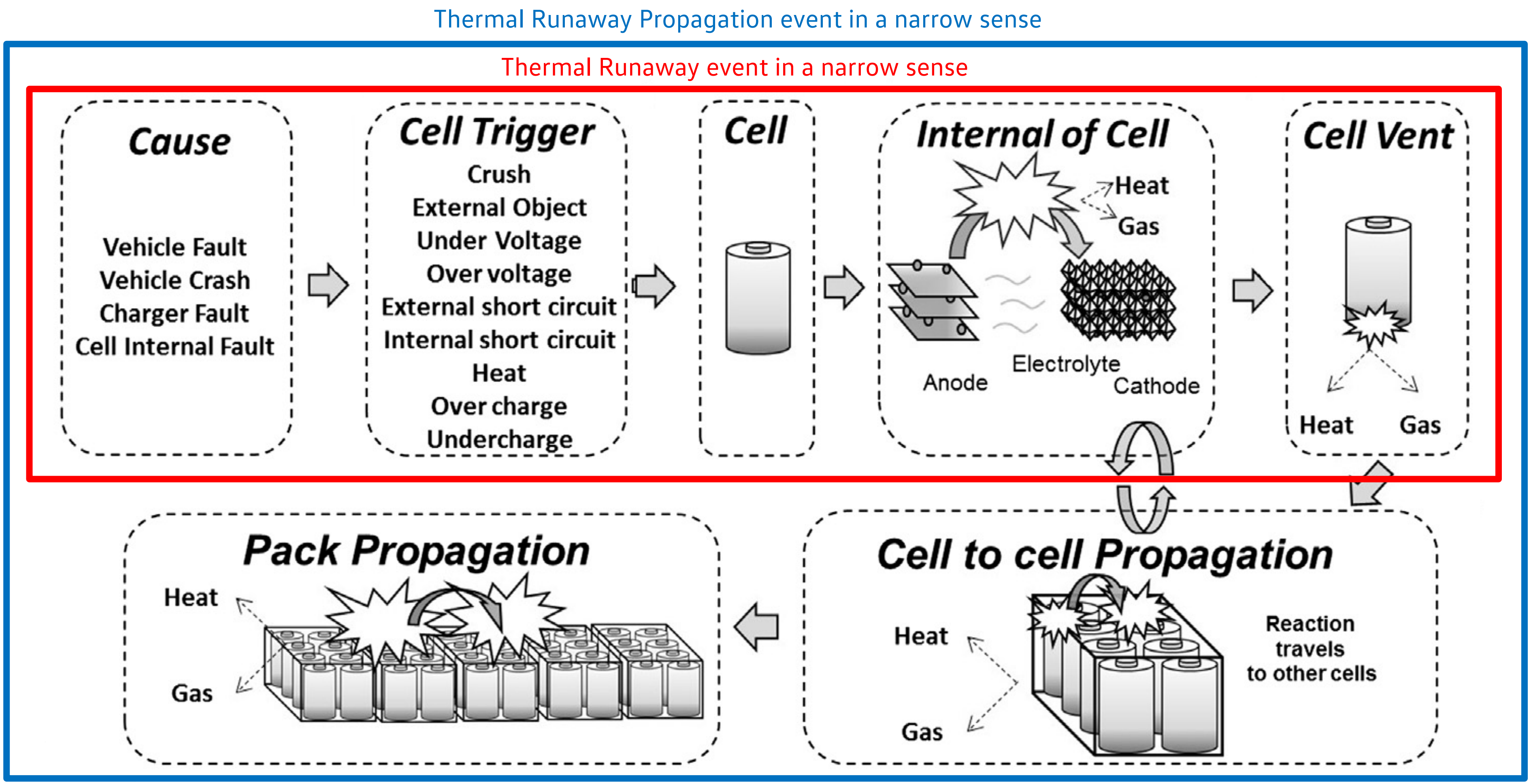


Figure 1 – Observational layer of Thermal Runaway and Thermal Runaway Propagation failure. source: modified, taken from [1]

Thermal events and their detection measures: overview

Process step	Event name	Corresponding EUCAR Hazard Level	Classification	Example for a possible detection method
1	internal short circuit	0 or higher	predictive	voltage measurement [...]
2	heating of the cell	0 - 2	predictive	temperature measurement; plausibility models [...]
3	swelling of the cell	1	predictive	strain measurement; force measurement [...]
4	electrolyte leakage/gas release/venting (white smoke)	3 or 4	reactive	gas sensors; gas pressure sensor in battery hosuing; smoke sensor; voltage measurement [...]
5	gas release/venting (black smoke)	>= 4	reactive	gas sensors; smoke sensor [...]
6	accelerated heating	>= 2	reactive	temperature measurement [...]
7	collapsing of separator	>= 2	reactive	voltage measurement [...]
8	thermal runaway of the cell	>= 5	reactive	temperature measurement; luminance sensor [...]

Table 1 – Correlation of EUCAR Hazard levels and examples for possible detection methods. source: [3]

Thermal events and their detection measures: classification

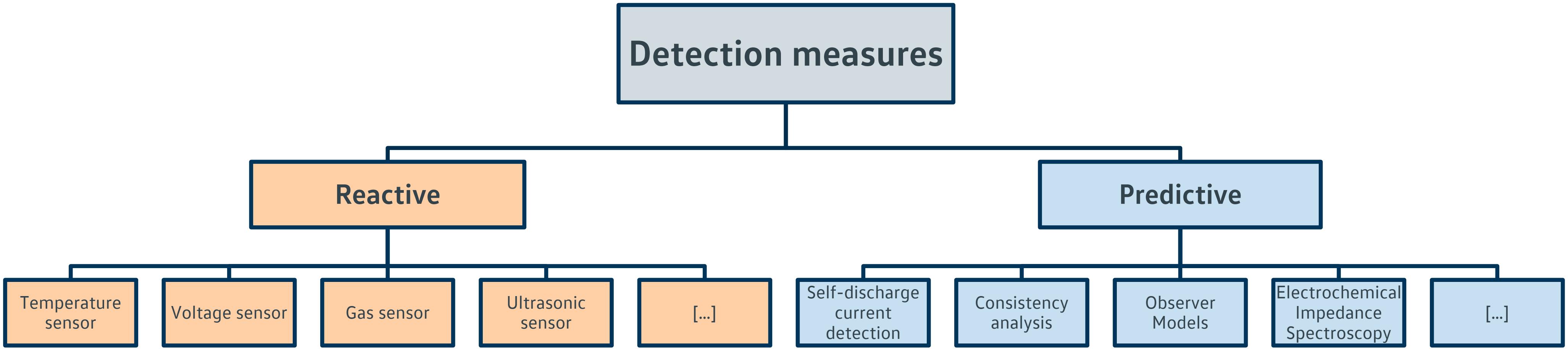


Figure 2 – Classification of detection measures.

- Lots of different detection measures exist
- Detection methods that react **directly** upon a thermal event can be called „**reactive**“
- Detection methods that react **in a certain advance of** a thermal event can be called „**predictive**“

Thermal events and their detection measures: examples

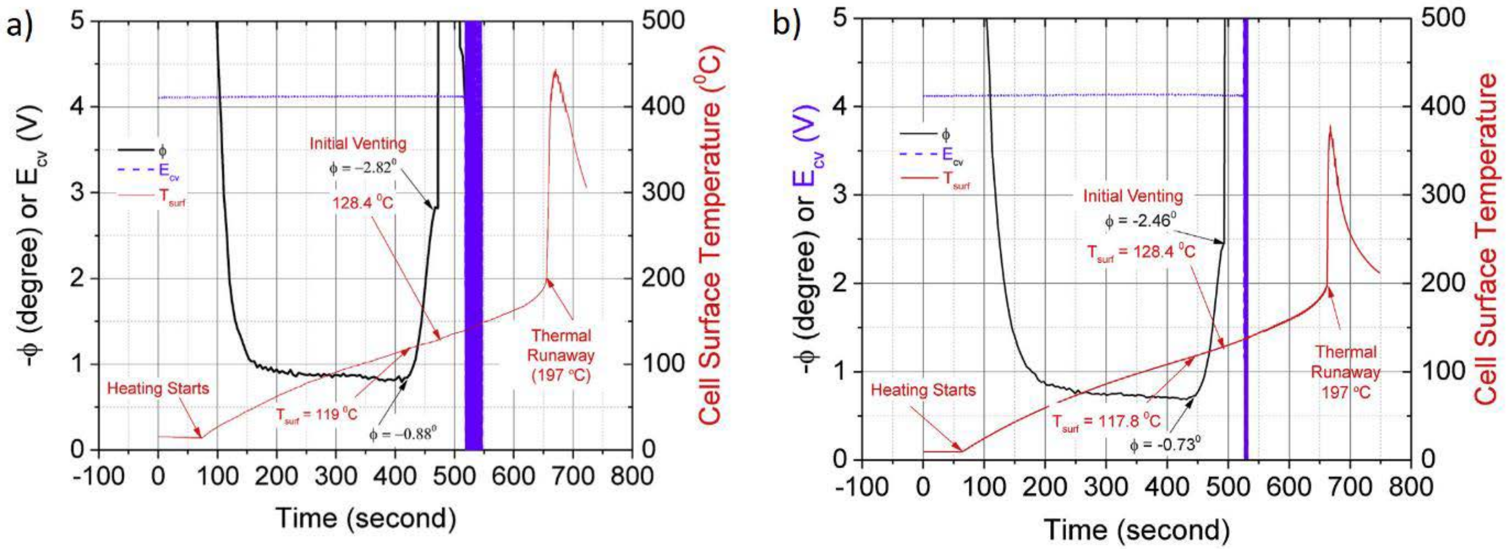


Figure 3 – Illustration of Electrochemical impedance spectroscopy. source: [3]

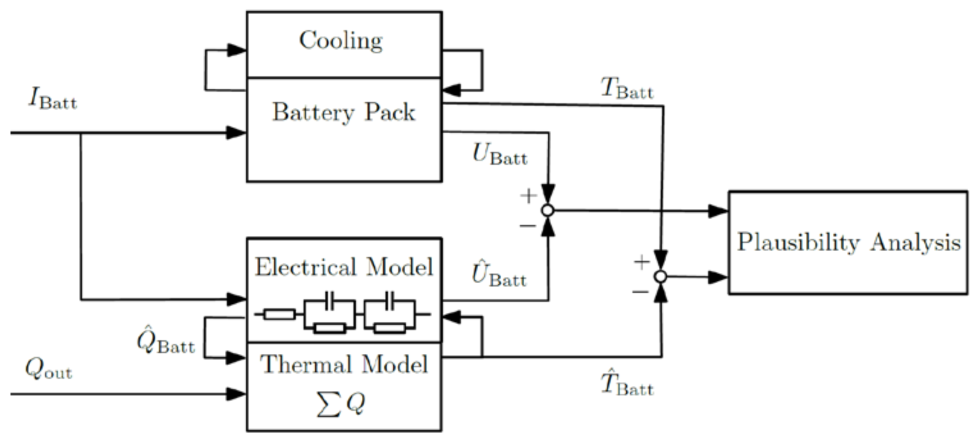


Figure 4 – Illustration of an observer model. source: [3]

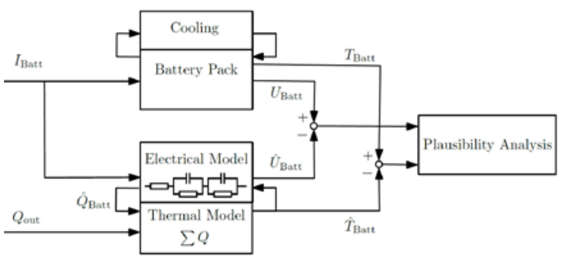
Thermal events and their detection measures: state of the art

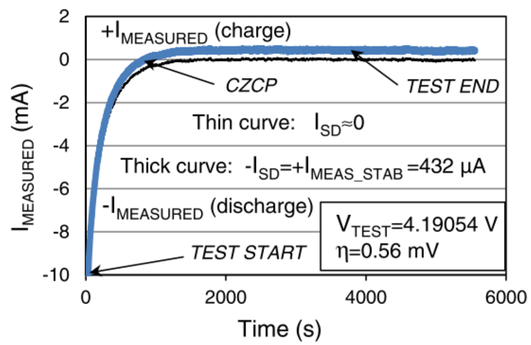
in application or in concrete development	in longer-term development or still research
voltage sensor	electrochemical impedance spectroscopy
temperature sensor	consistency analysis
gas sensor	self-discharge current detection
pressure sensor	observer models
	ultrasonic sensor

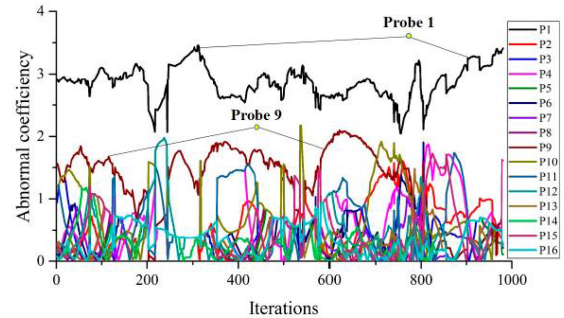
Table 2 – State of the art of detection methods

Thermal events and their detection measures: details on predictive m.

- Predictive methods are often more complex
- Predictive methods can yield higher time spans for mitigation measures
- Real-time applicability of predictive methods is under development







Observer models	Self-discharge current measurement	Consistency with battery pack
+ does not require additional sensors onboard (T, I and V sensors needed)	+ effective	+ inexpensive + easy to implement onboard
- complex - requires computational resources - can be hard to verify/adapt to different cell types	- time-intensive - costly - complex - no direct detection of TR triggered by thermal, mechanical or electrical abuse	- relies on external temperature readings - tresholds for deviations from conditions are arbitrary/empirical

Table 3 – Exemplaric Comparison of different predictive detection measures. Source: [3],[4]

Thermal events and their mitigation measures

- Lots of different mitigation measures exist
- Active mitigation measures can be controlled in real-time and can be triggered by **predictive detection techniques**
- Passive mitigation measures react in a predifined way if a thermal event occurs
- Electrode design plays a significant role

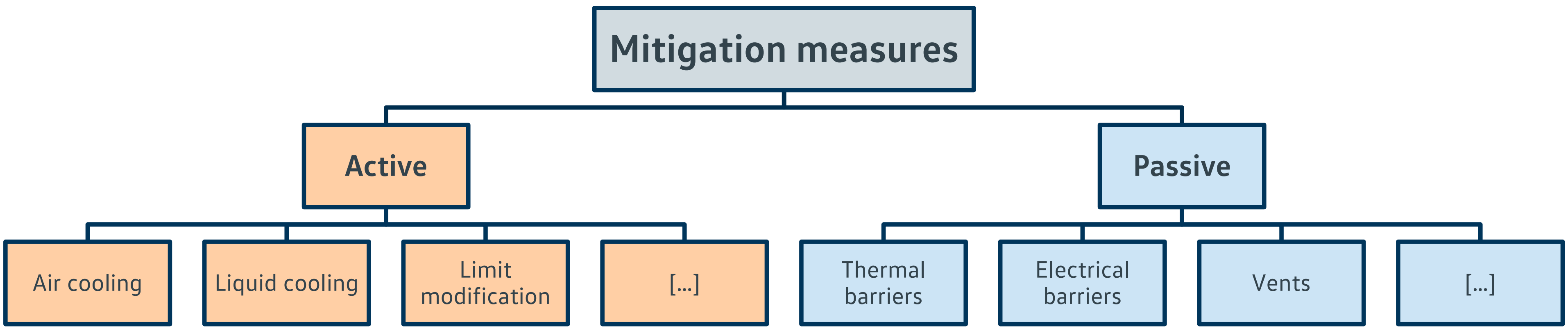


Figure 3 – Classification of mitgation measures.

Summary of Part 2

(1) Thermal runaway and thermal propagation can be described **well as a sequence of different chemical and physical events**. These events don't occur randomly, **but follow typical sequences**.

(2) All different events in a thermal runaway or thermal propagation situation can be detected by specific and dedicated detection methods that use different types of physical or chemical signals.

(3) Detection methods are widely independent from each other, have different timescales and correspond to different hazardous situation (as describable by EUCAR Hazard Level classification)

(4) Detection principles can be subdivided into predictive and reactive principles. **All of them have their benefits and drawbacks and their application is state of science and technology**.

Part 3 - Thermal Runaway and Thermal Propagation Detection for more than one cell

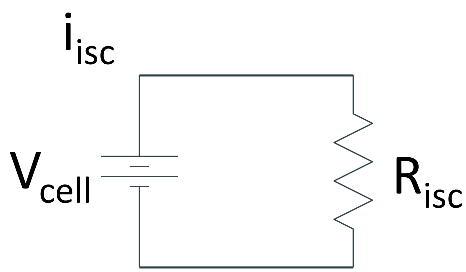
Types of Shorts

1. Immediate Short
    - Largely managed by cell design and manufacturing control
    - Possibly detectable during manufacturing process

2. Developing Short
    - Likely not possible to fully prevent
    - Possibly detectable during usage
    - Requires appropriate cell measurements and diagnostic algorithms
    - Assumes that short develops over multiple cycles / days

Why These Methods Work:

- Simple circuit model

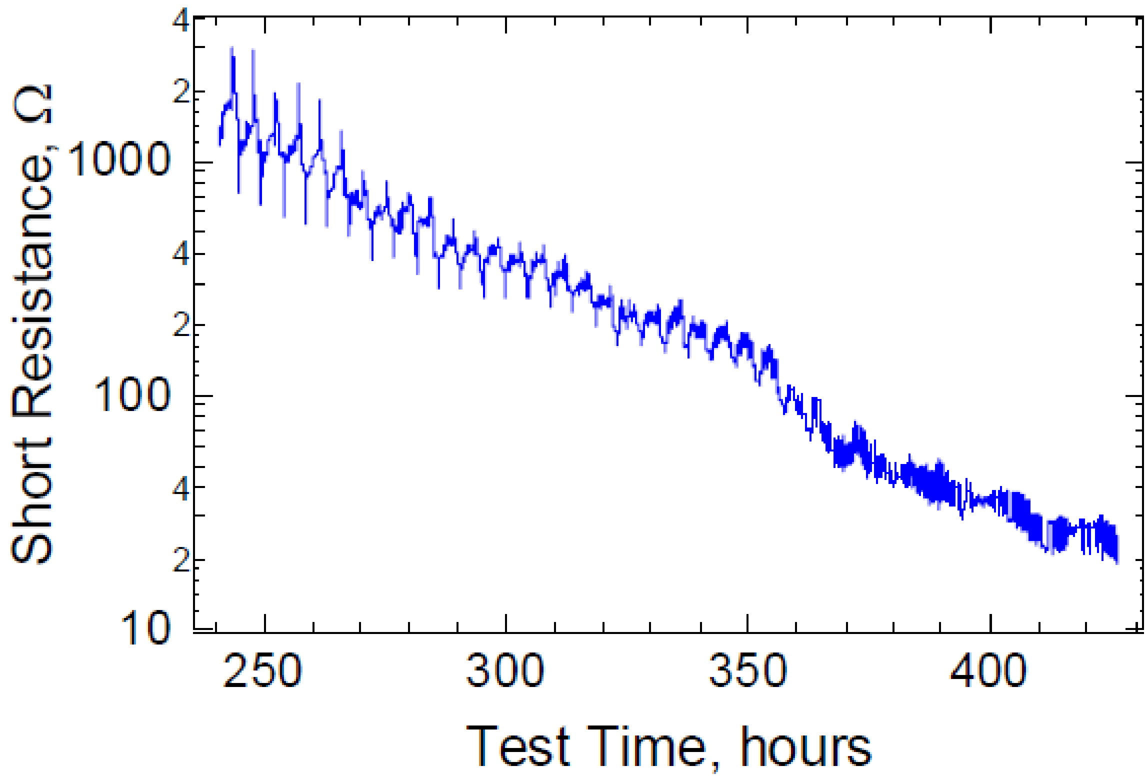


$$E_{dis} = \int V_{cell} \cdot i_{isc} \, dt$$

- Since stored energy is proportional to battery voltage, as energy is dissipated through resistance, battery voltage drops.

- Voltage reduction is observable.

Internal Short Resistance Behavior In Use



- Resistance reduces over time
- Cell energy (∴ voltage) is reducing throughout time
- As energy loss integrates over time, cell voltage may reach detectable level prior to short circuit at critical level

Figure 4 (from McCoy, C., Sriramulu, S., Stringfellow, R., Ofer, D. & Barnett, B. Lithium-Ion Battery Safety: Detection of Developing Internal Shorts and Suppression of Thermal Runaway. 46th Power Sources Conference, 2014.)

Internal Short Detection – Cells in Series Special Case

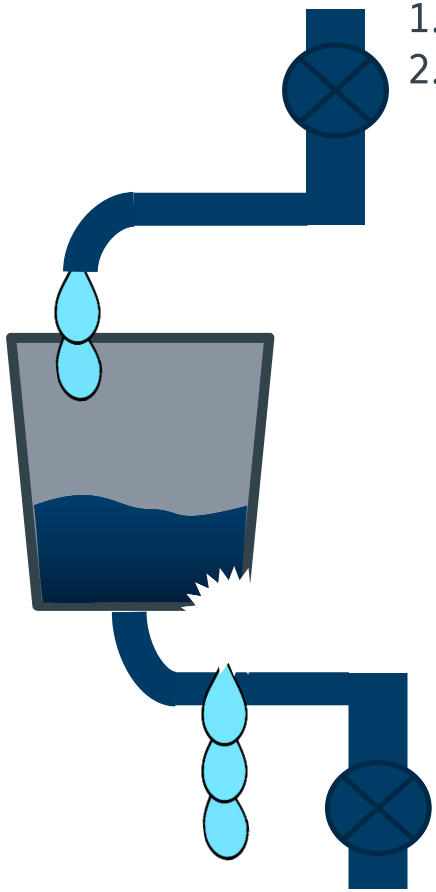
- A battery system with numerous cells in series may enable detection of an internal short before it reaches a critical level, unique from single cell configurations.

- The effect of the internal short integrates over time and may become detectable prior to reaching a critical level of resistance

- Due to the presence of other cells in series, the energy lost due to the internal short cannot be replaced during charging

- This may enable a voltage measurement to identify the presence of the internal short
  - Impacted by voltage balancing algorithms and hardware which will lessen the observed effect

Water Bucket Analogy – One Bucket

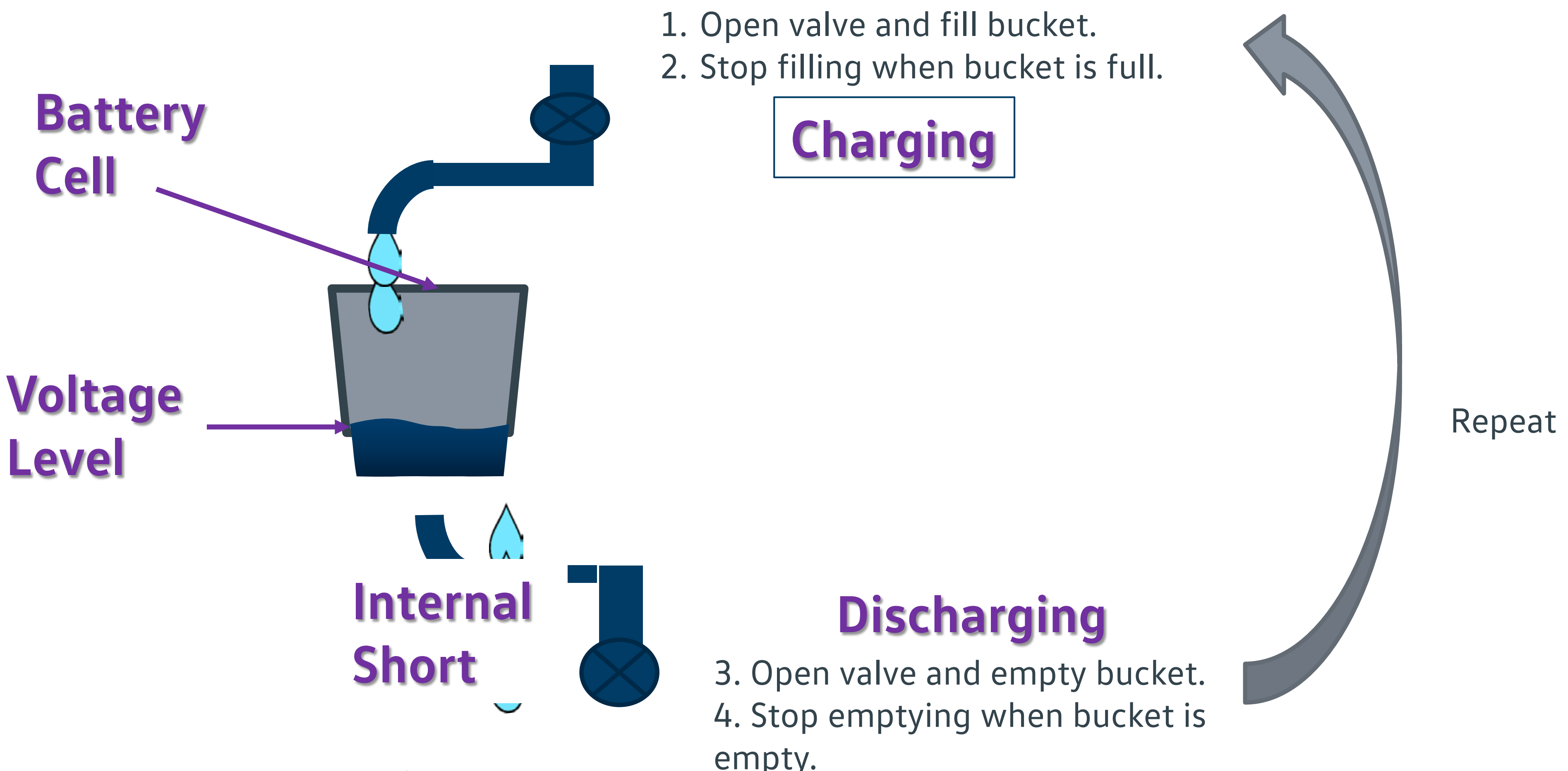


1. Open valve and fill bucket.
2. Stop filling when bucket is full.
3. Open valve and empty bucket.
4. Stop emptying when bucket is empty.

What happens over time?

Amount of water put into bucket is more than comes out (through pipe). If amount is small, unlikely to notice.

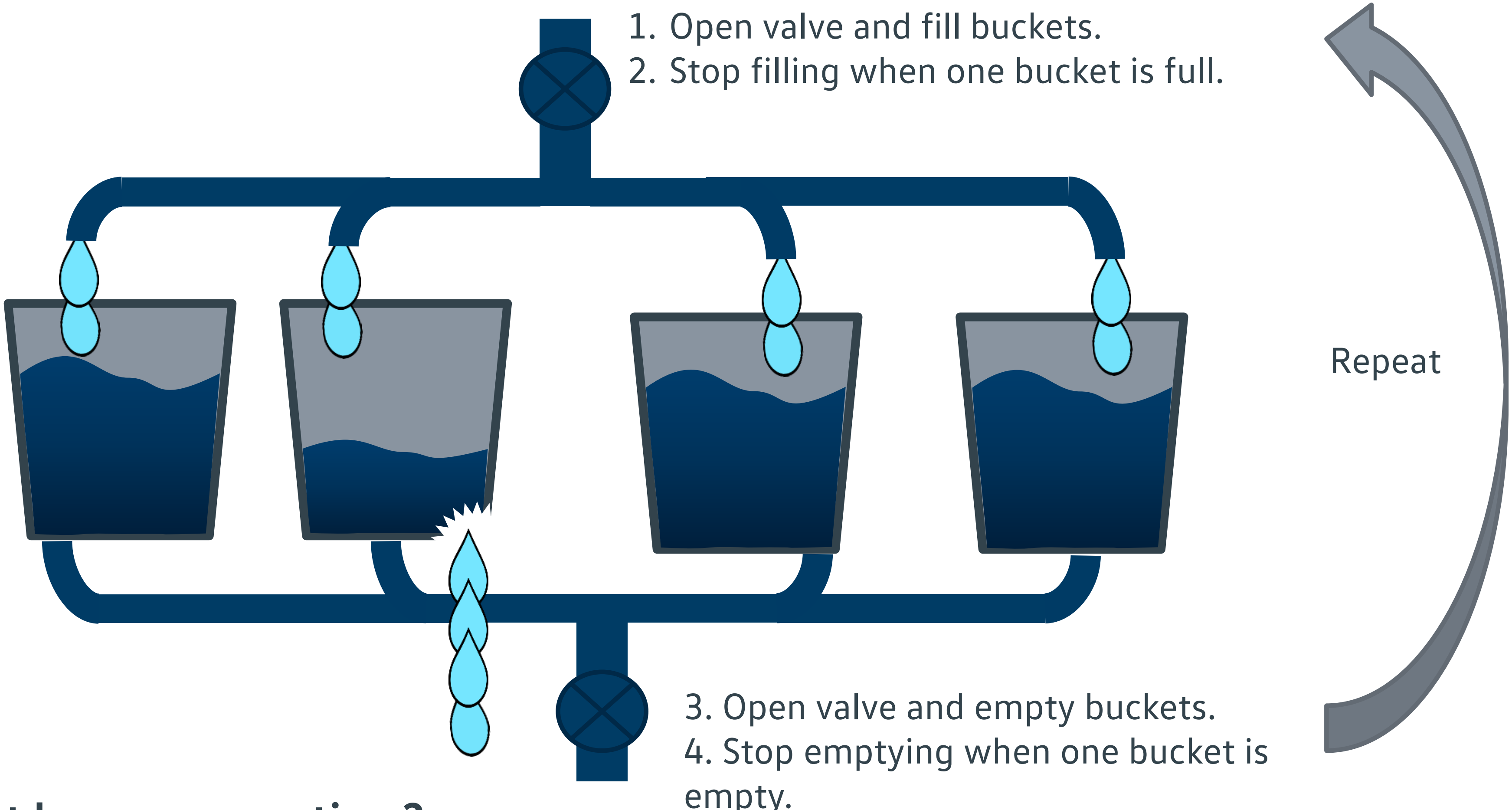
Water Bucket Analogy – One Bucket – Explained



What happens over time?

The voltage of the cell with an internal short is not different from normal. Leak simply looks like normal discharge.

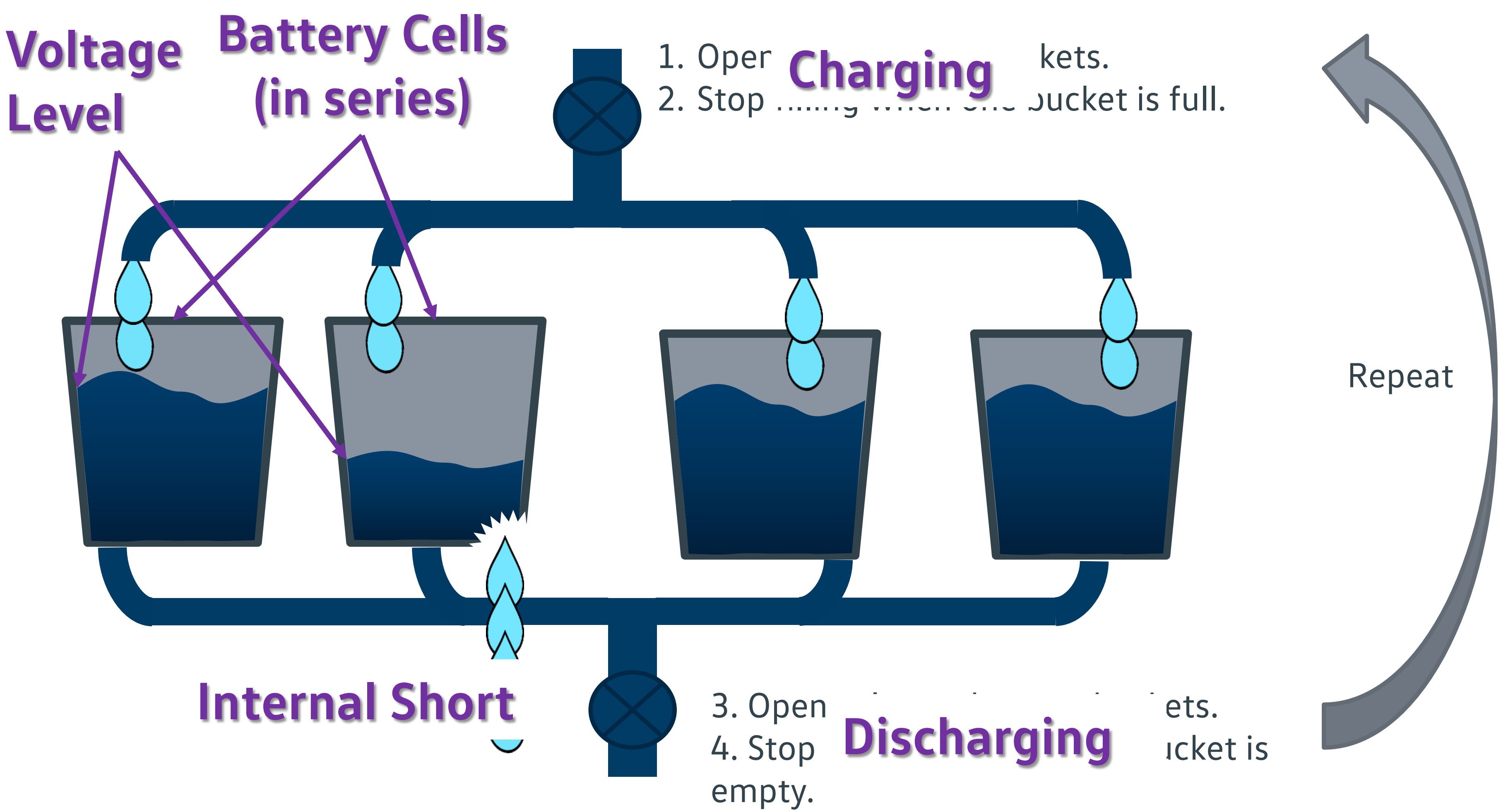
Water Bucket Analogy – Multiple Buckets



What happens over time?

The level in the leaky bucket goes down.

Water Bucket Analogy – Multiple Buckets - Explained



What happens over time?

The voltage of the cell with an internal short goes down, compared to the others.

Summary of Part 3

1. A battery system with numerous cells in series may enable detection of an internal short before it reaches a critical level

   A single cell cannot do this since the cell is completely recharged each cycle.

2. Early detection of an internal short may enable preventative actions to be taken, prior to entering thermal runaway.

Overall Conclusions

1. Since thermal runaway and thermal propagation can be described well as a sequence of different chemical and physical events, both of them detectable.
2. Detection principles can be subdivided into predictive and reactive principles. Predictive detection principles are increasingly applied in the automotive industry.
3. A battery system with numerous cells in series may enable detection of an internal short before it reaches a critical level.
4. Early detection of an internal short may enable preventative actions to be taken, prior to entering thermal runaway.

=> **Focus should be given on the detection and detectability of thermal runaway and thermal propagation and not on the creation of more or less artificial trigger situations.**

Backup

Literature

[1] Garche, J.; Brandt, K.; 2018. Li-battery Safety. Kidlington (Oxford, UK): Elsevier.

[2] Feng, X; Ouyang, M. et al.; 2018. Thermal runaway mechanism of lithium ion battery for electric vehicles: A review. Energy Storage Materials, vol. 10, pp. 246-267, 2018.

[3] Benger, R.; Grabow, J. et al.; 2019. Thermal runaway detection study. Goslar, 2019.

[4] Braglia, M.; Baxendale, A., 2019. Thermal Runaway and Thermal Runaway Propagation Detection. Warwickshire, 2019.

[5] Wu Y., Wang W., Yung W., Pecht, M., 2019. Ultrasonic health monitoring of lithium-ion batteries. In: Electronics, Vol. 8, No. 7, p. 751ff, 2019.

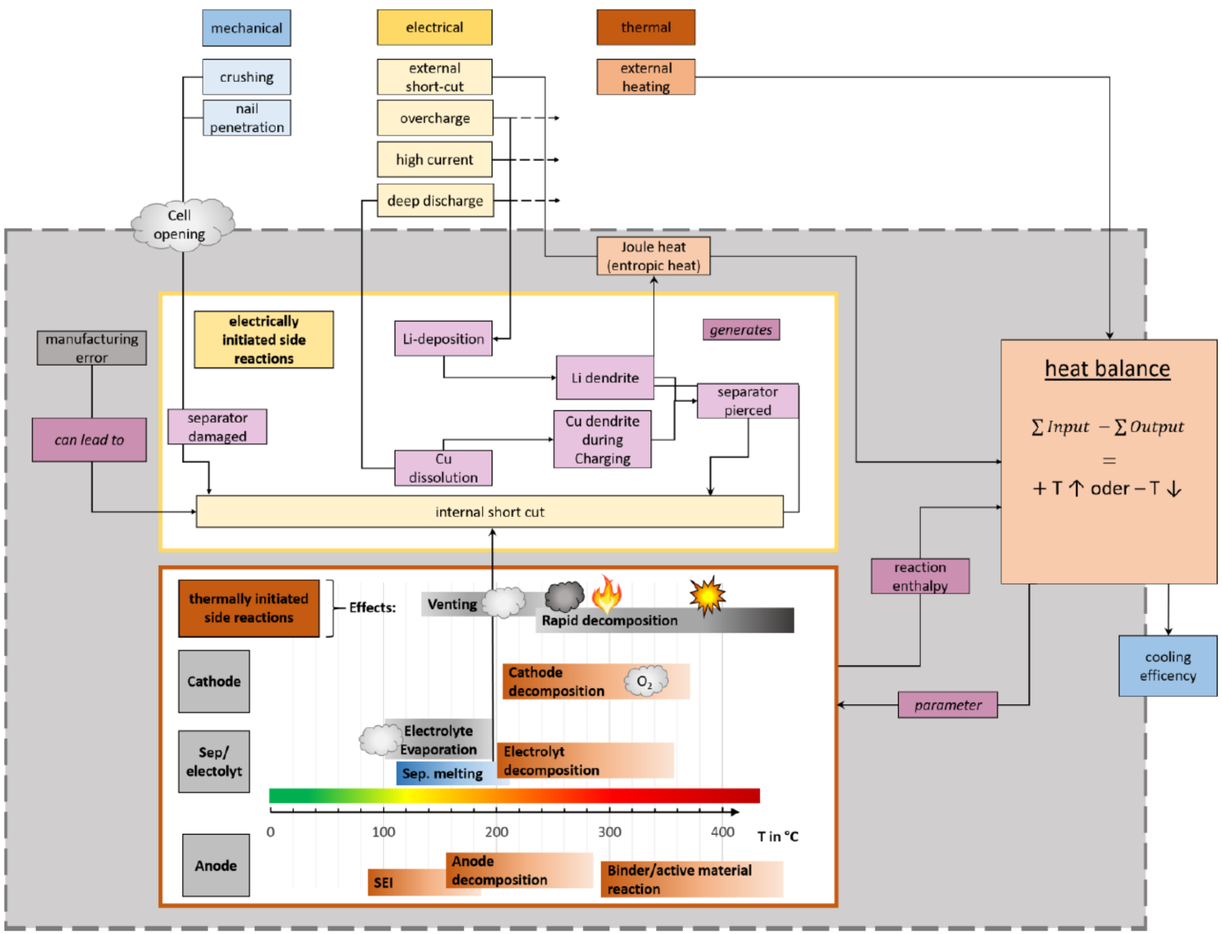
[6] Zheng Y., Han X., Lu L., Li J., Ouyang M., 2013. Lithium ion battery pack power fade fault identification based on Shannon entropy in electric vehicles. In: Journal of Power sources, Vol. 223, pp. 136-146.

[7] https://medium.com/udacity/shannon-entropy-information-gain-and-picking-balls-from-buckets-5810d35d54b4. Accessed on 20.09.2019

[8] Sun Z., Liu P., Wang Z., 2017. Real-time fault diagnosis method of battery system based on Shannon Entropy. In: Energy Procedia, Vol. 105, pp. 2354-2359, May 2017.

Process description of self-accelerating thermal runaway

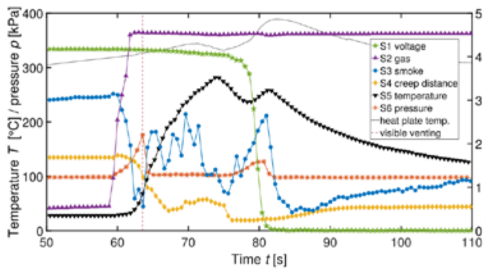
- The combination of the observational layer with the chemical layer gives access to a mathematical layer which (approximately) can describe thermal runaway processes

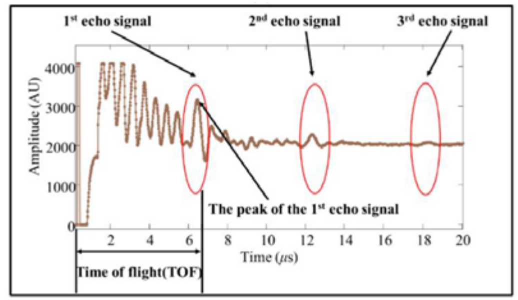


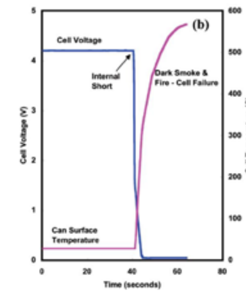
Mathematical layer of thermal runaway. source: [3]

Thermal events and their detection measures: reactive measures

- Reactive methods can provide warning signals
- Reactive methods are often late in detection and thus the time span to mitigate is smaller than for predictive methods







Multi-sensor	Ultrasonic sensor	Temperature sensor
+ can provide early warning of TR + easy implementation on-board possible	+ implementation as on and off-board-tool possible + can detect changes in internal structure and temperature of cells + can be applied on all kinds of cell chemistries	+ can infer the internal temperature of a cell + in case of certain I,V signals (i.e. square waves) it can be applied onboard
- temperature and voltage sensors are not effective to detect TR under certain conditions - more prone to sensor failure - increased system cost and complexity - false alarms can be generated since some signals (e.g. pressure signals) can occur during normal battery operation	- method is largely unexplored	- The adaption and interpretation for different cell chemistries might be cumbersome

Exemplaric comparison of different reactive detection measures. Source: [3], [4]