Date: 13.12.2024

Nordisk QKE Fire Resistant Container by Nordisk Aviation Products
Results of Li-ion full scale fire tests in 2022

1. Introduction – Risk of Li-ion battery fires

Under a variety of scenarios, batteries can self-ignite and undergo an unstoppable thermal runaway where the stored chemical energy is converted to thermal energy. In some cases, the initial discharge and heat release is primarily electrical and occurs due to a short circuit. Looking at the well-known fire triangle, all three elements heat, oxygen and fuel must be present for fire to occur. Since the organic liquid electrolyte inside Li-ion batteries is intrinsically flammable, high temperatures in combination with oxygen will inevitably lead to combustion or/and explosion of the battery. The design of the Nordisk QKE container minimizes the oxygen inflow in case of a thermal runaway considerably.

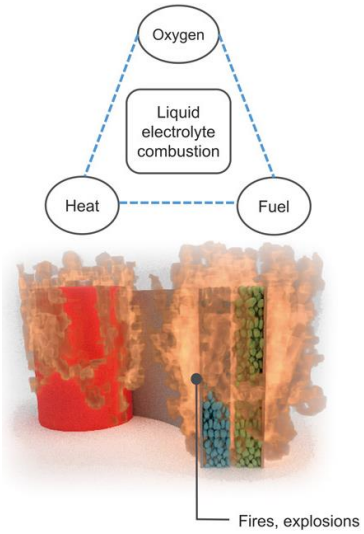


Figure 1: stage 3 in a thermal runaway [1]

Figure 2: Pallet with smartphone freight caught fire on Hongkong airport 12.04.2021 [3]

The frequency of reporting of such events unfortunately continues to rise. According to the FAA, there have been 354 aviation related incidents involving lithium batteries carried as cargo or baggage recorded between January 23, 2006 and February 25, 2022.[2] This amount includes just events that the FAA is aware of, the total number can be assumed to be significantly larger.

Table 1: Some reported Cargo incidents [2]

Date of incident	Reporter	Category	Reported Description
01/03/22	UPS	Battery Packs/Batteries	A box containing Lithium batteries reportedly ignited at a cargo sort facility.
12/28/21	DHL Airlines	Battery Packs/Batteries	During the transportation process a Lithium battery was discovered to have burnt through the outer packaging. It's unclear what caused the thermal event.
11/04/20	FEDEX	Battery Packs/Batteries	A Lithium battery fire ensued when a package was being off loaded from a cargo aircraft. Fire department personnel arrived to extinguish the fire.

2. Description of fire load and test cases

Due to the rapid increase in demand for Li-ion battery technology and the resulting increase in volume of shipments of devices including these batteries, there is an increasing risk for fire incidents caused by or involving Li-ion batteries. Considering these challenges, Nordisk Aviation Products conducted further tests in 2022 divided the testing program into two risk cases: Shipment of Declared Dangerous Goods according to UN3480 where the state of charge shall be limited to <30% by manufacturer and shipment of Undeclared Dangerous Goods typical of e-commerce/ postal shipments where state of charge is unknown.

Table 2: Details of risk cases tested

Declared Dangerous Goods / UN3480	**Undeclared Dangerous Goods***
▪ Bulk battery shipment ▪ Cell Type: INR18650-25r Samsung, 3.6V, 2500mAh ▪ Each cardboard package consisted of 100pcs 18650 Li-ion cells as delivered from supplier with cardboard dividers resulting in 900Wh / 5kg Net Li-ion ▪ Chemistry: LiNiCoAlO2 (NCA)	▪ Custom test batteries built to simulate an e-bike/ e-scooter battery (typical of the largest type of battery in common consumer products available to buy online). ▪ Packed without correct packaging ▪ High State of charge (SoC) ▪ Cell Type: INR18650-35e Samsung, 3.6V,3500mAh ▪ One battery pack consisting of 40pcs 18650 Li-ion cells resulting in 500Wh energy load ▪ Chemistry: LiNiCoAlO2 (NCA)

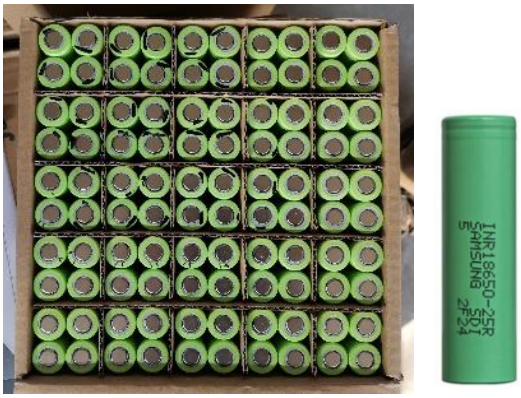


Figure 3: Bulk battery shipment

Figure 4: custom-built e-bike battery

** also be applicable to UN3481*

3. Test setup

The test unit is a Nordisk QKE. It consists of a frame structure made of aviation grade aluminum extrusions and a set of aluminum panels forming the walls, roof and base of the container. The aluminum panels have a nominal thickness of 0.8 mm and base sheet has a thickness of 2.5 mm. The container is equipped with a coated, fire-resistant fabric door tensioned with steel wire and over centric security bar on the bottom. The tare weight of this container is 72kg.*

Nordisk Aviation Products tested 9 test cases with the Nordisk QKE container. Of these, 8 test runs were made to analyze a Li-ion fire of undeclared dangerous goods while 1 test simulating declared dangerous goods bulk shipment of Li-ion Cells (UN3480).

Figure 5: Test setup

For every test the inside of the test unit was filled with cardboard boxes, each filled with 1,2kg of packing paper. Depending on the predefined test setup one or several cardboard boxes were packed with cells or battery packs (ref. Figure 3 and 4). To simulate worst case scenarios the fire load was primarily placed around the edges of the container, on the base, beside the door and side panels. A 100 W heating element was placed between the cells to induce the thermal runaway. Up to 5-10 heating elements were used in total per test to induce thermal runaway simultaneously in various positions inside the container. *See attached presentation for detailed setup, drawings, and pictures.*

To determine if damages to the container effects the severity of the fire, each 0.8mm aluminum panel was inflicted with a 100mm long cut on the final two tests.

Each test was monitored using:

- Up to 21 external K-type thermocouples 100mm from the container
- 6-10 internal K-type thermocouples placed in the cells / batteries and surrounding boxes
- 6-10 Copper surface thermocouples on panels / base measuring surface temperature.

* The new AKE 20000-series with a tare weight of 69kg has successfully been tested in 2024.

4. Test facility

The tests were conducted at RISE Fire Research AS, a fire research and testing facility in Trondheim, Norway. Rise Fire Research AS is owned and run by the two largest independent R&D organizations in Scandinavia, SINTEF Norway and RISE Sweden.

The tests were observed by RISE and Nordisk teams from a remote observation room and live streamed using three observation cameras and one High-definition Infrared camera giving live detailed data feedback. Two additional HD cameras were used for HD sound & video. The temperature and the humidity of the firehall were continuously recorded during all tests.

5. Test results

5.1. Test requirement

In the absence of a test standard for FRCs with fire loads containing Lithium-ion batteries, the test was conducted as a non-standardized test. However, the minimum performance requirements described in AS8992 issued October 2020, were used as one of the performance measurements of the test unit:

There shall be no flame penetration (burn-through) at any time, and the peak measured temperatures 100mm from the container shall at no time exceed 204 °C (400 °F).

NOTE 1: Exterior ignition of the test specimen not exceeding 60 seconds is permitted as long as the 204 °C (400 °F) requirement is not exceeded.

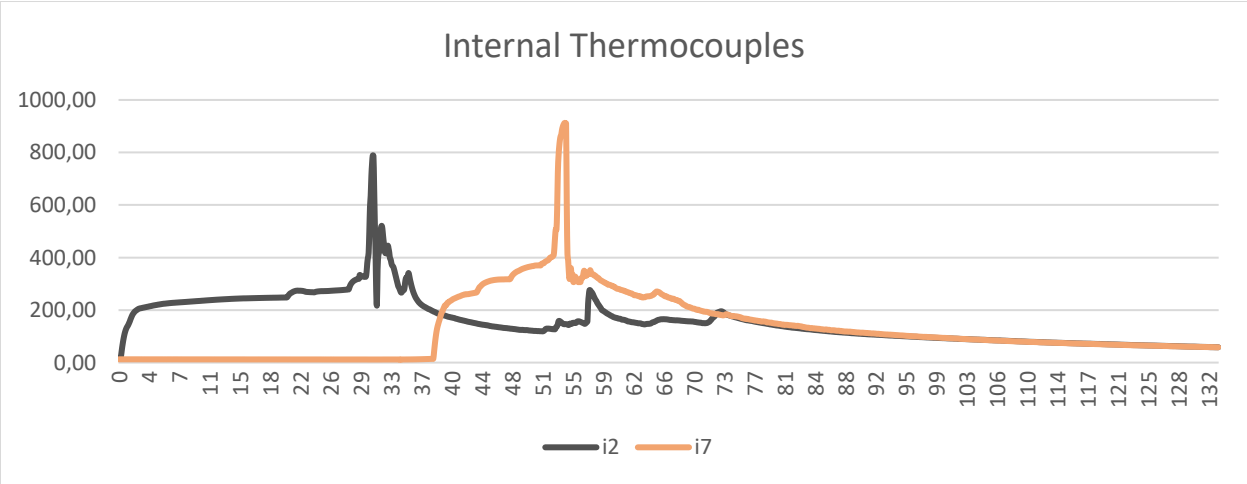
NOTE 2: Flame penetration is not to be mistaken with off gassing of certain non-metallic materials.

5.2. Test characteristics

Some general characteristics of the Li-ion fire which can be observed:

- The higher the state of charge (SoC) of the cells the more violent the resulting reaction which must be contained. The heat release rate (HRR) and ignition of flammable gases generated by the cells is almost linear to charge state.[4]
- The time period with peak temperatures is short relative to heat curve for the remaining test period. Once the chemical energy and flammable gases of the cells are consumed and contained the subsequent fire development is primarily defined by if enough oxygen to sustain, spread and increase the fire can replace the Carbon dioxide and other non-flammable gases generated during the primary phase of the fire (during TR of the cells).
- Small openings (for example the 100mm cuts to each panel) are not sufficient to sustain the circulation of airflow in the secondary phase of the fire (after TR), a critical factor in the fire triangle.[3]

Figure 6: A typical sample from Thermocouples measuring heat element /battery before and after TR. (test nr 4_nov)



5.3. Performance and limitations

Based on 9 full scale fire tests, the results show that the QKE FRC with 0,8mm aluminum panels:

- ✓ passed test with qty 5000 Li-ion cells at 40% SoC (10% at 50%), 25kg Net Li-ion pr package[1]
- ✓ passed test with qty 15 500Wh E-bike batteries at 60% SoC, 4kg Net Li-ion pr package[2]
- ✓ passed test with 100mm damage limit on each panel[3]

Table 3: Test setup and results

Test run	Energy Load nominal	SoC	Net Li-ion per package	Max. int. Temp.	Max. ext. Temp.	Result
1	80 cells 1 kWh	100%	4kg	743 °C	32 °C	• Flash flames outside the container for very short period • Small amounts of fire debris outside the container
2	280 cells 3.5 kWh	100%	14 kg	945 °C	834 °C	• Explosion causing holes in door and base
3	280cells 3.5 kWh	100%	6 kg	985 °C	540 °C	• Explosion causing holes in door and base
4	40 cells 500 Wh	30%	2 kg	769 °C	26 °C	• No visible flames or debris outside the container
1a	160 cells 2 kWh	40-70%	2kg	1200 °C	70 °C	• No fire breach or holes to container
1b	5000 cells 45kWh	40-50%	25 kg	813 °C	34 °C	• No fire breach or holes to container
2	160 cells 2 kWh	70%	4 kg	900 °C	470 °C	• No FR abrasion resistant cover on outside of the fabric door sustained flames >60s (removed for subsequent tests)
3	320 cells 4 kWh	70%	4 kg	1150 °C	70 °C	• Small amounts of fire debris outside the container • 3x Ø15mm holes in the base sheet of the container
4	600 cells 7.5 kWh	60%	4 kg	904 °C	34 °C	• Small amounts of fire debris outside the container • 1x Ø15mm hole in base sheet of the container

[1] Test run 1b (08.11.2022)

[2] Test run 4_Nov (11.11.2022)

[3] Different conditions in real life might result in a different test outcome. To mitigate the risk, Nordisk recommends to not allow any damages which could contribute to additional airflow into the container.

6. Product operational maintenance

The design of the Nordisk QKE provides the following benefits to our customers overall risk mitigation strategy against Li-ion fires during cargo shipments.

- No new repair methods or material training required.
- Allowable damage limits proven through testing facilitate shorter down time[3]
- Economical capital investment and total cost of repairs / ownership

7. References

[1] K. Liu, Y. Liu, D. Lin, A. Pei, Y. Cui, Materials for Lithium-ion Battery Safety, Science Advances 2018.

[2] www.faa.gov/hazmat/resources/lithium_batteries/media/Battery_incident_chart.pdf

[3] Hong Kong Air Cargo ban on Vivo phones after pallets catch fire at airport - The Loadstar

[4] https://www.fire.tc.faa.gov/pdf/systems/April21Meeting/Karp-0421-UNGas.pdf