



**HAL**  
open science

## Recent safety focused overall analysis, testing and accident reviews towards safer e-mobility and energy storage

C. Di Bari, Amandine Lecocq, Guy Marlair, Benjamin Truchot, M. Mazzaro, L.E. Mele, P. Russo

### ► To cite this version:

C. Di Bari, Amandine Lecocq, Guy Marlair, Benjamin Truchot, M. Mazzaro, et al.. Recent safety focused overall analysis, testing and accident reviews towards safer e-mobility and energy storage. International Conference on Fires In Vehicles (FIVE 2020), Dec 2020, Online, Sweden. ineris-03319973

**HAL Id: ineris-03319973**

**<https://ineris.hal.science/ineris-03319973>**

Submitted on 13 Aug 2021

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# Recent safety focused overall analysis, testing and accident reviews towards safer e-mobility and energy storage

C. Di Bari<sup>1</sup>, A. Lecocq<sup>2</sup>, G. Marlair<sup>2</sup>, B.Truchot<sup>2</sup>, M. Mazzaro<sup>3</sup>, M. L. Mele<sup>4</sup>, P. Russo<sup>4</sup>

1. ENEA (Italian National Agency for New Technologies, Energy and Sustainable Economic Development) – Italy; 2. INERIS (French National Institute for Industrial Environment and Risks) – France; 3. CNVVF (Italian National Fire Corp) – Italy; 4. Department of Chemical Engineering Materials Environment, Sapienza University of Rome– Italy

Corresponding authors: [cinzia.dibari@enea.it](mailto:cinzia.dibari@enea.it) & [guy.marlair@ineris.fr](mailto:guy.marlair@ineris.fr)

## 1 INTRODUCTION

Lithium batteries have wide application from electric vehicles (EV) to Energy Storage Systems (ESS) and consumer electronics. Their chemical composition and their behavior under abuse conditions pose a risk for safety and people health. The risk grows with the amounts of active material and flammable electrolyte and hence, with the number of cells which constitute the battery. In order to manage the risk, critical points during the entire life cycle of a lithium battery should be identified. To this aim, both chemical and electric characteristics of cell and battery have to be available. This information can be also useful to improve the acceptability of safety testing.

In January 2020, the CNVVF, in cooperation with ENEA, published the first Italian study on the safety of lithium batteries [1]. It focused on the assessment of the risk associated with the storage of innovative storage systems (i.e. lithium-ion batteries, lithium polymer, lithium metal), and on the preparation of specific prevention, protection and management measures to reduce fire and explosion risk during their storage. An accidentology analysis and an accident database have been also developed and attached to the report.

Moreover, experimental tests were performed on Li-ion cells and batteries by the Italian group in order to investigate their behavior under electrical and thermal abuse conditions, and also to test different fire extinguishing media [2-4]. The main results of the study will be reported in this paper, together with recent parent contribution to better understanding of safety issues pertaining to energy storage for both mobile and stationary application of Li-ion batteries resulting from long term dedicated research and testing [5,6] performed by INERIS . Additionally, INERIS will also report on safety important messages from recent literature review [7,8], and recent testing [9,10] and from standardization activities implemented in the last three years at level of IEC TC120 (electric energy storage systems), in which INERIS holds right from the beginning its WG5 (safety considerations) convenorship and till 6 months, overall TC chairmanship.

## 2 MAJOR LEARNINGS FROM ITALIAN DEDICATED STUDIES

### 2.1 Accident Database

Accident analysis and best practices as reported in the Italian study have been based on the following information sources: ARIA[11] and HAZMAT databases [12]); CPSC [13] and RAPEX[14] non-compliant products which represent a serious risk to health and consumer safety DBs; media information; scientific papers; web research on Korean and Chinese platforms. The analysis includes the following lithium – ion battery applications: EV (including e-bike, e-bus and two-wheels light vehicle like hoverboards), ESS (for home and industrial applications), consumer devices (i.e. mobile phones, e-cigarette, laptop), and intermodal transport of dangerous goods (i.e. spare batteries, vehicle, electronic equipment and batteries waste). Only few information about accident involving lithium battery factories and warehouses are available. It must be stated that some limitation in accidents review

from those various databases lie in the uneven reporting practices from most important areas where e-mobility and stationary energy storage making use of lithium-ion batteries. It looks quite obvious that information about EV accidents and fires from China which currently is the largest market for EVs is leading to underscoring incident statistics for several reasons including language barriers while much more easy and free access to EV statistics can be achieved from countries like USA, or European member states, or even South Korea. Finally, some case studies have been analyzed to understand the initiating event that leads to the accident: three cargo airplane accidents [15]; ESS accidents in Korea [16] together with the Chinese new technical specification for e-bike based on accident analysis (127 people died in the last 10 years) and some best practices for emergency intervention on EV and ESS.

## 2.2 Testing

In the recent years the Italian group performed thermal abuse tests on single Li-ion cells and fire extinguishing tests, in order to understand the risk related to their use in abuse conditions and their phenomenology. These tests are useful to develop protection measures against these types of fire and to establish first responders' procedures in the emergency case.

### 2.2.1 Thermal abuse tests

18650 lithium-ion unprotected cylindrical cells, NCR18650, from Panasonic were tested in a cone calorimeter. In Figure 1 a picture, dimensions and specifications of the cells are shown. Lithium cobalt nickel aluminum oxide ( $\text{LiCoNiAlO}_2$ ) (LNCA) and graphite (G) are the active materials for cathode and anode respectively, while the separator is made of polyolefins. The electrodes are immersed in an electrolyte solution made of ethylene carbonate ( $\text{C}_3\text{H}_4\text{O}_3$ ) (EC) and diethyl carbonate ( $\text{C}_5\text{H}_{10}\text{O}_3$ ) (DEC) as solvents, and lithium hexafluorophosphate ( $\text{LiPF}_6$ ) as salt.

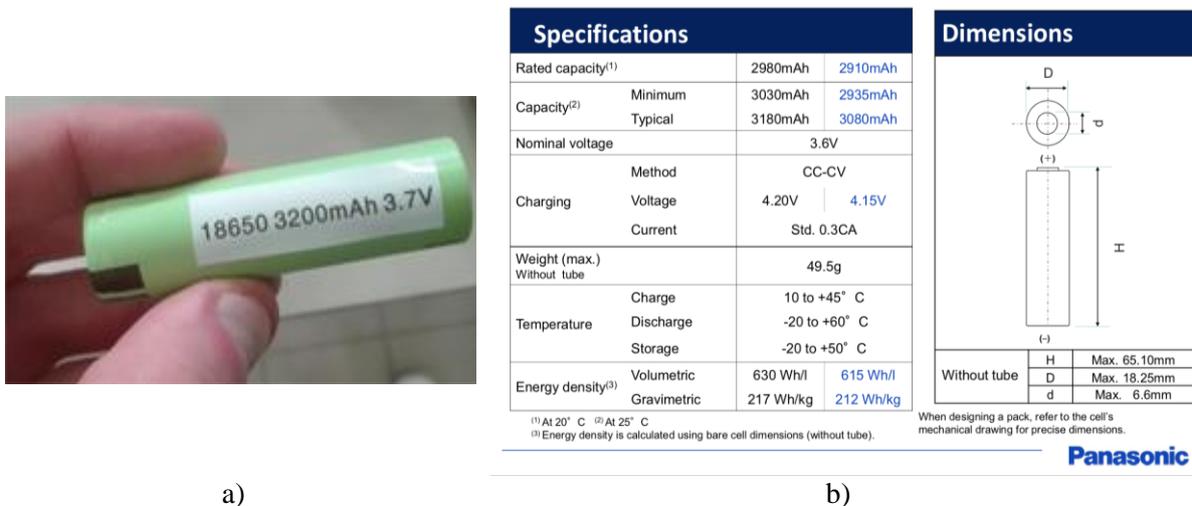


Figure 1: Panasonic NCR18650 cell (a) and its specifications (b)

Before testing, cells were charged using a PS 8000 2U series power supply from Elektro-Automatik. To achieve a state of charge of the cell (SoC) equal to 100%, charging phase was performed at a constant current of 12 A, imposing a maximum limit voltage of 4.2 V (accuracy <0.2%). A maximum limit voltage of 3.7 V was set to achieve a SOC of 50% while to obtain completely discharged cells with 0% SoC, an external load (EA-EL 9080-200) was applied, with a discharge current of 0.3 mV. In particular, the 0% cells underwent a deep discharge cycle and, by applying an external load, the discharge was forced below the minimum recommended voltage limit, until it reaches 0 V.

Thermal abuse tests on single cells were carried out in an ISO 5660 cone calorimeter by varying the SoC (0, 50, 100%) of the cells and the irradiance (15, 25, 35, 50 kW/m<sup>2</sup>) of the conical heater. Heat release rate (HRR) and surface temperature were recorded during the test as well as VOC released, which were measured by a photo ionization detector (PID). The VOC are expressed as ethyl methyl

carbonate concentration (ppm). Each specimen was weighed before and after each test to determine the total mass loss. The tests were also recorded by a video camera.

As an example, in figure 2 images taken from the video for test on NCR18650 cell (SoC=50%) at irradiance of  $50 \text{ kW/m}^2$  are reported.

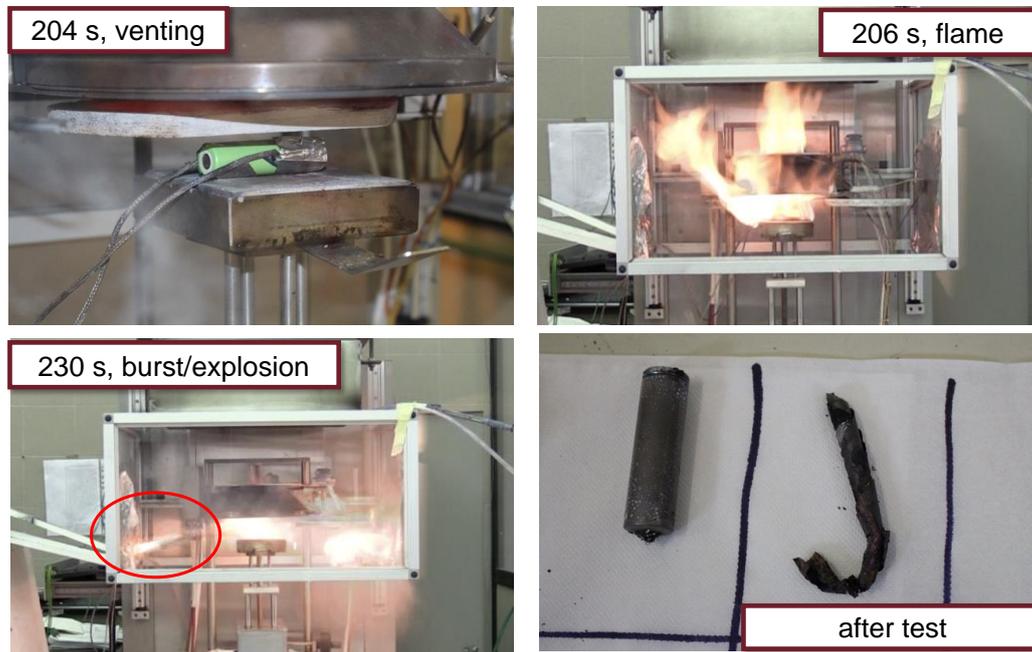


Figure 2: Video extracts for test on Panasonic NCR18650 cell (SoC=50%) at irradiance of  $50 \text{ kW/m}^2$

During the tests, three main phases were identified: i) onset of the thermal runaway; ii) venting of gases with eventual ignition (flames and / or smoke) and accelerating heating; iii) cell failure with flames and launch of fragments. The gas venting time was identified by a clearly audible sound, immediately followed by an aerosol jet. The explosion time was the time when the failure of cell was observed. At the end of the test, the cell case and the spiral wound electrodes were found separated from each other. Results for the same test performed with irradiance of  $50 \text{ kW/m}^2$ , but at three different SoC of cell: 0%, 50% and 100% were shown in Figure 3. It is evident that the SoC influences the onset of the thermal runaway, but an unexpected result was found for the completely discharged cell. For that cell which have undergone to a deep discharge cycle (overdischarge) it was found that thermal runaway occurred at shorter time (190 s) with respect to cells with higher SoC (220 s and 250 s for 100% and 50% SoC, respectively). Correspondingly, at the onset time the temperature starts to increase faster and the 0% SoC cell fails earlier than the other cells. It can be concluded that an overdischarge can be a very dangerous conditions like other electrical abuse. Comparing the results on cells at 50 % and 100% SoC, the full charged one showed a faster increase in temperature at the onset but a lower HRR peak. Moreover, integrating the HRR curves for the cells at the 3 different SoC the total energy values calculated are comparable (30-40 kJ/cell) (initial cell weight is about 47 g).

As reported in literature [17], in the overdischarge condition, the primary risk is presented from copper dissolution at the anode and deposition at the cathode, causing dendrite growth, eventually resulting in short circuits. Moreover, overdischarge has been shown to dissolve the SEI between 0 and 10% SoC. This may cause some gassing but its primary effect is on the aging of the cell, resulting in instantaneous loss of available capacity [17]

Finally, the comparison of tests relevant to cells at the same SoC (100%) but at different irradiance (from 15 to  $50 \text{ kW/m}^2$ ) showed that the total energy released by the cell decreased as the radiant power increased. This result was found in agreement with the VOC released by the cell during the test (Figure 4). VOC which are produced by the decomposition of electrolyte and/or its reaction with other cell

components, decreased as the irradiance increased. This behaviour is probably due to the extent of combustion reaction of the electrolyte which is almost complete at higher irradiance.

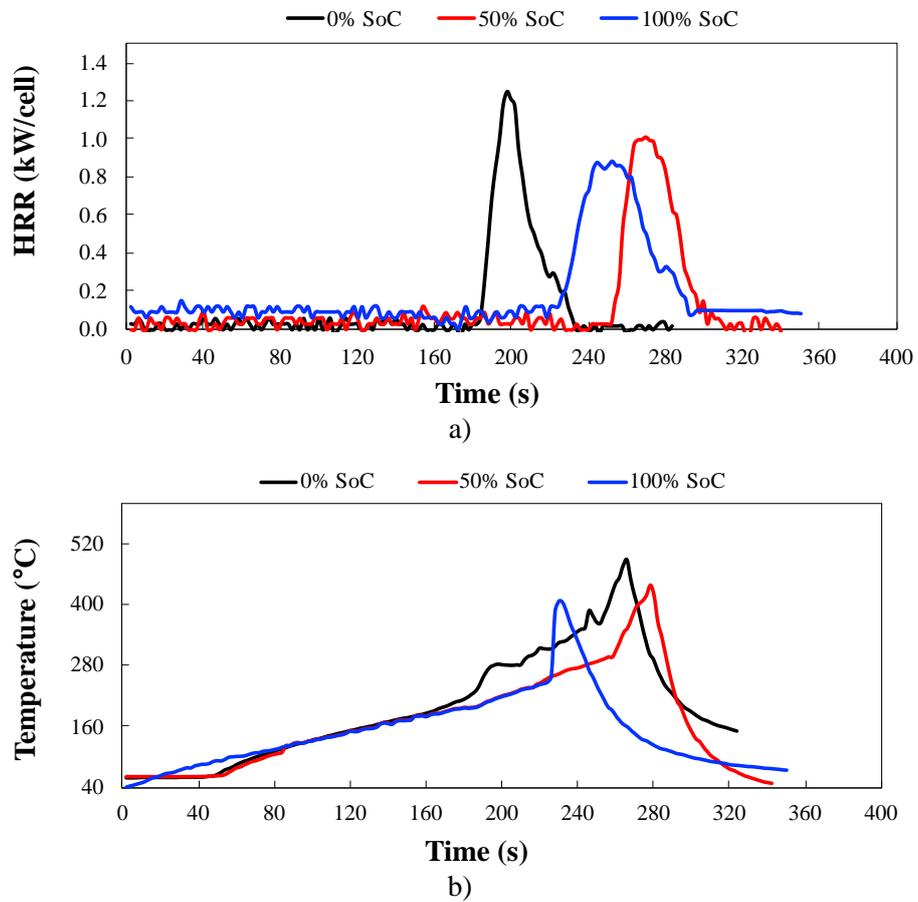


Figure 3: Heat release rate and surface temperature from tests of Panasonic NCR18650 cell at different SOC and irradiance of 50 kW/m<sup>2</sup>

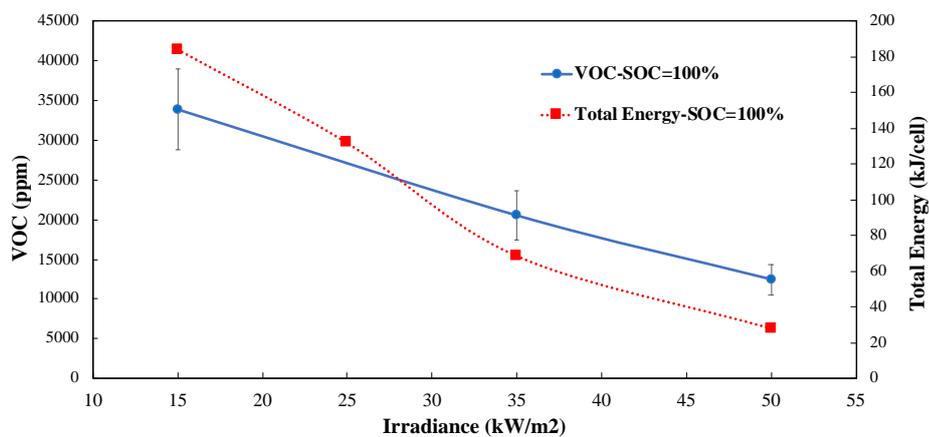


Figure 4: VOC and Total Energy for tests of Panasonic NCR18650 cell at 100% SoC and different irradiance

### 2.2.2 Fire extinguishing tests

The main characteristics of EIG C020 cells used for the fire extinguishing tests are reported in table 1. The cells prior to tests were charged to a SoC of 50%. During the tests the cell was exposed to the flame of a 7.5 kW LPG burner (figure 5); the temperature of the cell was monitored by a thermal imaging camera (FLIR), together with video recording.

During the cell exposure to the LPG flame, the cell reached a temperature of about 650°C in 2 min, then the burner was switched off, and the fire extinguishing agent was applied. Naturally, the cell temperature would be decreased to 400°C in 6 min. Carbon dioxide, foam, dry powder, pure water, and water mist were used to extinguish the Li-ion cell fire.

Table 1: Main characteristics of EIG C020 pouch cell.

		EIG C020 cell
Electric properties	Nominal Voltage	3.65 V
	Specific Energy	175 Wh/kg
	Voltage Limits	Charge: 4.15 V
		Discharge: 3.0 V
Geometric characteristics	Shape	Pouch
	Length	216 mm
	Width	130 mm
	Thickness	7.2 mm
	Volume	0.20218 L
	Anode	Graphite
Chemical composition	Cathode	Ni oxides
	Electrolyte	Mix of organic carbonates and LiPF6



Figure 5: Experimental setup for extinguishing tests.

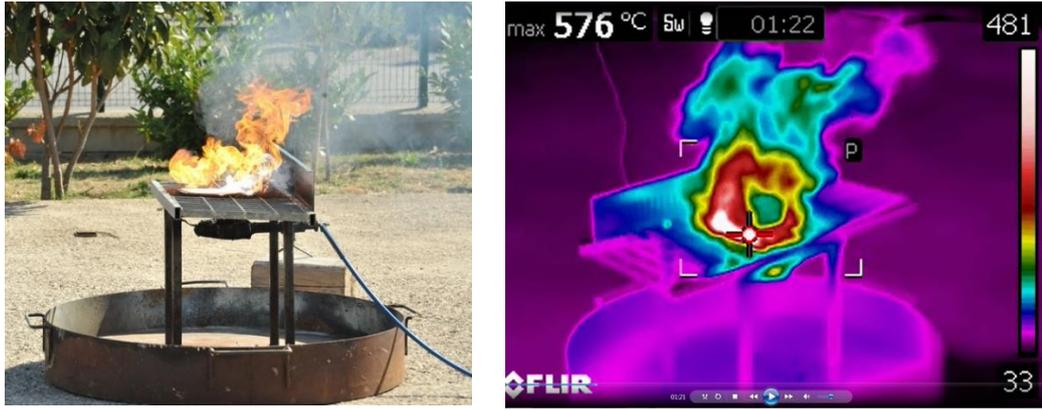


Figure 6: Video extract and maximum temperature of single cell during fire extinguishing tests.

During the tests, the following aspects were observed: the leakage of gases from the cell and their subsequent ignition; the swelling of the cell and the leakage of great quantity of gases and flames; the extinguishment of the fire as the leakage of gases stopped.

Results of fire extinguishing tests were reported in figure 7 in terms of maximum temperature of the cell as function of time. It was observed that water and foam were the most effective by rapidly (<20 s) reducing the temperature of the cell and extinguishing the fire. Water mist appeared less effective. This behaviour can be explained by the difficulty to assure uniformity of the water mist and the fact that liquid droplets reach the combustion surface with a certain amount of impulse. Finally, CO<sub>2</sub> and dry powder were observed as the least effective; in particular, in the case of dry powder the high-pressure jet caused the cell to fall on the ground.

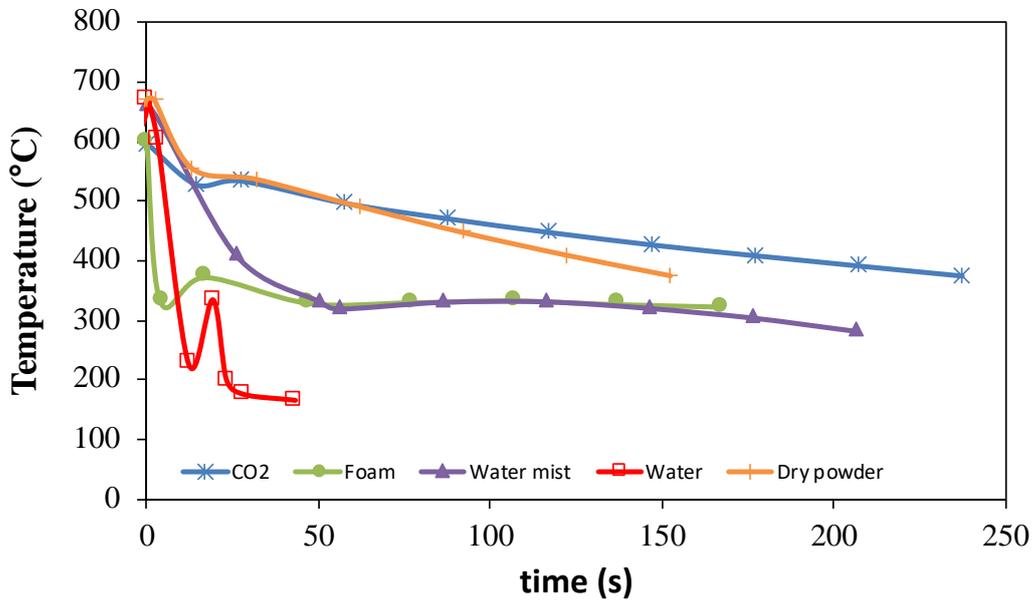


Figure 7: Maximum temperature of single cell during fire extinguishing tests.

In large scale batteries there are many individual cells which are linked together and, -if no proven effective heat transfer barriers be implemented between adjacent cells or cell clusters- fires normally propagate from cell to cell (*domino effect*) via the passage of heat from the external walls of the cells and from the electrical connection points which form the individual battery cells into multi cell modules and packs. As the cells reach high temperatures, they eventually go into a state known as thermal

runaway and this is achieved as a result of a chemical and physical processes which at a cell level are not reversible since the resulting cascading chemical reactions are exothermic.

In short it is essential to tackle a multi cell battery fire by extinguishing the fire which has been generated by the individual exploding cell and also by cooling the adjacent cells which will have been heated during the initial fire. It is frequently the case that one cell will heat several others each of which will in turn heat a number of others and the fire spreads on an exponential basis. It is therefore imperative to cool as many cells as possible in order to prevent the propagation of thermal runaway.

### **3 MAJOR FINDINGS REGARDING SAFETY OF LIBS FROM INERIS RECENT INVOLVEMENT IN TESTING, INCIDENT/ACCIDENT REVIEW AND OTHER ANALYTIC STUDIES**

Major findings regarding safety of LIBS from INERIS recent involvement in testing, incident/accident review and other analytic studies

INERIS has been working on modern energy storage and specially on Li-ion based cells and batteries in a very active way since 2005s, more specially focusing on e-mobility applications and more recently on Electric Energy Storage Systems for stationary applications. Early involvement in the safety analysis of e-mobility applications (not only EV cars, but also buses and e-bikes) has been supported by the implementation of a dedicated platform to perform abuse testing on lithium-ion cells, modules and packs of small to medium sizes, the so-called STEEVE platform [18]. Related contributions of INERIS staff to safety of lithium-ion batteries are not only dealing with research, but also have dealt so far with (i) first technical support of the safe promotion of e-mobility in France as decided by French Government decided in year 2008, by the production of an overall preliminary risk analysis of the full value chain of li-ion batteries in this context published on its web site in 2009; (ii) regular incidents reviews of Li-ion batteries, EVs and other Li-ion applications; (iii) technical contributions in support of the French competent authority presented at meetings (in Geneva twice a year) of the sub-committee of experts on the transport of dangerous goods in support of safe transportation of lithium and lithium-ion cells, modules and packs under UN numbers 3480/3481; iv) consultancy works provided for various private and public customers, based on paper studies, thermal, mechanical or electrical abuse testing, fire testing from cell components [6], [19-21] to full EV [18/22] safety focused modelling, incident investigations, and standardization commitments at national and international levels.

In the following part of this section we will essentially illustrate part of the work performed regarding safety testing in the project called DEMOBASE, funded under the H2020 EU framework programme [23] with some additional reporting about our review of incidents involving batteries as well as standardization activities.

#### **3.1 Testing**

##### ***3.1.1 Safety testing as a general approach towards safer batteries and energy storage systems relying on electrochemical physical storage***

Addressing correctly the level of complexity of fire and explosion safety of LIBS still requires today significant testing at various TRLs when putting new batteries on the market. Modern drivers for lithium-ion safety focused testing have evolved versus time in the last decade according to progress made in the understanding of multifold aspects of their hazardous profile as well as due to mandatory requirements or market-driven requests. Nowadays, testing rationale may come from:

- regulations requirements from cell to pack levels for their safe transport
- emerging safety-focused standards compliance
- testing requests from end-users
- calibration and validation purposes of prediction models (or thermal runaway of cells, of propagation model from cell to cell...)
- learning of intrinsic safety of potentially new components with less flammability properties (eg ionic liquid based electrolytes, fluorinated solvents...)
- testing efficiency of BTMS (battery thermal management systems)
- other safety devices testing (eg safety vents)

INERIS is contributing to this activity in several of those motivations making use of several of its key testing equipment like its STEEVE platform (dedicated fully to abuse testing of cells to small packs, its large-scale fire testing platform (including a 20 MW fire calorimeter) , or its Fire Propagation Apparatus

(ISO12136). We just illustrate in the following section part of our contribution brought experimentally in a recently completed H2020 EU funded project called *DEMOBASE* (see project web page for details: <https://www.demobase-project.eu/>).

### 3.1.2 Safety testing at module pack level

Multilayer protection systems must be implemented as to achieve “non propagation target” from single thermal runaway event. The role of thermal barrier was studied by relevant tests in the framework of Design and Modelling for improved Battery Safety and Efficiency (DEMOBASE) H2020 project coordinated by SAFT. Propagation tests were performed on two types of samples provided by IFEVS partner:

- a cluster specially assembled for safety tests, composed of 3 pouch cells (unrevealed innovative chemistries) provided by SAFT assembled in parallel separated by steel plates. The cluster contains a thermal pad on one side. The central cell of the cluster is equipped with an internal heater,
- a module used base unit in the final vehicle battery pack composed of 3 clusters in series. The central cell of the central cluster is equipped with an internal heater.

Propagation tests were performed in a 12 m<sup>3</sup> test chamber equipped with a ventilation system remotely piloted to fully extract combustion gases in the exhaust system. Continuous gas sampling was carried out in the extraction duct.

Samples (cluster or module) were fully charged (100% SOC) before safety tests.

The sample (cluster or module) was positioned on a weighing plate-form in the centre of the test chamber as represented in Figure 8.

Two heat flux sensors were positioned at around 1 m from the sample in the test chamber.

Filters were positioned at proximity of the sample in test chamber for particles sampling.

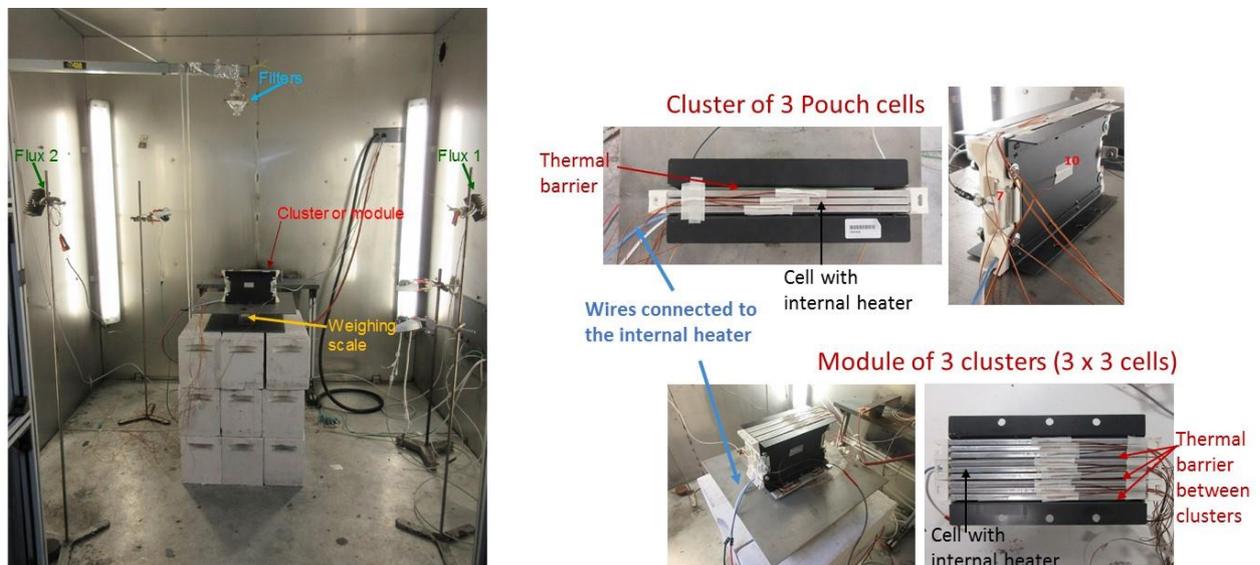


Figure 8: test set up for propagation test on clusters and modules

The propagation test consisted in triggering a thermal runaway in the central cell equipped with an internal heater, leading on the formation of an internal short-circuit of this cell. The testing procedure consisted on applying a current profile to this heater as follows: 5A for 5 s, 10A for 5 s, 15A for 5 s, 18A for 5 s, 23A for 5 s. If no reaction is observed, heater current is increased progressively: + 1A every 15 s up to 35A and then 35A as heater current during 1 m 30 s, and eventually 40 A up to thermal

runaway.

The measurements carried out during the non-propagation test are as follow:

- Evolution of the temperature ( $^{\circ}\text{C}$ ) with time,
- Evolution of the cell voltage (V)
- Evolution of the internal heater current (A) and voltage (V)
- Evolution of mass loss with time,
- Evolution of heat flux with time,
- On-line qualitative and quantitative analysis of gases:
  - $\text{CO}_2$ , CO by NDIR (non-dispersive infra-red sensor),
  - total hydrocarbons (HCT) by flame ionization detector,
  - $\text{NO}_x$  by chemiluminescence analysis,
  - Other specific gases such as electrolyte solvents carbonates (EC, DMC, EMC...), HF,  $\text{C}_2\text{H}_2$ ,  $\text{CH}_4$ , etc. by FTIR (Fourier Transformed Infra-Red spectroscopy)
- Filters positioned nearby the tested cell for particle analysis: Al, Co, Cu, Li, Mn, Ni, P, fluorinated species
- Video and video editing of the main events.

Some results of the propagation test on cluster level without cooling system are presented hereinafter.

During propagation test on cluster, the thermal runaway of the central cell was characterized by cell swelling, cluster widening, cell degassing (no flames), and projections of small particles, followed 102 s after by a fire of a second cell. 187 s after the second cell thermal runaway, a fire of the third cell accompanied with fumes emission occurred (Figure 9). A temperature up to  $750^{\circ}\text{C}$  was measured during the test (Figure 10).



*Figure 9: video extracts of the thermal runaway of the 3 cells of the cluster*

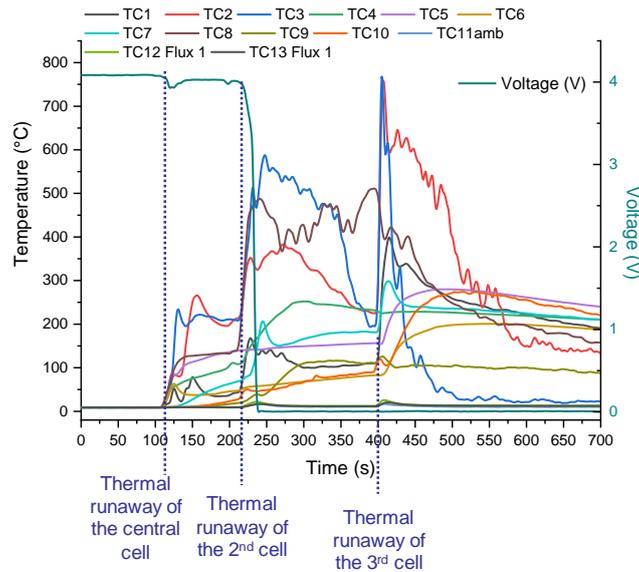


Figure 10: evolution of temperature during propagation test on cluster

Gas detected during the propagation test were CO<sub>2</sub>, CO, CH<sub>4</sub>, C<sub>2</sub>H<sub>4</sub>, DMC, EMC, EC, HF, POF<sub>3</sub>, H<sub>2</sub>, NO and NO<sub>2</sub> (Figure 11). During the thermal runaway of the central cell where only fumes were emitted, main gases detected were organic carbonates, CO, H<sub>2</sub>, ethylene, and methane. Formaldehyde (CH<sub>2</sub>O) and POF<sub>3</sub> were also emitted whereas the amount of HF and CO<sub>2</sub> emitted was low. During the thermal runaway of the second cell characterized by a strong fire, main gases measured were CO<sub>2</sub> and HF. Except NO<sub>x</sub>, no other gases were detected during this event. During the thermal runaway of the last cell, fire and fumes were observed, with CO<sub>2</sub> and HF as main gas detected, but also with a low emission of CO, carbonates, POF<sub>3</sub> and NO<sub>x</sub>.

When considering the total quantity of gases emitted throughout the test, CO<sub>2</sub> represented the main gas detected (86% wt). Formation of HF is favoured by the combustion.

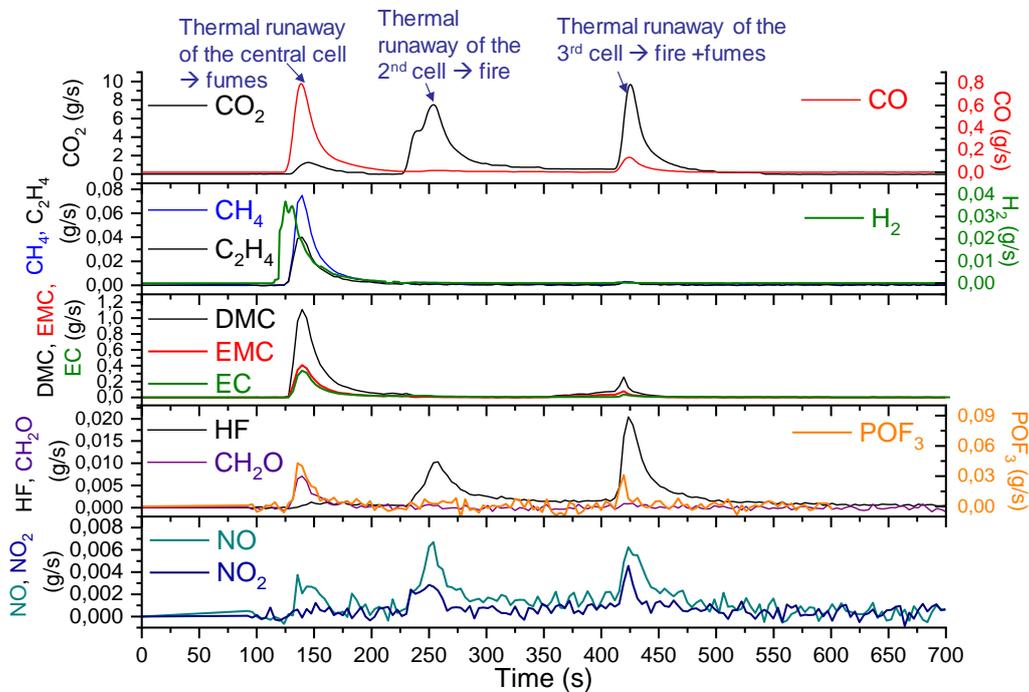


Figure 11: gas analysis during propagation test on cluster

The maximal heat release rate (HRR), computed using CO<sub>2</sub> and CO gas flow emission, reached 130 kW and the overall dissipated effective heat of combustion (integration of HRR profile) was of 18,4 kJ/lost

g, as represented in Figure 12.

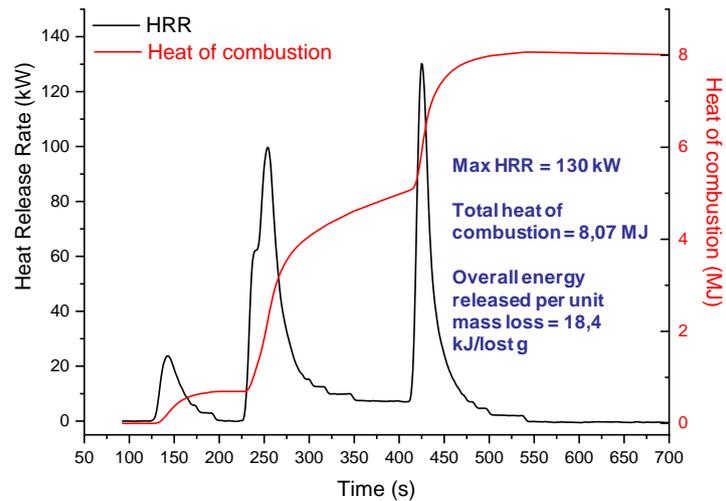


Figure 12: HRR and overall dissipated effective heat of combustion during propagation test on cluster

At module scale, thermal runaway of the central cell of cluster 2 was characterized by cell swelling, widening of the cluster, cell venting with smoke emission (no flames), and projections of small particles, as observed at cluster level test. 80 s after first cell thermal runaway, the second and third cells went into thermal runaway characterized by a fire (Figure 13). Although a temperature was measured up to 936°C during the test, no propagation to clusters 1 and 3 was observed (Figure 14), proving the efficacy of thermal barriers between clusters under these test conditions.



Figure 13: video extracts of the thermal runaway of the module

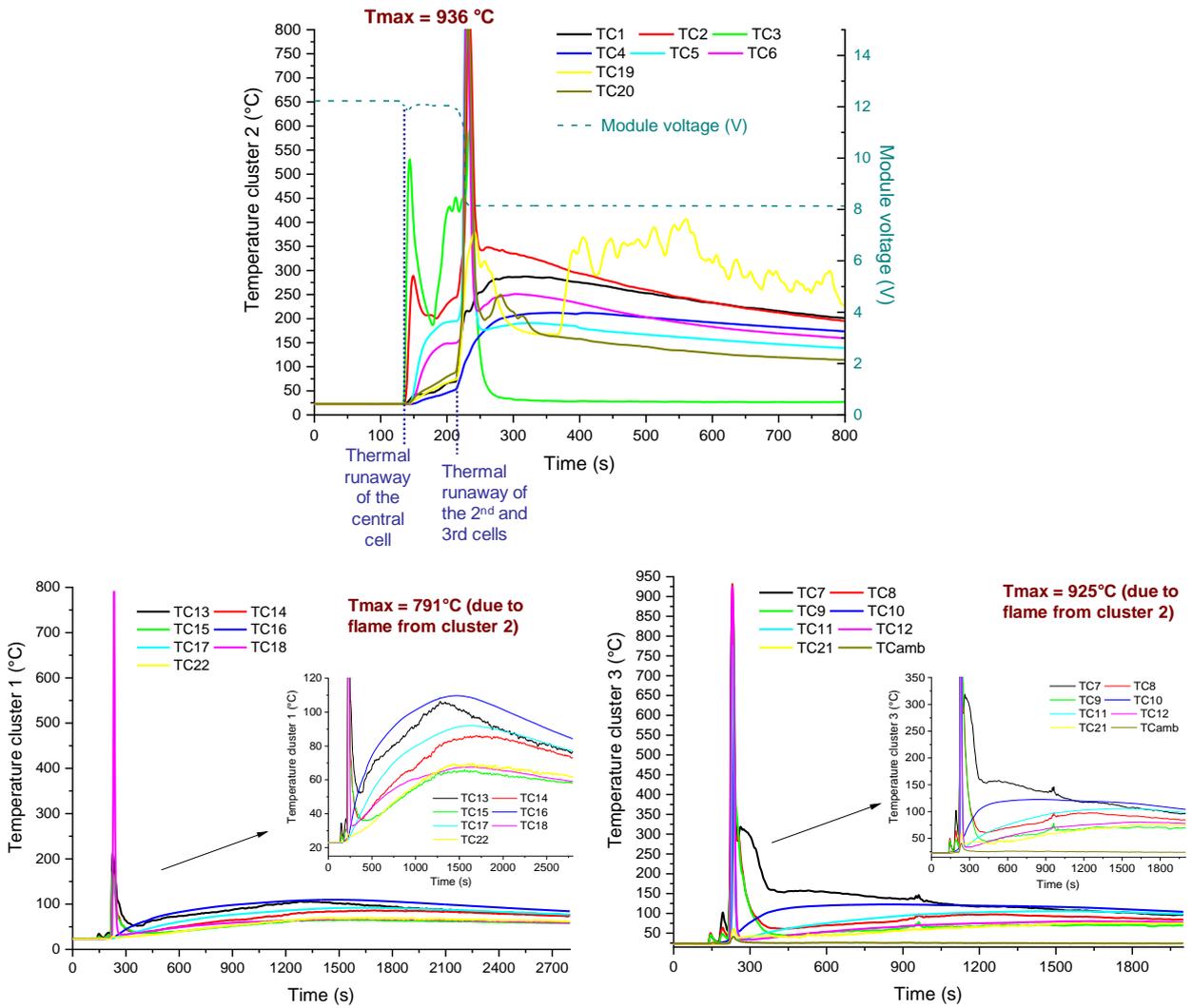


Figure 14: Evolution of the temperature of clusters during the propagation test performed on the module

As observed on cluster test, the nature and proportion of gases detected are clearly different in the occurrence of fire (Figure 15). During the thermal runaway of the central cell of the module where only fumes were emitted, main gases detected were organic carbonates, CO, ethylene, methane, formaldehyde and  $\text{POF}_3$ . During the thermal runaway of the other cells characterized by a strong fire, main gases measured were  $\text{CO}_2$  and HF.  $\text{NO}_x$  were also detected.

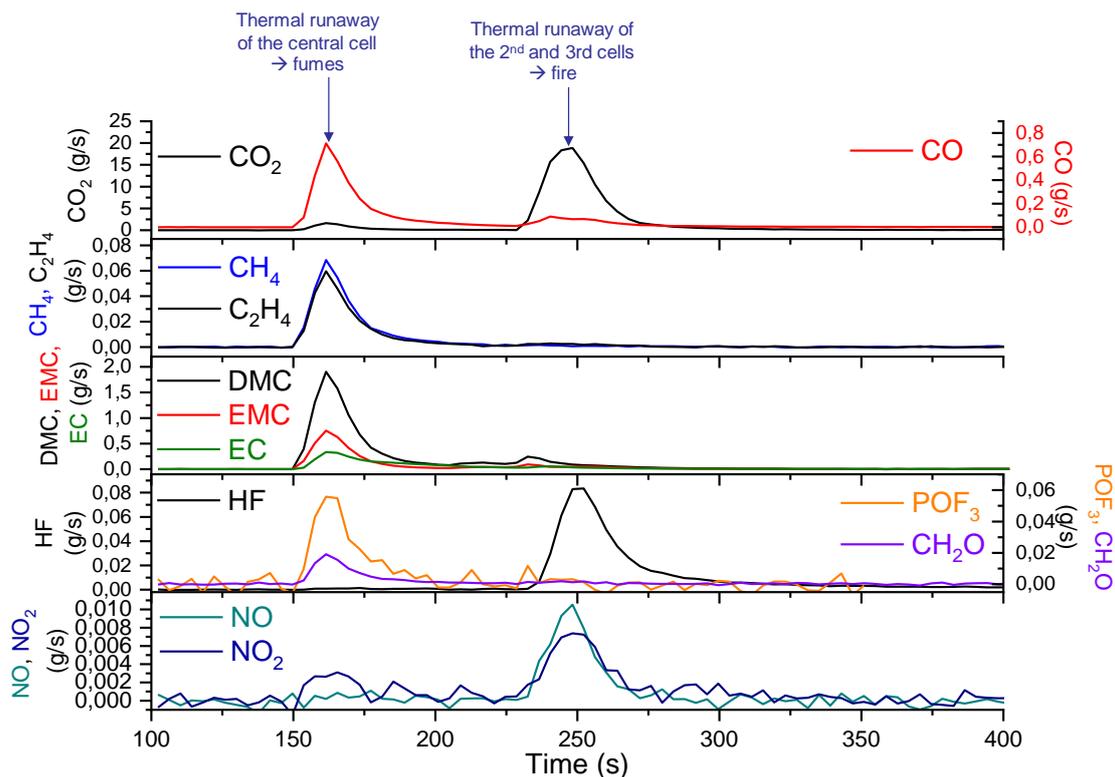


Figure 15: gas analysis during propagation test on module

Particle analysis of the filters positioned nearby the sample in the test chamber had shown the presence of metallic elements (Ni, Co, Mn, Al, Li) in particulate emissions and fluorinated species (Figure 16). 74% of particles mass come from the cathode (NMC) and 6% from positive current collector (Al). No copper particles were detected.

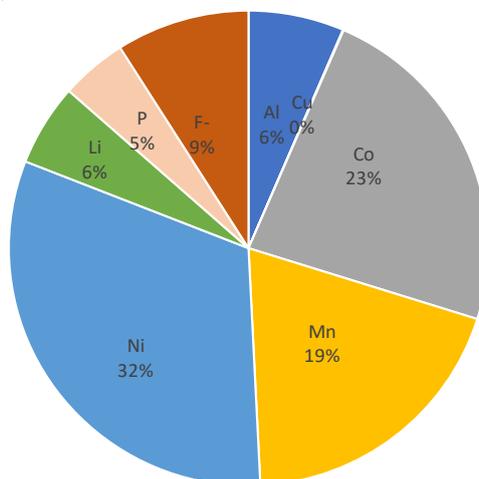


Figure 16: main results of the particle analysis performed during the propagation test on the module

### 3.2 Incident review and LIB failure statistics

Incident review is also performed at INERIS as a routine task and we globally agree with existing bias in existing databases as already mentioned in sub-section 2.1. However, despite of this drawback, existing databases and incident records archived and made more or less openly available to the public allow us to consolidate the following statements:

- from a statistical view point: (i), there is no indication so far of overrating accidents of EVs as compared to ICE cars, as early mentioned already for the first time by L. Holmoltz et al [24] (ii) whilst cell thermal runaway may originate from a manufacturing default,, we know that modern way of cell processing in clean rooms have rendered such root causes of cell failure very low, say in the order of 1 cell for 1 million to 10 million cells in the case of most 18650 cylindrical cells (may be should we remain cautious in trusting that this performance is also valid for high energy Ni rich cells which have not yet been widely spread at commercial level); by contrast, no statistics is yet available about this aspect for pouch and prismatic cells which by now are the most preferred types of cells by many EV manufacturers ;
- the analysis of battery field failures clearly shows that thermal runaway induced issues may arise on the full life cycle of batteries, from cell manufacturing to all types of applications under commissioning, use, repair, repurposing, up to recycling ;
- with regard to the EV case, there also, we see that many types of EV field situations may lead to incidents and fire events: such incident records have been listed on numerous EV models and trademarks showing that hazardous events with EV may take place on the road, during crash tests, during road testing, in park places, including underground and other confined spaces (including tunnels). Incidents may also result or be connected to (potentially fast) charging. An EV fire may be (rather often) the direct consequence of a car crash, the result of an intrusive impact of loose object in the battery pack during drive, and even be related to extraordinary salty environment (due to hurricane action on the seaside for instance) leading to battery external short circuiting ; Marlair et al already illustrated this statement from an analysis of a series of fire events concerning the Tesla car models (S, X) at last FIVE 2018 symposium [25]; see also Figure 17

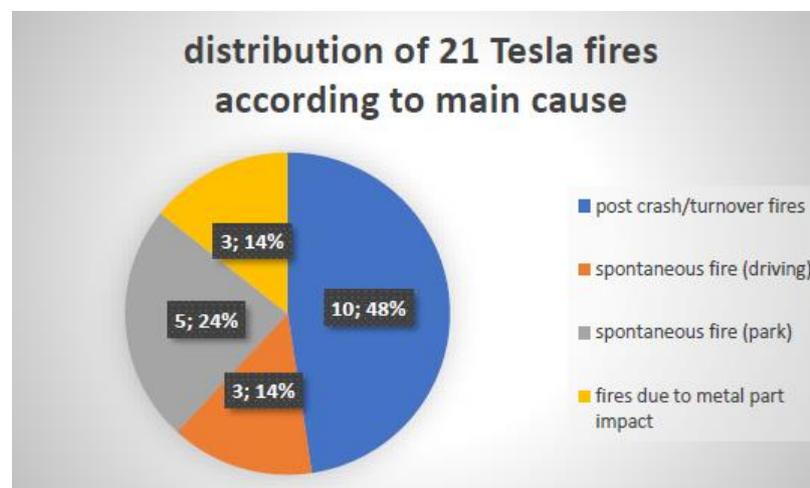


Figure 17: Distribution of main causes of Tesla model fires recorded in the INERIS database from early commercialization time, up to mid 2018

- more recently battery storage system level safety have been identified as a major root cause, that can be exemplified in the two different series or isolated incident: (i) les series of 28 incidents on EESS that took place from mid 2017 up to 2019, (ii) the specific incident that took place of a Norwegian „hybrid“ ferry (having both diesel engine and electric engine supplied by a battery energy storage system installed in a battery room), in October 2019. These case studies are briefly reported hereafter.

### ***3.2.1 Preliminary analysis of the fire on-board the hybrid ferry “Ytteroyningen” that occurred on Oct, 10th 2019***

From the information made so far by various sources (media, supplier of the battery system, Norwegian Marine Authority, this is what can be said today about the incident and its presumed root causes:

- (i) Originally, the ferry, built in 2006 was cruising with diesel engine only
- (ii) it was converted to hybrid ferry in mid 2019 by implementation of an electric power train making use of an EESS based on liquid cooled Li-ion battery of nearly 2 MWh of capacity installed supplied by Corvus
- (iii) On its cruise on Oct. 2019, while operating on diesel, a fire started in the battery room, likely bound to a leak of the cooling liquid that provoked an short circuit and set fire on the battery; However as the battery storage system was disconnected from the main control room, the BMS was not reporting the corresponding alarm to the captain ...
- (iv) dual fire extinguishing systems (inert gas NOVEC and salt water sprinkler system), operated successfully to put the incident under apparent control: subsequently all passengers were able to disembark safely in the nearby harbour of destination
- (v) however, hours after (~10 hours), an explosion occurred on board, likely to be due to the formation of an explosive atmosphere released from the battery room: the explanation could be the inadequate use of salt water in the sprinkler system, which may have provoked external short circuit on the EES!

### ***3.2.2 Early learnings of the Korean fires on the period mid 2017 – 2019 (28 fires in total, so far we know)***

As already mentioned previously in section 2.1, a series of fires have struck stationary energy storage systems based on lithium batteries in South Korea. Some of them are mentioned in Figure 18 up to a point that all new projects of EESS that were stopped by law enforcement until conclusions of an investigation team that was put in place to understand the root reasons (Part of the explanation can be accessed in [1]. I just provide here some more information kindly made available to experts of IEC TC120 by Dr Misung Kim, the current convenor of WG4 (environment issues) of this IEC standardization Committee/

What has been revealed notably by the enquiry is the following:

- (i) various types of stationary applications have experienced fires (frequency regulation, peak shaving, PV system and Wind Farms...)
- (ii) all ranges of capacity have been touched (from 0,2 MWh up to 22 MWh)
- (iii) all types of hosting infrastructures also (from concrete buildings to containers and temporarily installed enclosures)
- (iv) close to 70% of concerned EESS had been put in service for less than 1 year
- (v) no single manufacturer was responsible of having implemented a faulty battery pack nor PCS (power converter system)

One major conclusion hence was that essentially system level integration errors had been made during the design and implementation process of concern EESS, likely due to inexperienced integrators under the market push driven by Korean Authorities incentives to promote the use of renewable energies.

## EESS accidents in Korea

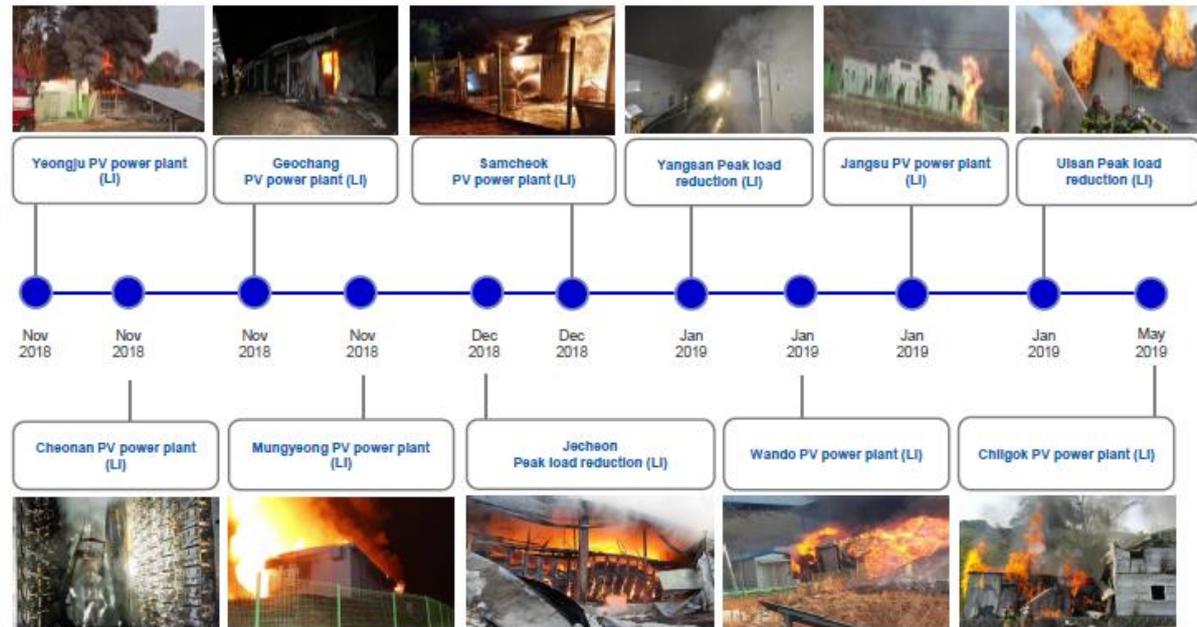


Figure 18: part of the history of EESS fires that took place in South Korea in recent past

### 3.3 Further considerations arising from literature review or dedicated studies

Literature review also routinely performed by INERIS researchers (including by manuscripts reviewing activity clearly shows that significant amount of scientific-sound works have been performed in support of safe development, use and even recycling of batteries of all sorts, but more specifically on the Li-ion type which by now is dominating the market in both stationary and mobile applications for some time. Among hot topics of interest by concerned researchers in relation with battery safety are (based on the existence of review papers):

- the development of methods for the estimation of state of health (SOH) -sometime called state of safety (SoS) of batteries and cells
- the design, testing and performance prediction of TBMS (thermal battery management systems) making use of air or liquid cooling media, heat pipes and phase change materials (PCM) or a combination of thereof
- Gaseous emissions during gassing and fire events in case of thermal runaway of cells and batteries
- the development of tests and models to qualify the thermal runaway process in detail (phasing the global event in relation with key sub-events
- thermal abuse testing under various circumstances (in open circuit state, under discharge, under overdischarge, under specific atmospheres (T and P related)
- electrical abuse testing of LIBs
- mechanical abuse testing of LIBs
- safety testing of Ni-rich cells, being more energetic
- review of LIBs standardization activity progress
- safety studies dedicated to various phenomena contributing to ageing of the cells (calendar ageing, cycling ageing, Li-plating...) and relating physics modeling testing safer cell components for reduced flammability of electrolytes, likewise the use of ionic liquids and related salts for partial replace of carbonate based electrolytes [26]

## 4 CONCLUSIONS/PERSPECTIVES

This paper reports: i) on a main Italian study where accidents involving lithium batteries that have occurred in the recent years as identified by different sources of information and ii) also complement/consolidate our results from parent work including testing and literature review performed by INERIS. The analysis of accident occurred over the world is important, for risk analysis and for the improvement of safety instructions and procedures to manage accidents involving lithium batteries. However, it is difficult to obtain detailed information and in particular to know the circumstances that led to the accident, given the limited information by rare exceptions that are accessible. One good point is that at least for the e-mobility case, we have no indication of significant over accidentology of EVs as compared to conventional fuel fired cars. This needs of course to be confirmed when the EV market penetration will allow consolidated statistical calculations

The knowledge of chemical and electrical characteristics of lithium batteries is very important because it affects their behavior in abuse conditions. In particular, the chemical composition of the electrodes is one of the crucial information required to predict their response to an external abuse and, consequently, to know the consequences of it. As exemplified in the DEMOBASE project, safety of lithium-ion battery will remain a hot topic, and operational success must be thought in terms of several layers of protection against propagation of a localized cell thermal runaway. Safety must also be addressed at integration level in which the battery and its auxiliaries (such as PCS and BMS) are only part of a whole system. already applicable standards from IEC TC21, SC21A, TC8 and TC120 may help in conjunction of dedicated testing and modeling to obtain fail safe operational battery systems for EVs in particular and stationary EESS based on LIBs. Both applications not being for a long time completely separated with the emergence of V2G (vehicles to Grid) interoperability.

## 5 ACKNOWLEDGMENTS

Part of this work has received funding from the EU Commission under the H2020 grant agreement # 769900 under the name DEMOBASE

## 6 REFERENCES

- 1 CNVVF & ENEA, *Rischi connessi con lo stoccaggio di sistemi di accumulo litio-ione*, edited by M. Mazzaro and C. Di Bari, Gennaio 2020.  
<http://www.vigilfuoco.it/allegati/biblioteca/RischiConnessiConLoStoccaggioDiSistemiDiAccumuloLitio-Ione.pdf>
- 2 Russo, P.; Di Bari, C.; Mazzaro, M.; De Rosa, A.; Morriello, I. Effective fire extinguishing systems for lithium-ion battery, *Chemical Engineering Transactions* 2018, 67, 727-732 DOI: 10.3303/CET1867122
- 3 Russo, P.; Mele, M.; Longobardo, G.; Mazzaro, M.; Di Bari, C. Investigation on the Fire Hazards of Li-Ion Cells. Springer Nature Switzerland AG 2020. W. Zamboni, G. Petrone (eds.), *ELECTRIMACS 2019, Lecture Notes in Electrical Engineering* 604, [https://doi.org/10.1007/978-3-030-37161-6\\_56](https://doi.org/10.1007/978-3-030-37161-6_56).
- 4 Russo, P.; Longobardo, G.; Mazzaro, M.; Di Bari, C., Cancelliere, P. Fire behaviour of NMC Li-ion battery cells. *Proceedings of the Ninth International Seminar on Fire and Explosion Hazards (ISFEH9)*, 2019, 2: pp. 881-890. Edited by Bradley D., Chaumeix N., Liu N.A., Molkov V., Snegirev A. and Tamanini F., Saint-Petersburg Polytechnic University Press.
- 5 Ribière, P.; Grugeon, S.; Morcrette, M.; Boyanov, S.; Laruelle, S.; Marlair, G. Investigation on the fire-induced hazards of Li-ion battery cells by fire calorimetry. *Energy & Environmental Science*, 2012, 5 (1): p. 5271-5280
- 6 Eshetu, G. G.; Grugeon, S.; Laruelle, S.; Boyanov, S.; Lecocq, A.; Bertrand, J-P.; Marlair, G. In-depth safety-focused analysis of solvents used in electrolytes for large scale lithium ion batteries. *Physical Chemistry Chemical Physics*, 2013, 15 (23): p. 9145-9155
- 7 Soares, F.J.; Carvalho, L. ; Costa, I.C. ; Iria, J.P. ; Bodet, J.M. ; Jacinto, G. ; Lecocq, A. ; Roessner ; Caillard, B. ; Salvi, O.; The STABALID project : Risk analysis of stationary Li-ion batteries for power system applications. *Reliability Engineering and System Safety*, 2015, 140: p. 142-175
- 8 Abada, S.; Marlair, G.; Lecocq, A.; Petit, M.; Sauvart-Moynot, V.; Huet, F. Safety focused modeling of lithium-ion batteries: A review. *Journal of Power Sources*, 2016, 306: p. 178-192
- 9 Abada, S.; Petit, M.; Lecocq, A.; Marlair, G.; Sauvart-Moynot, V. ; Huet, F. Combined experimental and modeling approaches of the thermal runaway of fresh and aged lithium-ion batteries, *Journal of Power Sources* 399 (2018) 264-273
- 10 Thi Thu Dieu NGUYEN, S. Abada, A. Lecocq, J. Bernard, M. Petit, G. Marlair, S. Grugeon & S. Laruelle, Understanding the Thermal Runaway of NI-rich Lithium-ion batteries, *World Electric Vehicle Journal*, 2019, 10, 79;

- doi:10.3390/wevj10040079
- 11 <https://www.aria.developpement-durable.gouv.fr/the-barpi/the-aria-database/?lang=en>
  - 12 [https://www.faa.gov/about/office\\_org/headquarters\\_offices/ash/ash\\_programs/hazmat/aircarrier\\_info/media/battery\\_incident\\_chart.pdf](https://www.faa.gov/about/office_org/headquarters_offices/ash/ash_programs/hazmat/aircarrier_info/media/battery_incident_chart.pdf)
  - 13 <https://www.cpsc.gov/>
  - 14 [https://ec.europa.eu/consumers/consumers\\_safety/safety\\_products/rapex/alerts/repository/content/pages/rapex/index\\_en.htm](https://ec.europa.eu/consumers/consumers_safety/safety_products/rapex/alerts/repository/content/pages/rapex/index_en.htm)
  - 15 IATA: “Three Accidents Involving Lithium Batteries”. ISBN 978-92-9229-410-6. © 2016 International Air Transport Association. All rights reserved. Montreal—Geneva
  - 16 Logan Goldie-Scott: “The Fire Risk of Batteries - A Delicate Balancing Act”. Bloomberg New Energy Finance. August 23, 2018
  - 17 Lyness, C. Sources of risk in Electrochemical Power Sources: Fundamentals, Systems, and Applications Li-Battery Safety Edited by J. Garche and K. Brandt, 2019, Elsevier pp. 145-166
  - 18 Lecocq, A. ; Bertana, M. ; Truchot, B. ; Marlair, G.; Comparison of the fire consequences of an electric vehicle and an internal combustion engine vehicle. 2. International Conference on Fires In Vehicles - FIVE 2012, Sep 2012, Chicago, United States. pp.183-194.
  - 19 Forestier, C.; Lecocq, A.; Zantman, A. ; Grugeon, S.; Sannier, L. ; Marlair, G. ; Laruelle, S., Study of the Role of LiNi<sub>1/3</sub>Mn<sub>1/3</sub>Co<sub>1/3</sub>O<sub>2</sub>/Graphite Li-Ion Pouch Cells Confinement, Electrolyte Composition and Separator Coating on Thermal Runaway and Off-Gas Toxicity, 2020 *J. Electrochem. Soc.* 167 090513
  - 20 Chancelier, L.; Diallo, A-O.; Santini, C.C.; Marlair, G.; Gutel, T.; Maillet, S.; Len, C. Targeting adequate thermal stability and fire safety in selecting ionic liquid-based electrolytes for energy storage, 2014, *Phyc. Chem Chem Phys.* (16), 4 pp, 1967-1976
  - 21 Eshetu, G.G.; Bertrand J-P.; Lecocq, A., Grugeon, S.; Laruelle, S.; Armand, M.; Marlair, G., Fire behavior of carbonates-based electrolytes used in Li-ion rechargeable batteries with a focus on the role of the LiPF<sub>6</sub> and LiFSI salts, *Journal of Power Sources* 269 (2014) 804e811
  - 22 Truchot, B.; Fouillen, F.; Collet, S.; An experimental evaluation of toxic gas emissions from vehicle fires, *Fire Safety Journal* 97 (2018) 111–118
  - 23 Bordes, A., Danilov, D. Desprez, P.; Lecocq, A.; Marlair, G. et al, A Holistic Contribution to fast innovation in Electric Vehicle, An overview of the DEMOBASE research Project, under submission process to *e-Transportation*
  - 24 Hollmotz, L.; Hackmann, M.; Lithium-ion batteries for Hybrid and electric Vehicles – Risks, Requirements and Solutions out of the Crash safety Point of View, Conference paper # 110269 [https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwiP0oTK-8jtAhUfBGMBHf8nC64QFjAAegQIAxAC&url=https%3A%2F%2Fwww-esv.nhtsa.dot.gov%2FProceedings%2F22%2Ffiles%2F22ESV-000269.pdf&usg=AOvVaw2sWi7c8fVPjbJ\\_YdwhzgzkQ](https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwiP0oTK-8jtAhUfBGMBHf8nC64QFjAAegQIAxAC&url=https%3A%2F%2Fwww-esv.nhtsa.dot.gov%2FProceedings%2F22%2Ffiles%2F22ESV-000269.pdf&usg=AOvVaw2sWi7c8fVPjbJ_YdwhzgzkQ)
  - 25 Marlair, G.; Lecocq, A.; Truchot, B.; Perlo, P. ; Petit, M. ; N’Guyen, D. ; Desprez, P., Promoting fire safety in innovating design of electric vehicles: the example of the EU funded DEMOBASE project, Proceedings 5<sup>th</sup> Int. Conference on Fires in vehicles (FIVE 2018), Boras, Sweden, Oct.3/4, 2018
  - 26 Eshetu G.G.; Jeong, S.; Pandard, P.; Lecocq, A.; Marlair, G., Passerini, S., Comprehensive Insights into the Thermal Stability, Biodegradability, and Combustion Chemistry of Pyrrolidinium-Based Ionic Liquids, *ChemSusChem* 2017, 10, 3146–3159