REPORT

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Contact person RISE
Roeland Bisschop
Division Safety and Transport
+46 10 516 65 97
roeland.bisschop@ri.se

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Firexo Group Ltd
c/o Coyle White Devine
Boughton Business Park
Bell Lane
AMERSHAM
Buckinghamshire
HP6 6FA
GBR

Fire suppression tests lithium-ion batteries

Summary

Firexo Group Ltd, approached RISE to perform fire suppression tests with their handheld fire-extinguisher on lithium-ion batteries after being recommended to do so by British Standards. The aim of the tests was to identify if the considered fire suppressant had an effect on the thermal runaway behaviour of lithium-ion battery cells. As no appropriate testing standard exists today, the client and RISE devised a custom test scheme, as a starting point for further experiments.

Two test scenarios were explored: one representing fire in a large automotive single battery cell and one representing fire in a small battery pack. Two tests were performed for each scenario, a reference free-burning test and an suppression test. The tests do not provide conclusive information, particularly due to the low number of tests, but they do provide some fundamental insight to the effect of the agent.

In the extinguishing test for the single cell, the fire-extinguisher appeared to reduce the severity of the battery fire. Specifically, the initial jet flame was extinguished and the size of following jet flames was reduced.

For the small battery pack, the fire-extinguisher suppressed the initial fire and there was no propagating thermal runaway. However, further testing is necessary to ensure this effect was not a result of stochastic uncertainties or uncertainties in the test procedure.

Overall, the test results indicate that the Firexo 9LTR Extinguisher has a positive effect on thermal runaway events under the considered circumstances. It can be stated that the Firexo fire-extinguisher, under the test conditions listed, demonstrated no negative effects on the lithium-ion battery fires. Furthermore the tests indicate that the Firexo 9LTR Extinguisher potentially may reduce the internal temperature of a battery cell undergoing thermal runaway, may reduce the size of resulting jet flames, and that it may inhibit thermal runaway and temperature propagation in the cells, which are critical factors to suppress and control lithium-ion battery fires.

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1. Background

The client, Firexo Group Ltd, approached RISE to perform fire suppression tests with their handheld fire extinguisher on lithium-ion batteries after being recommended to do so by British Standards. The aim of the tests was to identify if the considered fire suppressant had an effect on the thermal runaway behaviour of lithium-ion battery cells. As no appropriate testing standard exists today, the client and RISE devised a custom test scheme, as a starting point for further experiments.

2. Device under test (DUT)

The client supplied RISE with the DUT, the Firexo 9LTR Extinguisher. A total of 6 extinguishers were delivered to RISE on 2020-10-29. The specifications of this extinguisher, according to data provided to RISE by the client, is shown in Table 1.

RISE randomly selected three extinguishers from the batch of extinguishers that was supplied. Two of these extinguishers were used during the tests on the batteries, and one extinguisher was used for verifying their function and aim.

Table 1 Technical information concerning the tested extinguisher

Name	**Firexo 9LTR Extinguisher**	
Model	809-765-347-906	
Capacity	9	
Cylinder height (mm)	580	
Outer width (mm)	190	
Cylinder material	Steel	
Pressurizing gas	Nitrogen	
Test pressure	30 bar	
Working pressure at 20 °C	12 bar	
Weight full (kg)	15.79	
Weight empty (kg)	4.9	
Spray range (m)	1 – 4	
Discharge time at 20 °C (seconds)	45 - 55	
Temperature range (°C)	-18 / +60	

3. Fire source

Two test scenarios were explored: one representing fire in a large automotive single battery cell and one representing fire in a small battery pack. This section presents the fire sources that were considered for these cases.

3.1 Battery cell: Prismatic 50 Ah lithium-ion battery cell

Two prismatic 50 Ah lithium-ion battery cells were considered for the battery cell test scenario. The cells were donated to RISE by a battery cell supplier and the specifications of the cells are presented in Table 2.

Table 2 Technical information concerning cell

Name	**Prismatic lithium-ion battery cell**	
Cathode	NMC	
Nominal voltage (V)	3.6	
Nominal capacity (Ah)	50	
Nominal energy content (Wh)	185	
Weight (g)	856.6	

The cells were charged by RISE using a programmable DC power supply (inv. no. KWP02224) on 2020-11-18 to their maximum charging voltage. Results from charging the cell are shown in Figure 1. The charging procedure followed a CC-CV protocol where the cut-off voltage was set to 4.2 V and where the charge was set to 1C (50 Ah). Once charging was completed, the cells were stored in a temperature controlled room until testing took place on 2020-11-19.

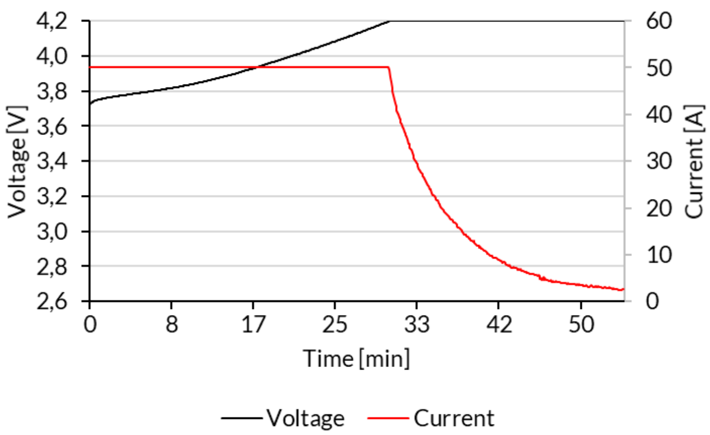


Figure 1 The cell was charged to their maximum charging voltage of 4.2 V.

3.2 Battery pack: Pack with cylindrical 18650 lithium-ion battery cells

A purpose built battery pack was constructed by RISE with acquired cylindrical 18650 lithium-ion battery cells. The specifications of the individual cells that were used to construct this battery pack are shown in Table 3. Note that the image shown presents the charger fit with four individual battery cells.

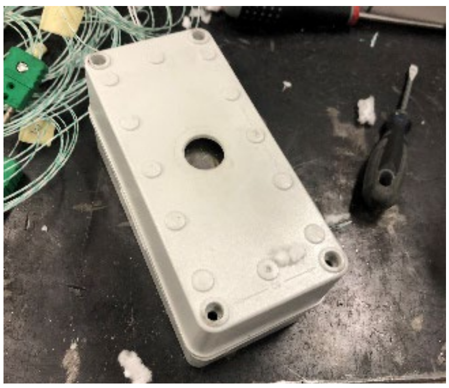
The NRC18650B cells that make up the battery pack were received by RISE on 2020-02-03. For the purpose of charging, Nitecore D4 chargers were used. Each of them were capable of charging 4 x NRC18650B cells simultaneously. The charging current supplied by these devices was 0.375 A. The charging procedure commenced on 2020-11-16. A total of 4 chargers were used, meaning that 16 cells could be charged simultaneously. Cells that were at their maximum voltage level, i.e. 4.2 V, were removed from the chargers and stored in a temperature controlled room until they were assembled in the pack on 2020-11-20.

Table 3 Technical information concerning the battery cells used to construct the battery pack.

Name	**NCR18650B cylindrical lithium-ion battery cell**	
Cathode	NMC	
Nominal voltage (V)	3.6	
Nominal capacity (Ah)	3.3	
Nominal energy content (Wh)	11.9	

The battery pack assembly consisted of an ABS pack filled with a total of 30 individual NCR18650B lithium-ion battery cells as seen in Table 4. This set-up was designed to represent a battery pack but there were no electrical connections between the battery cells nor were there any other combustible materials within the pack apart from the battery cells. Some insulating material was pushed around the cells to press them together so that the cells were in direct contact with each other.

Table 4 Technical information concerning the battery pack

Name	**Battery pack**	
Nominal voltage (V)	3.6	
Nominal capacity (Ah)	99	
Dimensions	170 mm x 80 mm x 85 mm	
Pack weight	1700 g	
Construction	Cylindrical NCR18650B cells (30 pcs.) surrounded by insulation material and ABS pack	

4. Test method

The test method was developed through exploratory discussions between the client and RISE, with the aim to investigate the fire suppression capabilities of the considered fire extinguisher, the DUT . The effectiveness of the DUT in dealing with the fire hazard was decided to be investigated through two difference scenarios, namely a large automotive single battery cell test scenario assuming there is direct access to the burning battery, and a small battery pack thermal propagation scenario to consider when there is no direct access to the burning battery. Note however that this does not cover all potential fire scenarios or fire safety issues related to lithium-ion batteries. For example, factors related to the risk for flammable and toxic gas release were not considered by these tests.

Two tests were performed for each scenario, one reference free-burning test and one fire suppression test. This allowed for direct comparison between the thermal runaway event with and without an attempt to suppress it, and thus gave insight to the potential effects the suppressant may have on lithium-ion battery fires.

Table 5 Test matrix

Scenario	Test	Battery	Treatment
Single cell	Test 1	Cell	None
	Test 2		Supress fire with the DUT
Thermal propagation	Test 3	Pack	None
	Test 4		Suppress fire with the DUT

The tests were performed in an explosion proof cage and underneath a mechanical exhaust fan to mitigate risks associated with projectiles and toxic gases as seen in Figure 2. Temperatures were measured with Type-K 0.25 mm thermocouple junctions and an infrared (IR) camera of type FLIR T420 25 WiFi. The thermocouples were positioned on the battery, their close vicinity and inside the gas exhaust duct. Furthermore, the tests were recorded with a video camera and observed visually by both the client and RISE personnel.

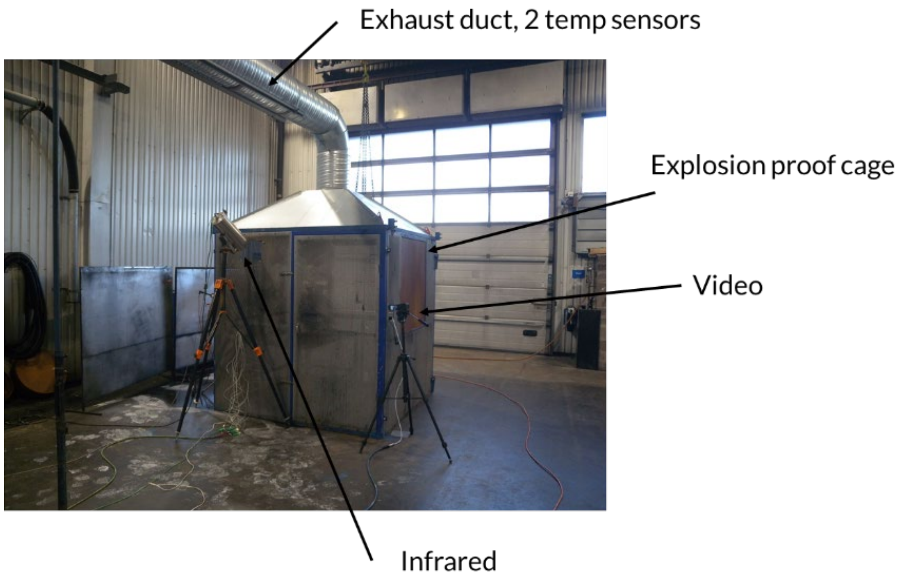


Figure 2 An overview of the test setup with a) the explosion proof cage, exhaust duct and recording equipment

The DUT was mounted within the cage at a fixed position. It was positioned according to recommendations provided by the client. Specifically, the nozzle of the DUT was mounted at a 45° angle with respect to the target, at a 1 m distance from the target. It was activated remotely, as soon as thermal runaway was observed. Remote activation was possible due to a pneumatic cylinder which pressed against the DUTs release mechanism when supplied with pressurized air. Note that this meant that the effect any operator may have using the fire extinguisher on an actual battery fire was eliminated. There were two reasons for this. Firstly, eliminating the operator removes one factor that may cause variations in the results. Furthermore, manually suppressing lithium-ion battery fires is dangerous and persons should not come near such a fire unless absolutely necessary. In a real life situation, this risk may be worth taking, but in a professional environment where hazardous tests are performed on a daily basis, this is unsuitable.

Figure 3 Fixture for the fire extinguisher including pneumatic cylinder for remote activation

4.1 Single cell scenario

A relatively large prismatic lithium-ion battery cell was selected to ensure there was a distinct thermal runaway which lasted sufficiently long to see any effects of a fire extinguisher.

Thermal runaway was initiated in the battery cell by exposing it to an external heat source, in the form of a small burner. This way, it was assured that any flammable gases released by the cell were immediately ignited. Once thermal runaway occurred, the burner was switched of. In addition, the external surfaces were freely exposed, allowing the suppressing medium to directly access the test object. Initially, during the reference test, the burner was aimed at the bottom of the cell. It was expected that gases would still vent through the safety valve of the cell which was on the opposite end of this cell. However, this did not happen during the reference test. The burner position was thus changed so that it aimed at the safety valve directly.

External surface temperatures on the cell were measured at several different locations, as shown in Figure 4. In addition, thermocouples were positioned in front of the cell, where a jet flame, generally occurring during thermal runaway, was expected to appear. This was not the case in the reference test, *Test 1*, but the jet flame appeared from the place where the cell was heated. As such, these thermocouples did not provide any useful information. During the second test however, *Test 2*, the jet flame did appear from the safety valve. This gave meaningful temperature recordings that indicate flame and gas temperatures.

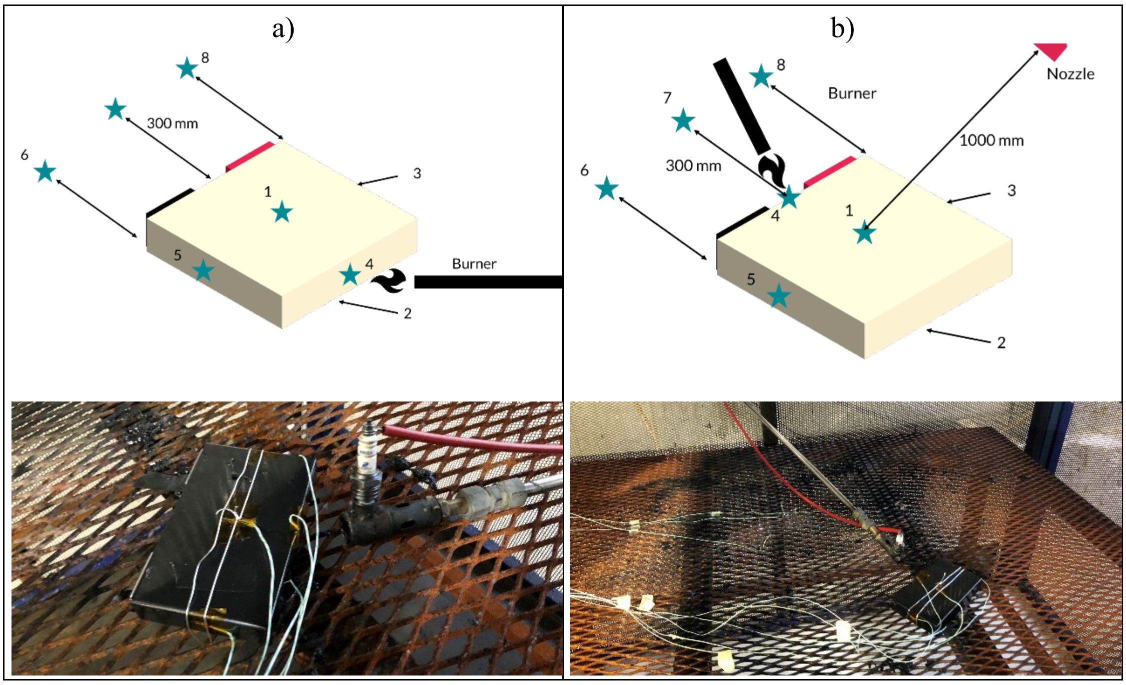


Figure 4 Instrumentation of the cell in a) *Test 1*; and b) *Test 2*, including the nozzle of the DUT . Note that thermocouple junctions were taped to the cell with Kapton tape and that the cell was fixed to a steel table with steel wire to prevent it from becoming a flying projectile.

An overview of the measurement channels that were used for the data acquisition unit is shown in Table 6.

Table 6 Channel list for the data acquisition unit

C1	Thermocouple, cell	Centre, top of cell
C2	Thermocouple, cell	Centre, underneath cell
C3	Thermocouple, cell	Centre, right side cell
C4	Thermocouple, cell	Centre, burner side cell
C5	Thermocouple, cell	Centre, left side cell
C6	Thermocouple, vent	Left edge, 300 mm from cell
C7	Thermocouple, vent	Centre, 300 mm from cell
C8	Thermocouple, vent	Right edge, 300 mm from cell
C9	Thermocouple, duct	Near duct entrance
C10	Thermocouple, duct	Further from duct entrance

4.2 Thermal propagation scenario

The thermal propagation scenario considered a custom-made battery pack. This pack consisted of an ABS pack filled with cylindrical 18650 cells. On one side of the pack there was a small hole for routing electrical cables. Between the hole and the battery cells was a 1 mm thick steel plate. Typically, electrical components are installed on this plate, but for these tests the plate ensured both that the extinguisher did not have direct access to the cells and provided a stable measuring point within the pack. Due to its thermal mass, its temperature may be considered as an average temperature for the battery pack.

Figure 5 Overview of the pack, the opening, and the steel plate mounted within.

A total of 30 individual cells were installed in the pack. They were pushed towards one another as much as possible, by stuffing the edges of the pack with insulating mineral wool. One cell (marked ½) was rigged with a Kapton heater, measuring 65 mm x 57.5 mm, covering as much of its external surface as possible. A proportional-integral-derivative (PID) controller supplied the heater with 24 VDC and a maximum output of 100 W. This PID controller allowed for the heating of the initiating cell within the pack to be controlled incrementally. In this case, the fastest possible ramp rate was selected. This selection was made as to limit heating of other cells within the pack.

Type-K 0.25 mm thermocouple junctions were taped to the external surface of several cells in the pack. The cells were selected to give information on how thermal runaway progressed between cells inside the pack. To ensure a fast response, the plastic wrapper from the cells was removed. Then the thermocouple junction was taped to the shell with Kapton tape. Cells that were considered for temperature measurements were marked with Kapton tape and numbered as shown in Figure 6.

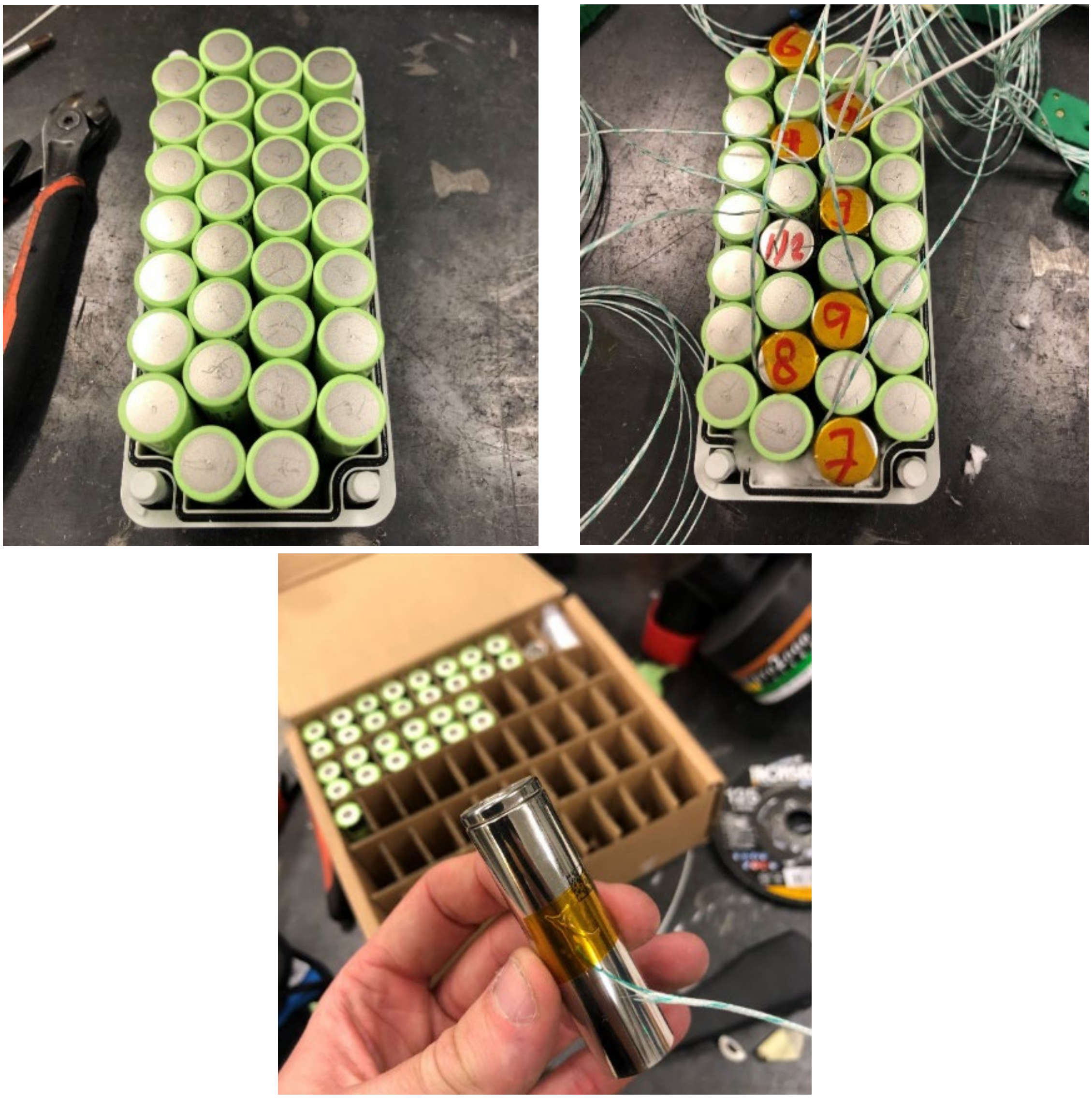


Figure 6 The contents of the battery pack and placement of thermocouples.

The battery pack was fixed to a steel table with steel wire as shown in Figure 7. A gas burner was placed nearby to ignite the pack in case not all battery cells had gone into thermal runaway. Note that the opening in the container was facing upwards and that three thermocouples were located around the opening. Hot gases and the jet flames were expected to be ejected from this opening. When this occurred, their gas temperatures would be recorded by the thermocouples.

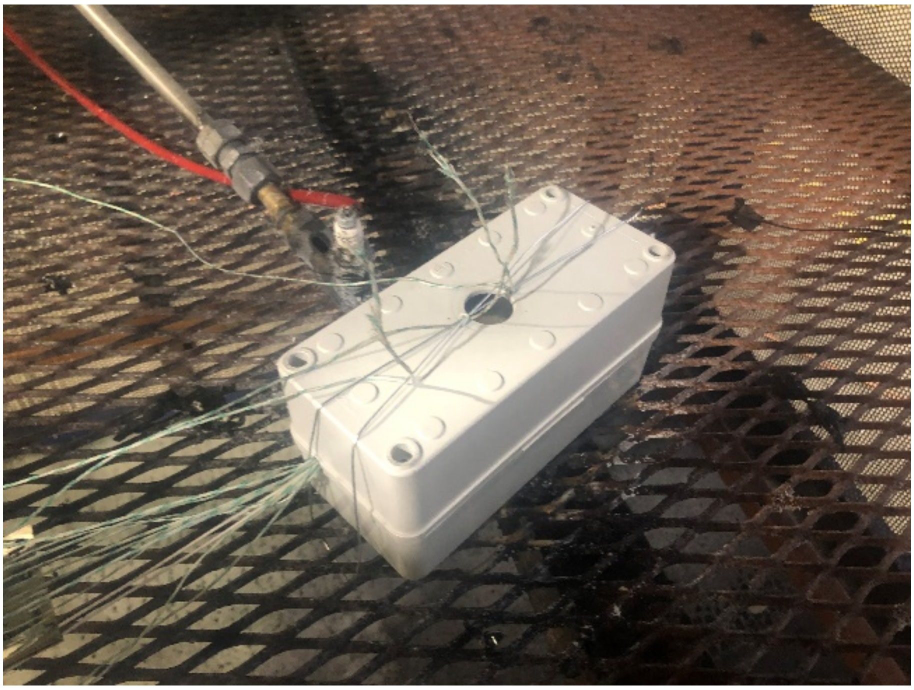


Figure 7 Overview of how the battery pack was positioned on a steel table.

A complete overview of the different thermocouple channels and their locations is shown in Table 7.

Table 7 Channel list for the data acquisition unit

C1	Thermocouple, cell	Feedback to PID controller, initiating cell
C2	Thermocouple, cell	Initiating cell
C3	Thermocouple, cell	Cell marked with 3
C4	Thermocouple, cell	Cell marked with 4
C5	Thermocouple, cell	Cell marked with 5
C6	Thermocouple, cell	Cell marked with 6
C7	Thermocouple, cell	Cell marked with 7
C8	Thermocouple, cell	Cell marked with 8
C9	Thermocouple, cell	Cell marked with 9
C10	Thermocouple, exit	Left of opening
C11	Thermocouple, exit	Centre of opening
C12	Thermocouple, exit	Right of opening
C13	Thermocouple, duct	Near duct entrance
C14	Thermocouple, duct	Further from duct entrance

5. Results

This section presents the results from the different tests. Especially those obtained from recordings with the video and IR cameras. An analysis of the different results follows after this section.

5.1 Single cell scenario – *Test 1*

A selected sequence of events following thermal runaway is shown in Figure 8. Thermal runaway commenced with a jet flame that ejected at the place where the external heater was aimed. The high temperature due to the gas burner likely made the steel case sufficiently soft, so that the cell ruptured here prior to the safety vent opening. The entire thermal runaway event was less than 1 min in duration and resulted in several jet flames. Following the jet flames there was a period of stable combustion for 1 min and 10 s. The total event, jet flames and combustion combined, lasted for 1 min and 30 s after thermal runaway initiated.

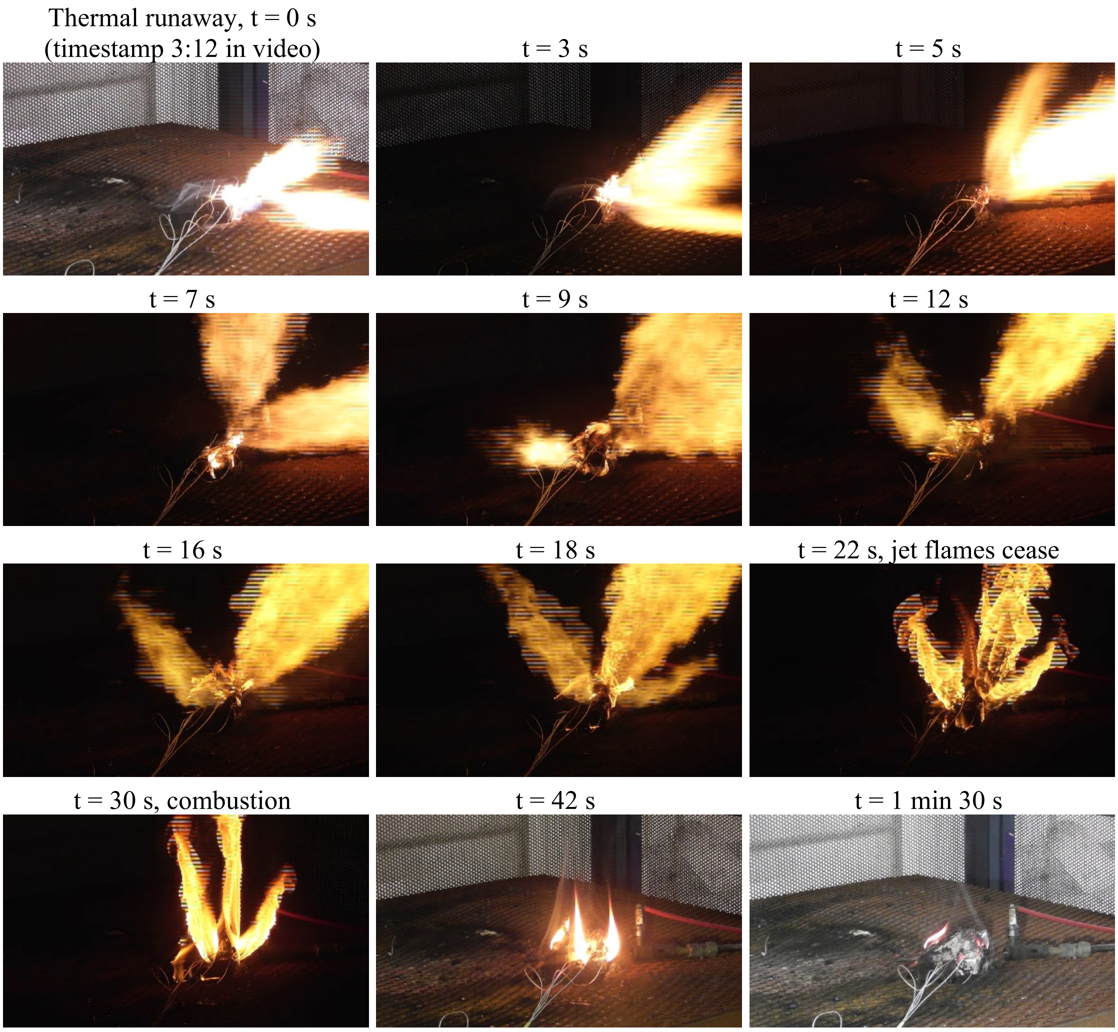


Figure 8 Fire development after thermal runaway in *Test 1*.

Footage taken by the IR camera, presented in Figure 9, shows in more detail how thermal runaway progresses and the direction in which combustible and hot gasses were emitted. The main flow of flammable gasses exits the cell from the location weakened by the gas burner. Eventually, the increasing pressure results in a small jet flame aimed towards the right side of the cell.

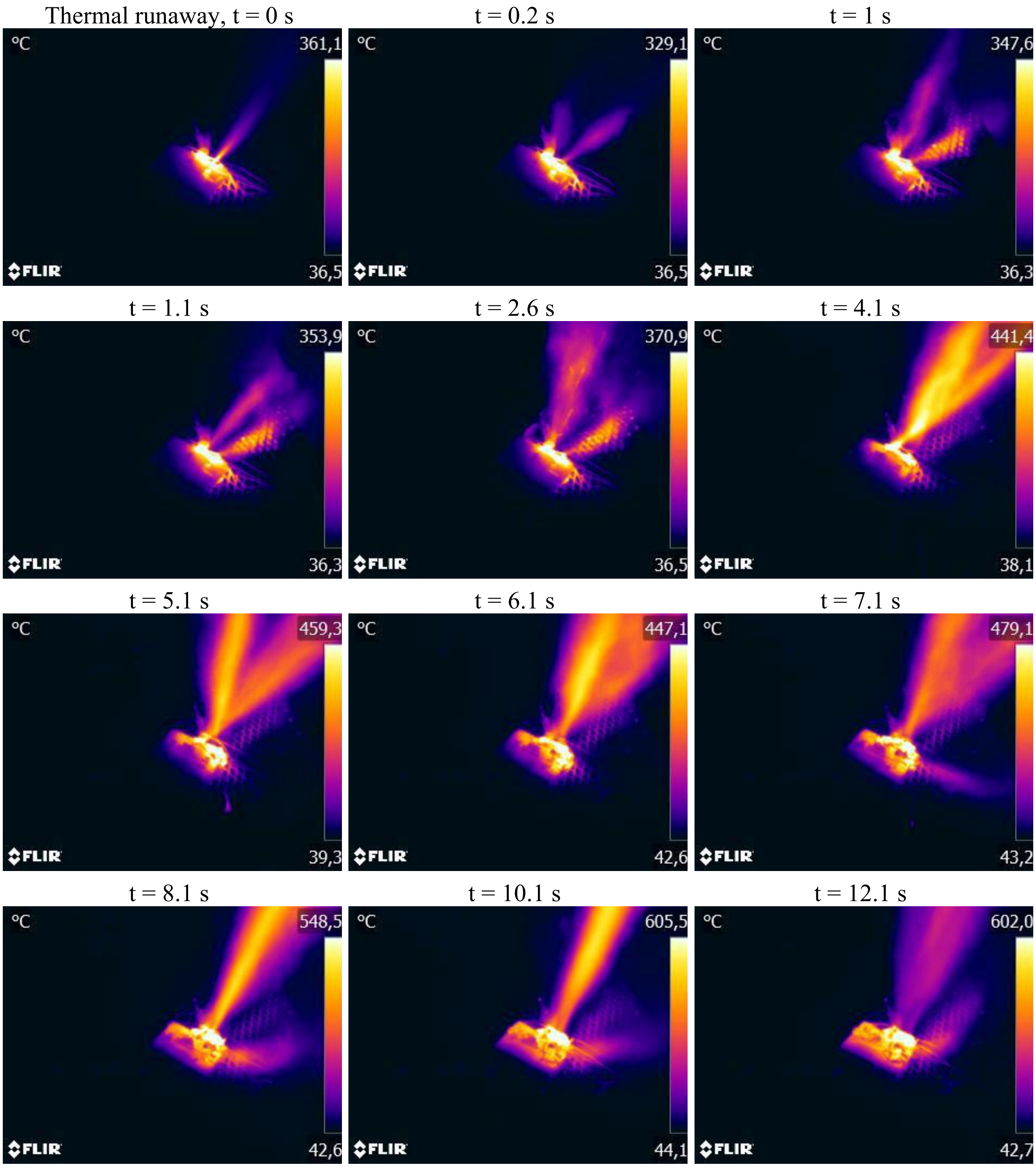


Figure 9 Fire development after thermal runaway in *Test 1*, footage taken by the IR camera.

Recorded temperatures on the external surfaces of the cell are shown in Figure 10. The gas burner was activated at 2 min and was kept active until thermal runaway occurred. The temperatures recorded at C1 give the clearest indication of thermal runaway. This occurred at time 3 min and 12 s. Temperatures increased rapidly while the first jet flames were observed. As thermal runaway resulted in the ejection of hot gases and flames, the cell cooled down. Temperatures at the other thermocouples on the cell then started to increase again once no more jet flames were observed around 3 min and 32 s.

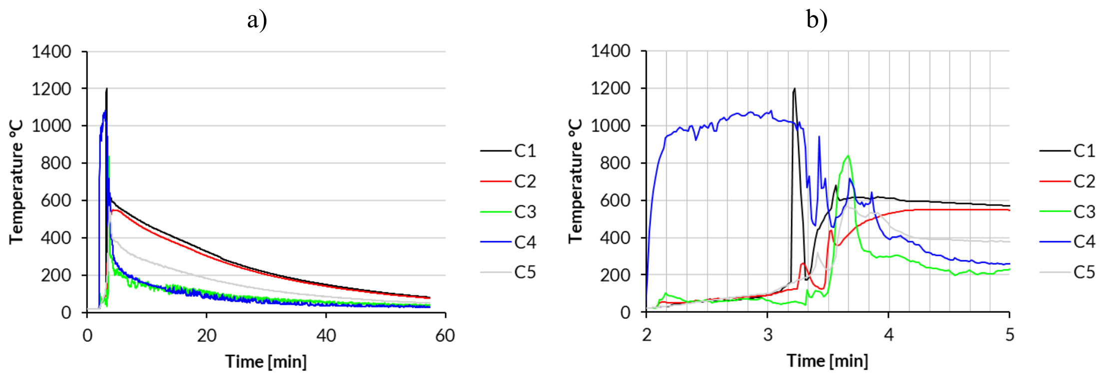


Figure 10 External surface temperatures of the cell, a) for the duration of the test; b) close-up of thermal runaway period.

Gas temperatures were recorded near the safety vent of the cell, and may be seen in Figure 11. However, since the jet flames and ejecta were not emitted in this direction during the test, this result is not very useful. It does give an idea on the overall gas temperatures around the cell, as a result of the surrounding air having its temperature elevated due to the fire. Temperatures in the gas duct temporarily increase as hot smoke gasses are evacuated.

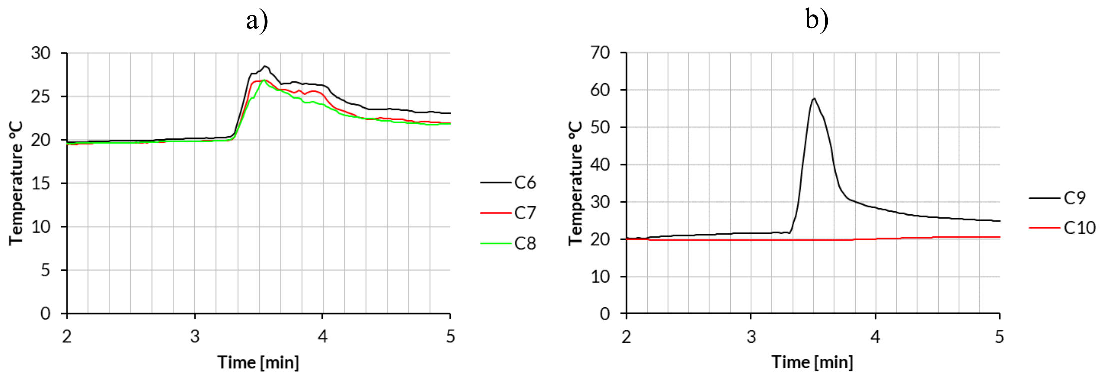


Figure 11 Gas temperatures measured a) near the safety vent of cell; b) in the gas duct.

5.2 Single cell scenario – *Test 2*

The sequence of events following thermal runaway are shown in Figure 12. The extinguisher was activated as soon as possible, after thermal runaway was observed. This resulted in the jet flame to be initially extinguished. However, the jet flame itself was observed to be reducing at the time the extinguisher was activated. When the suppressing medium was released, there was no more fire but the cell continued to release gas. About 8 s after the thermal runaway began, the cell swelled up more and some sparks were observed. Sparking continued until flammable gases were ignited.

Ignition of the flammable gases resulted in several jet flames, first one towards the right side of the cell, followed by another from the safety vent. The size of these jet flames began to reduce within 7 s and were extinguished within 20 s. Thereafter there was no more combustion. As the DUT started to become empty, some of the media appeared to evaporate and generate a lot of vapour. The fire did not reignite.

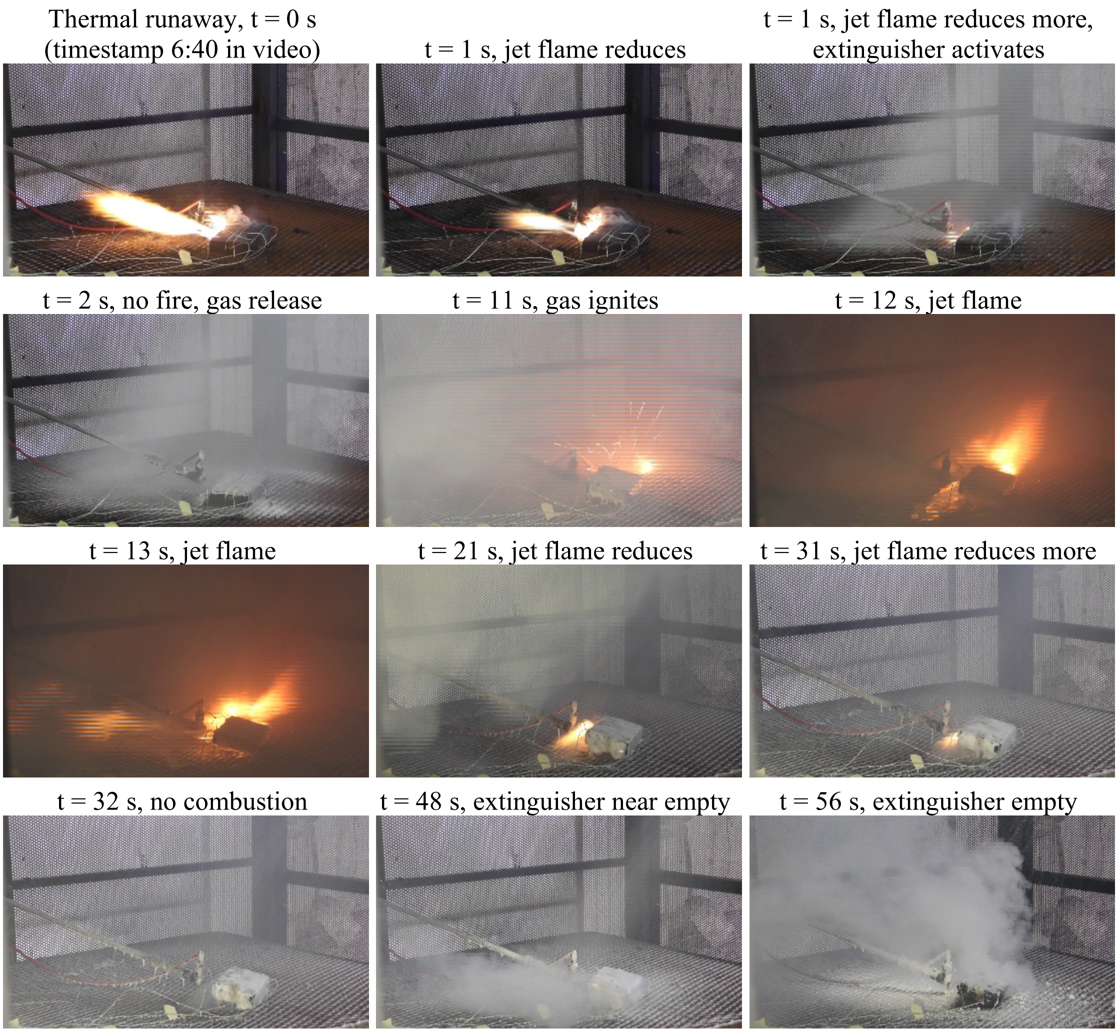


Figure 12 Fire development after thermal runaway in *Test 2*.

Figure 13 shows the footage taken by the IR camera. Initially the jet flame was ejected straight from the safety vent. This jet flame was extinguished by the extinguisher initially. However, as this occurred at the same time as the jet flame was reducing, it is not clear whether the extinguishment was only due to the DUT. Thereafter, another jet flame ignited perpendicular to the initial jet flame.

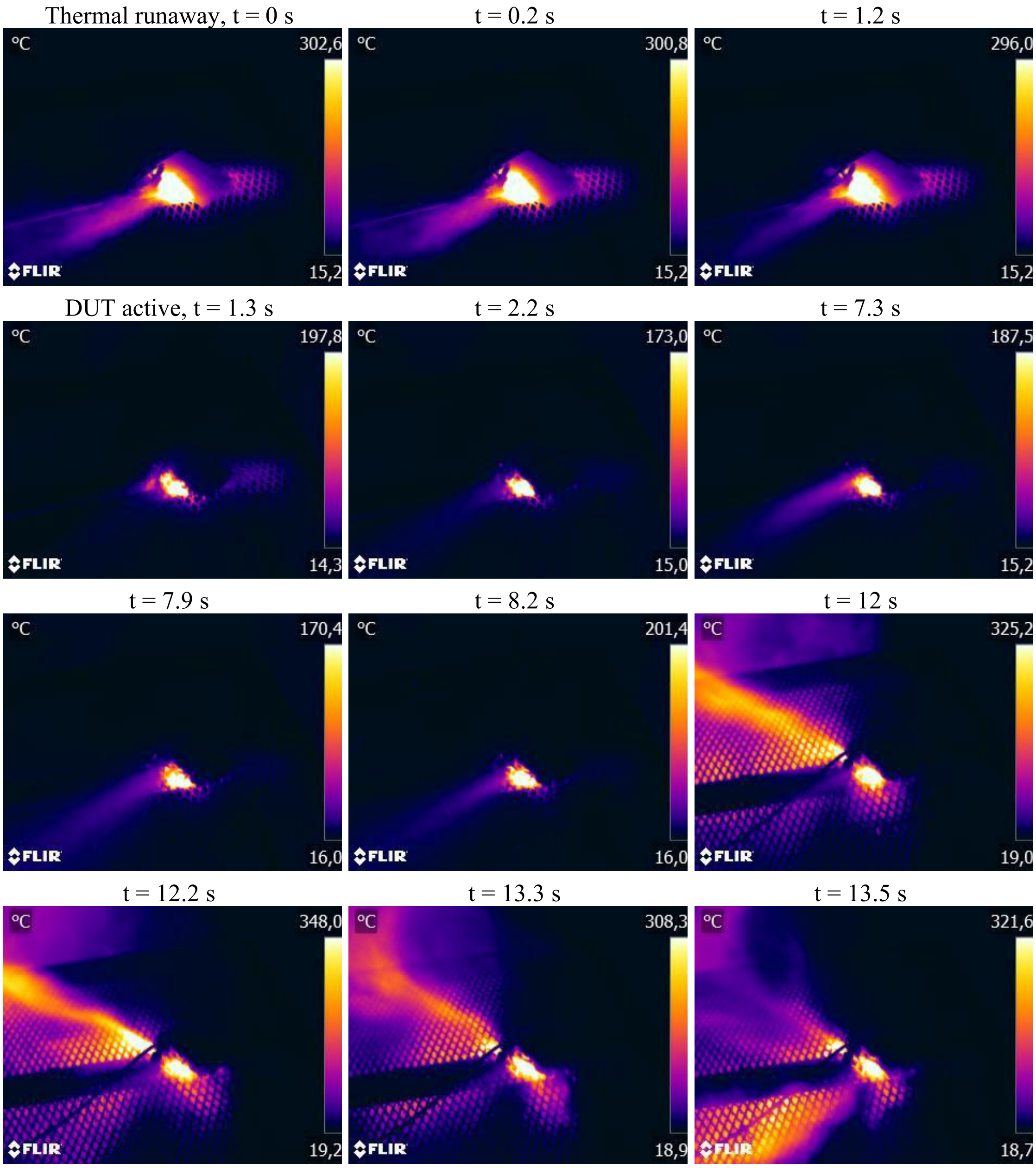


Figure 13 Fire development after thermal runaway in *Test 2*, footage taken by the IR camera.

External surface temperatures for the cell were measured with thermocouples. These measurements are shown in Figure 14. Thermal runaway occurred around 6 min and 40 s. The gas burner was activated at 4 min and 30 s. In this case, the recorded temperature remained around 400 °C, which was much lower than in *Test 1* with temperatures around 1 000 °C. This may be the result of the aim of the gas burner and thermocouple placement. The gas burner was namely aimed directly on the safety vent, whereas the thermocouple was located slightly above that point as it was not possible to fit it on the safety vent. When thermal runaway occurred, it did not take much time for the DUT to activate. This resulted in a rapid drop in temperatures, except underneath the cell. The suppressing media did not come in contact with that surface, hence there was no cooling there. Once the DUT had been emptied, temperatures began to climb again as the cell was still hot within.

Gas temperatures that were recorded may be seen in Figure 15. They show how the initial jet flame reduced and was extinguished, and how the second and third jet flames were formed. Finally, around the 7 min mark when the DUT was empty, temperatures increased. Temperatures inside the exhaust duct were kept low when the first jet flame was observed, and increased slightly during the remaining jet flame events.

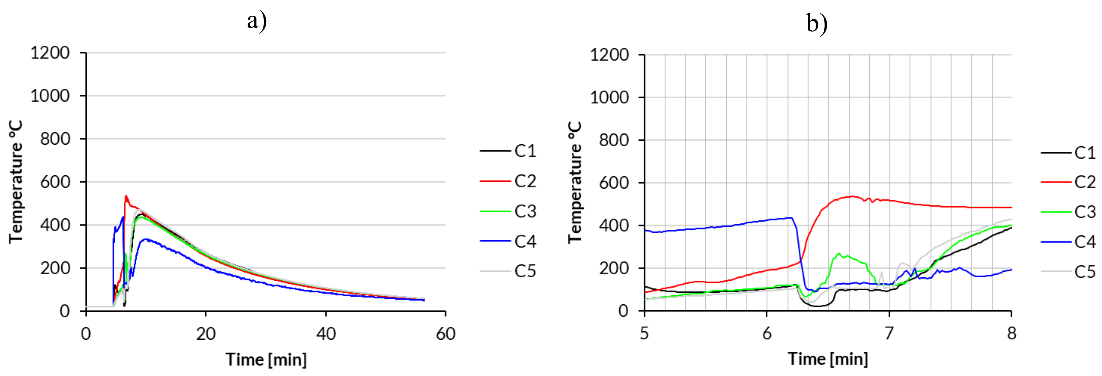


Figure 14 External temperatures recorded on cell, a) duration of the measurements; b) close-up of the thermal runaway event.

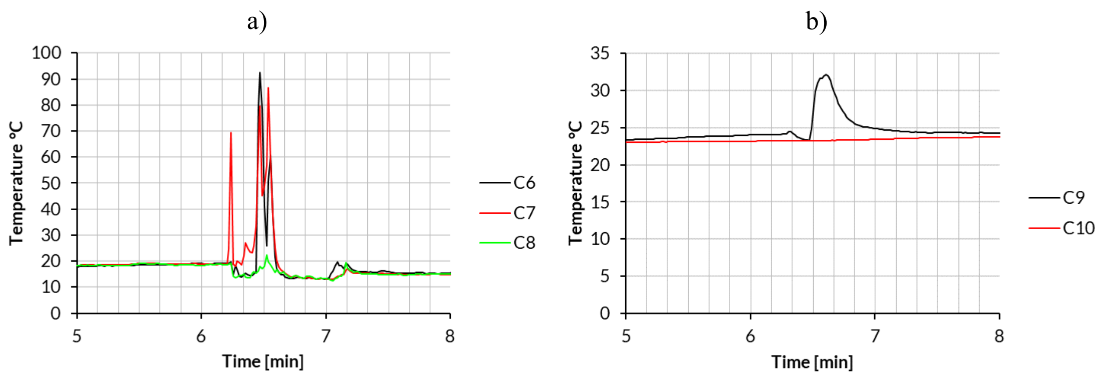


Figure 15 Gas temperatures recorded on the cell, a) thermocouples near the safety vent; b) inside the exhaust duct.

5.3 Thermal propagation scenario – *Test 3*

The chain of events following thermal runaway in the initiating battery cell, in the pack, is shown in Figure 16. First a stream of flammable gas was ejected through the opening in the pack. This was followed by sparks from underneath the pack, which finally ignited gas that was escaping from the pack. The fire burning underneath the pack then ignited the gas stream through the hole, which led to strong jet flames. The upwards gas stream stopped burning momentarily, only to be ignited again by the flames ejected from the pack.

Eventually a small opening burned through by the side of the pack, and jet flames began to originate from here. Flammable gas was still ejected at this point, through the top of the pack, but this did not ignite until the jet flames began to reduce in size. Once the jet flames reduced in size and disappeared it was observed that only the pack remained burning. It took approximately 7.5 min from this point on for the complete plastic pack to be consumed.

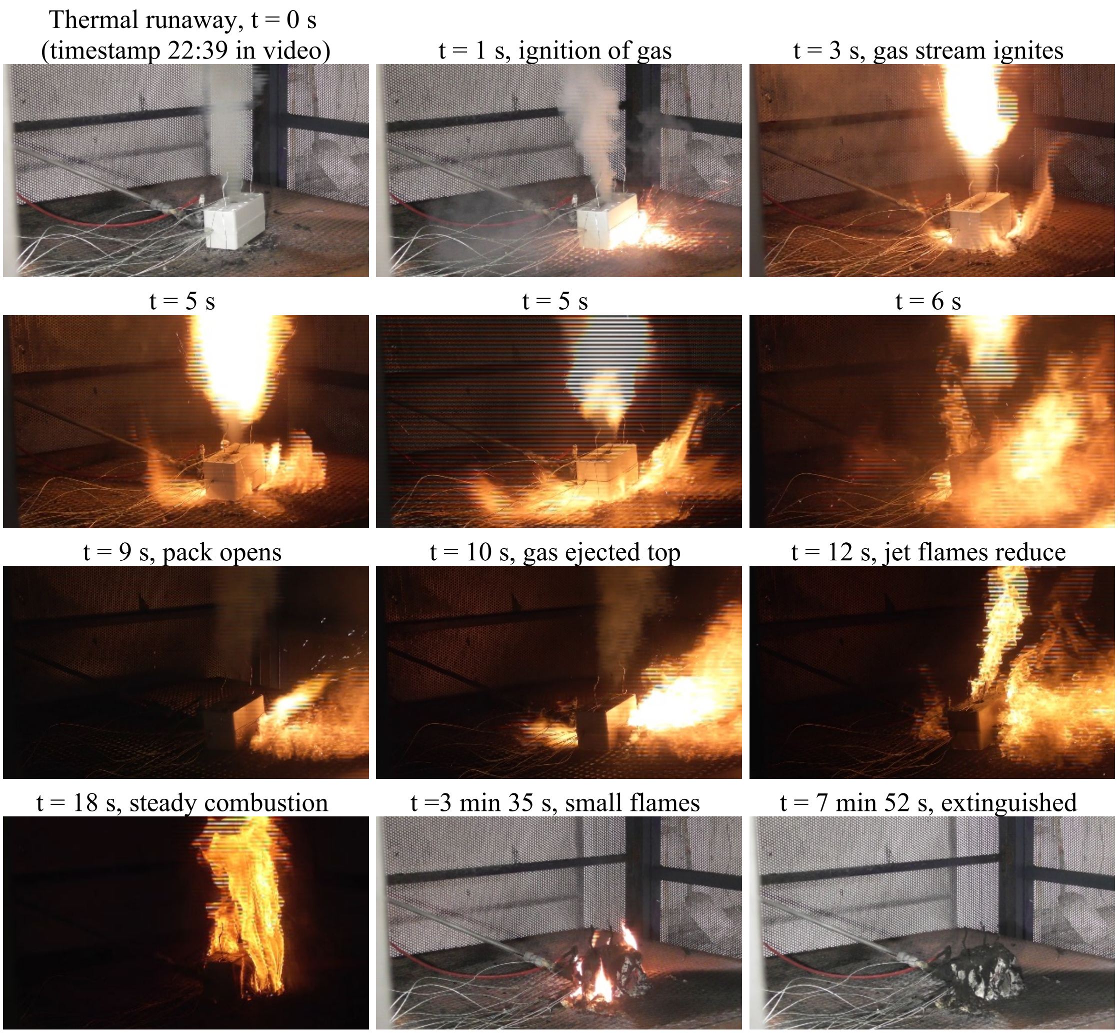


Figure 16 Fire development after thermal runaway in *Test 3*.

Footage taken with the IR camera, seen in Figure 17, shows how a stream of relatively cold gas exits through the pack hole initially. The temperature of this stream then increases rapidly and material is ejected from the battery pack. Following this, combustion mainly takes place underneath the battery until the gases ejected through the opening were ignited again. This indicates that a lot of pressure was generated within pack, causing multiple gas streams to be ejected. In future tests this should be prevented, to reduce variation between tests.

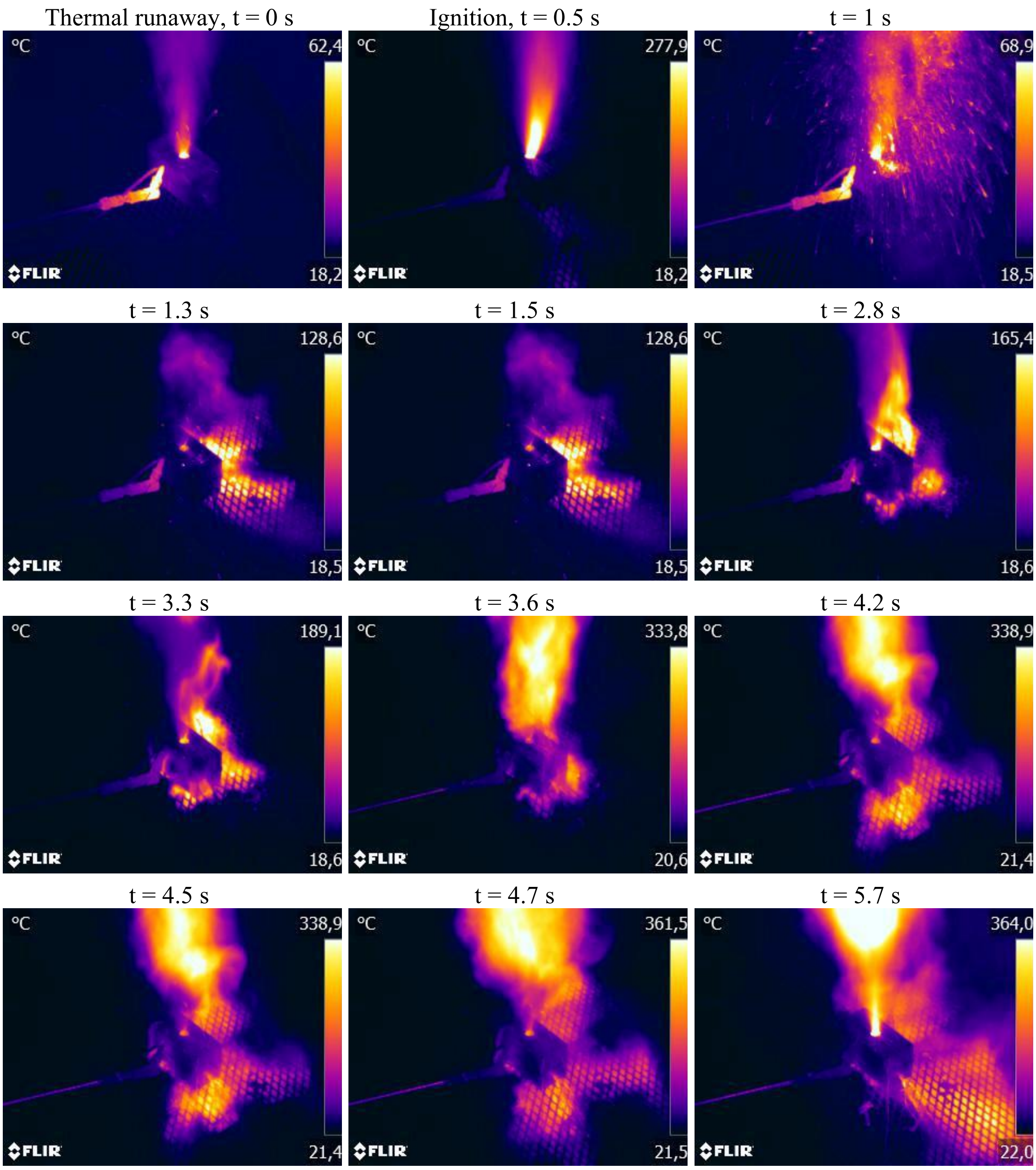


Figure 17 Fire development after thermal runaway in *Test 3*, footage taken by the IR camera.

Temperatures recorded on the different cells in the pack are shown in Figure 18. These results show that all measured cells went into thermal runaway within 12 s after thermal runaway began in the initiating cell. As summarized in Table 8, the initiating cell, denoted C2, reached a critical temperature of 201 °C upon which it went into thermal runaway. Following this, C8 failed, then C3, C7 and C9, followed by C4 and C5, and finally C6. It is possible that other cells failed before these, since only 8 out of 30 cells inside the pack were monitored by thermocouples. Note that the critical temperatures recorded at the time of failure varied significantly. This variation is not unlikely due to flames in various locations within the pack, in some cases burning directly through and igniting adjacent cells while other cells may have needed to be heated up externally until thermal runaway ensued.

The average temperature in the pack, represented by the metal plate, gives insight into how many cells were involved at a given time. This is also shown in Figure 18. Initially, when the first cell entered thermal runaway, temperatures within the pack were still low. As more cells were triggered, the situation got out of control. This stresses the importance of activating the extinguisher as early as possible. It also suggests that more useful test results would be obtained if the fire propagated more slowly between the battery cells. For example by increasing the distance between each cell in the pack to delay the fire spread. In this way, it would be more straightforward to interpret the results and see the effect of the DUT .

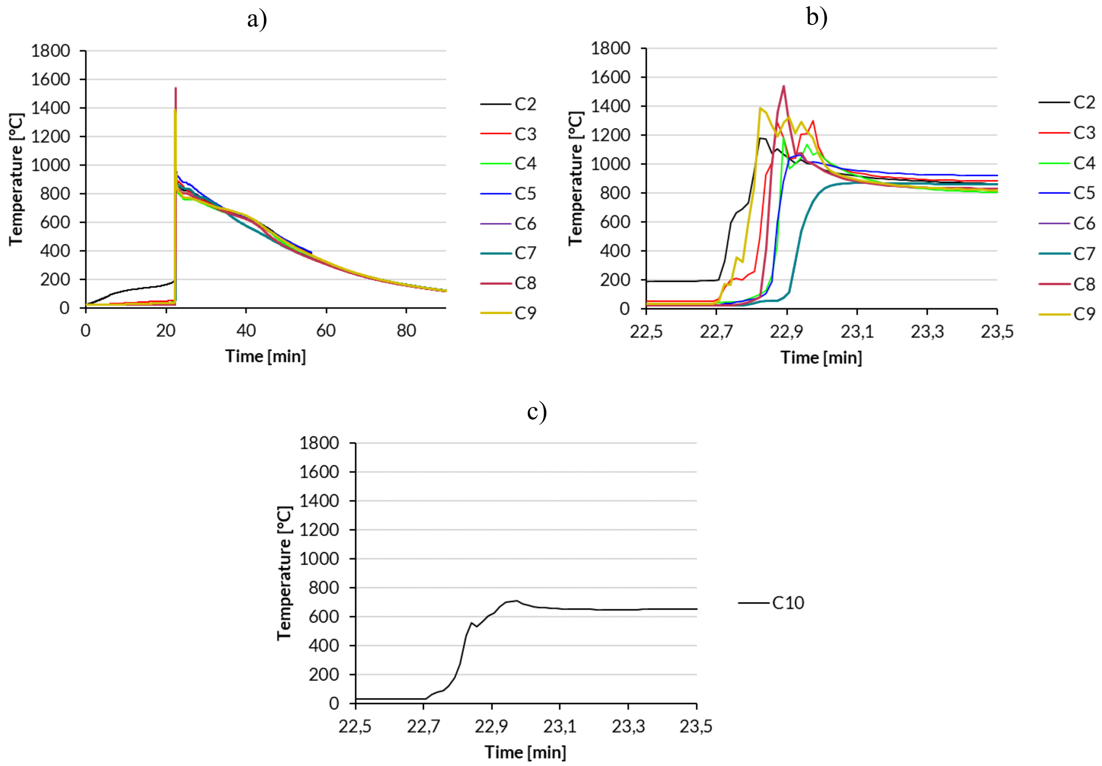
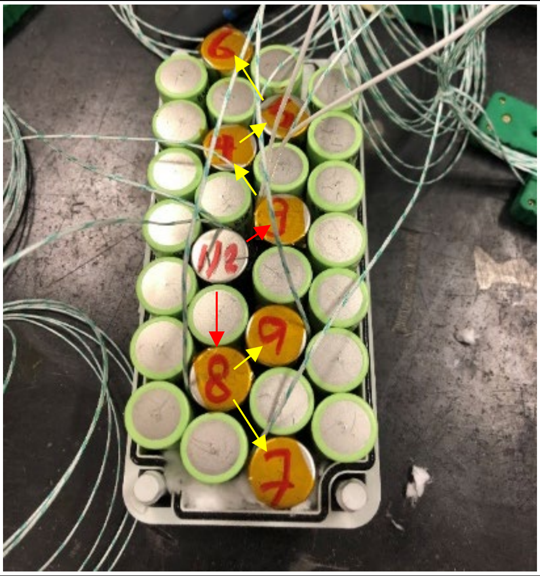


Figure 18 Overview of temperatures in the pack in *Test 3*, a) battery cell temperatures; b) close-up of battery cell temperatures during thermal runaway; c) average temperature of the pack during thermal runaway.

Table 8 Summary of thermal runaway propagation through the pack

Order	Cells	Propagation time	Critical temperature
1.	C2	0 s	201 °C
2.	C8	2 s	165 °C
3.	C3	6 s	259 °C
4.	C7	7 s	82 °C
4.	C9	7 s	212 °C
5.	C4	9 s	230 °C
5.	C5	9 s	188 °C
6.	C6	12 s	114 °C



Gas temperatures recorded for the battery pack during this test are shown in Figure 19. When the first stream of gas was released, the temperatures started to increase. Once ignited, temperatures reached up to 1 000 °C. When only plastic was burning, temperatures hovered around 800 °C. Duct temperatures reached a maximum of 70 °C.

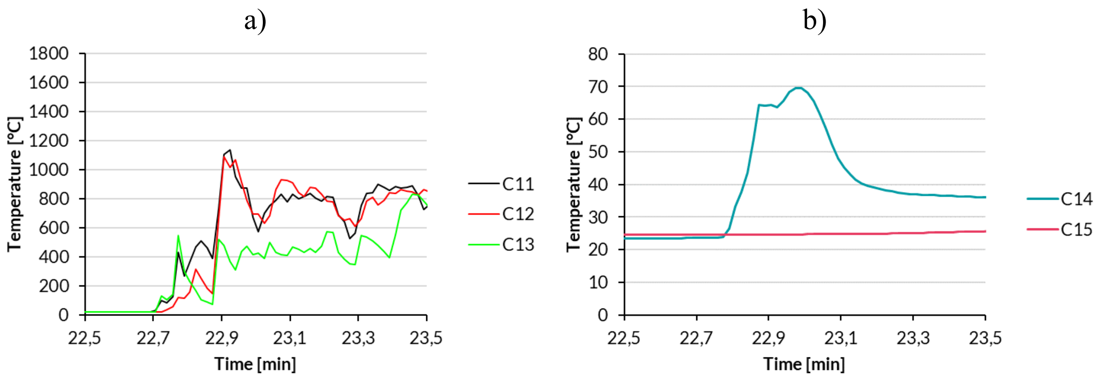


Figure 19 Gas temperatures measured a) with thermocouples near pack; b) inside the gas duct.

5.4 Thermal propagation scenario – *Test 4*

The events following thermal runaway initiation in *Test 4* are shown in Figure 20. In this case, the initial thermal runaway event, before the extinguisher was activated, appeared to be similar to that of *Test 3*. That is, gas was released through the pack opening and underneath with some sparks. In this test however, when the DUT was activated there was no further activity in the battery pack. The fire did not propagate to the other cells in the pack, and this there was no further activity apart from some flaming underneath the pack due to the thermal runaway in the initiating cell. Further testing could show clearer results and consistency in the effects of the fire extinguisher.

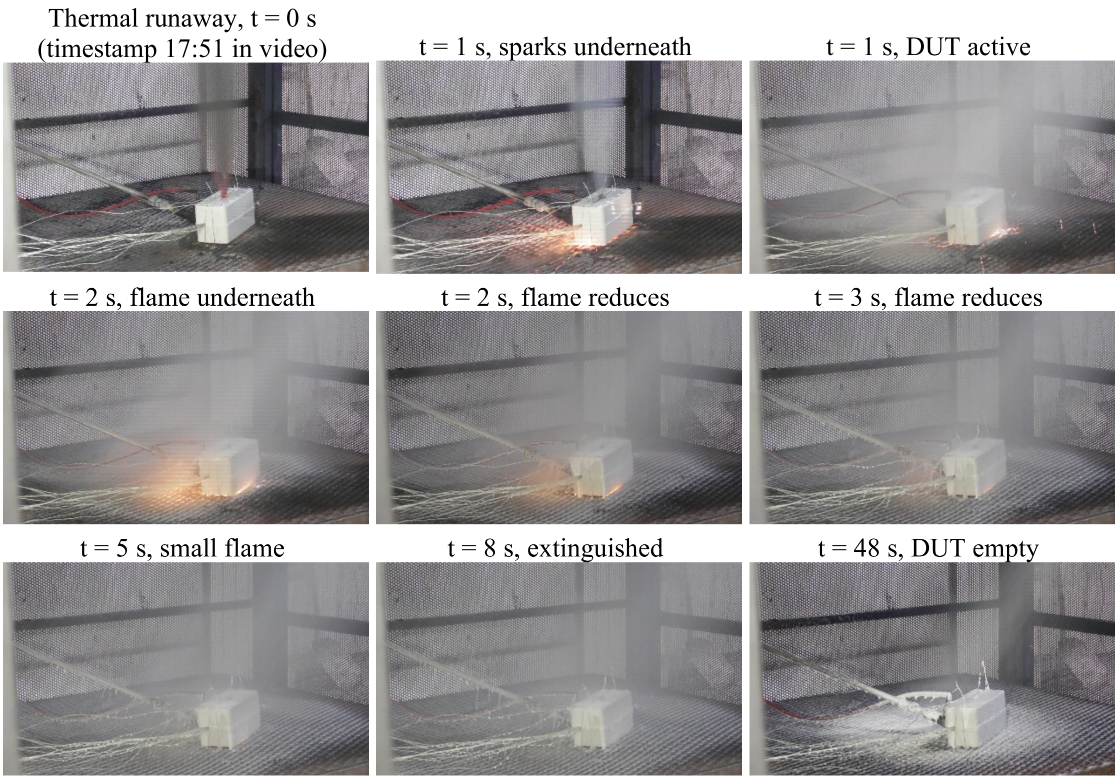


Figure 20 Fire development after thermal runaway in *Test 4*.

Footage taken by the IR camera is seen in Figure 21. This shows how the gas stream exiting the DUT did not reach as high temperatures as in *Test 3*. When the fire extinguisher was activated, this stream had still not ignited and combustion only took place underneath the DUT.

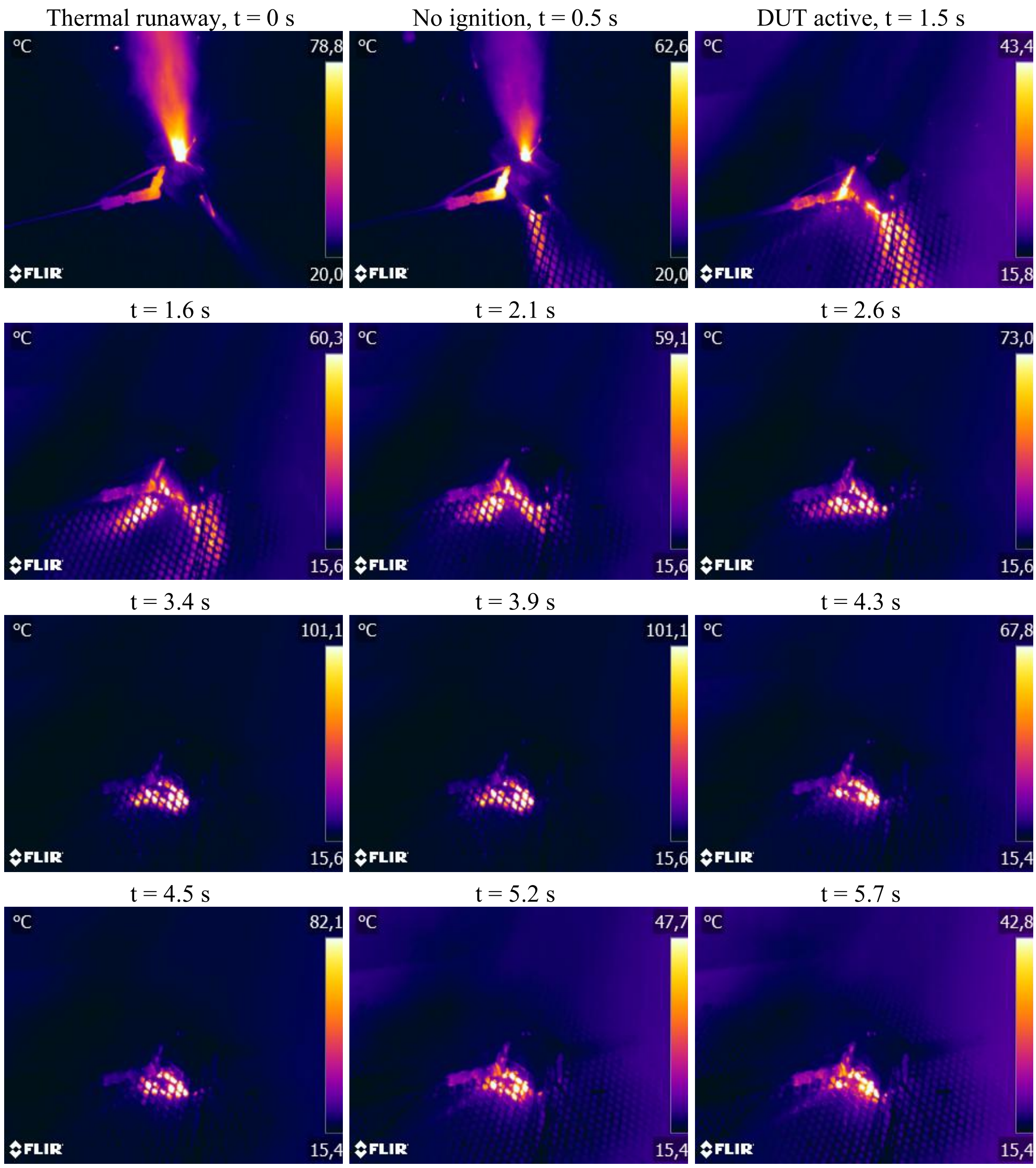


Figure 21 Fire development after thermal runaway in *Test 4*, footage taken by the IR camera.

Temperatures recorded for the different cells in the pack are shown in Figure 22 The temperature of the initiating cell, represented by C2, increased early on as well as during the thermal runaway event. This may indicate that this thermocouple did not have good contact with the initiating cell. Remaining temperatures were relatively stable however. After the thermal runaway in the initiating cell, several cells close to the initiating cell reached well above 200 °C. This did not result in thermal runaway, despite this temperature theoretically being sufficiently high to do so. An overview of the peak temperatures and whether thermal runaway occurred may be seen in Table 9. It is unclear whether this result is due to the extinguisher or due to other factors involved.

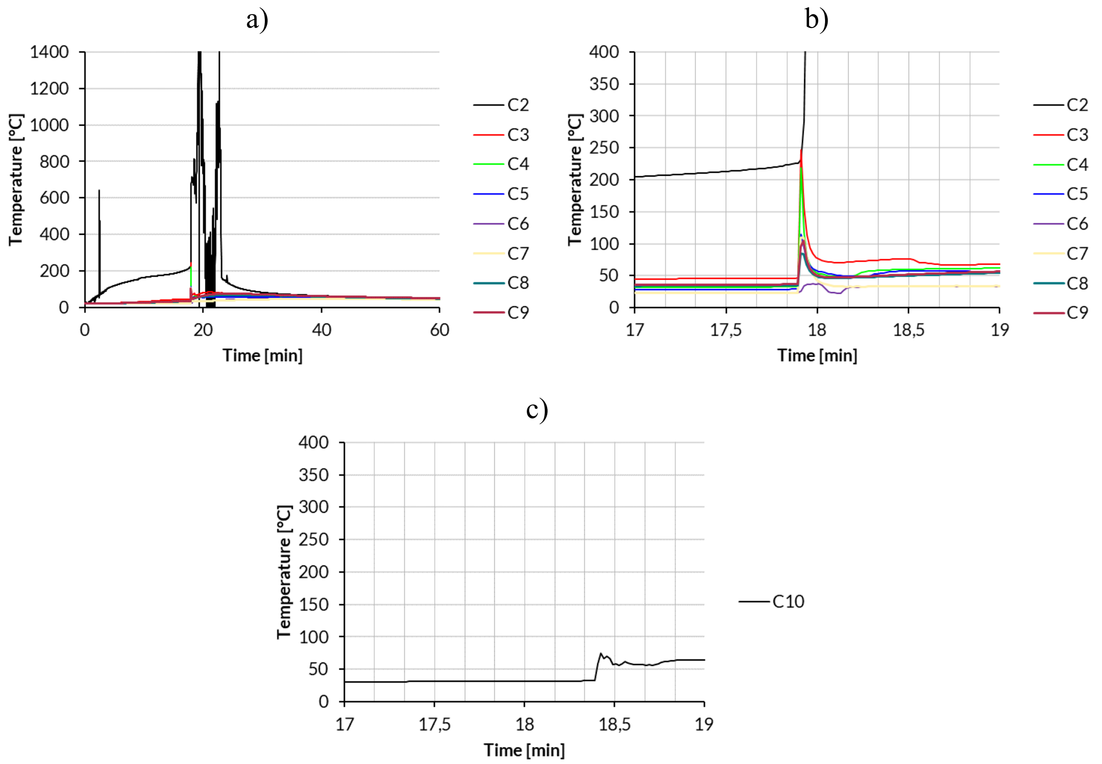


Figure 22 External surface temperatures of the cells in the pack, a) overview of the test; b) close-up of the thermal runaway event; c) average temperature.

Table 9 Summary of thermal runaway propagation through the battery pack

Order	Cells	Propagation time (time to peak temp)	Critical (peak) temperature	
1.	C2	0 s	231 °C	
2.	C3	(0 s)	(246 °C)	
2.	C4	(0 s)	(218 °C)	
2.	C5	(0 s)	(114 °C)	
2.	C8	(0 s)	(84 °C)	
3.	C7	(1 s)	(109 °C)	
3.	C9	(1 s)	(104 °C)	
4.	C6	(4 s)	(37 °C)	

Gas temperatures recorded for this test are shown in Figure 23. A small increase in temperature was observed in the thermocouples close to the battery pack opening up. This was due to the hot gasses that were ejected from the pack.

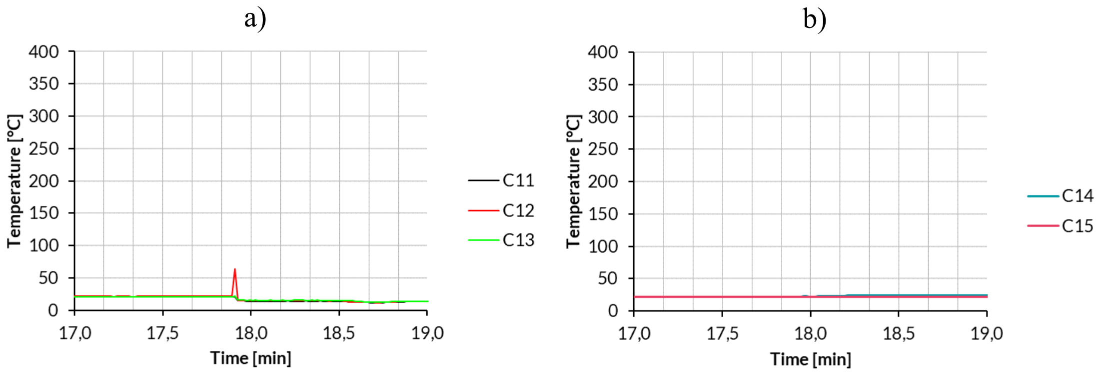


Figure 23 Gas temperatures a) near the pack; b) in the duct system

6. Analysis

This section focusses on comparing the different test results and discusses the effects of introducing the DUT to the fire scenarios.

6.1 Single cell scenario

External surface temperatures for the battery cell are given by Figure 24, where thermal runaway starts at 3.2 min. It can be seen that the surfaces that were directly exposed to the extinguisher were effectively cooled down once it was activated. Initially, temperatures were kept well below 200 °C but once the fire reignited, at 3.5 min, temperatures started to increase at C2 and C3. At C3 however, they are still kept relatively low. Since the extinguisher had no access to C2, it was not able to keep this surface cooled during this time. The results suggest that the immediate cooling effect of the extinguisher was effective.

Once the extinguisher had been emptied, temperatures began to increase again. Similar temperatures were reached as when no extinguisher was considered, and in some locations these temperatures were even exceeded. It is possible that this was a result of a thermal insulation effect provided by the medium, as it covered the cell which was still very warm within.

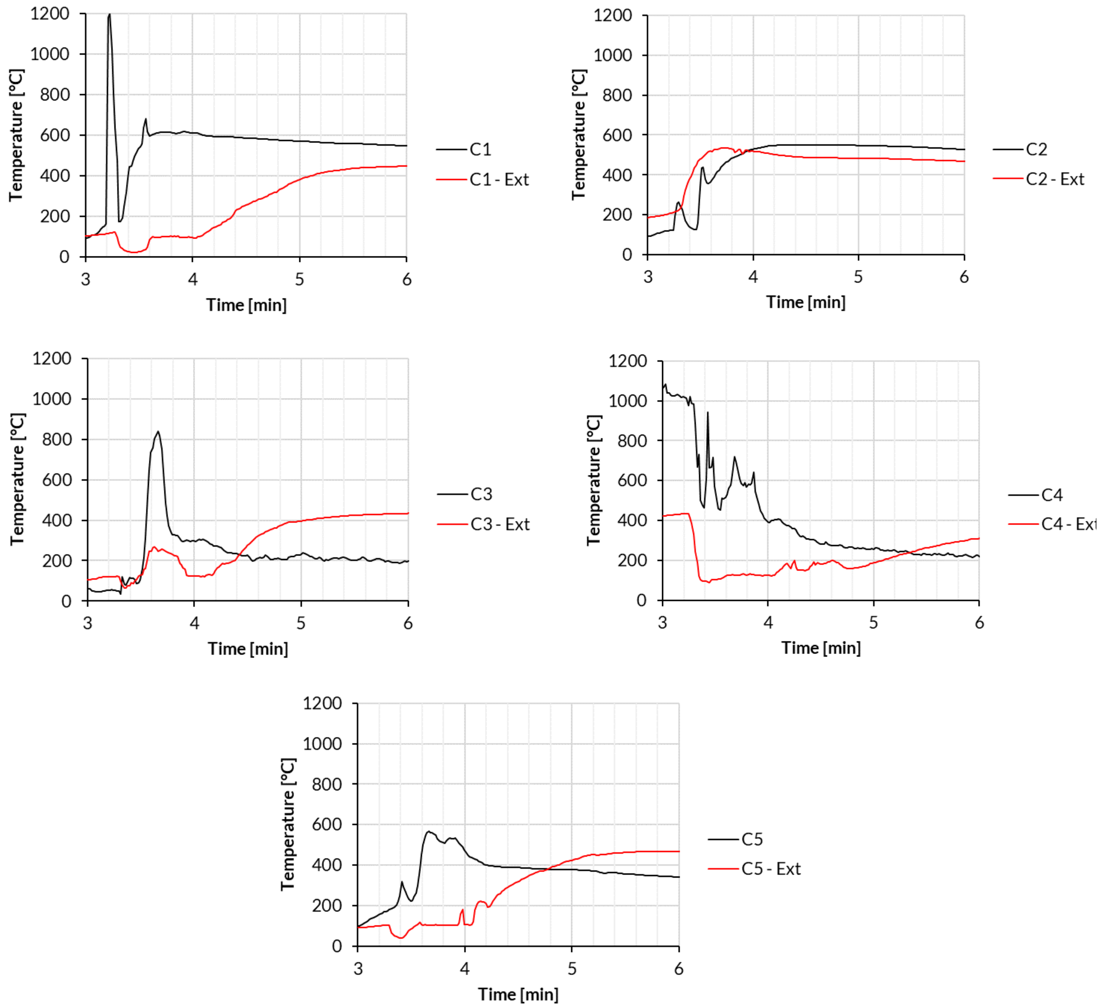


Figure 24 Cell temperatures. Note that the times are synchronised with respect to when thermal runaway began.

Figure 25 shows the gas temperatures measured. The data for the thermocouples near the safety vent o were unfortunately not useful in *Test 1* as the jet flame ejected from the opposite end of the test object. Regardless, results from *Test 2* indicate how the jet flame pulsated in intensity and changed directions during the course of the thermal runaway. First it fired straight from the vent, towards C6, and then more towards the right side of the cell. This led to temperature spikes at C6 and C7. Gas temperatures in the exhaust duct were remained low when thermal runaway initiated and the jet flame was quickly extinguished after the fire extinguisher was activated. When the fire reignited, temperatures went up but were still kept below the temperatures that were observed when no extinguisher was considered.

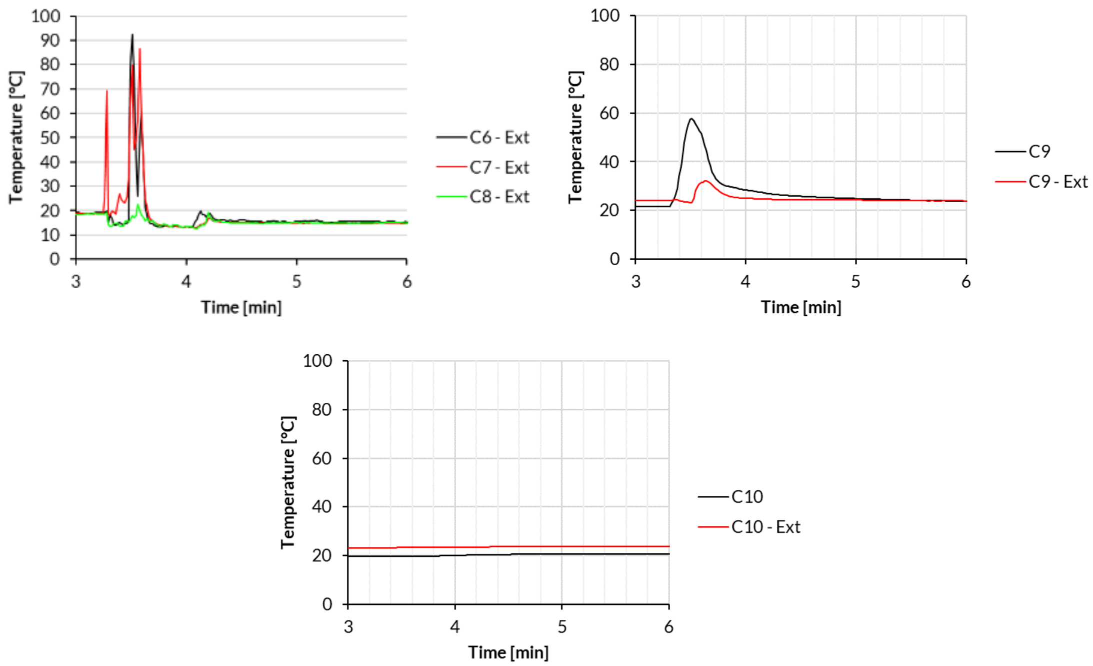


Figure 25 Gas temperatures. Note that the times are synchronised with respect to when thermal runaway began.

One factor that introduced some differences in the test results was the burner placement. Ideally the cell would vent gas and eject jet flames from the same location in both tests of the scenario. This was more likely achieved if the gas burner was placed in a way that ensured the flame impinged on the safety valve of the cell.

6.2 Thermal propagation scenario

External surface temperatures measured on individual battery cells close to the initiating cell in the battery pack are compared in Figure 27. Note that these are close-ups focussed on the time shortly after thermal runaway to gain a better understanding of how thermal runaway propagated. Temperatures of the initiating cell were similar in both tests, however in *Test 4* the thermocouple likely failed as a result of thermal runaway. Cells close to the initiating cell, such as C3 and C4, recorded high temperatures at this time, especially C3 which recorded 250°C. Considering thermal runaway initiated at 200°C in *Test 3* and 225 °C in *Test 4*, this was high enough to potentially trigger thermal runaway in C3 as well. It did not, but it is unclear whether this is due to the extinguisher or due to other factors involved.

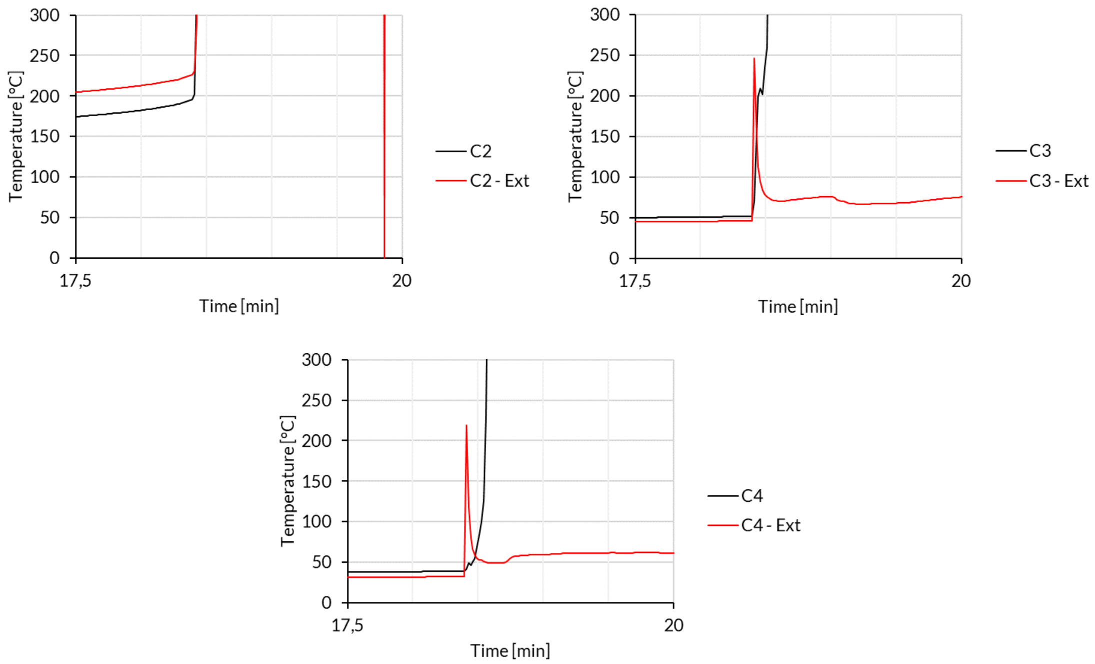


Figure 26 Comparison of temperature evolution on C2, C3, and C4 in the thermal propagation scenario.

As there was no further propagation, temperatures at all other measurement locations were significantly lower in *Test 4* than they were in *Test 3*. A comparison of this result is given by Figure 27 and Figure 28.

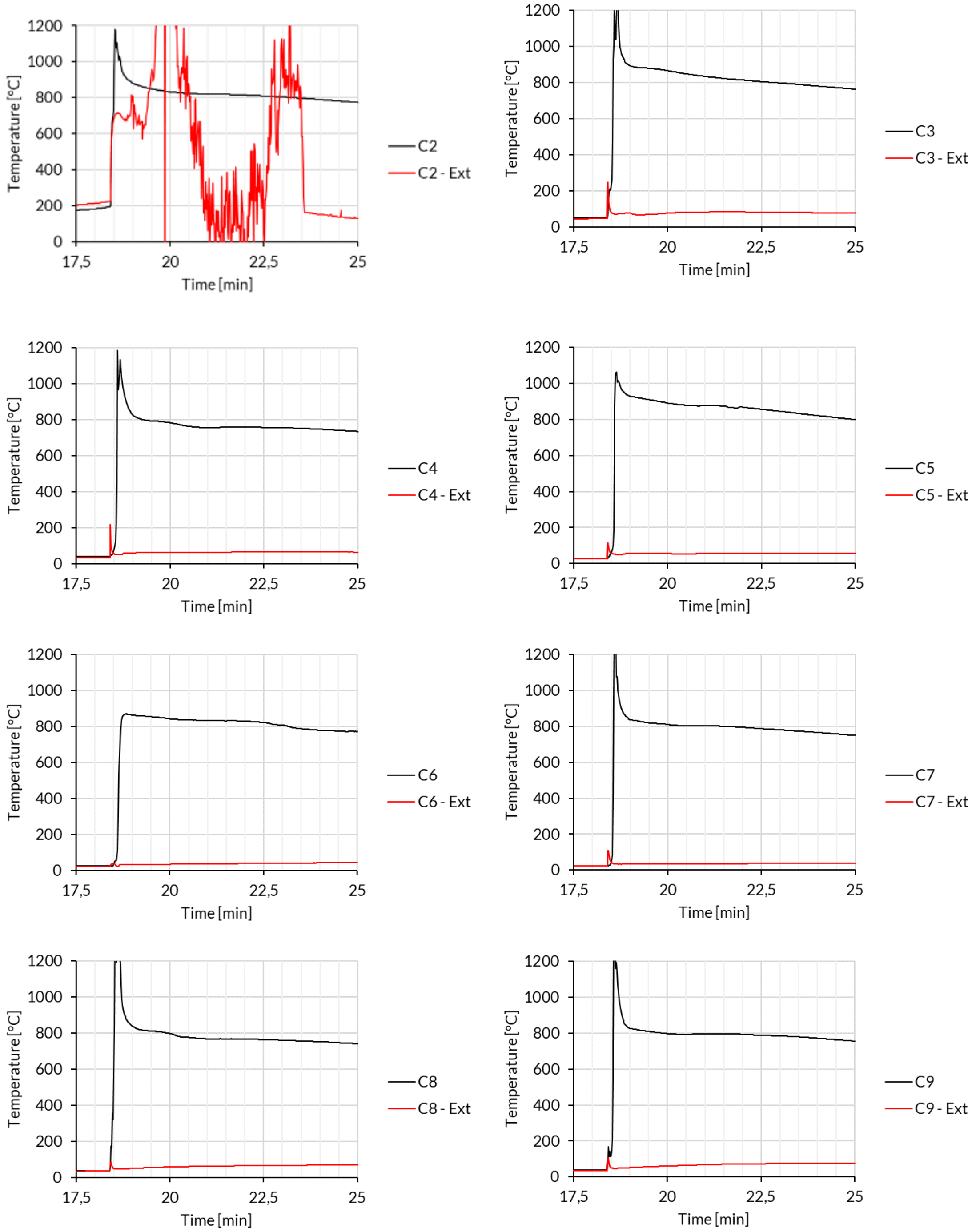


Figure 27 Comparison of recorded temperatures in *Test 3* and *Test 4*. Note that the caption "-ext" refers to the tests where the DUT was considered.

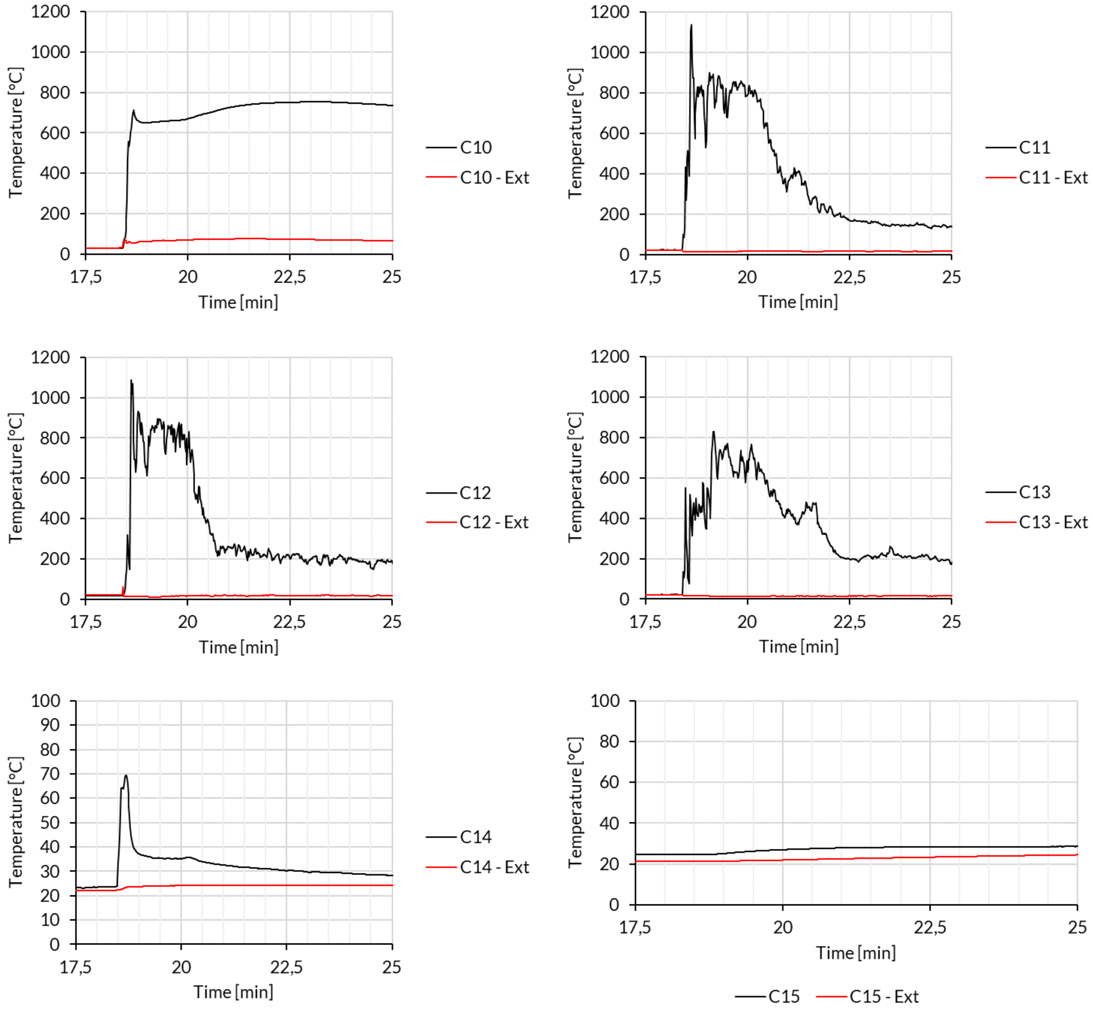


Figure 28 Comparison of recorded temperatures in *Test 3* and *Test 4*. Note that the caption "-ext" refers to the tests where the DUT was considered.

It is evident that the outcome of this test scenario is heavily influence by whether thermal propagation occurs or not. To obtain a good test methodology, this variance should be reduced further. Several suggestions for improvement in future rounds of testing are as follows:

- <u>Consistent contact conditions between heating element and initiating cell.</u> This needs to be kept the same between the tests as much as possible, since insufficient contact in some areas can affect the total heat input to the initiating cell, and thus when and how it fails.
- <u>Slower temperature ramp for the initiating cell.</u> In the performed tests the temperature ramp used was "as fast as possible". This exacerbates any poor variations in contact conditions. A slower ramp rate would be preferred, as this allows heat to transfer more evenly throughout the complete initiating cell rather than supplying heat quickly at discrete points.
- <u>Consistent positioning of the individual cells inside the pack.</u> In the performed tests, the cells were pushed towards each other as much as possible by pushing insulating wool around them. To reduce variations, filling material of standard dimension should be inserted in the pack so that the exact individual cells end up in exactly the same location at all times or a fixture needs to be considered that keeps the cells at fixed distances from each other.
- <u>Better sealed pack.</u> During the tests it was observed that gas escaped from underneath the pack, not only from its opening. To reduce variations, gas should release from the same position in all the tests. Some modifications are thus needed for the pack, such as a smaller or perforated metal plate inside the pack to reduce the pressure in the pack and more easily allow gas to escape. In addition, any other small holes made in the pack for routing thermocouple wires, should be sealed off with sealant.
- <u>More controlled ignition.</u> Thermal runaway is a chaotic and uncontrollable process once it occurs. Sometimes gases released by a cell will ignite due to sparks or autoignition, and other times they won't. To reduce this uncertainty in the results, gases released by the cell should be ignited remotely either by an external flame or spark plugs.

7. Conclusions

RISE performed tests for Firexo to investigate whether their handheld fire-extinguisher could suppress fire in lithium-ion batteries. For this purpose, exploratory tests were performed representing two scenarios: fire in a large automotive single battery cell and fire in a small battery pack. Two tests were performed for each scenario, a reference free-burning test and a suppression test. The tests provide some fundamental insight to the effect of the agent but further testing is critical to attain reliable results.

In the extinguishing test for the single cell, the fire-extinguisher appeared to reduce the severity of the battery fire. Specifically, the initial jet flame was extinguished and the size of following jet flames was reduced. The fire did not reignite after the extinguisher had been emptied.

For the small battery pack, the fire-extinguisher suppressed the initial fire and there was no propagating thermal runaway. However, further testing is necessary to ensure this effect was not a result of stochastic uncertainties or uncertainties in the test procedure..

Overall, the test results indicate that the Firexo 9LTR Extinguisher has a positive effect on thermal runaway events under the considered circumstances. It can be stated that the Firexo fire-extinguisher, under the test conditions listed, demonstrated no negative effects on the lithium-ion battery fires. Furthermore the tests indicate that the Firexo 9LTR Extinguisher potentially may reduce the internal temperature of a battery cell undergoing thermal runaway, may reduce the size of resulting jet flames, and that it may inhibit thermal runaway and temperature propagation in the cells, which are critical factors to suppress and control lithium-ion battery fires.

RISE Research Institutes of Sweden AB
Department Safety Research - Fire Safe Transport

Performed by

Signed by: Roeland Bisschop
Reason: I am the author of this document
Date & Time: 2021-01-08 09:43:23 +01:00

Roeland Bisschop

Examined by

Signed by: Franz Evegren
Reason: I have reviewed this document
Date & Time: 2021-01-08 09:37:37 +01:00

Franz Evegren