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SUVEREN 2use

THERMAL RUNAWAY IN LITHIUM-ION-BATTERIES: HOW EMERGENCY COOLING REGAINS CONTROL

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MOTIVATION

Thermal runaway is a critical failure mechanism in lithium-ion batteries, characterized by a self-sustaining and uncontrollable rise in temperature and pressure within the cell. This phenomenon typically begins with localized **overheating due to internal short circuits**, overcharging, mechanical damage, or exposure to external heat sources. As the battery's internal temperature rises, it triggers exothermic chemical reactions, such as the breakdown of the electrolyte, or electrode materials, releasing additional heat and gases. [1,2]

Once initiated, thermal runaway rapidly propagates through the cell, often resulting in venting of **flammable gases, fire, or even explosion**. The released gases, including hydrogen, carbon monoxide, and hydrocarbons, contribute to the fire's intensity and pose significant health and environmental hazards. This chain reaction can spread to neighbouring cells, escalating into a catastrophic **battery pack failure**. Preventing thermal runaway is a critical focus of battery safety research. Strategies include improved thermal management systems, safer battery chemistries, and advanced sensors for early detection. In some scenarios, mitigating thermal runaway also involves assessing whether intensive cooling methods or controlled burning present a safer and more effective approach. Understanding the causes and **mitigation techniques** for thermal runaway is essential for **improving the safety and reliability** of lithium-ion batteries in various applications. [3,4]

METHOD

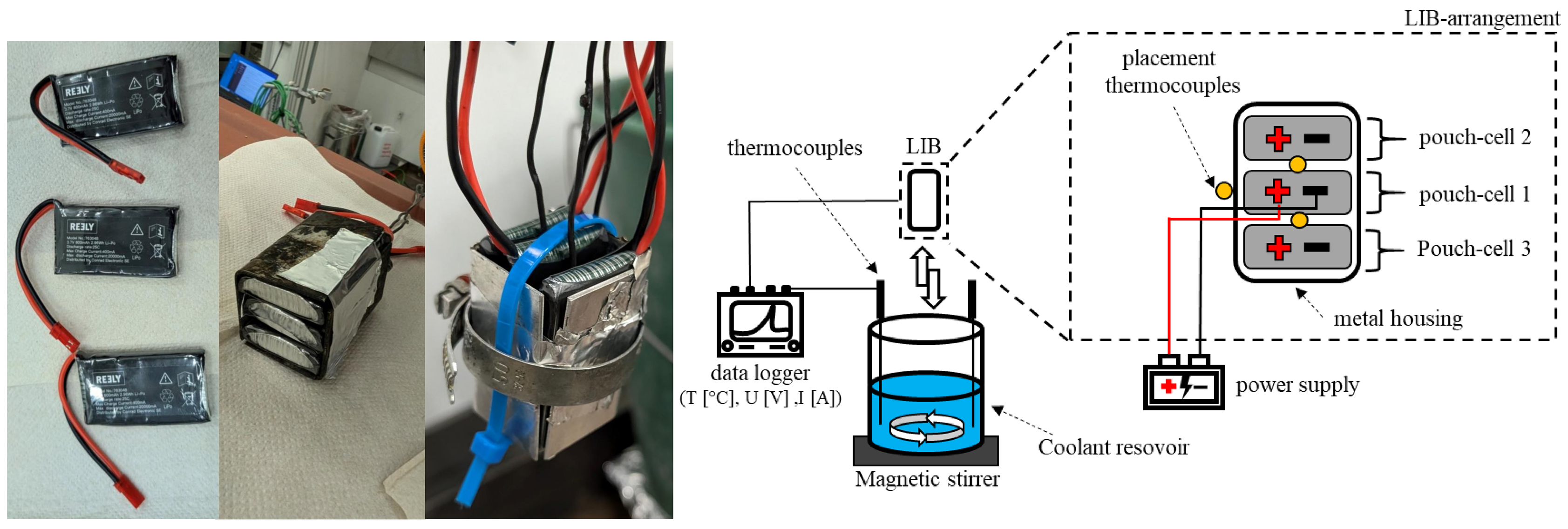

Figure 1: Experimental setup. Three cells packed together in a metal housing with thermocouples in between and on the outside of the housing (left) and schematic test setup (right)

Table 1: Relevant battery parameters of the used Li-Po pouch cells

Description	Manufacturer	Capacity [mAh]	Chemistry	L x B x D [mm]	Weight [g]
RE3LY 800	Conrad Electronic SE	800	$LiCoO_2$	51.5 x 39.8 x 8.2	25.88
RE3LY 400	Conrad Electronic SE	400	$LiCoO_2$	38.8 x 20.0 x 8.1	11.88

- **Arrangement:** Three cells in metal housing
- **Abuse:** Overcharging (constant current, 3C)
- **Record:** Temperature (type K thermocouples), voltage, current, video
- **Coolant:** Ultra-pure Water (18.2 MΩcm, 0.055 µS cm^{-1})
- **Analytic:** Ion chromatography ICS-200 System from Dionex

RESULTS

- Free Burning -

Figure 2: Thermal runaway of lithium-ion pouch cell.

Table 2: *Relevant timestamps in the thermal runaway of the analysed Li-Po cells. The data includes three experiments from free-burn testing and two experiments with emergency cooling. Timestamps were extracted from video recordings. The mean is denoted by $\bar{x}$, the standard deviation by s, Δ refers to the preceding point and the time of first venting*

Capacity [mAh]	First venting	First visible flame	Δ	Ignition of second cell	Δ	Ignition of third cell	Δ	End of visible reaction	Δ
	t [min]								
400	32.6	32.7	0.03	34.07	1.5	34.1	1.5	35.9	3.3
800	32.0	32.0	0.02	32.62	0.6	32.9	0.9	34.0	2.0
800	35.5	35.6	0.06	35.8	0.3	36.3	0.8	38.3	2.8
800	34.8	34.8	0.03	-	-	-	-	-	-
800	35.6	35.9	0.33	-	-	-	-	-	-
$\bar{x}$	34	34	0.1	34	0.8	34	1.1	36	3
s	2	2	0.1	2	0.6	2	0.4	2	1

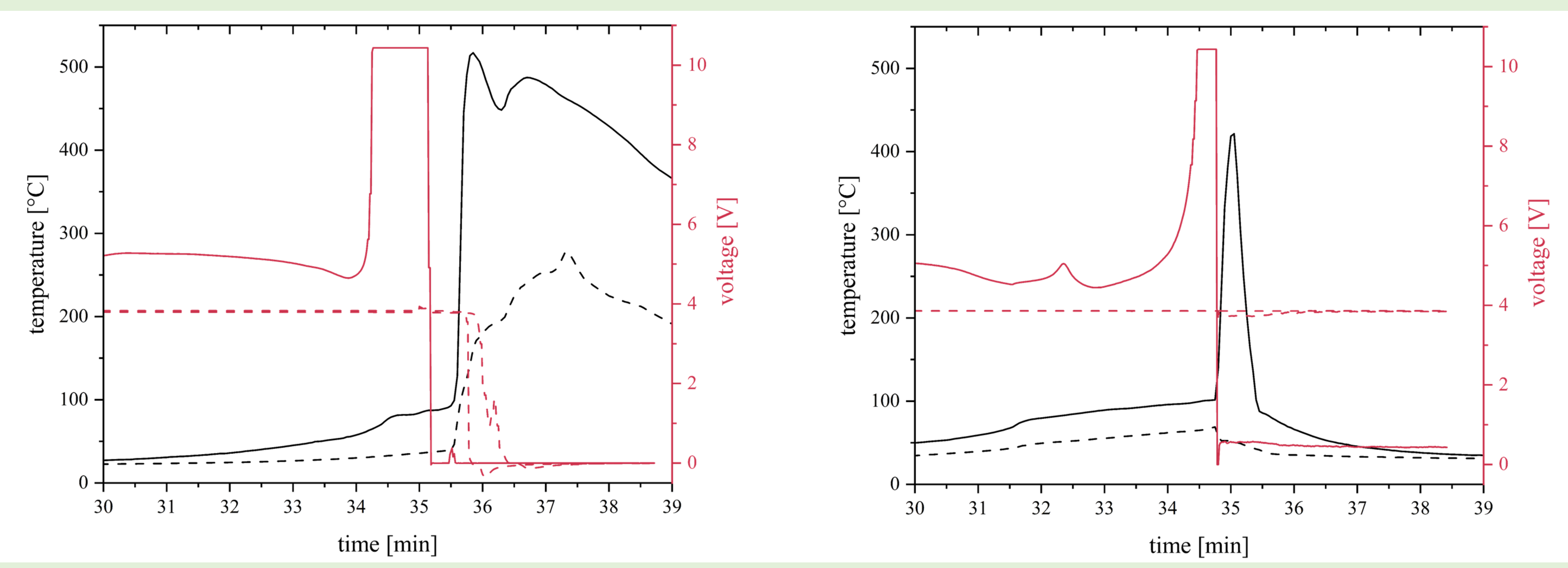

Figure 3: Temperature and voltage profiles of the free-burning test (left) and the test with emergency cooling (right). Black lines: temperature, solid line represents temperature between cells; dotted line represents temperature on the metal housing. Red lines: voltage, solid line represents the main cell; dotted line represents the neighbouring cell.

- Emergency Cooling -

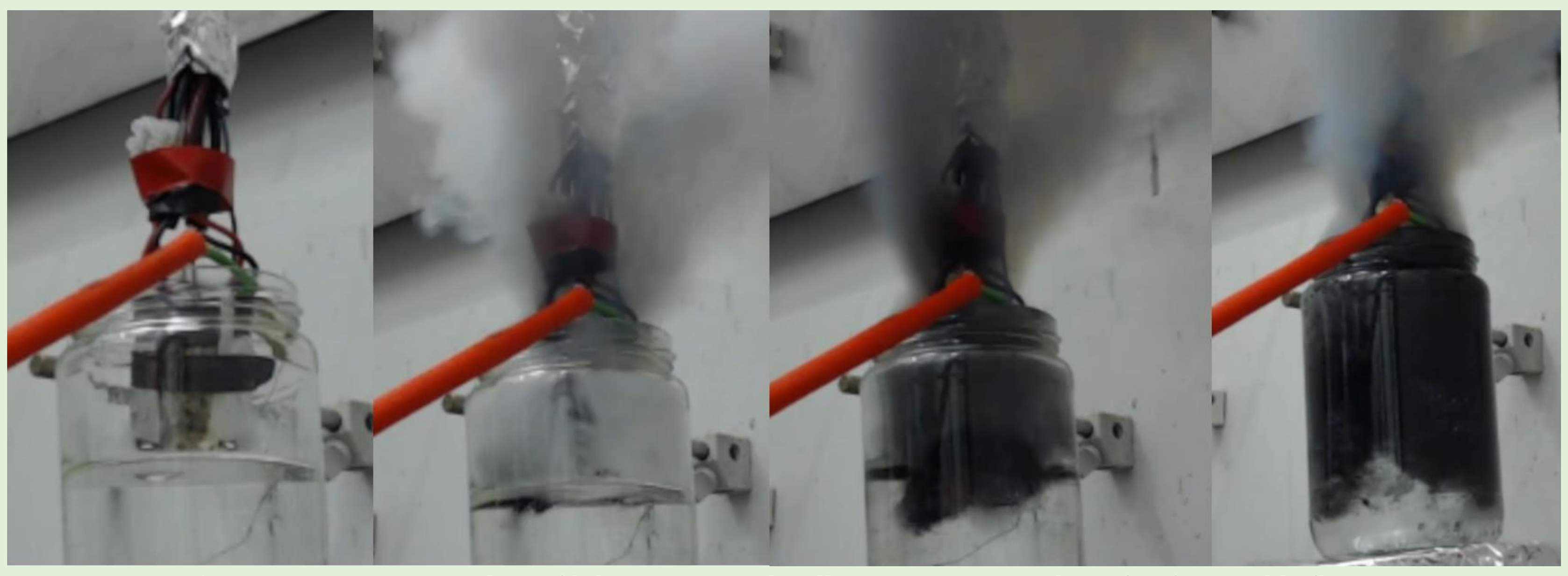

Figure 4: Emergency cooling of lithium-ion pouch cell. Immersion in coolant after first visible flame.

Table 3: *Mass of fluoride, calculated amount of $LiPF_6$ in the volume of the coolant and the recovery compared to the total mass $LiPF_6$ with $\omega(LiPF_6)_{400mAh} = 2.22$ % and $\omega(LiPF_6)_{800mAh} = 4.83$ % [5], respectively.*

Capacity [mAh]	β_{F^-} [mg L^{-1}]	$V_{coolant}$ [L]	n_{F^-} [mmol]	m_{LiPF_6} [g]	Recovery [%]	Commentary
400	56 ± 1	0.617	1.83	1.67	75.22	Ignition in coolant
400	55 ± 1	0.601	1.74	1.59	71.59	Ignition in coolant
400	37.6 ± 0.5	0.602	1.19	1.09	49.00	Immersed during venting
400	26.9 ± 0.4	0.576	0.81	0.74	33.51	Immersed right after ignition
800	15.5 ± 0.2	0.399	2.60	2.37	49.13	Immersed right after ignition
800	22.7 ± 0.4	0.484	2.31	2.11	43.67	Immersed right after ignition
800	23.8 ± 0.2	0.334	1.67	1.52	31.59	Extinguished with coolant
400	13.5 ± 0.2	0.595	0.42	0.38	17.35	Extinguished with coolant

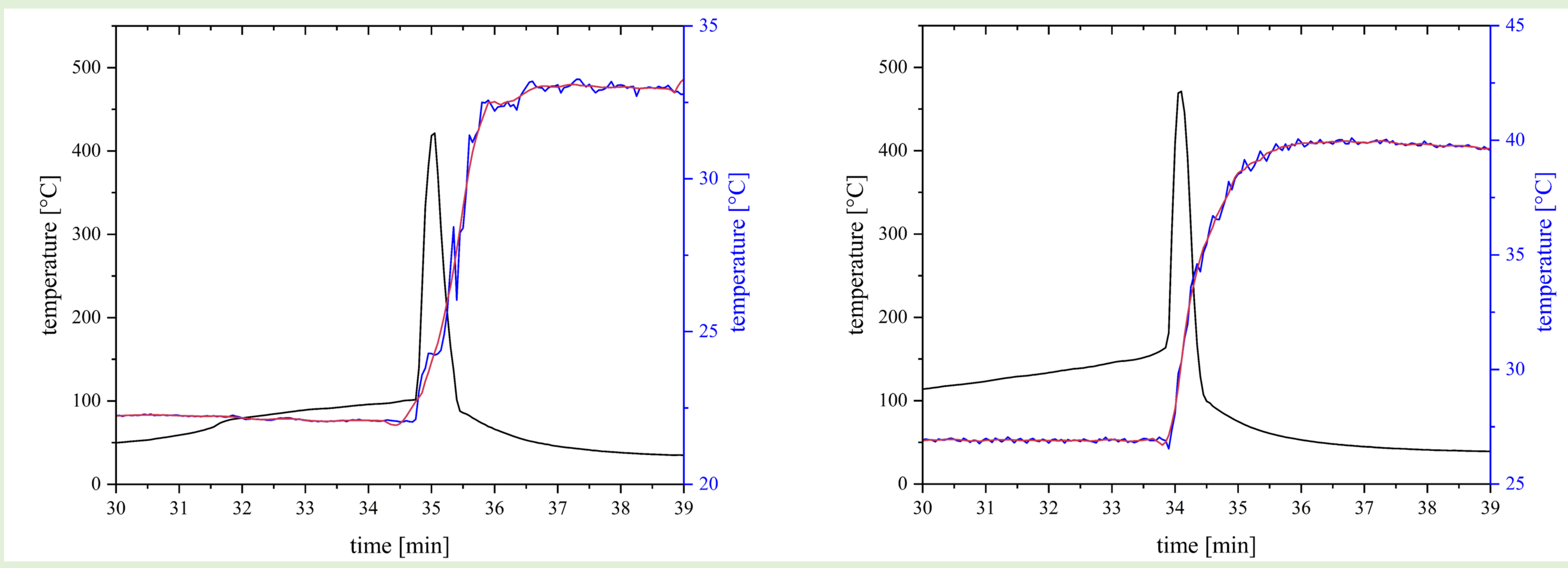

Figure 5: Temperature profiles of the main cell (black line) and the coolant (blue line) and smoothing by Savitzky-Golay filter, 21-point window (red line).

SUMMARY

This study investigated the thermal runaway behaviour of $LiCoO_2$ lithium-ion pouch cells under overcharge conditions and evaluated the effectiveness of emergency cooling using ultrapure water. The experiments demonstrated that **emergency cooling can effectively halt TR propagation** if applied at the first visible flame. Key warning signs, such as voltage spikes, collapse, and venting, reliably indicate the onset of thermal runaway, allowing for manual intervention, though an automated system could respond more quickly and consistently. Without intervention, adjacent cells also enter thermal runaway within minutes, and temperatures exceed 500 °C. Cooling without intervention takes up to 40 minutes, whereas immersion in water reduces surface temperatures below 100 °C in under a minute.

Although the main cell is irreparably damaged, propagation can be stopped. The **water absorbed (21.8 ± 0.2) kJ** of heat. However, when handling lithium-ion batteries, the release of electrolyte and formation of hydrofluoric acid from $LiPF_6$ pose safety concerns. The **amount of fluoride** released into the coolant water **depends highly on the time of intervention**. It can be assumed that, without intervention using water, large quantities of gaseous HF are released into the environment. An open question remains regarding the optimal coolant volume, temperature, and required contact area to prevent thermal runaway propagation effectively. Further research is needed to refine these parameters for real-world applications.

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