Promoting fire safety in innovating design of electric vehicles: the example of the EU-funded DEMOBASE project

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Outline

- Project ID & Rationale of DEMOBASE
- Fire research dedicated strategy and relating commitments in the project
- Results achived at 1/3 project time scale
  - Focus on analytical approaches
  - Status of experimental and modeling approaches
- Conclusions/ perspectives

DEMOBASE Project ID and Rationale

❑ Real market penetration of e-mobility worldwide depending on:

- drastic reduction of costs
- increased performances not forgetting safety
- increased availability

⇒ faster evaluation and integration of innovative technology of key components of Evs

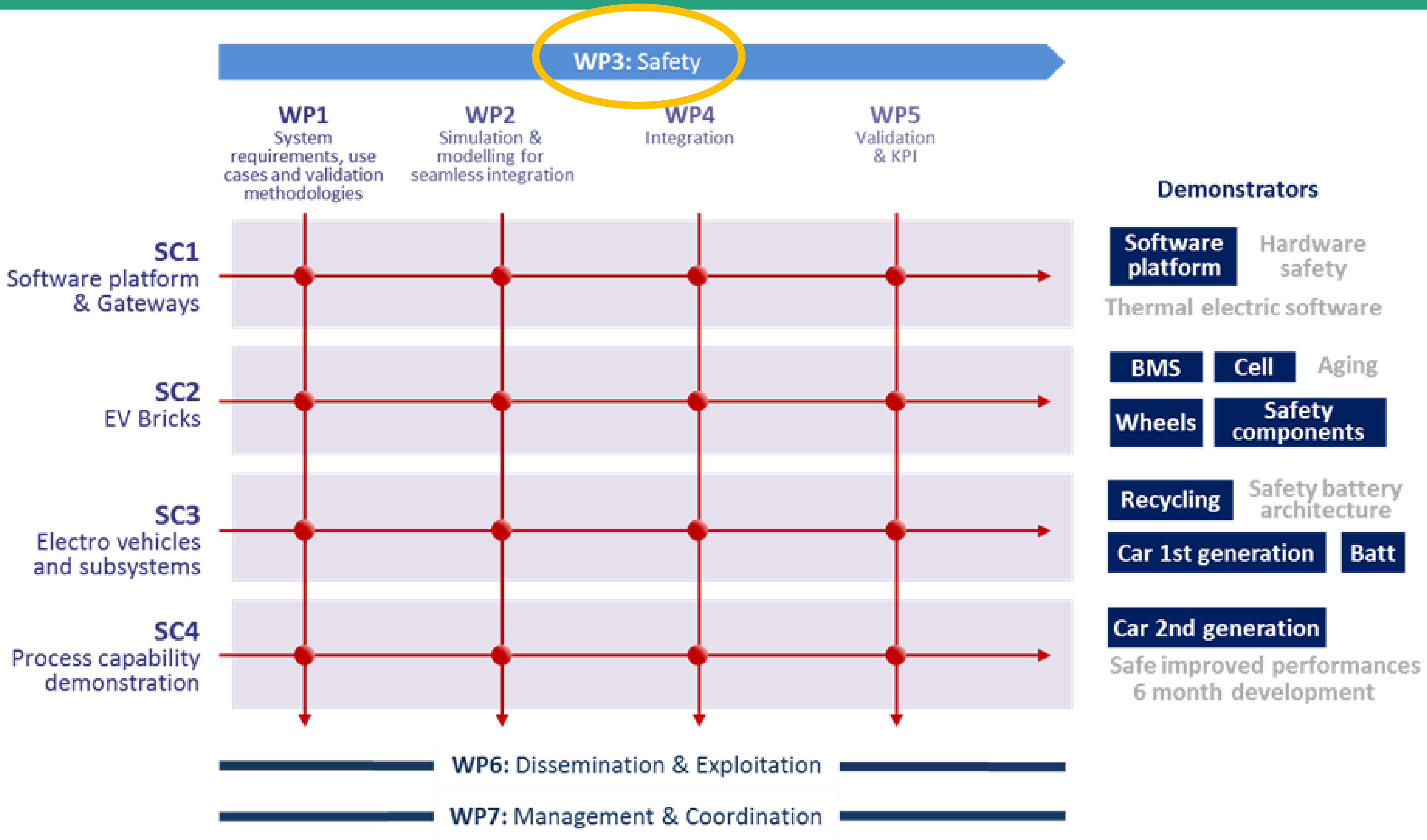
❑ H2020 DEMOBASE project

- DEsign amd MOdeling for Improved Battery Safety and Efficiency
- stands as a closed loop project response in direction of market driven demand
- Objective:
  - implementation of **innovative and continous process** for i**ntegration of new active materials, component and cells** iin EVS by use of **multi-scale modeling and testing** integrating battery management, and taking due account of ageing, safety and recycling issues and challenging built car prototype against KPIs

DEMOBASE EU-funded project data

- UE grant # 769900, RIA type of project
- Priority addressed: GV7-H2020: multilevel modelling and testing of electric vehicles and their components
- Consortium: 11 partners
  - Scientific coordination SAFT
  - Project management: K&S GmbH Projektmanagement
  - WP leader safety: INERIS
- Estimated project cost: 7,451,520 €
- duration: 36 months, started 1st Oct. 2017
- URL: www.demobase-project-eu
- Contact: info@demobase-project.eu

Overall organization of the project and relation to safety



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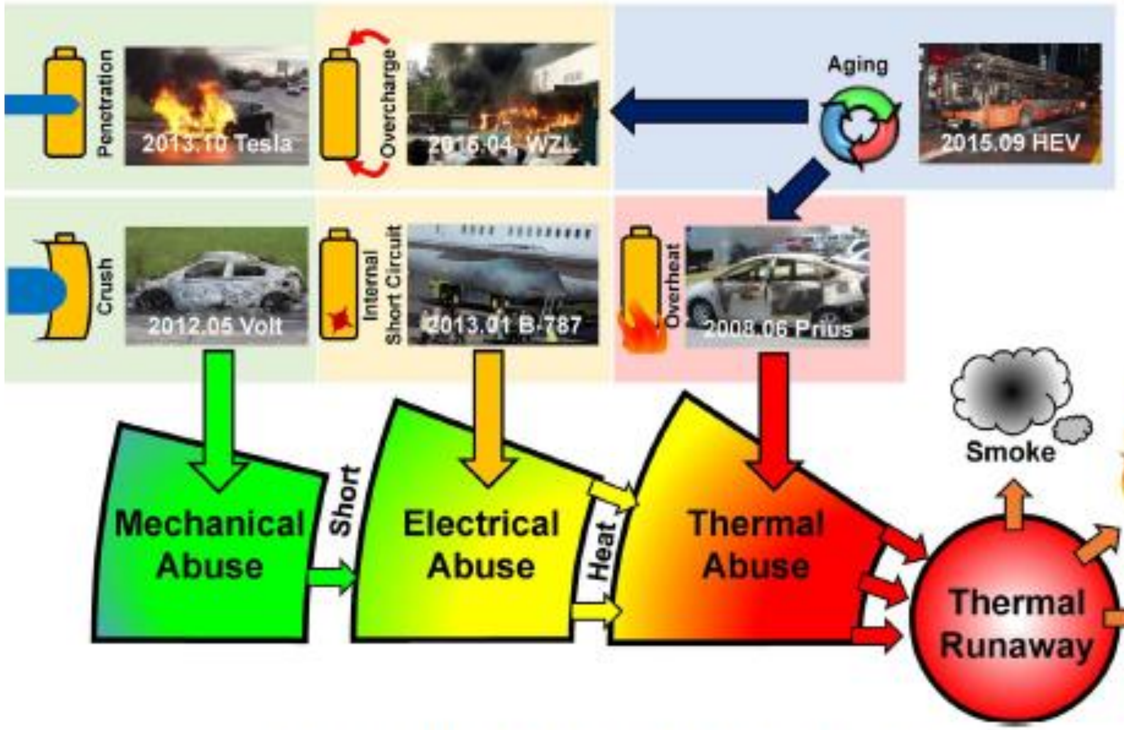
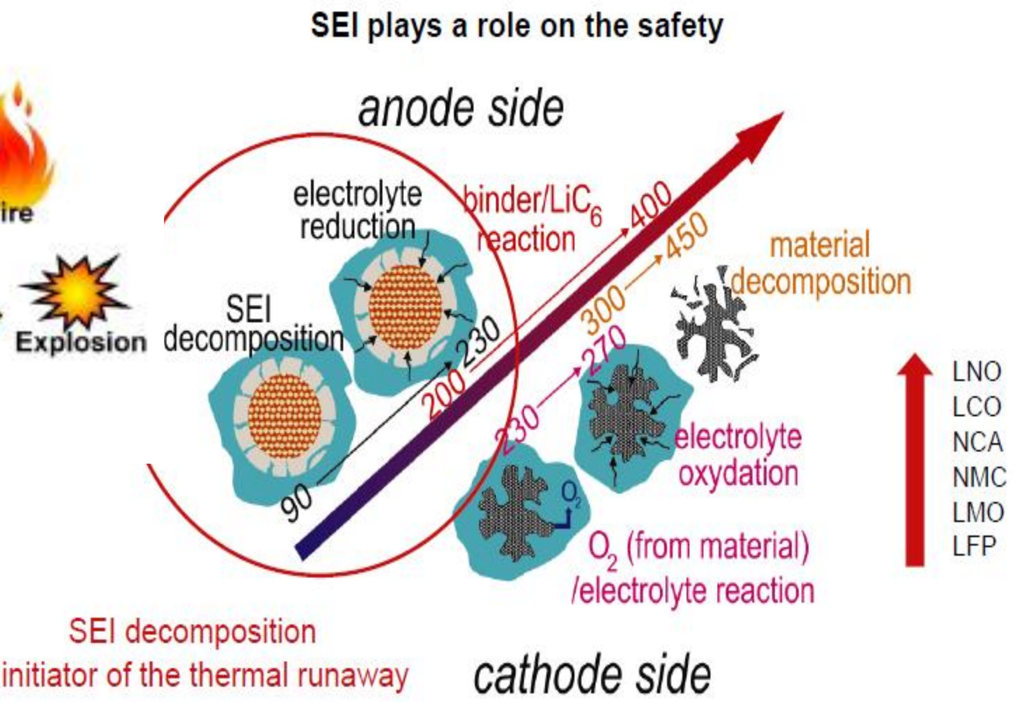
The fire safety challenge in relation of the thermal runaway hazard



Feng et al, Ener. Storage Mater.10 (2018), 246-267



- Need for better understanding and modeling of the TR for each chemistry, including most reactive cathode materials !
- Better battery SOH prediction and improved safety management devices
- System safety also needed, BMS related, but not only

Fire safety research dedicated strategy in the project

❑ Preliminary paperwork (first round completed):

- Accident review
- PRA
- BMS (fire) safety management optimisation (pending)

❑ Experimental approaches on key EV components

- Cell components, battery cells & modules, packaging materials
- Feeding component/cell selection, package design and modeling needs
- Started in 2018

❑ Fire safety related Modeling

- Multiphysics, multi-scale, multi-tools approaches, multi-objective
- Pluri-partners synergism seeked for
- Work started at IF-PEN, SAFT and INERIS on ES level

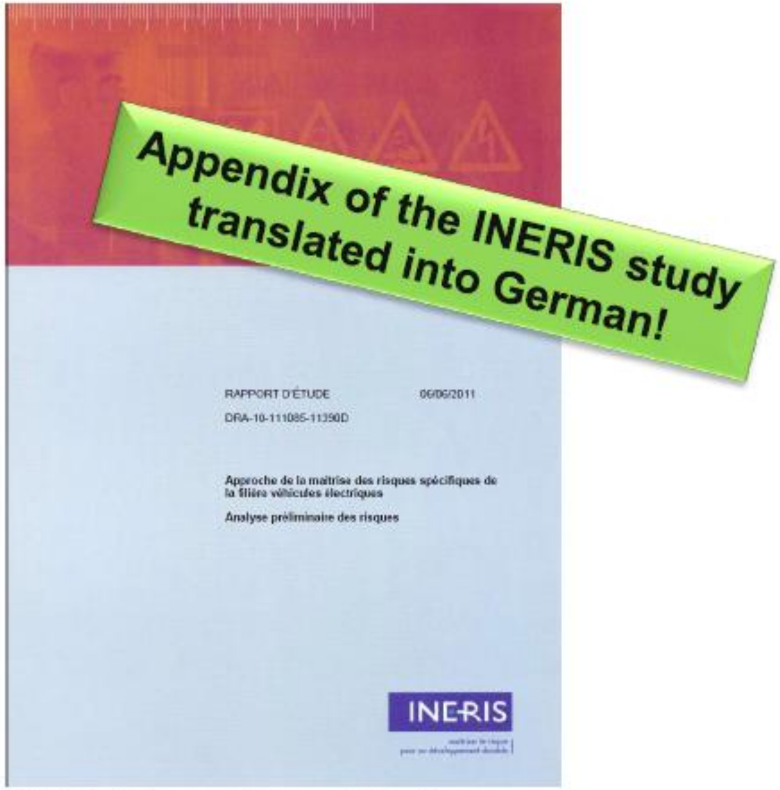
Preliminary Risk Analysis (EV deployment)

From a full value chain perspective

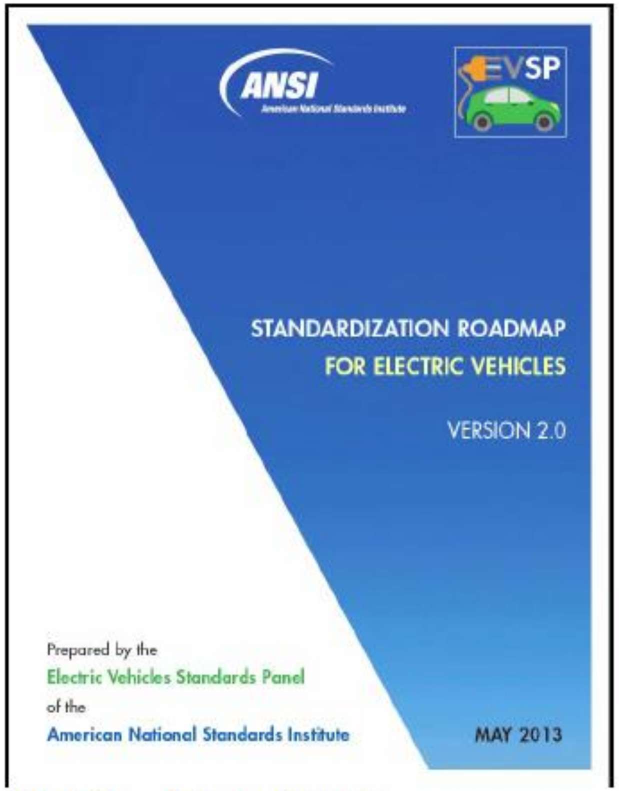
❑ Methodology based of previous studies

- Review of past accidentology of lithium-ion batteries with a focus on Evs
- Scenario-based PRA, starting from EV/energy storage design to end use and recycling

Already existing studies



INERIS – June 2011



ANSI – May 2013

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Accidentology review: methods

- Examination of incidents/accidents from lithium batteries (LI-ion and Li Metal Polymer) identified from various sources relating to e-mobility
  - Existing official databases (eg ARIA), or originating from blogs (www.wreckedexotics.com/)
  - Expert network
  - Internet searches with web browsers

- Possible biais in the analysis due to uneven access to info and reliability issues, at world level

- Databases built up in the project did not dig in issues about consumer market batteries, …)

Accidentology: analysis performed vs location in the value chain

Example: partial view of incident logs regarding EVs or hybrid buses during use phase

Incident/ accident type	Date	Location	Type of batteries/ vehicles	Causes	Consequences	Summary of the incident
Fire (storage)	18/10/2016	Santa Barbara[25] (USA)	Li-ion Battery pack used in MTD buses	Battery pack internal short caused by dripping water at a storage location	2 employees received medical attention after being exposed to smoke	A battery unit used on Metropolitan Transit District buses caught fire during its storage at the MTD maintenance yard. MTD employees noticed smoke coming from the batteries, and attempted to put the fire out using dry chemical extinguishers and a Class D Metal extinguisher. Santa Barbara City firefighters and the Hazardous Material Unit were dispatched to the scene. Fire investigators say the fire appears to have been caused by a small amount of water leaking through the metal roof and onto the batteries, which may have caused an external short between the battery terminals.
Fire (driving)	02/10/2016	London (UK)[26]	Double-decker hybrid bus	Unknown	No severe casualties. Driver treated for smoke inhalation	A double-decker hybrid bus burst into flames outside Liverpool Street Station in London. No passengers were on board at the time, and the driver alighted safely. Videos and pictures show smokes and fire from the rear of the bus. The bus fire was later extinguished by the London Fire Brigade leaving 50 percent of the vehicle destroyed. The cause of the fire was unknown.
Fire (driving)	27/07/2016	Maryland[27] (USA)	Frederick County TransIT bus - Li-ion (fully electric)	Assembly defect (failed electrical connection near the positive terminal of the battery), temperature rise and cells thermal runaway	No injuries	A fire in the rooftop battery compartment of an electric bus occurred on Sept. 27 when driving (without passengers on board). The driver went out of the vehicle safely. It took one hour to extinguish the fire by Fire and Rescue services. A failed electrical connection near the positive terminal of the battery led to a rise in temperature. The rise in temperature was caused by an improperly crimped wire on the roof of the TransIT buses when they were being assembled. The temperature at the faulty electrical connection led to an increased temperature in the nearby battery cells, which then led to "a cascading chain of cell failures". The higher temperature wasn't reported because of a loss of fiber-optic communication between the battery and a system that monitors data for the vehicle, few days before. The county's four other electric buses were temporarily taken out of service while they were inspected for similar problems, but were placed back into service when no problems were found. Since the fire, the county has methods to send an alert when temperatures rise and software on all buses to notify them when modules fail.
Fire *(no data on phase)*	July 2016	Nanjing[28] (China)	Li-ion EV bus battery pack	Short circuit in contact with water	No injuries	The battery pack of an EV bus caught fire after heavy rain. Possible cause is attributed to a short circuit due to water immersion.

➔Similar tables set up for all stages of the EV value chain (**design, manufacture, transport, storage, use, recycling)**

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Accidentology review: main observations

- Some incidents involving Li-ion batteries still arising from mishaps at design/quality control stages (Innovation ➔ risks)
- Thermal and mechanical protection, also positioning of battery important to avoid abuse conditions leading to accidents
  - (nearby fire, car crash of runover, impact with sharp objects on roadways…)
- electrical protection against water/moisture driven short circuit importance also revealed from EV accidentology
- Accidentology also reveal the importance of the alert function in case of EV battery failure to allow fast abd safe evacuation
- Fire risk management in recycling sites may lead to significant damage in case of fire due to projections of battery components and release of fire brands and toxic smoke
- Fire-fighting of battery fire may be very difficult and require training, late reignition of EV batteries after incidents must be anticipated
- no sign in our view of increased fire hazard as compared to ICE cars, but fire hazard typology a bit different and fire prevention/protection need to be customized to EV peculiarities

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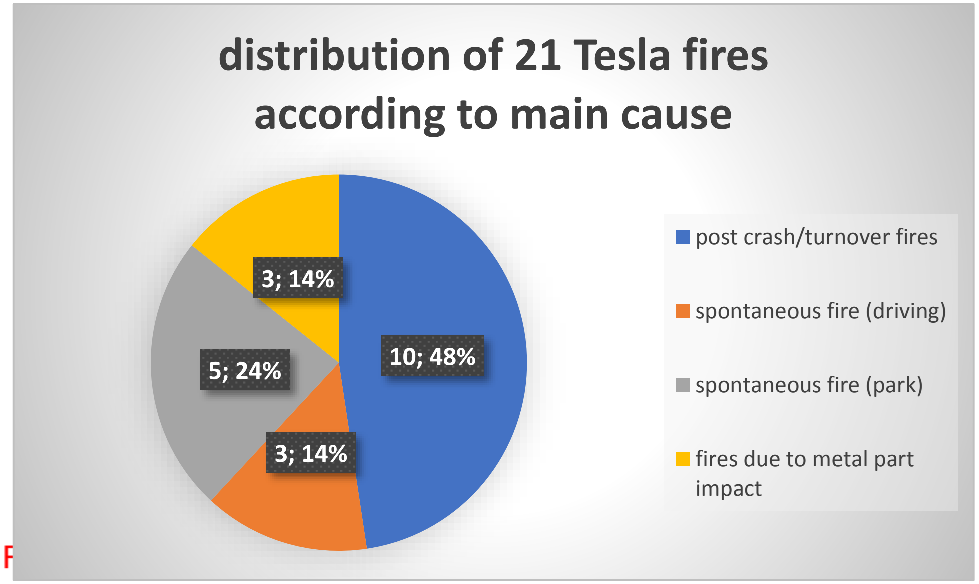
Fire Accidentology review on EVs: a focus on the **Tesla models**

- Collecting, and sortingTesla cars crash/runover and relating fire events according to incident outcomes have been performed
- Analysis in terms of
  - circumstances
  - Seriousness
  - Comparison with ICE cars (tentative)
- As for all other EVs, Tesla accidents do not necessarily end up by a fire event!

13	Aug. 2017 Lake Forest, CA USA		Car went off the road, crashed into home, setting fire on a garage	Driver injured	
14	Oct. 2017, Austria	Model S	Post crash fire after car hit concrete barrier on the side of a road, **35 firefighters tackled the blaze**		
15	March 2018, Mountain View, CA, USA	Model X	Post-crash fire involving a Tesla car and involving 2 other vehicles **Autopilot implication questioned (it was in use), speed increased from 100 to 114 km/h 3 seconds before crash Reignition of car wreckage…5 days after the incident**	Driver killed	
16	May 10th, 2018, A2 motorway, Ticino, (Switzerland)	Model S	Car caught fire after hitting crash barrier in central reservation of the motorway	German driver killed	

Tesla EV fires: some trends and statistics

- Models investigated: Tesla Roadster (Lotus platform), Model S, (sedan) Model X (SUV), Model 3
- 21 reported fires, most info from web sites and Tesla media reports + one scientific report (about 3 first scenarios in USA and Mexico)
  - need to be related to some 300,000 -350,000 Tesla cars sold so far in some 5 years
  - some 150,000 car fires in USA, some 30,000 car fires in France on a annual basis
  - 131 Tesla car crashes/overturn reported (www.wreckedexotics.com/)
    - Model S: 79 ; Model X: 16 ; model 3: 3; model Roadster: 34
  - 100% of fire deaths in Tesla fires are relating to post crash fires, currently
- To be noted: early recall of over 400 Roadster model 2010 carsl for fire hazard reasons pertaining to inadequate battery cable routing



Tesla post-crash fire events/vs all Tesla post-crashes (with/without fire event)trend: ~ 12,5%

comparison with ICE car fire trends from NFPA 2010 stats:

- post crash fires: 3% of all vehicle fires holding for 58% of vehicle fire deaths

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PRA update from original INERIS study: scope, methods and follow-up

- Re-rating previously identidied scenarii seriousness making use of a risk matrix from inital 2011 study (revised already in 2013)
- Completing analysis in terms of new pertinent incident scenario deserving examination at light of field experiene
- Back-up info to all stakeholders of DEMOBASE, according to involvment in concerned EV building-blocks for due consideration

- *Risk Criticity*

Risk criticality is determined according to 4 levels of criticality depending on the assessment of potential consequences pertaining to:

- economy loss,
- impact level on environment, population, fauna, flora, ...
- importance of firefighting means,
- importance of the quantities of dangerous goods stored.

No quantitative threshold has been determined on each importance level; instead, risk criticality is ranked qualitatively from 1 to 4, corresponding to:

- 4 : very important,
- 3 : important,
- 2 : serious,
- 1 : low.

Risk management level	1	2	3	4
Maturity	Very good management of the risk	Good management of the risk	Issue addressed or studied	No visibility
Risk mitigation measures	Risk mitigation measures optimized and applied by industrials	Risk mitigation measures proven and being applied by industrials	Few risk mitigation measures identified	No risk mitigation measures identified
Experience feedback	Important	Good for considered technologies	Limited feedback for similar situations	No feedback
Regulatory / standard framework	Existing and proven regulatory and standard barriers	Regulatory and standard barriers under revision or final stages	Regulatory and standard barriers considered or in development	No regulatory and standard framework

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Revised PRA → renumbering and re-rating incident scenarios through establishment of relating database (abstract of the 52 scenarii identified)

N°	Life Cycle	Identified Hazard	Causes	Known consequences	Risk criticity (severity in case of occurrence) quoted from 1 to 4	Level of management of the risk (existing or lack of framework, identified safety functions or not,...) quoted from 1 to 4	*Initial quotation (PRA 2013)* *Risk criticality / level of control of the risk (reason of quotation change or not)*	Recommendations / Comments
44	Use excluding driving (parking, emergency services intervention, etc.)	Risk of electric shock	- Electrical insulation failure,				*2/2 (no documented*	
45	Recycling/ disposal							

N°	Life Cycle	Identified Hazard	Causes	Known consequences	Risk criticity (severity in case of occurrence) quoted from 1 to 4	Level of management of the risk (existing or lack of framework, identified safety functions or not,...) quoted from 1 to 4	*Initial quotation (PRA 2013)* *Risk criticality / level of control of the risk (reason of quotation change or not)*	Recommendations / Comments
39	Use (driving)	EV battery safety issues by contact with a large quantity of water (heavy rain, flood,...)	- Electrical insulation failure, - introduction of water inside the battery pack or another organ of the vehicle - External electric short possibly aggravated in case of salt water	- Electric shock, - short-circuit, - battery thermal runaway, - flammable gas formation in contact with water (explosive atmosphere formation) - delayed EV fire, - simultaneous EV fire	3	3	*2/2 (several accidents reported)*	- Water tightness and protection against external short of the pack as prevention measures - Scenario to be indicated in manual of use
40	Use excluding driving (parking, emergency services intervention, etc.)	Simultaneous presence of different hazard typology for emergency services during intervention on EV in accidental situations (crash, EV and/or battery fire, EV immersion, ...)	- Difficulties to control battery fire - Simultaneous presence of electrical, thermal, mechanical and chemical (toxicity, inflammability and corrosivity) risks - Difficulty to identify an EV / hybrid vehicle - Lack of training of emergency services	- Thermal and toxic effects following fire and/or gas dispersion, - electric shock, - corrosive effect (contact with electrolyte), - mechanical effect (projections), - flammable gas formation in contact with water (explosive atmosphere formation)	4	3	*4/3 (Some progress has been made to address this issue in terms of drafting guidances and training program to some emergency services Lack of significant return from field experience)*	- To continue to train emergency services to EV risks in accidental situations - Consider emergency service needs at design stage of battery pack and EV

PRA EV update: major results

*Figure 1 : PRA – Cartography of identified scenarios **in 2013***

Risk Criticity level				
4		16	17; 19; 21; 22; 25; 37; 40; 45	26
3		8; 10; 13; 18 ; 34; 38	1; 2 ;3; 6; 7; 24; 27; 30; 31; 33; 36; 48	4; 20; 23
2		9; 11; 14; 32; 35; 39; 43 ; 44	5; 12; 15 ; 29; 41; 47 ; 42; 49	28; 46; 50
1		7bis		
Criticity matrix	1	2		
	Risk management level			

2013

2018

*Figure 2 : PRA – Cartography of identified scenarios **in 2018***

Risk Criticity level				
4	34	16 ; 37 ; 45	21; 40	52
3		8; 10; 13; 17 ; 19; 22 ; 25 ; 27 ; 31 ; 38	1; 2 ; 15; 20;24; 26 ; 33; 36; 39 ;48	
2	9 ; 14	5 ; 11; 12 ; 18; 32; 35; 43 ; 44, 51	6; 7 ; 29; 30 ; 41; 47 ; 42; 49 ; 50	3 ;28; 46
1		7bis	4	
Criticity matrix	1	2	3	4
	Risk management level			

- ❑ 21 scenarii found less critical than initial PRA 2011 study,
- ❑ 3 scenarii found more critical than in initial INERIS PRA study,
- ❑ 26 unchanged criticity rating
- ❑ 2 new scenarii

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Fire / thermal abuse testing strategy

❑ Priorities:

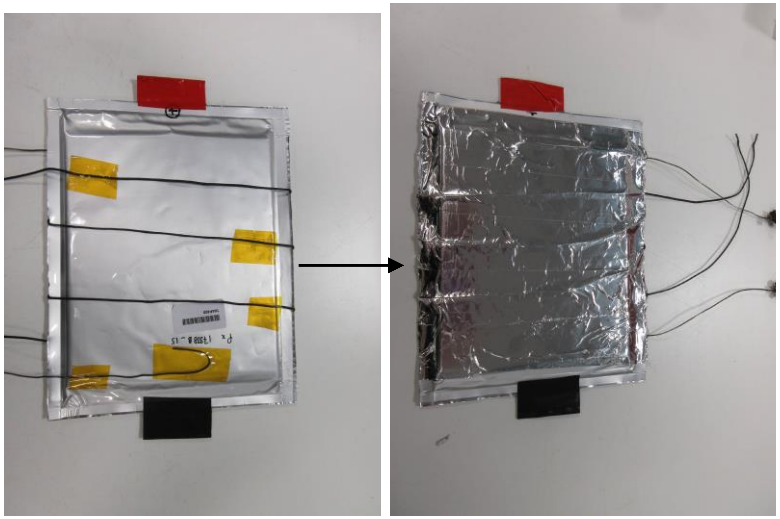
- Contribute to qualify electrode materials/cell options in terms of fire safety aspects (thermal and electrical abuse)
- Provide calibration data for multi-physics TR prediction model, cell level on fresh and aged cells
- Provide calibration data for CFD computation (cell and module level)
- Test reaction-to-fire of key battery pack casing/insulation material for EV battery integrator

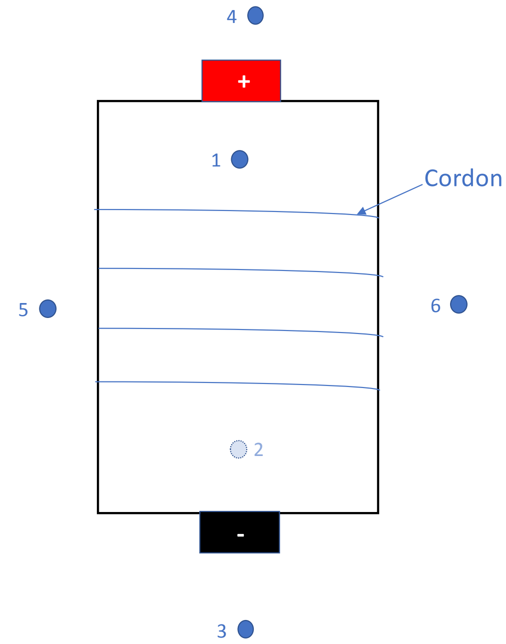
Testing approaches Protocol and testing device

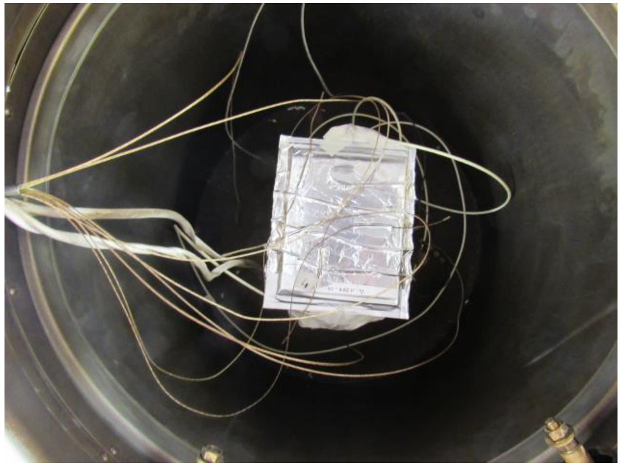
❑ Testing device and instrumentation

Thermal tests performed in BTC 500 from HEL

- 2 thermocouples for regulation measurement positionned on each side of the cell
- 4 thermocouples around the cell
- 4 others thermocouples inside the equipement
- Cell voltage measurement



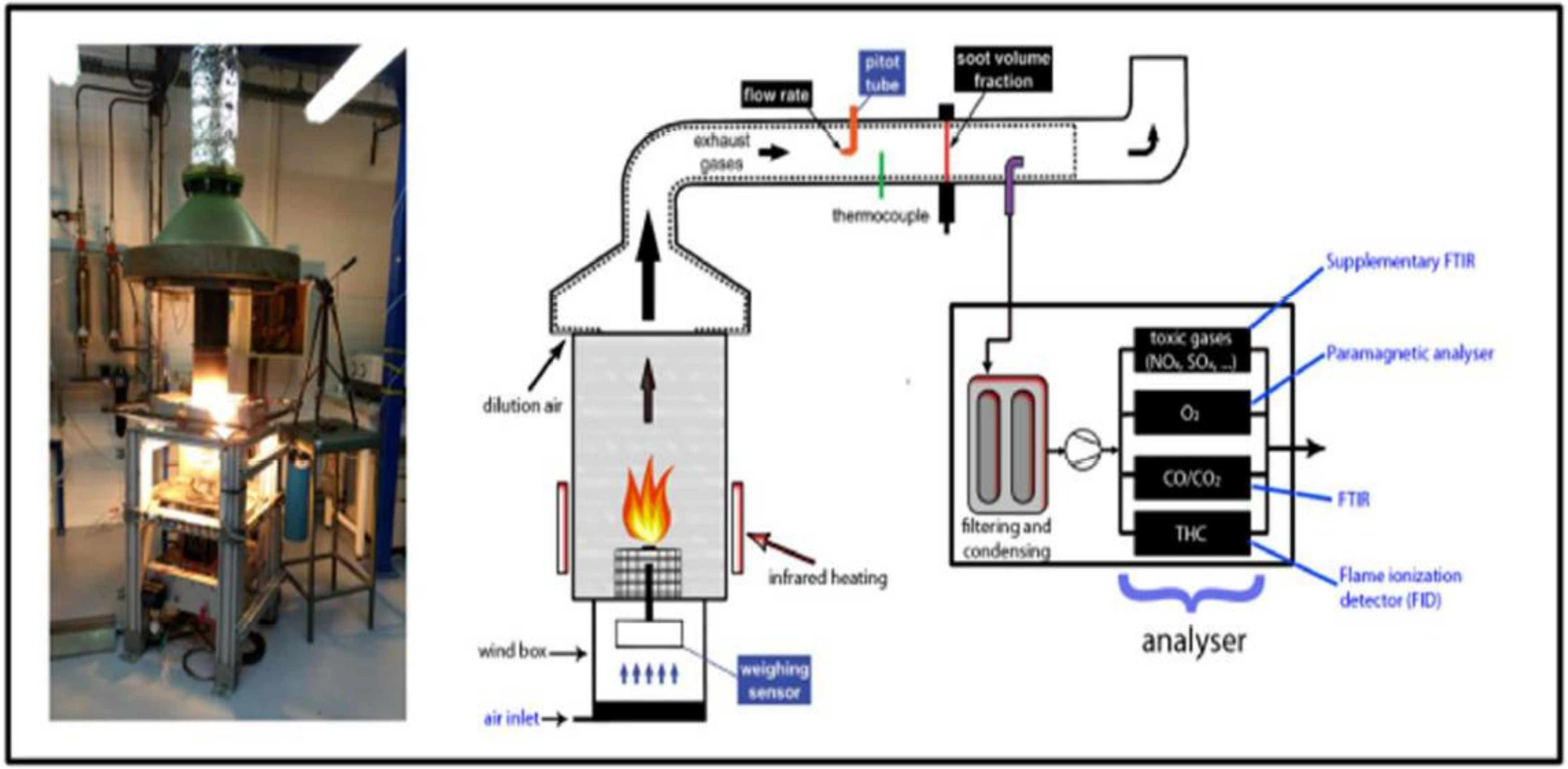




- Heater wire enrolled around the cell
- Cell positionned at the center of the equipment on a support
- **Cell charged at 100% before test**

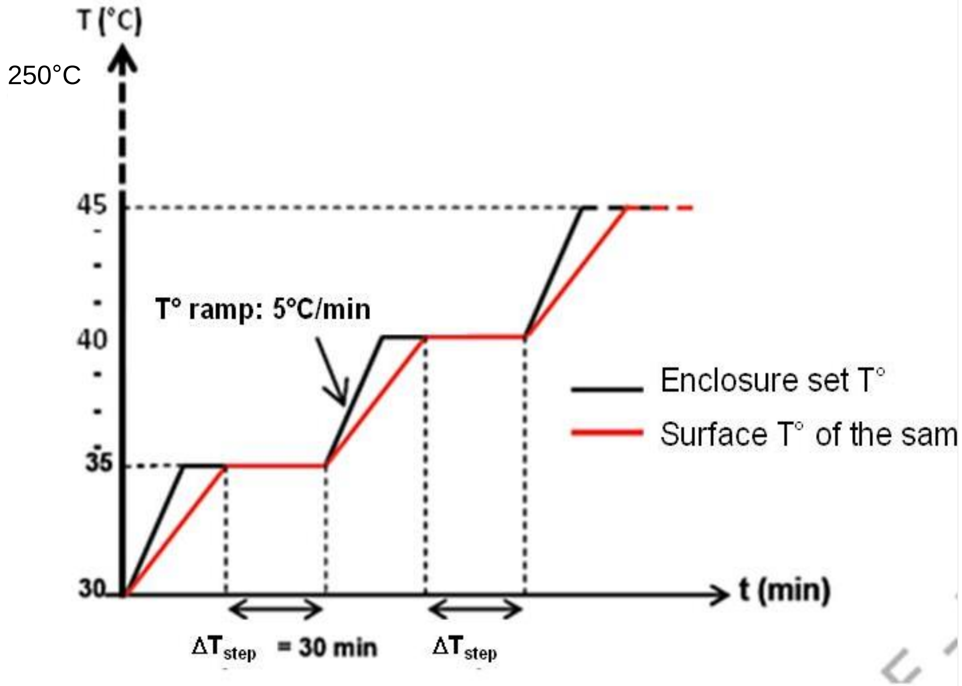
Testing reaction to fire on key combustible pack materials

- Use of FPA apparatus (ISO 12136) coupled with FTIR instrument (18 gas exploitation method):
  - tests carried out on pack insulation material candidate

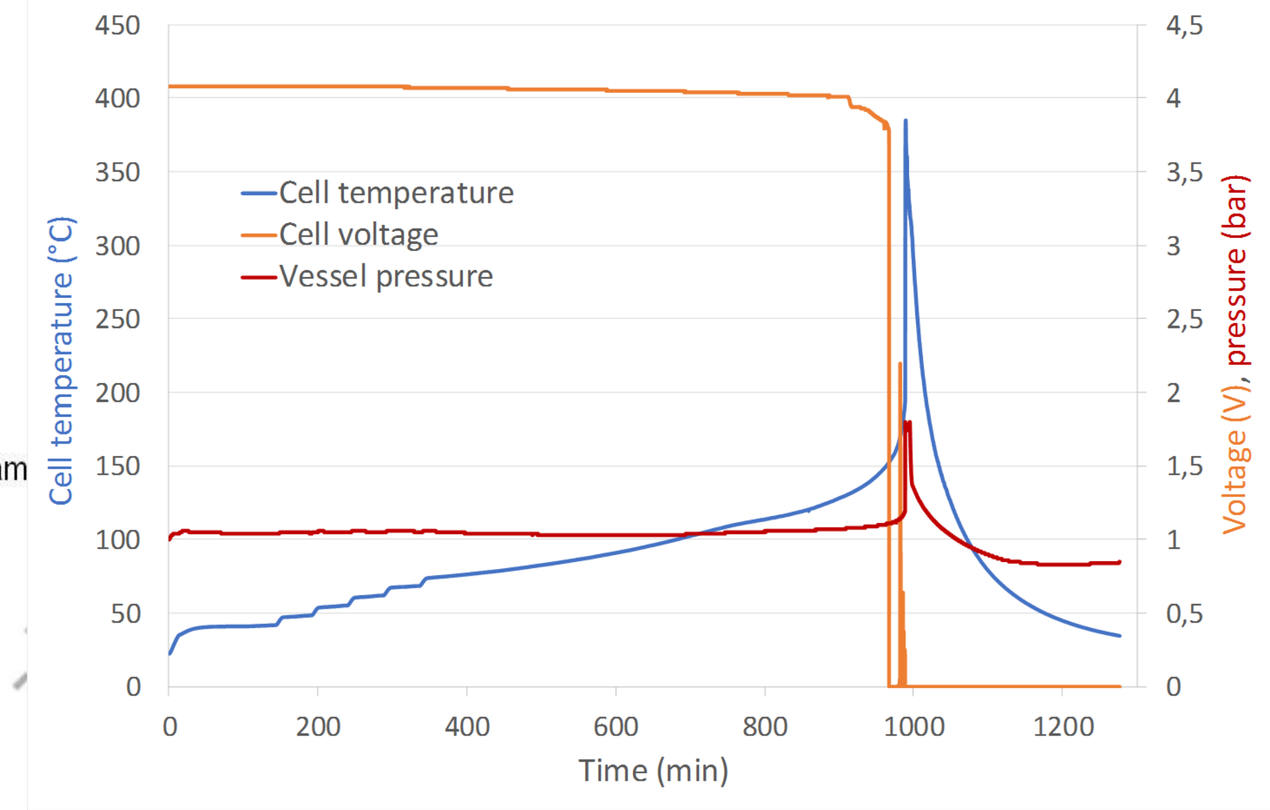


Protocol and testing device

❑ Protocol



Example of result from early testing on fresh cell in DEMOBASE



- Adiabatic conditions, heat-wait-search process (ARC) to characterize on-set temperatures of thermal events pertaining to TR phenomena
  (Use of BTC HEL model 500)
- First series of pouch cells tested in BTC, exploitation pending…

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(thermal abuse/Fire) Safety Modeling

Fire/ TR issues (prediction/propagation/ignition) modeling making use of various tools such as:

- TR multiphysics 0D/3D thermal runway model (coded with COMSOL®) (improved model from work of Sara Abada et al, Journal of Power Sources 399 (2018) 264–273)

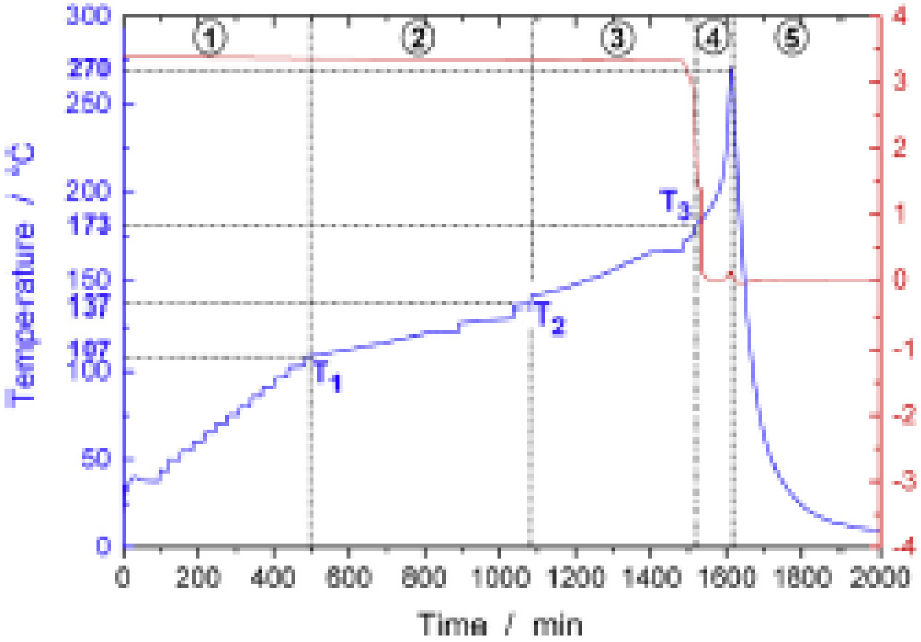

Fig. 2. Surface temperature and voltage of a fresh A123 battery cell measure during the calibration experiment in the BTC.

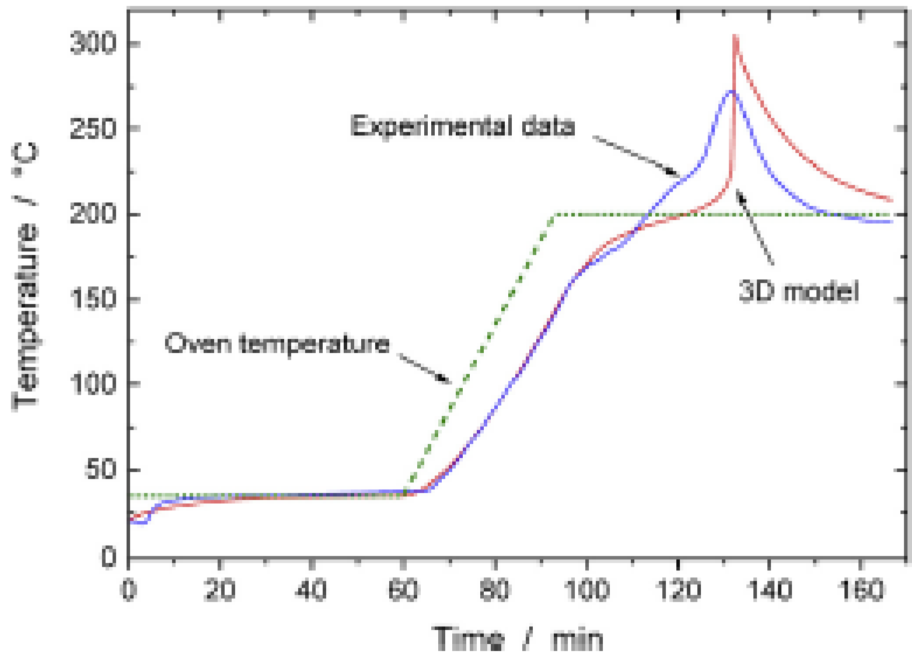

Fig. 4. Experimental and simulated evolution of the average surface temperature of a fresh A123 cell during the oven test.

Combined experimental and modeling approaches of the thermal runaway of fresh and aged lithium-ion batteries

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(Thermal abuse/fire) safety modeling (Cont'd)

- Other interactive modeling exercises with tools to obtain guidance/response of design option at various level of integration of building blocks of the EV (just started) up to recycling issues
  - use of Simcenter Amsesim (IFP-EN), based on Siemens PLM software
  - Coupled modeling between INERIS and SAFT with Firefoam v2.4 and NX Simcenter V 11.0.2 for TR propagation issue within pack, with input data from INERIS and IFP-EN)
  - (possibly) scenario based modeling of EV incident, such as fire-induced toxicty in garage ?
    - See Lecocq et al. J. of Power Source.

Journal of Power Sources 316 (2016) 197–206

Contents lists available at ScienceDirect

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journal homepage: www.elsevier.com/locate/jpowsour

Scenario-based prediction of Li-ion batteries fire-induced toxicity

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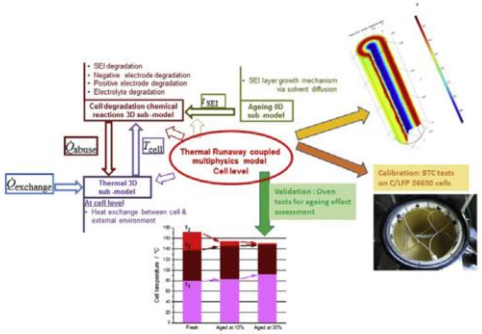
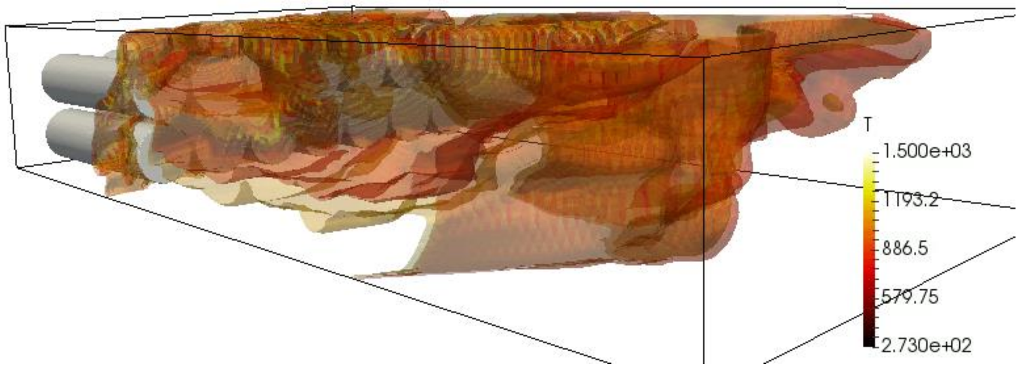


Fire behavior comparison in an open field, unfortunately

- Battery tests are not designed for CFD code validation

The flame is 3 times longer than the cell and as large as the module

- Flame length is quite correct
- Temperature is in the correct order of magnitude
- But how is representative the boundary condition?



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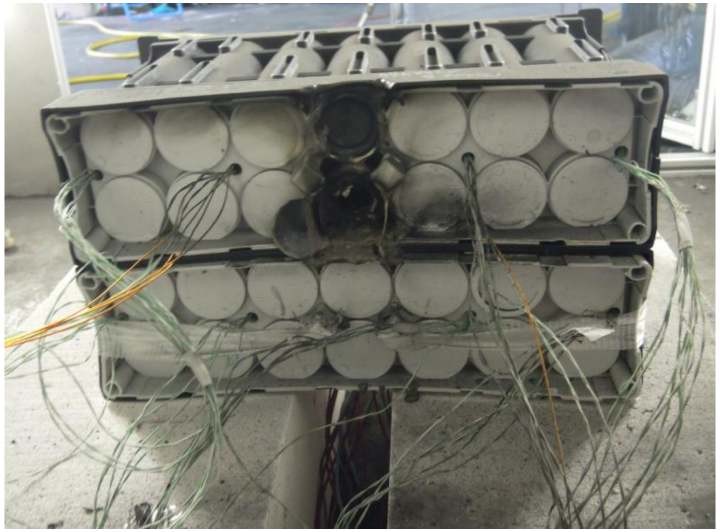
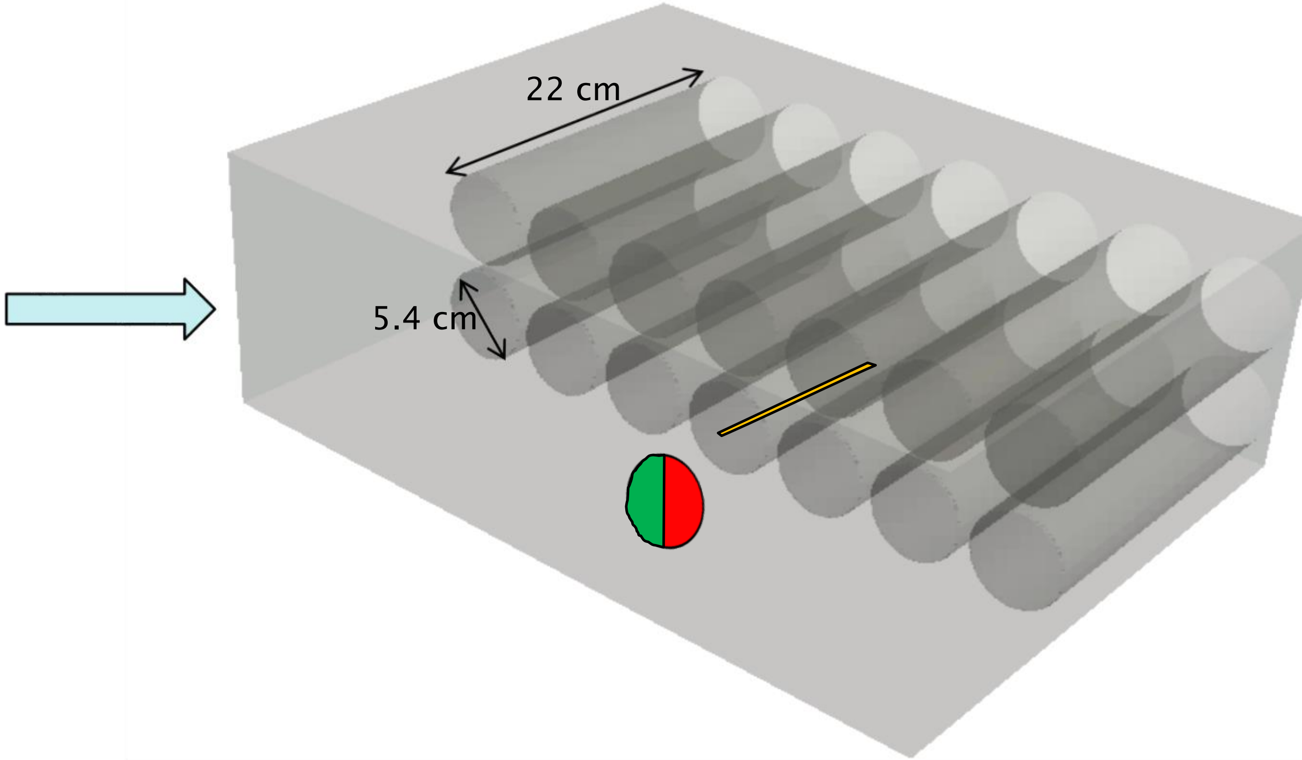
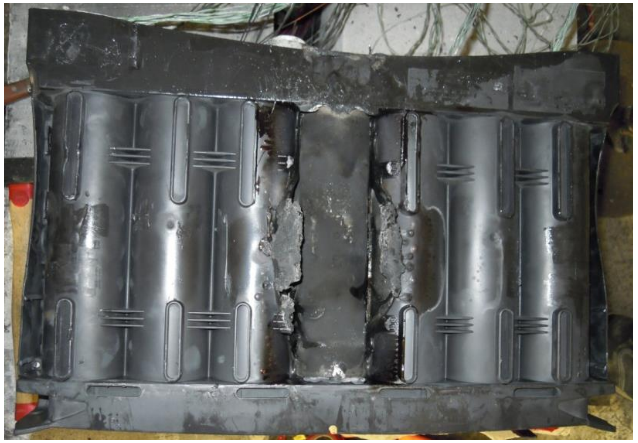
But inside a module the flame geometry is complex;;;





The cell opening mode is crucial

- The whole back face
- A part of the back face
- An opening along the external surface



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Conclusions / perspectives

- The DEMOBASE project offer a unique experience /partnership to promote safer, faster to market of innovative affordable Evs
  - looping process
  - Making use of interactive testing and modeling
- Paperwork also welcomed by partners in terms of guidance from the safety viewpoint, as well as revised APR
  - Some safety goals appear challenging, such as fail-safe module or pack in case of TR in one cell
  - Post-crash scenario deserve further examination and show importance of pack localisation and mechanical protection againt impacts and deformation during car crash
  - However, EV car will happen, as it happens on a regular basis with ICE cars, incl. most exotic ones ! IN addition, there is no evidence of increased frequency of fire event in existing EV fleet by comparison of ICE fleet,
- A reminder:
  - still many results to come, last but not least, check of performance of genuine concept car issuing consolidated design process developed inside the consortium

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Thank you

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DEMOBASE

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