Blunt Nail Crush Internal Short Circuit Lithium-ion Cell Test Method

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Presentation Outline

- **Internal short-circuit of Lithium-ion Battery (LiB)**
  - Root cause(s) of internal short-circuit
  - Characteristics of internal-short circuit
- **UL Blunt Nail Crush (BNC) test**
  - Objectives and background of battery research
  - Summary of test method
  - Observed failure modes via BNC test
  - Cell properties vs. BNC test results
- **Summary**

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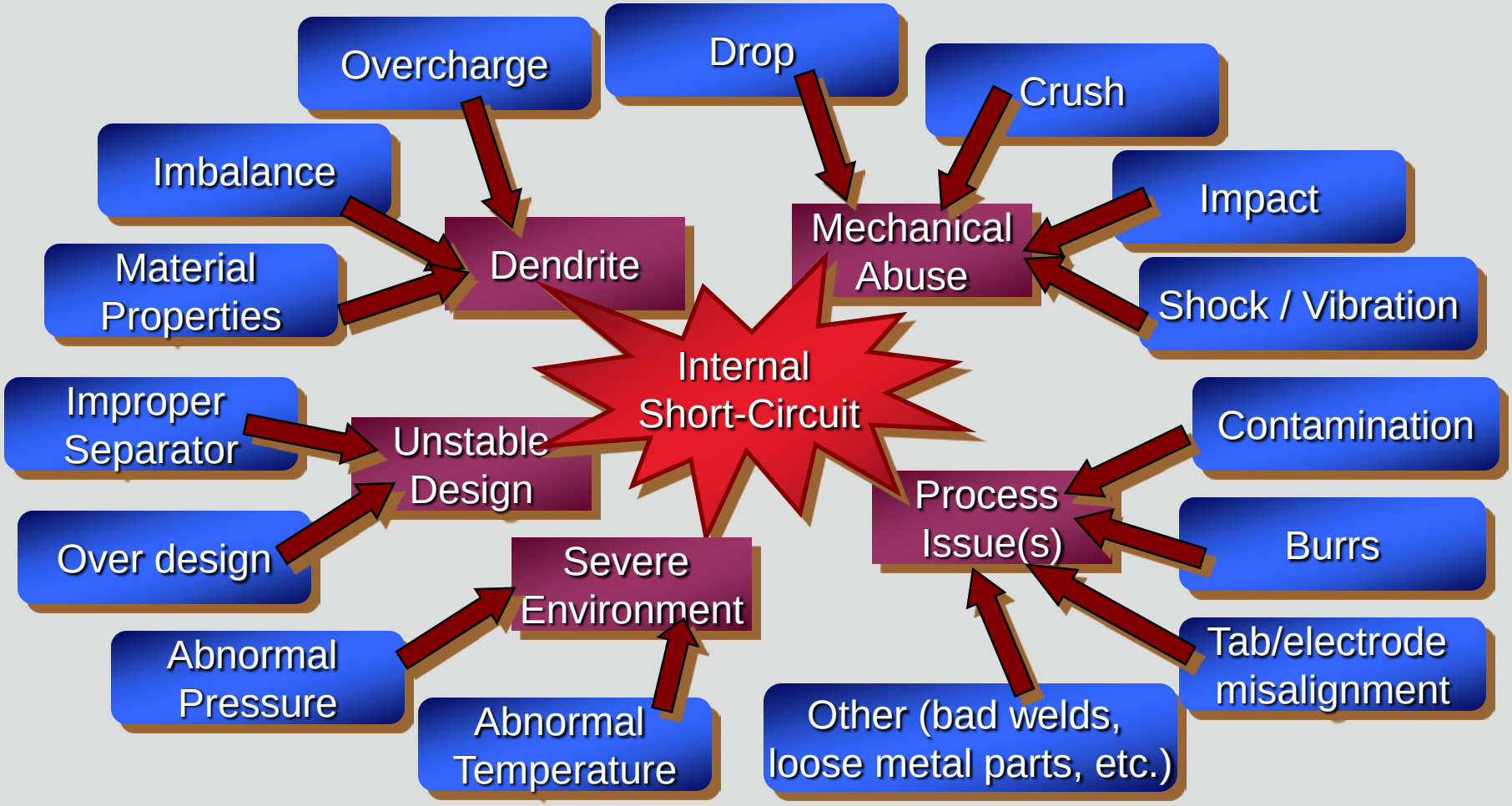
Root Causes of Internal Short Circuit



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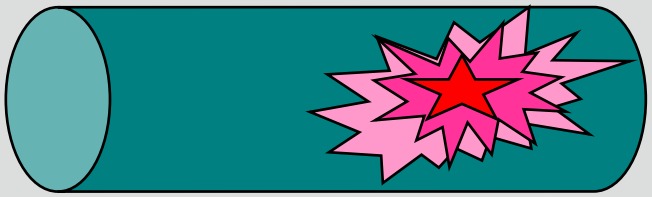
Characteristics of Internal Short-circuit

Localized

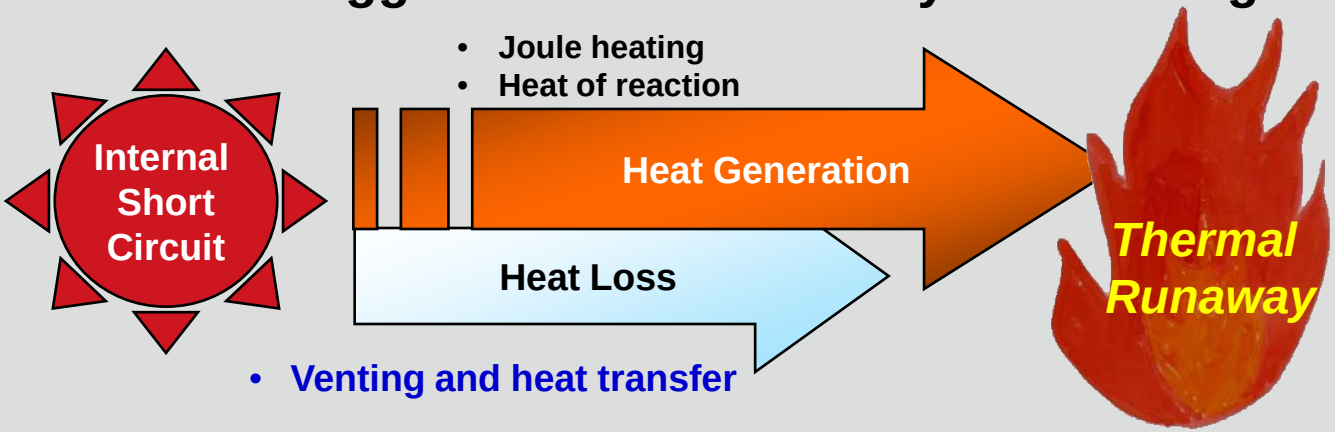


Internal short – localized heating

Uniform

External short – heating throughout the battery

Internal short could trigger 'Thermal Runaway' if not designed safely



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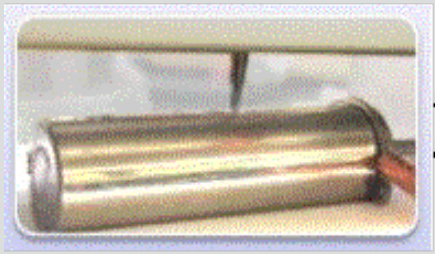
UL BNC Test Method

- **Objective:**
  - To create a simulated localized internal short circuit condition within the cell representative of a complete cell to understand its' behavior.
  - Incorporate method into UL battery safety standards to require cells to fail safely during an internal short-circuit.
- **History of BNC test:**

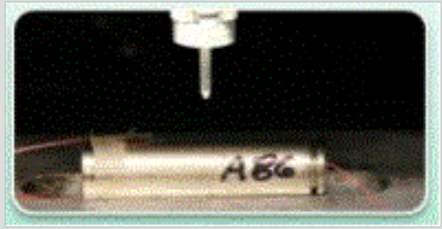
Rod Crush Test

Localized short but excess deformation



Nail Penetration Test

Less deformation but not localized short



Blunt Nail Crush test

Less deformation and localized short

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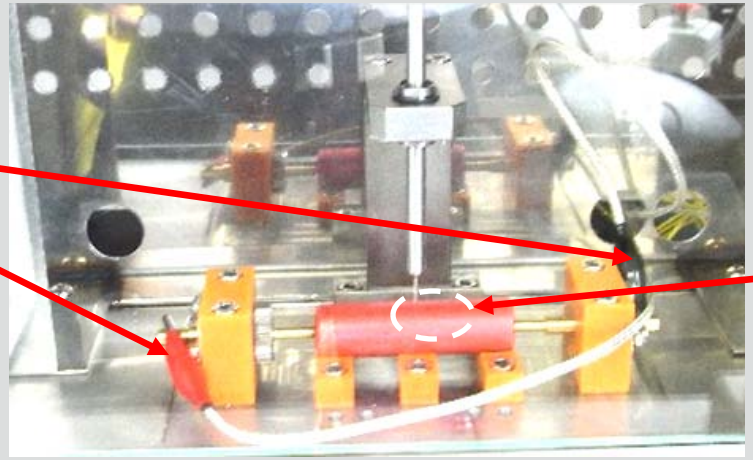
BNC Test Method, cont'd.

- Samples required: 22 fresh samples (2 for construction review prior to test)
  - Samples shall be charged to maximum charging voltage (i.e. 4.2V for common $LiCoO_2$ batteries) for 3 complete charge/discharge cycles prior to test.
  - Samples shall be conditioned at 60ºC for a minimum of 45 minutes, but no longer than 2 hours before testing.

OCV measurement



Thermocouples are attached to test samples to measure cell temperature during test

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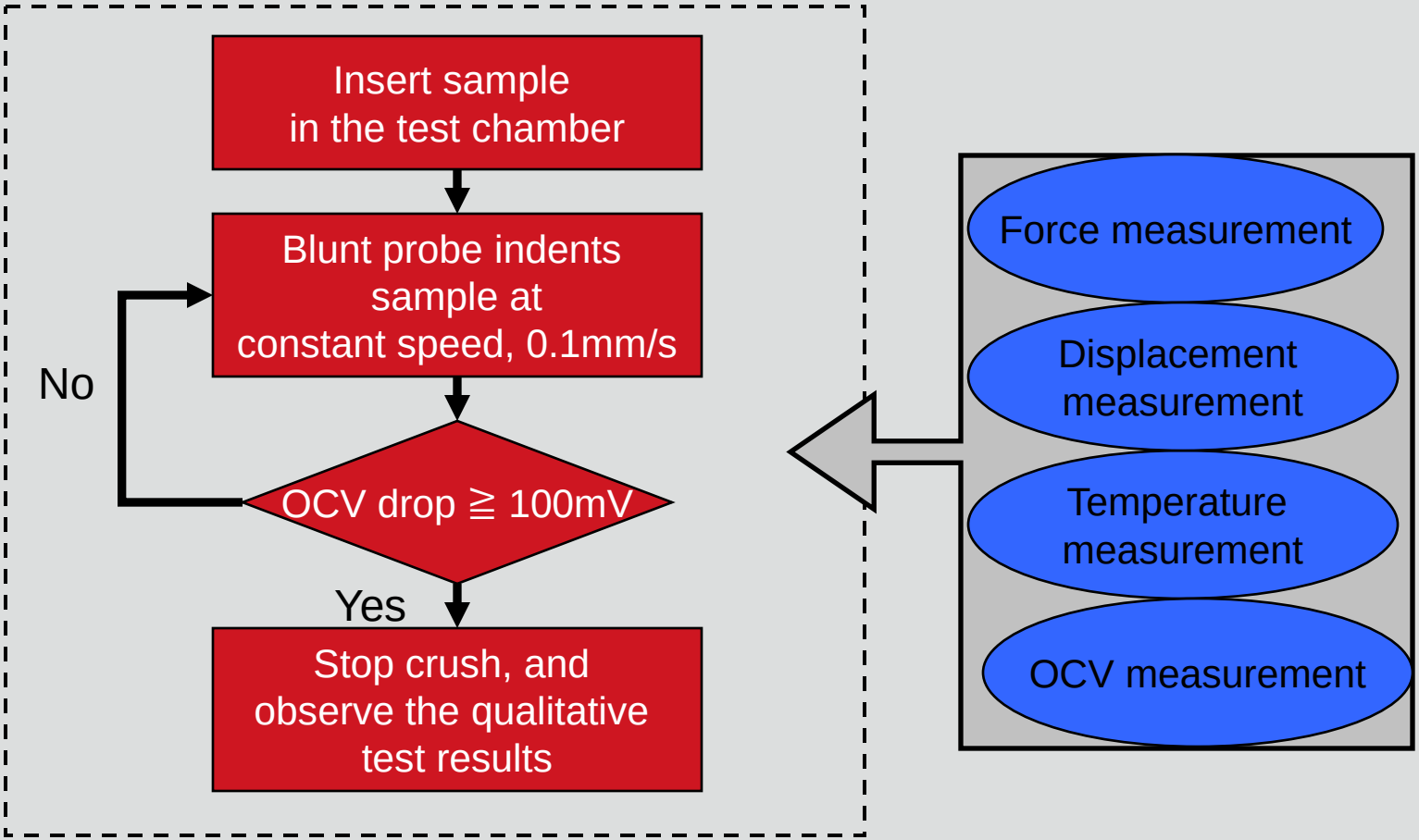
BNC Test Method, cont'd.

- **Test summary:**



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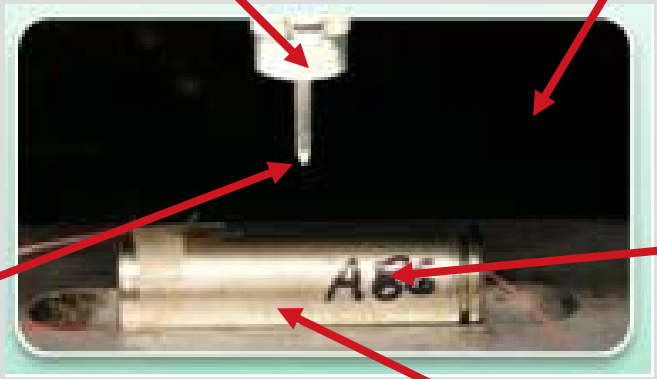
BNC Test Method, cont'd.

- **Rationale**

Constant press speed (0.1mm/s) is used to achieve accurate and precise control of the internal short with a press response time of ≤ 0.01s.

Testing is conducted at 60°C, which represents the typical maximum use temperature condition for common cell designs



Test Battery is 100% SOC

In most cases, the blunt probe will not penetrate the cell to avoid interference with the internal short-circuit reaction

To achieve a localized internal short, the OCV is monitored at the sampling frequency of 100Hz. A 100mV OCV-drop is regarded as the indication of an internal short-circuit.

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Overview of BNC Test Results-off Tab Position

Cell Maker	Battery Type	Nominal Capacity	Charging Voltage	Quantity of Samples	Pass, %	Fail, %	Hard/Soft Short	Failure Mode	Chemistry
A	18650	2600 mAh	4.25 V	20	100	-	Hard	-	$LiCoO_2$
B	18650	2600 mAh	4.35 V	20	100	-	Hard	-	$LiCoO_2$
C	18650 High Power	2000 mAh	4.25 V	20	100	-	Hard, Soft	-	$LiMn_{1.6}Co_{0.1}Ni_{0.3}O_4$
D	18650	2600 mAh	4.25 V	14	71	29	Soft	Mode 1	$LiCoO_2$
E	18650	2600 mAh	4.25 V	10	-	100	-	Mode 1, 2, 3	$LiCoO_2$

Note: Internal shorts are induced on the "off-tab" position for all 18650-type cells.

Criteria: **PASS→** No fire, spark or visible smoke, no rupture of casing or explosion, however venting and electrolyte leakage is allowed

FAIL→ Fire, spark, rupture of casing and explosion

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Effect of Blunt Probe Location

Cell B and C

Crush Position	Off-tab	Position 1	Position 2	Position 3	Position 4	On-tab
Test no.	n=20	n=3	n=3	n=3	n=3	n=5
Pass/Fail	Pass	Pass	Pass	Pass	Pass	Pass

Cell E

Crush Position	Off-tab	Position 1	Position 2	Position 3	Position 4	On-tab
Test no.	n=20	n=2	n=2	n=2	n=2	n=2
Pass/Fail	Fail	Fail	Fail	Fail	Pass	Pass

At different locations, different internal short-circuit conditions are likely to be induced for certain cell designs

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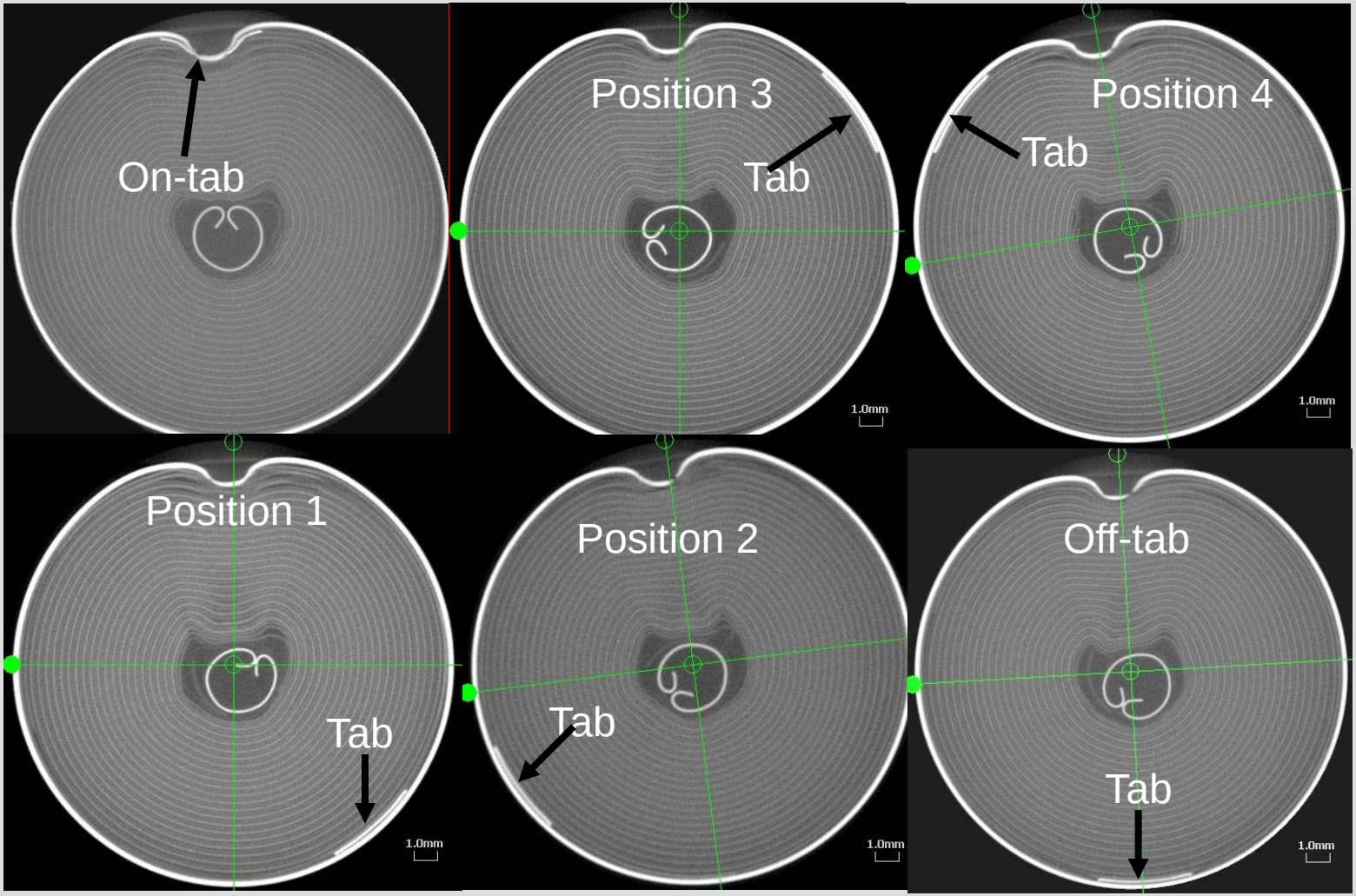
CT Scans on LiB Cells



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Tolerance of Different Cell Designs to BNC Test

Cell B

Charging Volts	4.35V	4.45V	4.45V
Test Temperature	60°C	70°C	80°C
Test no.	n=20	n=1	n=2
Pass/Fail	Pass	Pass	Pass

Cell E

DOD%	0%	0%	0%	20%	40%	40%
Test temperature	60°C	45°C	25°C	25°C	45°C	25°C
Test no.	n=10	n=2	n=2	n=2	n=2	n=2
Pass/Fail	Fail	Fail	Fail	Fail	Fail	Pass

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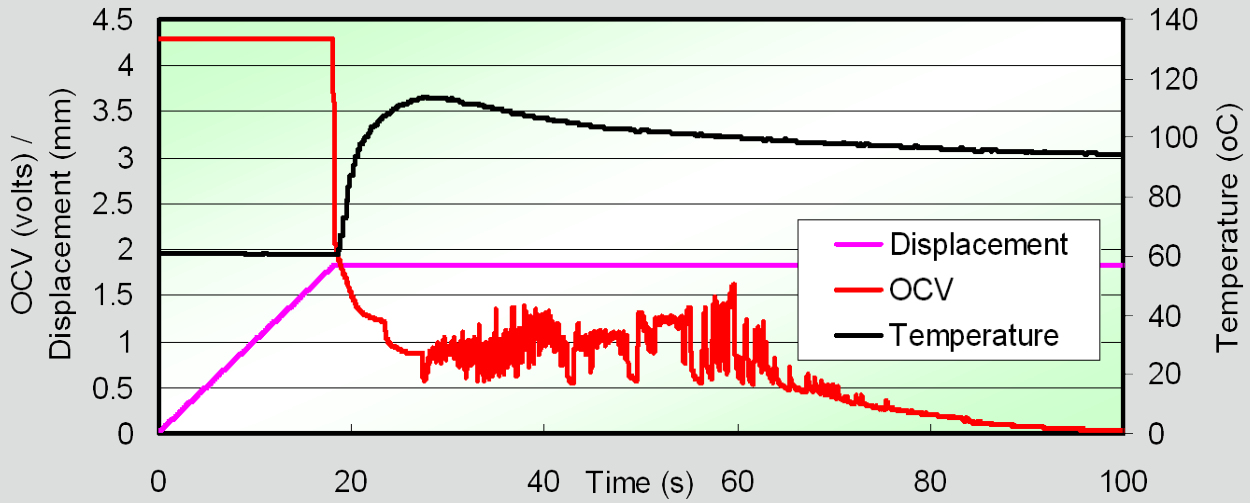
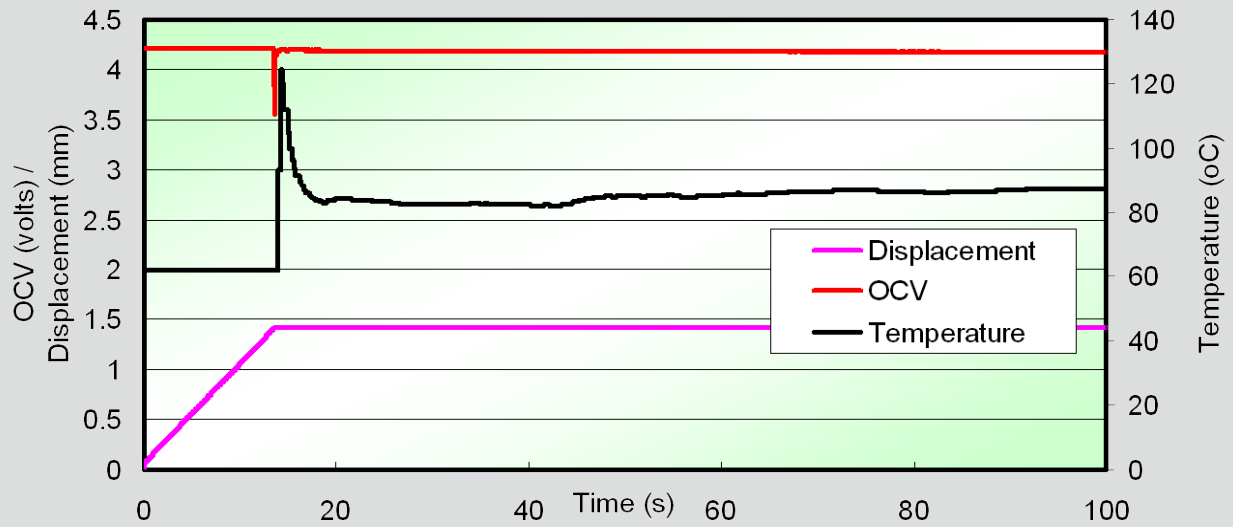
Behavior of Passing Cells





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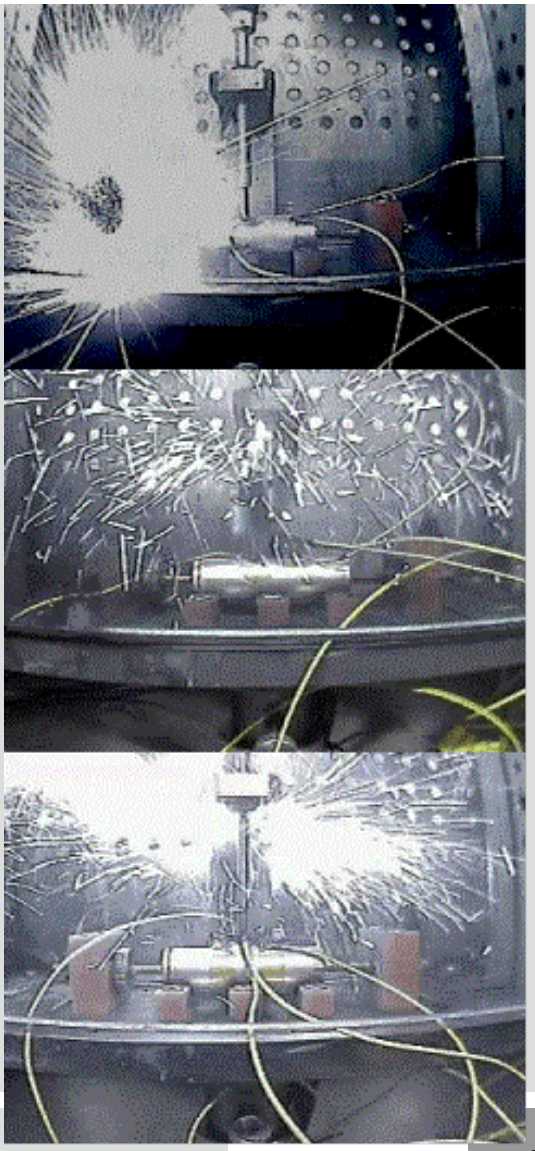
Behavior of Failing Cells

- **Failure Mode 1:**
  - Fire/Spark emits from the vent side
- **Failure Mode 2:**
  - Explosion, spark, but no sustained fire
- **Failure Mode 3:**
  - Explosion, spark, and sustained fire



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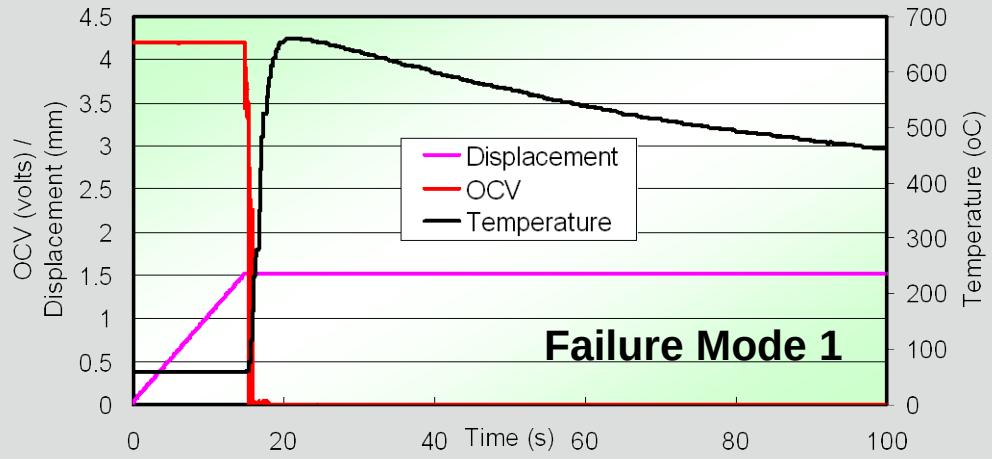
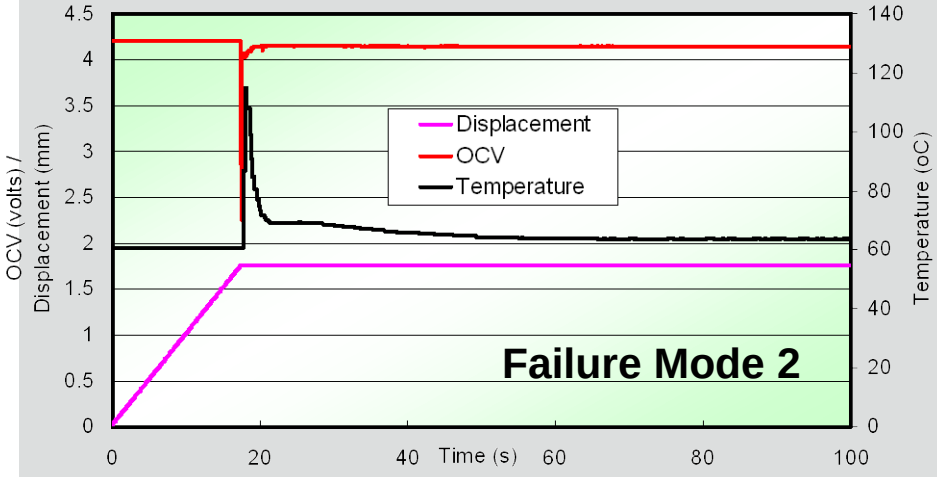
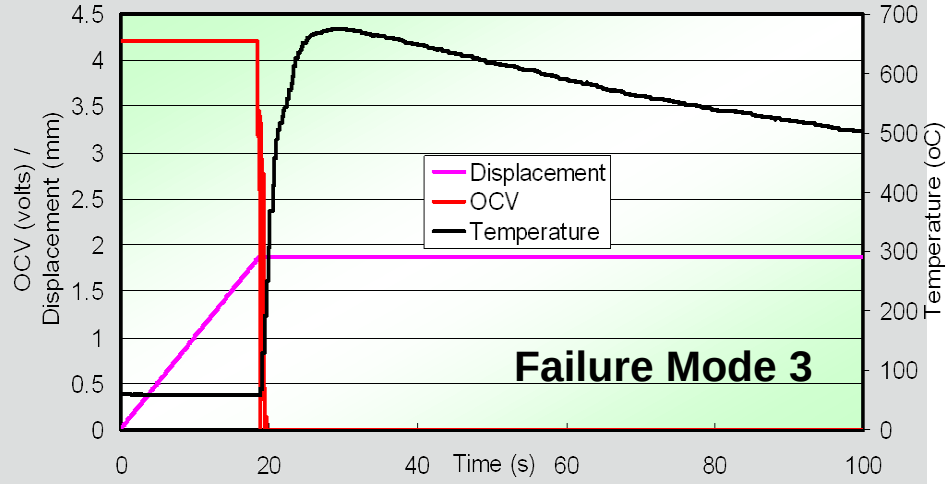
Observed Failure Modes, cont'd.







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Cell Properties Vs. BNC Test Results

- **Energy density**
- **Differential Scanning Calorimetry (DSC)**
- **Cell chemistry and morphology (SEM EDS)**

The results show correlation between the cell properties and BNC test results

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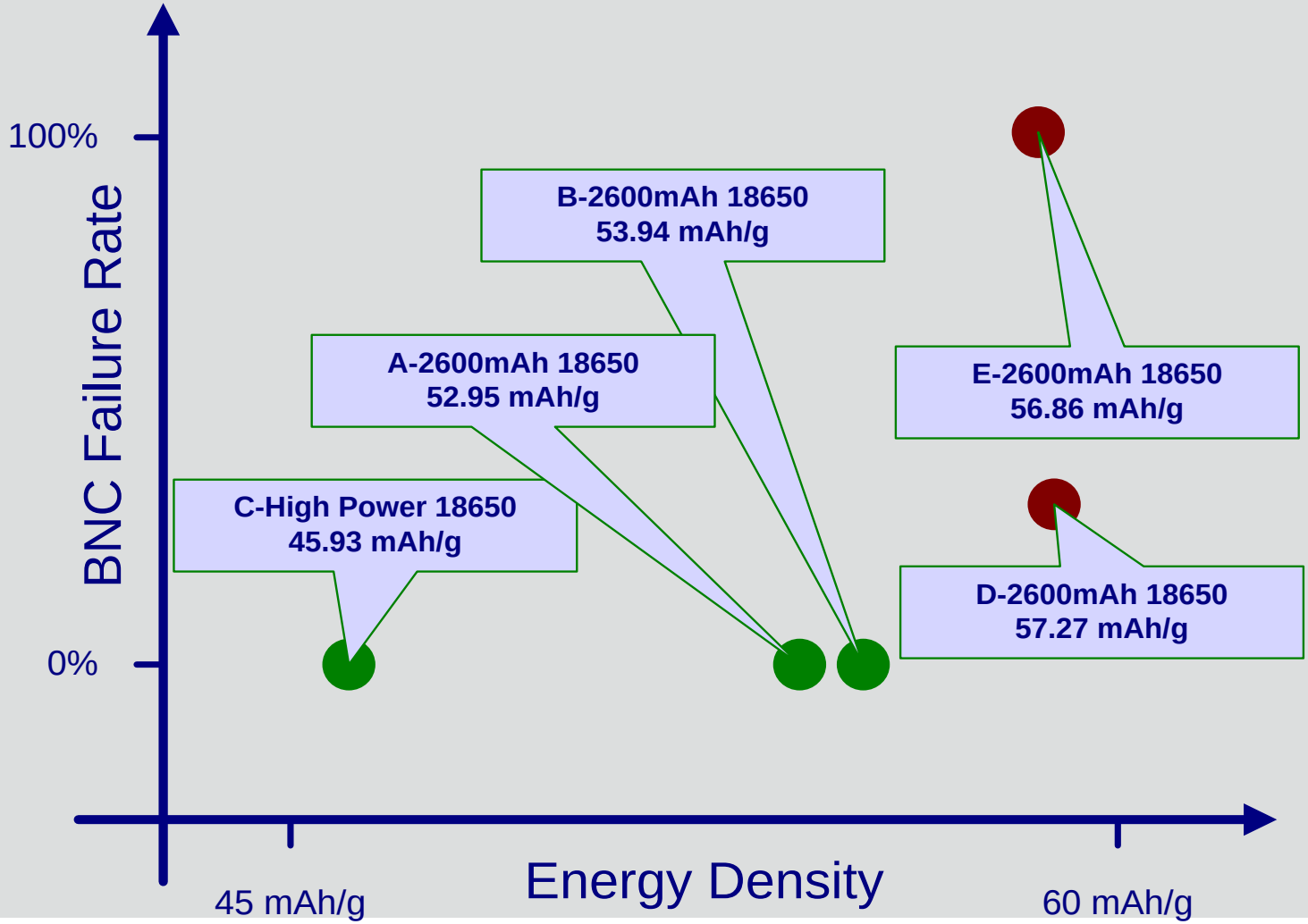
Energy Density vs Pass Rate



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Thermal Stability – DSC Analysis

	Cell B-2600mAh		Cell C-High Power		Cell D-2600mAh		Cell E-2600mAh *	
	Heat release	Onset	Heat release	Onset	Heat release	Onset	Heat release	On-set
Cathode/ electrolyte	-258.7 J/g	157.4°C	-220.6 J/g	151.5°C	-247.8 J/g	138.0°C	>-200J/g	<150°C
Anode/ electrolyte	NA	>200°C	NA	126.1°C	NA	125.6°C	NA	NA
BNC result	Pass		Pass		Fail		Fail	

1. The cathode/electrolyte of Cell B released more heat than others but has a slightly higher onset temperature. Cells B and C passed the BNC test
2. Cells D and E have lower onset temperatures and failed the BNC test
3. Based on the test results, the onset temperature of the exothermic reactions may be a critical factor to the safety behavior of cell designs.

*The DSC on Cell E was conducted at heating rate 10°C/min and the others at 5°C/min

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Chemistry of Cells – SEM/EDS

❖ 18650 Cylindrical-type with various chemistries

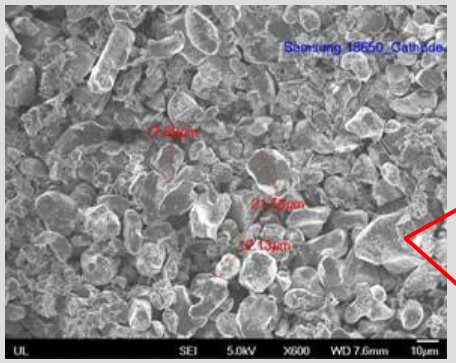
Layered $LiCoO_2$

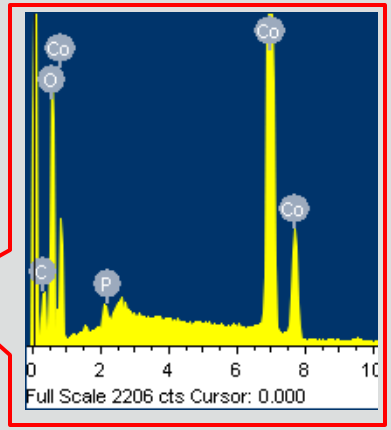
B – Pass

A – Pass

E – Fail

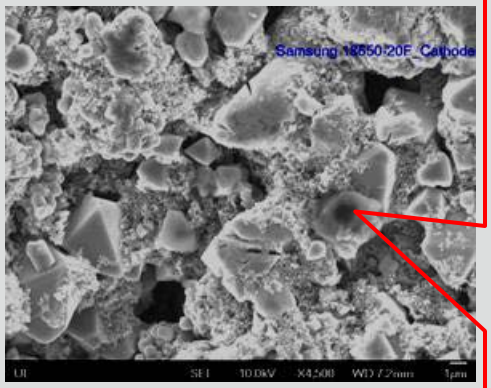
D – Fail

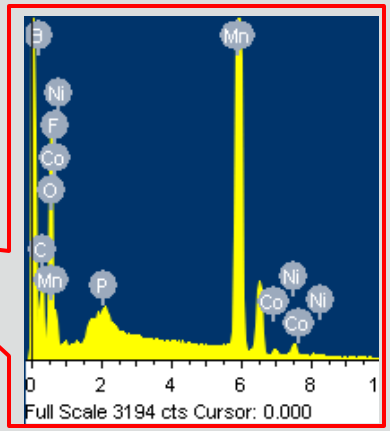




Spinel $LiMn_{1.6}Co_{0.1}Ni_{0.3}O_4$

C-High Power – Pass





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Summary and Conclusions

- The UL BNC test is an effective way to simulate the localized internal shorts for 18650 and similar cylindrical-type cells.
- DSC analysis supports the potential correlation between cell properties and cell safety behavior. Energy density indicates some correlation to pass/fail results according to limited samples tested., but more testing is planned.
- Testing at minimum 60°C is recommended because manufacturers specify cells to be discharged and stored up to that temperature.
- The BNC test is applicable for cylindrical cells with any chemistry, including Li-Co, Li-Mn, and trinary.
- Cell indentation locations around the radius may result in different test results. Cell constructions review is required prior to testing to identify the appropriate crush location.

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Appendix

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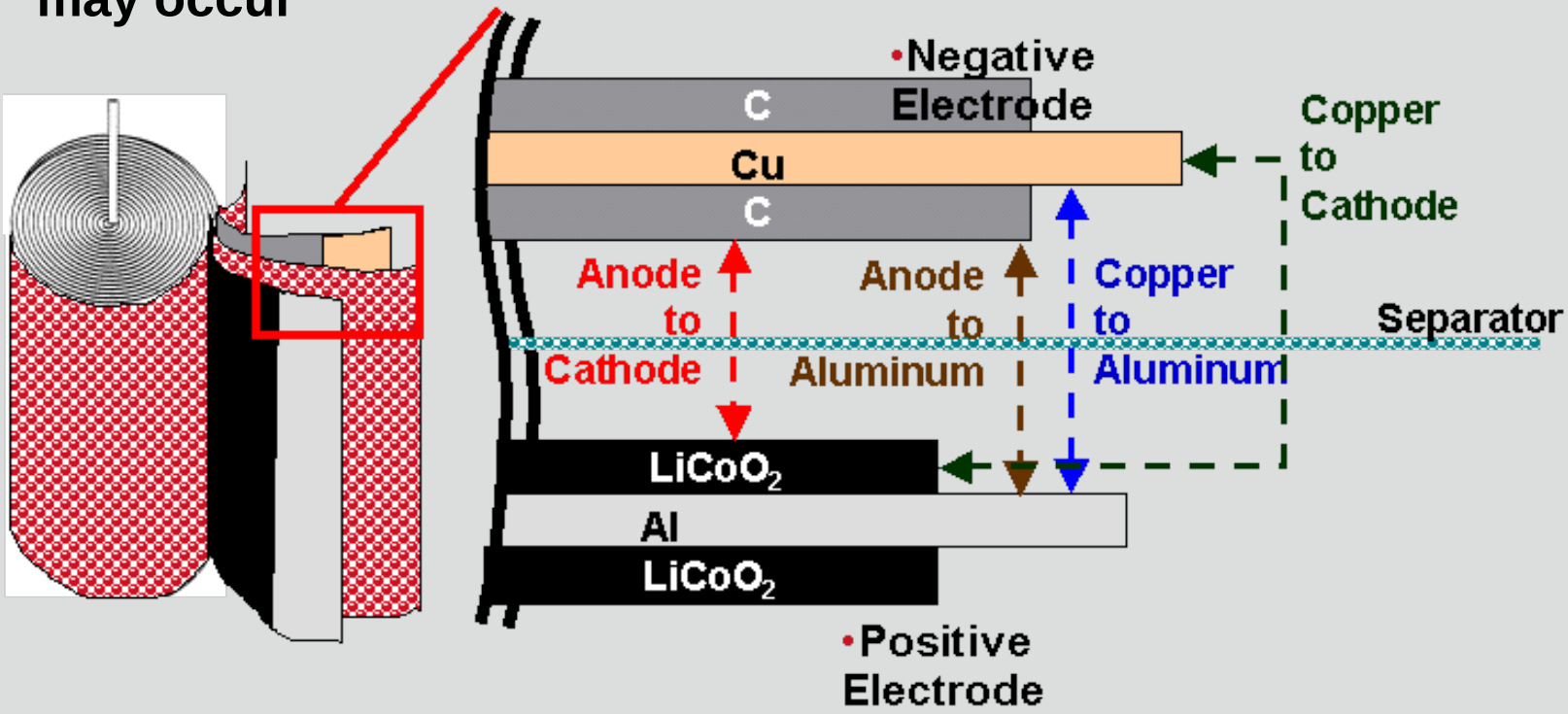
Types of Internal Short-circuit

- **There are basically 4 types of internal short. However, an internal short could be much more complicated than any of the simple types indicated below, due to short-circuit combinations that may occur**



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Comparison of Internal Short Simulation Tests

	Damage on Structure	Type(s) of internal short-circuit	Objective	Strength (s) and Issue (s)
Forced Internal Short Circuit (FISC)	**No casing**	**Single layer; Localized short; Can selectively induce anode-to-cathode or aluminum-to-anode**	**To simulate the internal circuit caused by contamination(s) coming from process**	**Strength (s):** 1. Capable to selectively induce the type(s) of anode-to-cathode or aluminum-to-anode; 2. The internal short is localized **Issue (s):** 1. Potential safety issue while disassembling cell 2. Complex cell preparation process 3. Test is conducted on cell without casing.
Nail Penetration	**Casing is penetrated**	**Multi-layers; Internal short throughout the cell; Mix of 4 types**	NA	**Strength (s):** 1. Test is easy to conduct 2. No safety issue if appropriate precautions are taken **Issue (s):** 1. Not a localized internal short-circuit 2. The internal pressure of the cell could release from the penetrated hole
Blunt Nail Crush	**Small dent on cell casing**	**Within 2 layers; Localized short; Cannot selectively induce the type(s) of short**	**Battery shall always fail safely under the occurrence of internal short-circuit**	**Strength (s):** 1. Test is easily conducted 2. No safety issue if appropriate precautions are taken 3. The internal short is localized **Issue (s):** 1. Cannot selectively induce certain type of internal short

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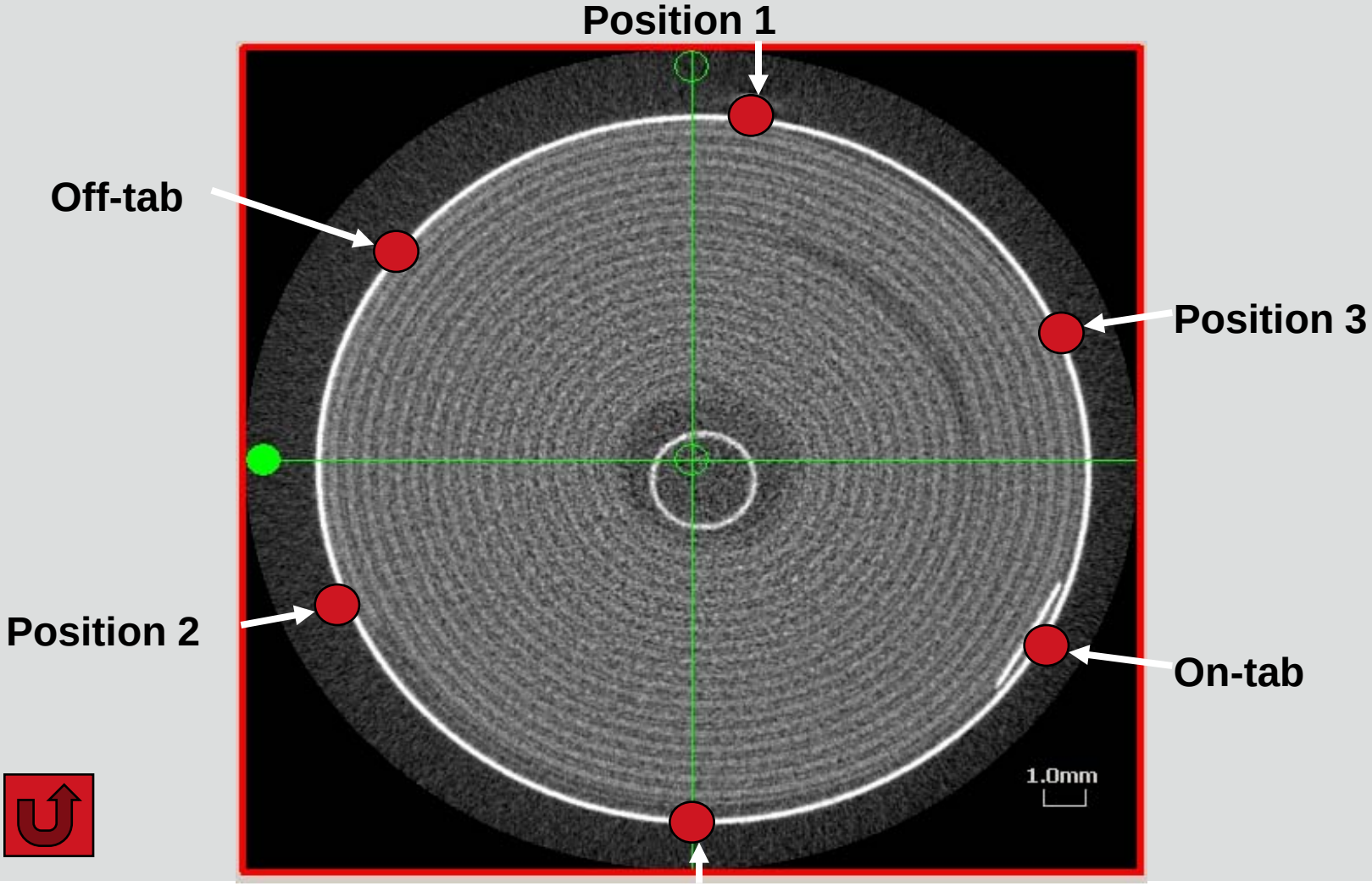
Crush Position for 18650-type Cells



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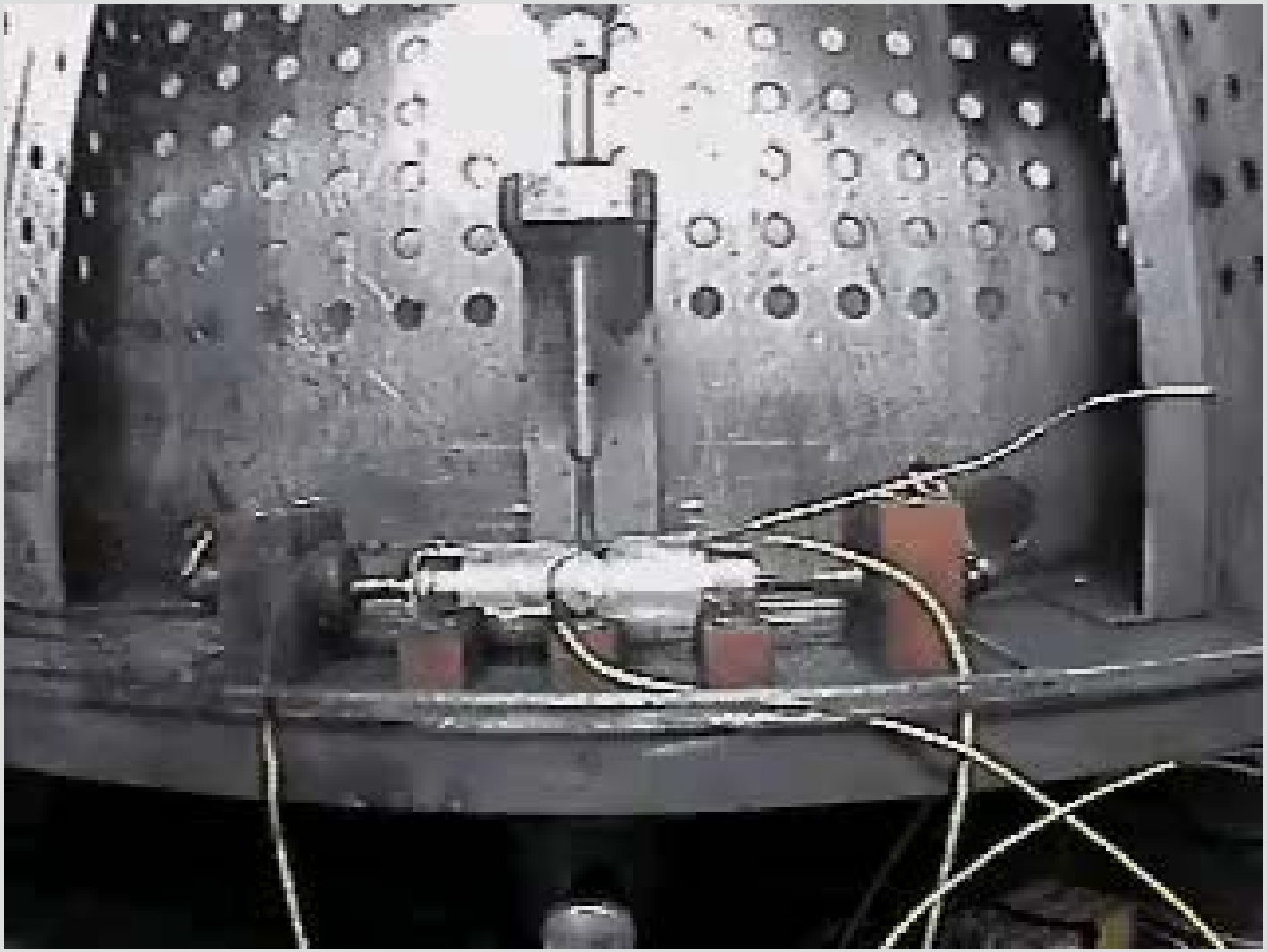
Failure Mode 1



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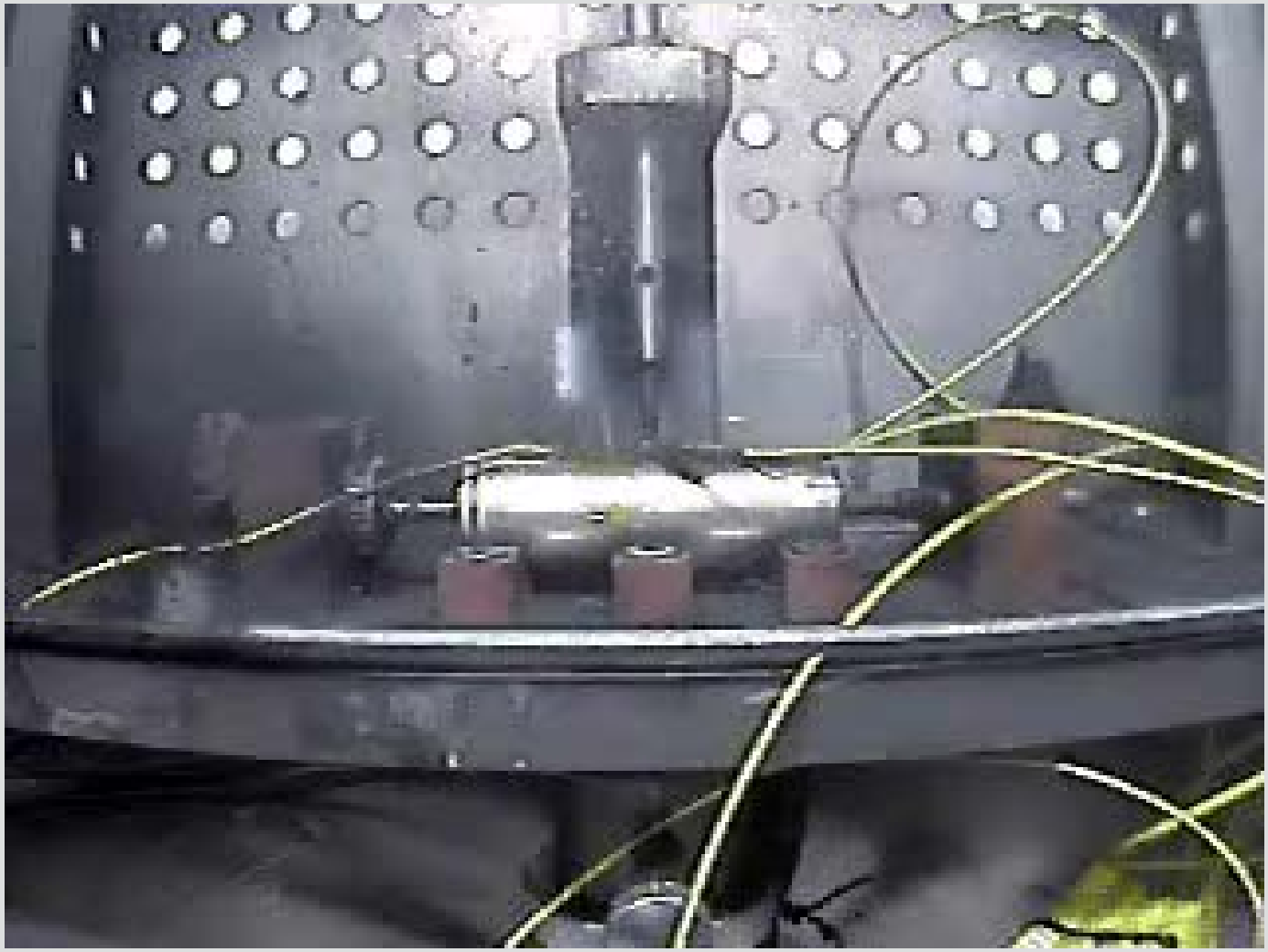
Failure Mode 2



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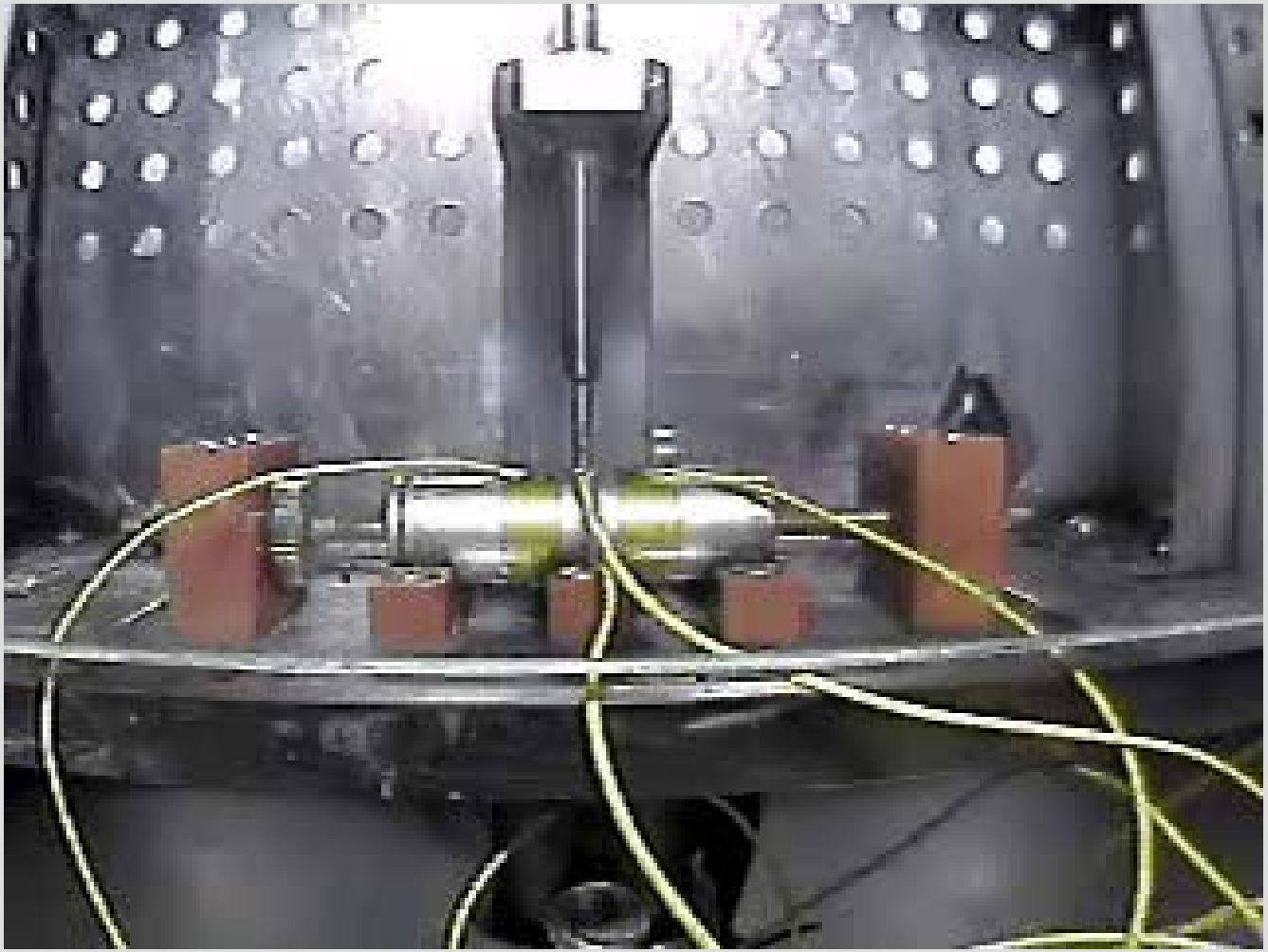
Failure Mode 3



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