

Full-Scale Experimental Analysis of the Behavior of Electric Vehicle Fires and the Effectiveness of Extinguishing Methods

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Abstract

The emergence of electric vehicles (EVs) has brought specific risks, including the possibility of fires or explosions resulting from mechanical, thermal, or electrical failures, which can lead to thermal runaway (TR). There is a great lack of knowledge about how to act safely in this type of fire. This study carried out two full-scale fire experiments on electric vehicles to investigate response strategies to electric vehicle fires caused by thermal runaway. Centro Zaragoza provided technical advice for these tests, so that they could be carried out safely, controlling the risks. This advice has allowed Centro Zaragoza to analyze different response strategies to the fires in electric vehicles caused by thermal runaway. On the other hand, the propagation patterns of thermal runaway fires in electric vehicles were investigated. The early-phase effectiveness of fire blankets and other extinguishing measures was tested, and the temperature distributions inside the vehicle and the type of fire generated were measured. The results showed that fire blankets successfully extinguished flames by cutting off the oxygen supply. These findings contribute to the development of effective strategies for responding to electric vehicle fires, enabling the establishment of good practice for fire suppression in electric vehicles and their batteries.

Keywords: fire blanket; fire; thermal runaway; firefighter; thermocouple; temperature



Academic Editors: Ying Zhen Li,
Jinlong Zhao and Jiaqiang E

Received: 13 May 2025

Revised: 14 July 2025

Accepted: 25 July 2025

Published: 29 July 2025

Citation: Olona, A.; Castejon, L. Full-Scale Experimental Analysis of the Behavior of Electric Vehicle Fires and the Effectiveness of Extinguishing Methods. *Fire* **2025**, *8*, 301. <https://doi.org/10.3390/fire8080301>

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1. Introduction

Billions of internal combustion engine vehicles account for nearly 87% of global oil consumption and significantly contribute to various environmental impacts, such as atmospheric pollution and global warming [1]. To reduce the impacts of climate change and preserve natural energy supplies, electric vehicles (EVs; electric vehicles) and hybrid electric vehicles (HEVs; hybrid electric vehicles) have emerged as an alternative to conventional vehicles.

At present, lithium-ion batteries (LIBs) are considered a crucial energy vector in EVs and HEVs, as they do not produce carbon emissions during operation. However, due to their high energy density and limited safe operating temperature range, they pose significant safety challenges: LIBs can suffer TR (thermal runaway) when subjected to overheating, overcharging, or mechanical damage [2]. The thermal hazards of LIBs under TR involve high temperatures, material ejection, combustion reaction, detonation, and the release of hazardous gases. The battery packs used in electric vehicles consist of many individual cells connected in series and in parallel. If one cell experiences a TR reaction, heat is transferred to adjacent cells, which can lead to a serious fire in the EV or explosion [3], as

flames due to TR from the battery pack can spread to the entire vehicle and ignite it. The unpredictable working environment of EVs also increases the risk and danger of fire [4]. For example, in 2013, a Tesla Model S caught fire after its battery was pierced by a metal object while driving on the road [5]. In a similar case, an electric bus burst into flames after colliding with a guardrail on a highway in China on 25 November 2020 [6]. In addition to possible battery damage caused by collisions, the combustion of EVs during the charging or operating process is responsible for a lot of the EV fires. In a parking lot located in China, a Weima EX5 caught fire during the charging process [7]. Another Tesla Model S in Texas spontaneously caught fire and its passenger seat was severely damaged in the fire [8]. The fire started on the underside of the electric vehicle where the battery was located. The various fires involving electric vehicles that have occurred in recent years highlight the need to establish new safety protocols to manage the extinguishing of fires involving this type of vehicle.

Although these accidents have raised concerns about EV fire safety, the popularization of EVs has not been hindered. As EV sales largely grow, the incidence of such accidents is likely to increase [9,10].

Internal combustion engine vehicles (ICEVs) were tested and their fire safety improved before they were a mature technology [10,11], so EVs will go through the same process in the future. Large-scale (on-vehicle) electric vehicle fires have been preliminarily studied, but electric vehicle fire suppression techniques still use the traditional methods used by firefighters to cool traction batteries. These methods require a large amount of water, and once the water supply is interrupted, if the battery is not sufficiently cooled, the electric vehicle can re-ignite [12]. The lack of cooling of battery packs experiencing TR is the main cause of re-ignition of EV traction batteries. Although water mist can cool the batteries at a rate of 1.23 °C/s [13,14], it is not suitable for extinguishing EV fires, because the water droplets do not reach the interior of the batteries [3]. Other extinguishing agents, such as C₆F₁₂O, CO₂, and HFC-227, lack sufficient heat absorption capacity, and LIBs will experience a second TR reaction after the cessation of agent application [13,15–17].

This study compiles the analysis conducted on the efficiency of different EV fire suppression methods because, although EVs are evolving rapidly, the development of fire protection systems and EV accident response strategies are progressing at a slower rate. It is crucial to effectively suppress EV fires and stop the spread of the hazard in fire scenarios with a high density of vehicles, such as parking lots, tunnels, or storage sheds [18]. Therefore, the investigation of EV fire characteristics and extinguishing measures is crucial.

Some EV fire tests have focused, so far, on studying different aspects or characteristics of EV fires. Thus, Amandine et al. [19] measured the heat release rate (HRR) of two EVs based on O₂ consumption, obtaining a maximum heat release rate between 4.2 MW and 4.7 MW. Cui et al. [20–22] conducted a series of fire tests on EVs. In these tests, it was observed that the battery pack emitted white smoke before the EV caught fire under thermal runaway conditions, i.e., before TR occurred. It was concluded that, compared to internal combustion vehicles, EVs spewed flames that were conducive to flame propagation. Kang et al. [23] disassembled an electric vehicle, separating the battery pack from the body to test them separately and determine their combustion parameters. Due to the high energy density of lithium-ion batteries, electric vehicle fires have a high flame intensity, exhibiting rapid propagation and high explosion potential. In addition, the electrode material of lithium-ion batteries can generate oxygen at elevated temperatures, which increases the difficulty of extinguishing the fire and the risk of re-ignition [24,25]. Dry chemicals, carbon dioxide, and foam are commonly used to extinguish battery fires because they reduce the risk of electrocution [26]. The NFPA's (National Fire Protection Association) guide for EV emergencies indicates that a large volume of water can extinguish EV fires in most

cases, which can only be accomplished by fire departments [27]. However, first responders, particularly fire departments, may not arrive immediately after an EV fire. To prevent a fire from spreading until firefighters arrive, containment measures must be taken. Fire blankets and water mist are two simple methods to control the spread. Kwon et al. [28] used a fire blanket (without using water) in a vehicle fire test by placing it at the point of the highest fire intensity. As a result, the fire spread was successfully controlled using the fire blanket. Xie et al. [29] extinguished the fire of a ternary battery, a large-capacity lithium-ion battery used in electric vehicles, with three cathode components—nickel, manganese, and cobalt. They used a mobile fine water mist device for extinguishing, and the maximum cooling rate reached $-26.9\text{ }^{\circ}\text{C/s}$.

Despite initial concerns, existing studies show that BEVs (battery electric vehicles) do not present a higher fire risk than ICEVs (internal combustion engine vehicles) [30], which catch fire up to 20 times more often than BEVs, according to the MSB (Swedish Civil Contingencies Agency) [31]. However, fires involving lithium-ion batteries pose specific problems, such as thermal runaway, jet fires, and vapor cloud explosions. In addition, the condition and reliability of the recharging infrastructure can pose fire safety issues. The BEV fleet is still relatively young compared to ICEVs, so as BEVs age, there may be an increase in fire incidents, especially among privately owned vehicles that are not properly maintained. In 2022, the MSB reported a total of 106 fires in various types of electrified transport modes in Sweden [32]. Of these, 38 were in electric scooters and 20 in electric bicycles, while 23 were in electric cars, representing only 0.004% of the 611,000 BEVs registered in Sweden [32]. In contrast, during the same period, 3400 fires were recorded in the 4.4 million gasoline and diesel cars on the road in Sweden, equivalent to 0.08% of the fossil fuel vehicle fleet [32].

Similarly, in Norway, data from the DSB (Norwegian Directorate for Civil Protection) system recorded 998 fires between 2016 and 2018, of which 109 were attributed to electrical equipment, and 65 originated in vehicles—only 2 of them in electric cars [32]. In the Netherlands, in 2023, there were almost half a million BEVs [33] in circulation. That year, only 181 fire incidents involved all types of electric vehicles (including BEVs, light-duty vehicles, and heavy-duty vehicles), evidencing a very low frequency of BEV-related fires [34].

Fires in electric vehicles seem to be decreasing. According to the MSB, the number of electric car fires has remained at around 20 fires per year for the past three years, even though the number of electric vehicles has almost doubled in that time in Sweden [32]. This decrease is probably attributed to improvements in fire extinguishing designs in newer BEV models. Norway, which has the highest proportion of BEVs globally, reported that electric vehicles account for only 2.7% of vehicle fires, despite making up 17.3% of the passenger car fleet in 2020 [35]. Data suggests that electric vehicle fires are less frequent than ICEV fires by a factor of 8 to 10 [36]. Most fires in electric transport devices (78.2%) involve scooters, kick-bikes, hoverboards, and electric bicycles or motorbikes, rather than cars [35].

Electric vehicle fires are no larger or more dangerous than internal combustion vehicle fires [37]. Research conducted by RISE through the LASH FIRE project, which tested different fire suppression systems in both internal combustion vehicles and electric vehicles, concluded that electric vehicle fires do not present greater fire management challenges than internal combustion vehicle fires, provided that the current international recommendations for sprinkler systems are met [35]. While electric vehicle fires share some similarities with internal combustion vehicle fires, they also present unique risks that require specific attention.

The spread of fires in electric vehicles to nearby vehicles is no faster than that of fires in internal combustion vehicles. While lithium-ion batteries can produce jet flames that can

spread the fire, internal combustion vehicles often carry large amounts of liquid fuel [32]. In the case of a fuel leak from the fuel tank, it can cause a pool of fire that extends several meters. In terms of fire propagation, the polymer fuel tank of an internal combustion vehicle will ignite more quickly than the lithium-ion battery of an electric vehicle when exposed to an external heat source [32]. However, according to NFPA data, extinguishing electric vehicle and hybrid vehicle fires takes longer (36–60 min and 15–56 min, respectively) than extinguishing conventional vehicle fires (5 min) [9].

A common misconception about electric vehicle fires is that they burn at extremely high temperatures. The temperature of any fire depends on several factors, such as fuel type, atmospheric pressure, ambient temperature, and oxygen levels. There is no evidence that electric vehicle fires reach higher temperatures than internal combustion vehicle fires.

Although recent studies suggest that electric vehicles do not present a significantly higher fire risk than internal combustion vehicles, long-term statistical data remains limited. Insurers and researchers need more comprehensive data to better assess and mitigate these risks.

Due to the high cost and complexity of conducting EV fire tests, few EV fire tests are available. To investigate response strategies in the early stages of an electric vehicle fire, the Zaragoza fire brigade carried out two electric vehicle fire tests, with technical advice from Centro Zaragoza, ensuring that they were carried out safely, controlling the existing risks. Firstly, with a Nissan Leaf, and secondly, with a Smart EQ ForFour, in an open space, using a fire blanket as a fire suppression method in the first test in the first phase and adding water in the second phase. In the second test, only a fire blanket was used. The objective was to analyze the characteristics of the EV fire process and to evaluate the effectiveness of the fire blanket. These results are expected to provide information on emergency response plans for EV hazards.

An external ignition source, namely a fossil fuel burner, was used for the tests. While it is true that ignition within the battery represents a critical failure mode, many real-life electric vehicle fires do not originate within the battery, but spread towards the battery. Therefore, we believe that comparing the fire behavior of batteries and internal combustion electric vehicles with external ignition provides valuable information on the evolution of heat release, fire spread, and containment effectiveness. However, we recognize that this configuration limits conclusions on the intrinsic behavior of battery ignition.

2. Materials and Methods

The following are the fire tests of an electric vehicle carried out at full scale, specifically of a Nissan Leaf and a Smart ForFour, carried out by the Zaragoza City Council fire brigade at their facilities, specifically at Zaragoza Fire Station 5. As indicated above, Centro Zaragoza provided technical advice on these tests so that they could be carried out safely, controlling the risks. This advice has allowed Centro Zaragoza to analyze different response strategies to electric vehicle fires caused by TR.

2.1. Nissan Leaf Electric Vehicle Fire Test

2.1.1. Electric Vehicle Used During the Tests (Nissan Leaf)

First, Zaragoza firefighters carried out a controlled fire test on a complete electric vehicle, specifically a Nissan Leaf (Figure 1), in which the temperature progression and the behavior of the battery were analyzed. The fire started by placing a fossil fuel burner on the bottom of the high voltage battery of the electric vehicle. This method avoids violating the sealed structure of the battery and better represents fire propagation from typical external ignition sources, such as a road debris fire or a collision-induced flame. The duration of the test and the temperature of the battery were monitored throughout the test with the help of

a thermographic camera. Table 1 below shows the main specifications of the tested battery of the burned Nissan Leaf vehicle.



Figure 1. Electric vehicle used during the tests (left) and location of the high-voltage battery (right).

Table 1. Battery specifications of the burnt Nissan Leaf vehicle.

Vehicle	Electric Battery
Date of first registration	17 December 2015
Range	121 km (EPA test)
Battery specifications	
Energy it can supply	24 kWh
Battery voltage	360 V
Battery type	Lithium-ion battery
Cell type	Laminated type, pouch cells
Active cathode material	LMO (LiMn ₂ O ₄) with LNO (LiNiO ₂)
Active anode material	Graphite
Battery capacity	32.5 Ah
Nominal cell voltage	3.75 V
Battery modules	48
Cells per module	4
Energy density	157 Wh/kg
Battery weight	~180 kg
Battery price	7000 €
State of Charge (SoC)	68.0%

2.1.2. Nissan Leaf Vehicle Fire Test Setup

As shown in Figure 2, a fossil fuel burner was used to start the EV fire and cause the TR on the battery pack of the electric vehicle. When heat is generated faster than it can be dissipated to the environment, the temperature rises, especially in the presence of an external heat source (fossil fuel burner). The thermal discharge of the battery occurs once it reaches a critical temperature, particularly when the separator’s breakdown temperature threshold is exceeded.



Figure 2. Location of the thermal imaging camera and video camera in relation to the tested vehicle.

An infrared thermographic camera was placed in front of the vehicle to monitor the temperature reached by the vehicle at each instant of the test. A video camera was also placed in front of the vehicle to record the test. Thermocouples were not used on this occasion.

2.1.3. Nissan Leaf Vehicle Fire Test Procedure

In this test, the electric vehicle was set on fire with a fossil fuel burner placed on the bottom of the high-voltage battery. Once the fire had spread, the blanket was placed sequentially, and pressurized water (Figure 3) was used to extinguish the flames and continuously cool the battery.



Figure 3. Image showing spray pattern of the pressurized water.

Prior to this, a perforation was made in the battery casing to allow firefighters to direct the water jet to this location and greatly reduce the amount of water needed to control the fire (Fireman Access idea developed by the Renault Group and the French fire brigade).

The following Table 2 shows the characteristics of the fire suppression methods used.

Table 2. Parameters of fire extinguishing devices used.

Device	Parameters
Fire Blanket	Size: 6 m × 8 m (28 kg) Graphite + silicone coating
Pressurized water + orifice (Fireman Access, Renault idea)	Flow rate: 125 L/min and 45° cone (in attack–extinction phase) Distance: 10 m (in attack–extinction phase) Volume of water required: 400 L

2.2. Smart EQ ForFour Vehicle Fire Test

2.2.1. Electric Vehicle Used During the Tests (Smart EQ ForFour)

Secondly, the Zaragoza firefighter department carried out a supervised fire test involving a fully electric vehicle—a Smart EQ ForFour (Figure 4)—in which they analyzed temperature progression and battery behavior. Thermocouples were placed on the battery, and gas emissions were also characterized. Several methods were used to try to initiate thermal runaway, such as overcharging and heating one of the modules, but neither approach was successful. Therefore, thermal runaway was ultimately triggered by placing a fossil fuel burner beneath the high-voltage battery of the electric vehicle, following the same procedure as in the previous test.

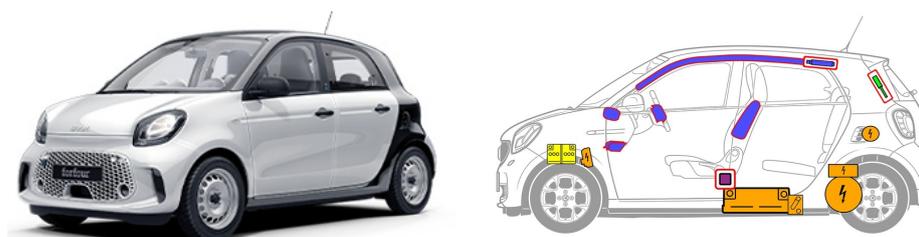


Figure 4. Electric vehicle Smart EQ ForFour used during the tests (left) and location of the high-voltage battery (right).

The duration of the test and the battery temperature were monitored throughout using a thermal imaging camera. Internal battery temperatures were measured with K-type thermocouples, and emitted gases were analyzed using standard Blackline Safety G7 portable multi-gas detectors. The G7 continuously measures ambient gas concentrations and triggers alerts when certain thresholds are exceeded, allowing operators to respond quickly and safely to changes in their environment.

Table 3 below presents the main specifications of the Smart EQ ForFour vehicle battery used in the fire test.

Table 3. Battery specifications of the burnt Smart EQ ForFour vehicle.

Vehicle	Electric Battery
Date of first registration	28 November 2019
Range	93 km (EPA test)/19.2 kWh/100 km
Weight	1560 kg
Battery specifications	
Energy it can supply	17.6 kWh
Battery voltage	400 V
Battery type	Lithium-ion battery
Cell type	LGX E51 Laminated type, pouch cells
Active cathode material	NMC/Lithium Nickel Manganese Cobalt
Active anode material	Graphite
Battery capacity	52 Ah
Nominal cell voltage	3.52 V
Battery modules	3
Cells per module	32 pouch cells
Energy density	189.27 Wh/kg
Battery weight	~169 kg
Battery price	12,324.10 €
State of Charge (SoC)	40.0%

2.2.2. Smart EQ ForFour Vehicle Fire Test Setup

To subject this vehicle’s battery to a failure that would lead to TR, a single-cell overcharge was first attempted with an external 30 V power source, but this failed, as the overload melted the connecting cables to the battery due to the incorrect cable cross-section. The setup prepared for overcharging the battery is detailed below (Figure 5).

An attempt was also made to thermally isolate a cell in one of the modules using a diesel engine heater that can heat up to 400 °C (Figure 6), but this also failed because the heater’s exposure time was insufficient. It melted the plastic casing, but did not short-circuit the cell.

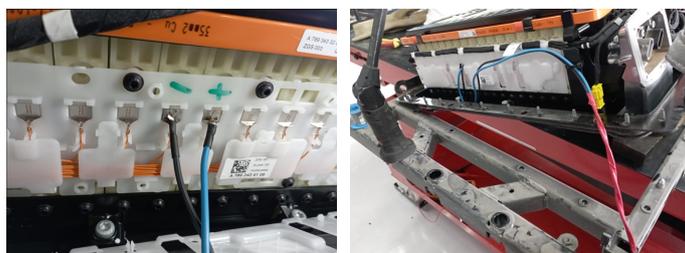


Figure 5. Setup to overcharge the Smart EQ ForFour vehicle battery with an external 30 V power supply.



Figure 6. Image of the diesel engine heater used (left) and detail of the area where the heater was placed on the battery (right).

As shown in Figure 7, a fossil fuel burner placed on the underside of the Smart EQ ForFour vehicle was ultimately used to start the EV fire and cause the TR on the vehicle's battery pack. If the heat generation rate exceeds the heat dissipation rate to the environment, the temperature will increase due to the presence of an external heat source (fossil fuel burner). The battery undergoes thermal discharge when a critical temperature is reached, particularly when the separator rupture temperature is reached.



Figure 7. Location of the fossil fuel burner placed on the underside of the Smart EQ ForFour vehicle to start the fire.

In the image above, you can see how the firefighters placed the fossil fuel burner well in front of the battery, which, as can be seen in Figure 4, is located under the rear seats. A FLIR T640 infrared thermal imaging camera was placed in front of the vehicle to monitor the temperature reached by the vehicle at every moment of the test. A video camera was also placed to record the test, and on this occasion, type K thermocouples (AISI 310 Type K Thermocouple with Stainless Steel Sheath), which withstand temperatures of up to 1100 °C at a time and 1050 °C at a sustained temperature, were placed inside the battery to measure the temperature in different modules. The orange one (T_1) was placed on the right side, the red one (T_2) was placed on the left side, and the green thermocouple (T_3) was placed on the battery casing to measure the temperature. Blackline Safety G7 portable multi-gas detectors were also installed. To measure the temperature at different points on the battery, in addition to K-type thermocouples, a Keysight 970 A datalogger is used to measure, record, and store the temperature values. A connection panel is used to connect the thermocouples to the datalogger for measurement purposes.

Below are several images (Figure 8) of the fire test setup carried out for the Smart EQ ForFour vehicle.



Figure 8. Location of the portable detectors around the vehicle (gas detection), the external charging source, and the Keysight 970 A Datalogger temperature measuring equipment, relative to the vehicle being tested (left). Details of the thermocouple connection panel (right).

To install the heater, wiring, and thermocouples, the vehicle’s battery must first be removed, instrumented, and then reassembled, always following the manufacturer’s instructions. Below are various images of the battery removal and reassembly process (Figure 9).



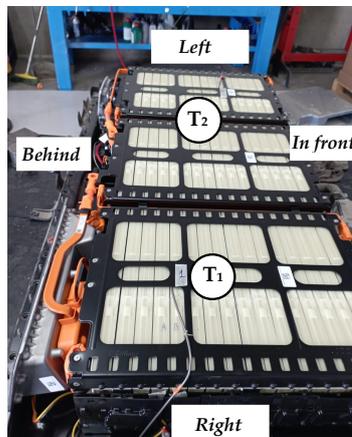
High-voltage battery of the Smart EQ ForFour vehicle removed for instrumentation.



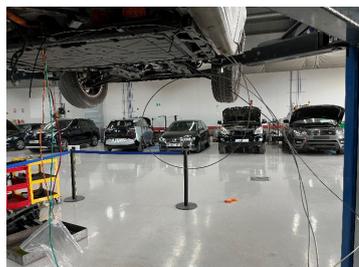
Wiring placement on the + and – poles to perform overload with an external power supply.



Placing a heater in a cell to cause thermal failure of the cell.



Battery orientation according to the direction of travel of the vehicle (thermocouple arrangement is observed).



Battery mounted on the vehicle after instrumentation; the different wiring and thermocouples can be seen.



Detail of the wiring placed in the battery to perform the different measurements.

Figure 9. Images explaining the disassembly, instrumentation, and assembly of the battery, carried out before the fire test.

2.2.3. Smart EQ ForFour Vehicle Fire Test Procedure

In this test, after other procedures that triggered the thermal runaway failed, the electric vehicle caught fire, with a fossil fuel burner placed under the high-voltage battery of the Smart EQ ForFour electric vehicle. Once the fire had spread, a single-use fire blanket was placed over the fire blanket—that is, the professional blanket was not used—and secured with a wire rope and a hose to prevent it from rising.

Temperature measurements continued with thermocouples and a thermal imaging camera until the afternoon. After that, measurements were taken only with the handheld thermal imaging camera until 24 h had passed since the test. The objective was to verify the performance of the fire blanket and the recorded temperature.

The following Table 4 shows the characteristics of the fire suppression methods used.

Table 4. Parameters of the fire extinguishing devices used in the Smart EQ ForFour vehicle fire test.

Device	Parameters
Fire Blanket	Size: 6 m × 8 m (28 kg) Pyroxene + silicone coating

3. Results

3.1. Nissan Leaf Electric Vehicle Fire Test Results

3.1.1. Combustion Behavior of an Electric Vehicle Fire Process

The test began, and the vehicle's temperature increased steadily as the combustion process progressed. Three minutes into the test, the battery pack reached a temperature close to 805 °C. This temperature corresponds to the external surface temperature of the battery pack. It was not until approximately eight minutes into the test that small explosions began to be heard from the vehicle's airbag gas generators, followed by the sound of the TR phenomenon, in which the battery cells entered an uncontrollable state of self-heating.

Batteries are made up of numerous individual cells that together form a battery pack capable of supplying the voltage and power required by vehicles. During an overheating process, a phenomenon called thermal runaway can occur. When this happens, after one of these cells overheats and explodes, a chain reaction occurs that spreads the fire from one cell to another in the battery. This phenomenon can only be stopped by directly cooling the battery cells with large amounts of water. However, this cannot be carried out in most vehicles because the battery is housed and protected by a thick steel sheet beneath the vehicle floor. Furthermore, the leachate produced, and the mixture of water vapor with battery acids, are highly harmful and dangerous. For this reason, in some cases, firefighters have opted to let the battery fire extinguish itself. However, this process can take up to 24 h.

The fire was initially suppressed using a fire blanket (Figure 10). Slightly over ten minutes after the test began, temperatures in the battery area surpassed 1000 °C. At that point, firefighters deployed the fire blanket over the vehicle. Immediately following its application, the vehicle's surface temperature decreased sharply, from approximately 850 °C to around 350 °C. From that moment onward, the blanket acted as a thermal insulator, shielding the vehicle from fire-induced radiation, preventing the release of hazardous substances into the environment, and contributing to the vehicle's cooling. In addition, the blanket restricted the oxygen supply, extinguishing the fire once the remaining oxygen trapped beneath it was depleted. The fire blanket reduces oxygen availability and external combustion, but does not stop thermal runaway within the battery pack. However, by significantly lowering the temperature and cutting off oxygen, the blanket slows down heat propagation and contributes to eventual containment.



Figure 10. Zaragoza City Council firefighters covering the burning vehicle with a fire blanket.

As time progressed, thermal imaging data (Figure 11) indicated a decrease in temperature to approximately 100 °C. Nevertheless, electric vehicle fires pose a significant risk of re-ignition, as the battery continues to generate the three fundamental components of the fire triangle: heat, fuel, and oxygen.



Figure 11. Thermal imaging camera image to record and document the vehicle's temperature during the test.

When the vehicle is covered with a fire blanket, the risk of re-ignition is effectively eliminated, as the battery temperature gradually decreases over time. In contrast, if the vehicle remains uncovered, the likelihood of re-ignition remains high. To illustrate this behavior, the fire blanket was removed 9 min after the full coverage of the vehicle. Immediately upon removal, flames were observed re-igniting in the battery area and rapidly propagating throughout the vehicle once again (Figure 12).



Figure 12. Frames of the moment when the fire restarts after the vehicle is discovered.

As the test continued, the fire continued to rise in temperature over the next two and a half minutes, reaching a maximum temperature of approximately 600 °C. Once this temperature was reached, the vehicle was again covered with the fire blanket to isolate and extinguish the fire, as the blanket is reusable. The condition of the battery pack (Figure 13a) and a detailed view of the battery modules (Figure 13b) before the fire test are shown below.

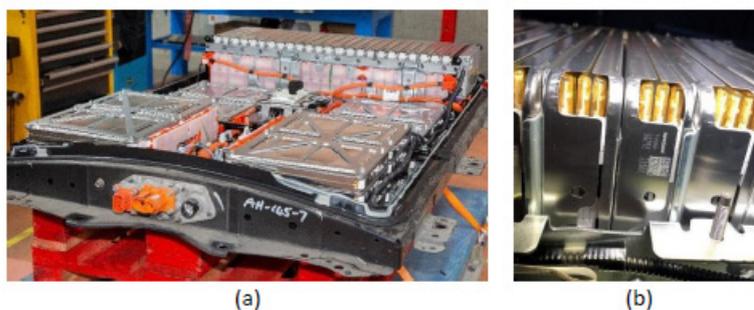


Figure 13. (a) Battery pack before fire testing. (b) Detail of a battery module constructed with a 4-cell configuration.

To conclude the test, once the fire blanket was removed, the battery was cooled with water and the vehicle was quarantined to ensure that the fire did not restart. Due to the risk of fire in electric vehicles after a major accident, or the risk of a fire restarting after it has been extinguished, a 48 h quarantine period must be observed in these cases. The vehicle must be parked in a location where there is no risk to people or the surrounding environment and must remain unused for at least 48 h. Currently, vehicles must remain quarantined in locations far removed from population centers, making it unfeasible for workshops or assistance services. The blanket is a very effective solution in these cases, as it allows the vehicle to be easily isolated without the need for a dedicated area. It would be a good containment method.

Below are images of the Nissan Leaf vehicle (Figure 14), with first responders applying water to cool the battery and prevent the fire from restarting.



Figure 14. Images of the first responders extinguishing the fire with water and cooling the battery to prevent the blaze from re-igniting.

The following images (Figure 15) show the condition of the vehicle after the fire test.



Figure 15. Images of the final state of the Nissan Leaf vehicle after the fire test.

The fire test specifications are detailed in the following Table 5.

Table 5. Controlled fire test specifications performed on the Nissan Leaf vehicle.

Vehicle	Electric Battery
Fire test specifications	
Vehicle	Vehicle with high-voltage battery
Fire	Ignition burners (fossil fuel)
Method of extinguishing the fire	Fire blanket for vehicles
Temperature monitoring	Infrared thermal imaging camera FLIR T640
Infrared thermal imaging camera	
Distance	13.7 m
Ambient temperature	7.1 °C
Average wind speed	2.5 m/s
Maximum wind speed	8.9 m/s
Maximum temperature reached	~1.000 °C
Start time of thermal runaway	~8 min
After removal of fire blanket	157 Wh/kg
Amount of water required to extinguish the fire	400 L

Figure 16 presents a sequence of images from the electric vehicle fire test described above. The elapsed time, in minutes, from ignition onset is indicated in the top-left corner of each image. Approximately 7 min into the test (second image, top right), the battery pack reached a temperature nearing 960 °C. Around the 8 min mark, minor explosions from the airbag gas generators were first detected, shortly followed by the onset of thermal runaway in the battery cells (fourth image). The initial temperature range associated with the thermal event was between 80 °C and 150 °C.

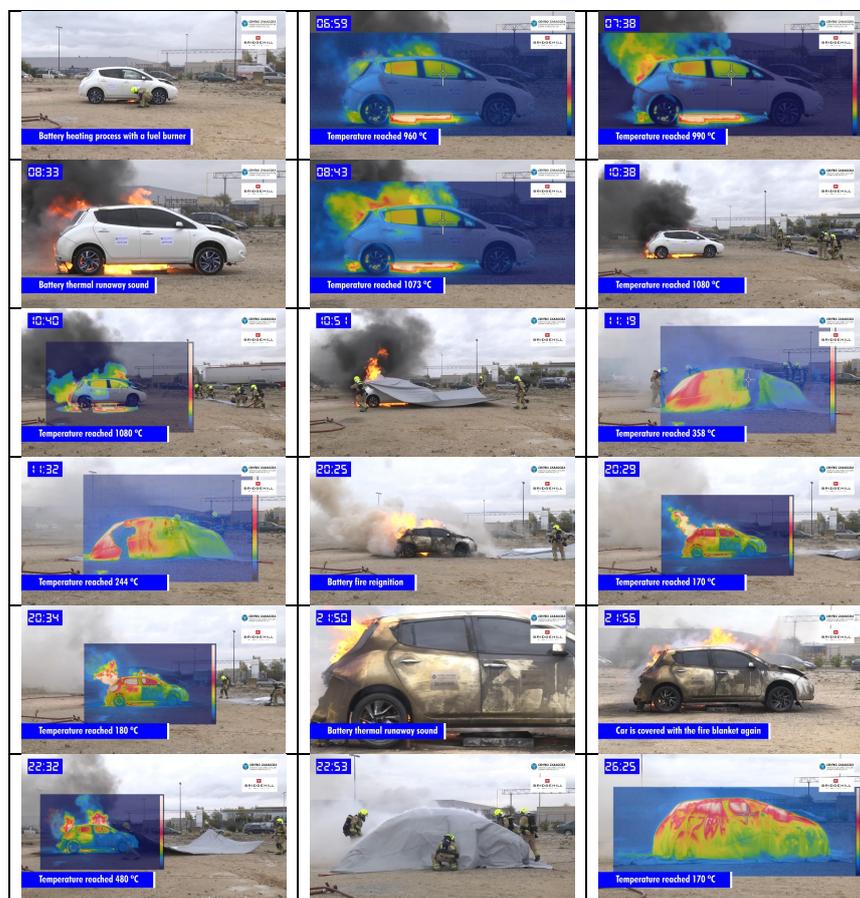


Figure 16. Images of the controlled fire test performed on the Nissan Leaf vehicle under study.

As in previous studies, the TR ignition phase of a battery pack produces white smoke, hot sparks, and jet flames [38]. The vehicle can be divided into four sections: the battery pack, the engine compartment, the trunk, and the passenger compartment (Figure 17). The passenger compartment is highly flammable. The fire spread through the chassis and body after the battery pack caught fire. Following the appearance of a three-jet flame, unrecorded due to its position at the rear, a localized flame developed near the left rear wheel. Hot smoke infiltrated the passenger compartment through the rear seat cavity and door gaps. The fire subsequently advanced from the left rear wheel to the trunk, ultimately consuming the rear section of the vehicle. Since the windows remained closed during the test, a marked temperature increase was observed inside the cabin. During this phase, the maximum external surface temperature recorded was approximately 150 °C. In the early stages of an electric vehicle fire, combustion generally has a limited effect on the cabin and surrounding areas; however, jet flames represent a significant hazard that warrants close attention.



Figure 17. Flame and smoke propagation (red arrows) (at the beginning of the Nissan Leaf vehicle fire test).

3.1.2. Jet Flares (Nissan Leaf Fire Test)

According to estimates, approximately 50% of jet fires can trigger at least one secondary event that worsens the overall incident [28,29]. The height of the jet flame was determined through image processing, using the vehicle's height as a reference scale. A total of four jet flares were identified prior to the deployment of the fire blanket. Unfortunately, the jet flame temperature could not be obtained because a thermocouple was not fitted; for future tests, thermocouples will be available to measure this temperature. The maximum jet flame length observed prior to deploying the fire blanket (2.564 m) was consistent with the findings reported by Cui et al. [22]. When treating the jet as a turbulent gas flame, its length remains largely unaffected by variations in the fuel flow rate. Instead, the flame length is primarily influenced by the fuel's properties and the nozzle diameter [30].

Next, the flame height is analyzed at several instants during the test, showing the time elapsed since the start of the fire (Figure 18).

There are two main sources of heat that contribute to the peak fire of an electric vehicle. The heat released via thermal runaway from the battery and combustible gases burning in the trunk and chassis of the vehicle constitute one source of the heat. The other part is due to the burning of materials inside the passenger compartment; this process produces flammable gases that leak through door gaps and result in a flame plume emerging from the vehicle's roof (see Figure 19). Fumes from the battery can enter the passenger compartment through the hole made in the casing, or if the top plate of the battery casing is burned.

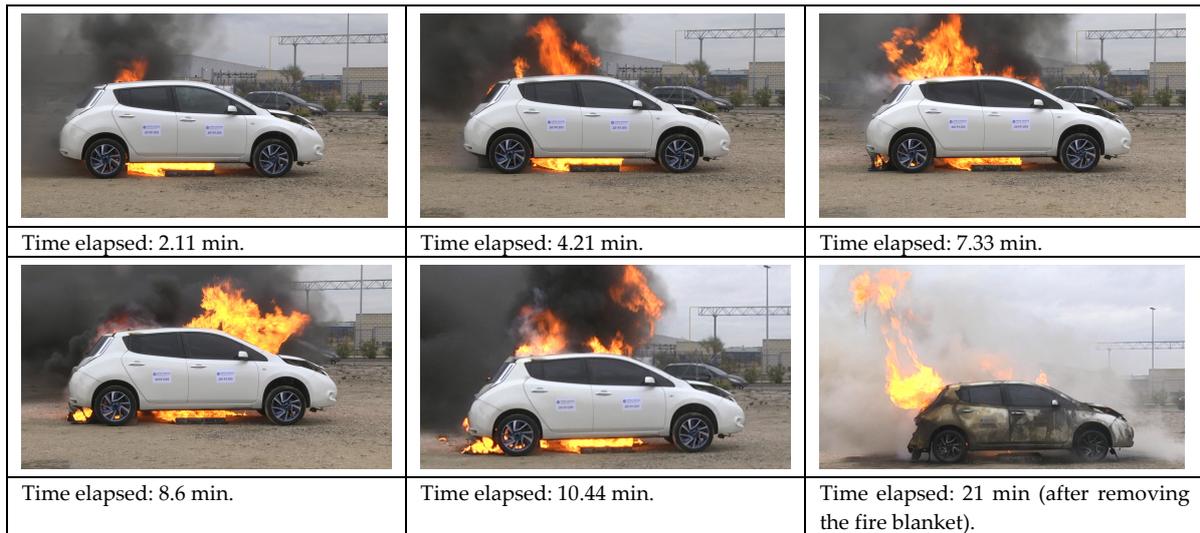


Figure 18. Flame height for various instants of the fire test.

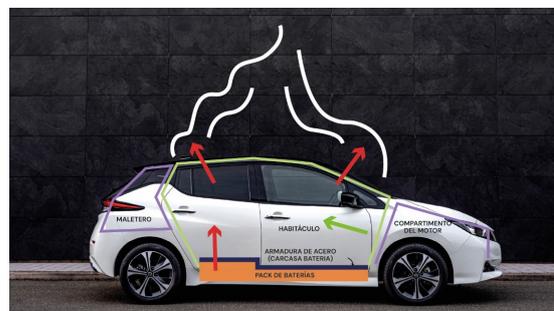


Figure 19. Smoke and flame propagation (red arrows and white lines) (at the end of the Nissan Leaf vehicle fire test before putting on the fire blanket).

The height of the fire column was measured using an image processing tool, taking the height of the car as a reference (see Figure 20). The maximum height observed was 2.7 m above the ground (Figure 21). According to Heskestad’s empirical formula [39], the flame heat release rate can be estimated from the flame height. The habitat was assumed to be a square fire source with a 1.7 m side. The flame heat release rate was estimated to be 1.55 MW.



Figure 20. Image of an instant of the fire test in which the height of the flame is measured (time elapsed 7.33 min).



Figure 21. Image of an instant of the fire test in which the flame height is at its maximum (2.7 m) (time elapsed 10.06 min).

Heskestad’s formula [40] (Equation (1)) for calculating the heat release rate is as follows:

$$L = 0.235Q^{2/5} - 1.02D \tag{1}$$

where

L is the flame height (m);

Q is the heat release rate (kW);

D is the equivalent diameter of the fire (m).

When considering a square fire source, D is equal to the diameter of the fire, therefore it is equal to the side of the square, i.e., D is equal to 1.7 m.

This formula is valid for circular free fires; in this case it approximates a circle. From the above formula (Equation (1)), Q is cleared to obtain the heat release rate from the flame height (Equation (2)).

$$Q = \left(\frac{L + 1.02D}{0.235} \right)^{5/2} \tag{2}$$

Below are images of the moments in the fire test when the flame is highest. In Figure 20, the height of the flame is 2.5 m (time elapsed 7.33 min), while in Figure 21, the height of the flame is the maximum it reaches, which is 2.7 m (time elapsed 10.06 min).

Once the fire blanket has been removed after its placement, the fire is reactivated almost immediately and the flame height is observed to be greater (3.6 m) than at the instant of the fire test when it reaches the maximum height (time elapsed 31 min), as shown in Figure 22. Using Heskestad’s formula, we obtain that the heat release rate at this instant is 2.45 MW, 1.58 times more than the heat release rate before putting the fire blanket on.



Figure 22. Image of the moment when the fire blanket is removed, and the flame reaches a greater height (3.6 m) (time elapsed 21 min).

3.1.3. Use of Fire Blanket in Nissan Leaf Fire Test

A fire blanket works as a protective film that prevents the spread of combustion to surrounding combustibles. In most cases, preventing the supply of air, i.e., oxygen, can prevent the spread of combustion. But avoiding oxygen supply cannot extinguish the chemical reactions of lithium-ion batteries. Therefore, fire blankets can isolate electric vehicles from the outside world and prevent fire from spreading. The efficacy of fire blankets has been validated through vehicle fire tests carried out by multiple manufacturers [41]. The fire blanket immediately isolates toxic gases and smoke, reducing exposure to these gases. It quickly blocks the fire and prevents its spread.

The blanket used during the test is a professional use blanket—it has dimensions of 6 × 8 m and is reusable for about 30 vehicles on fire, depending on the virulence and wear, in any vehicle. It weighs about 28 kg. The material is graphite 340 gsm (grams per square meter) coated with a silicone polymer (160 gsm). It is intended for personnel who must extinguish fires on a more recurrent basis, such as firefighters or emergency personnel. There is also another model, which has the same dimensions, but is for single use only and is intended for workshops, shopping center parking lots, and preventive use in quarantine vehicles, etc. There is a very large potential market for this product. Potential customers who can benefit range from professional fire departments, rescue services, roadside assistance, and in parking lots, tunnels, and places where there is a high accumulation of vehicles, to repair shops that are exposed to many risks when handling damaged vehicles.

In the current test, a fire blanket was placed only 10 min after the start of the test (see Figure 16). Upon placement of the fire blanket, the temperature outside the vehicle immediately dropped to near ambient levels as the flames were effectively extinguished by the fire blanket. After covering the fire blanket, the temperature inside the vehicle did not suddenly increase, because the fire blanket did not change the hot smoke output from inside the vehicle because it was no longer coming out initially due to the windows being rolled up. If the windows had been down during the test, this increase in temperature inside the passenger compartment would have been noticeable, as the smoke would not have escaped through the windows when the fire blanket was placed. Immediately after covering the vehicle with the blanket, the surface temperature of the vehicle decreased from approximately 850 °C to around 350 °C. From that point forward, the fire blanket acted as a thermal barrier, shielding the vehicle from fire-induced radiation, limiting the release of hazardous materials into the environment, and simultaneously contributing to the cooling of the vehicle. It was observed (Figure 23) that the temperature in the trunk area was higher than in the passenger compartment. This phenomenon was observed in a previous study [29]. The presence of a well-defined thermal stratification indicates the absence of turbulent combustion inside the vehicle.

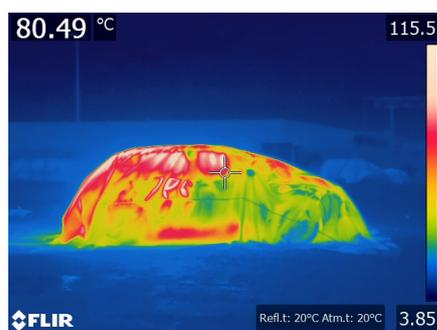


Figure 23. Image showing that the temperature in the trunk area is higher than in the passenger compartment area.

When the fire blanket was removed, the temperature inside the vehicle did not drop, because the smoke was still hot inside and could not dissipate due to the windows being up (Figure 24). The fire in the electric vehicle quickly rekindled after the flammable gas and air mixed and the temperature rose rapidly. The asterisk * in the image on the right indicates that the value shown corresponds to an active measurement point.

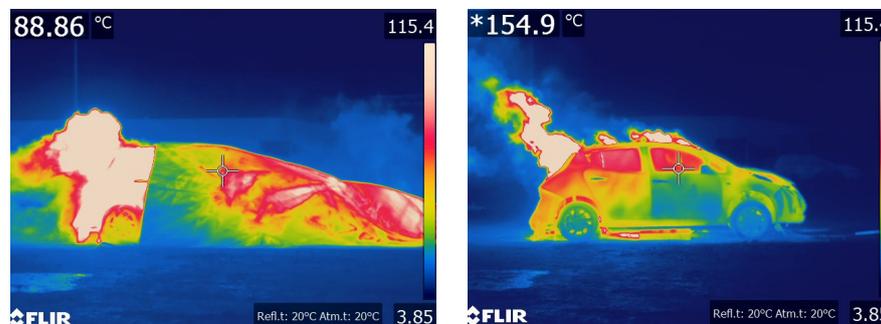


Figure 24. Images of the moment when the fire blanket is removed (left) and the immediate moment when the fire blanket is removed (right).

The white smoke coming from the battery is believed to be electrolyte vapor, $CxHy$, CO , and H_2 . A previous study identified the explosion limits of gases released during thermal runaway in batteries [39]. Over time, these gases gradually dissipate and become barely visible. Upon removal of the fire blanket, a substantial release of white smoke was observed. After approximately 40 s, re-ignition occurred, accompanied by a shift in smoke color from white to dark gray (Figure 25). This clearly indicates that the combustion and flame intensity were significantly greater than prior to the deployment of the fire blanket. Consequently, the associated heat release rate increased accordingly, reaching a peak value of 2.45 MW.



Figure 25. Smoke evolution after removing the fire blanket and reactivation of the Nissan Leaf electric vehicle fire.

3.1.4. Water and Fireman Access Idea

The result of close collaboration between the Renault Group and the French fire department, Fireman Access, is an exclusive innovation that enables emergency services to extinguish a fire in an electric vehicle in practically the same time as in a combustion vehicle. It consists of an opening in the housing of the traction battery that is covered with a thermofusible material, effectively sealing it to its standard. If the vehicle catches fire and the flames spread to the battery, the first thing to melt is this hot-melt cap; the firemen know this and thanks to the rescue sheets they know its location. They direct the powerful jet of

the water hose to that hole and in this way, a battery fire can be extinguished in just a few minutes, thanks to controlling the TR of the battery because it is cooled directly, compared to several hours and much more water needed to extinguish a fire of an electric vehicle that does not have this development.

Using this idea from Renault and the French fire department, a hole was drilled in the battery casing of the Nissan Leaf vehicle to prove that a smaller volume of water and less time is needed to extinguish this fire (Figure 26).

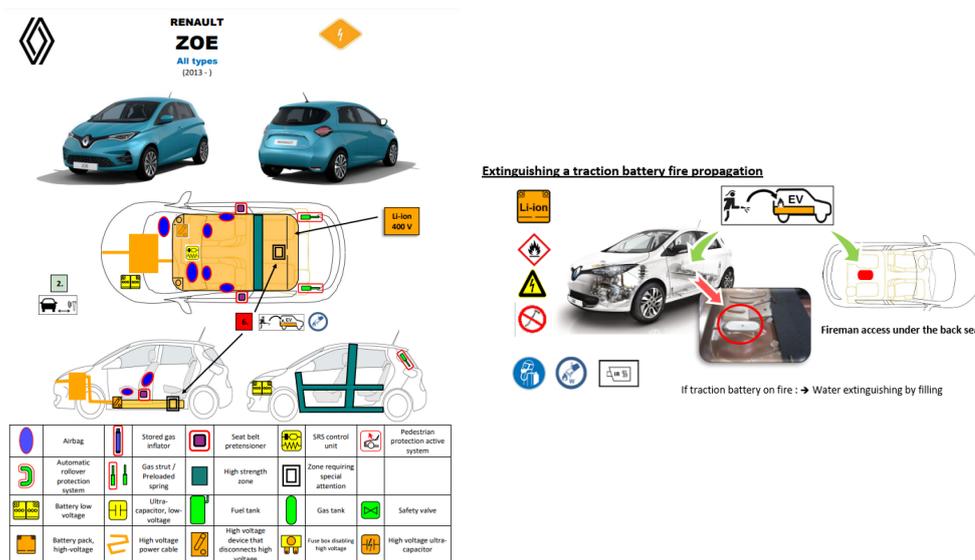


Figure 26. Explanation of the location of Fireman Access in the Renault Zoe (Rescue Sheet).

Below is the hole (Figure 27) made in the battery casing of the Nissan Leaf vehicle tested.

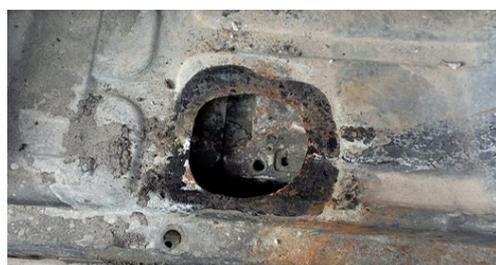


Figure 27. Hole made in the battery casing of the burned Nissan Leaf vehicle (image taken after the fire test).

In the test, water was used to smother the fire once it was reactivated after the fire blanket was removed. At this stage, the dense black smoke began to mix with the white vapor, resulting in a lighter-colored smoke (see Figure 28). Under the kinetic energy of the pressurized water, the inclination of the fire flow changed, and a “flare” of a duration of several seconds was produced at the instant of first contact with the water. The pressurized water increased the concentration of OH- radicals within the flame zone, thereby intensifying the combustion reaction [42]. Subsequently, the cooling effect of the water was then put into action until the fire was extinguished. In this test, the battery pack was configured with a higher density of cells in the rear section, where thermal runaway originated. Therefore, the rear of the vehicle had a stronger fire in the early stages of fire development. The fire initially spread to the rear due to natural winds.



Figure 28. Images of the Nissan Leaf vehicle fire smothered with pressurized water and Renault's Fireman Access idea.

3.2. Smart EQ ForFour Electric Vehicle Fire Test Results

3.2.1. Combustion Behavior of the Fire Process of a Smart EQ ForFour Electric Vehicle

The test began (it was very windy on the day of the test), and the vehicle's temperature increased steadily as the combustion process progressed, but it was not as high as in the Nissan Leaf test. One minute after the fire started, a plastic cover located on the lower front of the Smart EQ ForFour vehicle was seen melting (Figure 29).



Figure 29. Instant of the Smart EQ ForFour vehicle fire test 1 min after the start of the fire.

One and a half minutes after the start of the test, a gas leak was heard, and a jet of flame was observed. This could be due to some component that uses gas: shock absorbers, pretensioners, or airbags, etc. One minute and 44 s after the start of the test, a gas leak was heard again and a jet of flame was observed at the rear, which could be attributed to small explosions from the vehicle's gas generators (airbags, pretensioners, etc.). At 2 min and 49 s, the explosion of the left rear tire was heard, and at 3 min and 5 s, the explosion of the right rear tire. Shortly after, explosions were heard, which the firefighters determined were explosions that may have come from the battery, and they placed the blanket 6 min after the start of the fire, placing a hose over the blanket to prevent the fire blanket from moving due to the wind.

The fire was extinguished with a fire blanket (Figure 30). Just over 6 min after the start of the test (in the previous test, the vehicle was covered after just over 10 min), the firefighters proceeded to cover the vehicle with the fire blanket. Immediately after covering the vehicle with the blanket, the temperature of the vehicle's surface dropped

to approximately 200 °C (Figure 31). From that moment on, the blanket insulated the vehicle from the radiation emitted by the fire, preventing any elements from spreading into the environment and, at the same time, cooling the vehicle. Furthermore, the blanket prevented the supply of oxygen, thus preventing the fire from continuing when all the oxygen confined under the blanket is consumed.



Figure 30. Zaragoza firefighters covering the burning Smart EQ ForFour vehicle with a fire blanket.

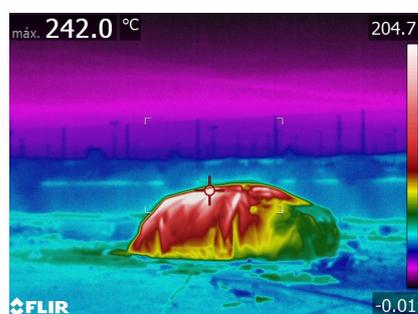


Figure 31. Image of the surface temperature of the Smart EQ ForFour vehicle immediately after the fire blanket was placed.

Over time, thermal imaging revealed a gradual decrease in the surface temperature to approximately 100 °C. Despite this decline, electric vehicle fires pose a significant risk of re-ignition, as the battery continues to generate the three essential components of the fire triangle: heat, fuel, and oxygen. When the vehicle is covered with a fire blanket, this risk is mitigated, as the battery temperature will eventually fall. In contrast, if the vehicle remains uncovered, the likelihood of re-ignition remains high. For this reason, the fire blanket is not removed and replaced in this test because it is a single-use blanket; once in place, it is left on the vehicle until the following day. Since the battery will be dismantled after the test to determine the severity of the damage, the condition of the battery pack (Figure 32a) and a detailed view of the battery modules (Figure 32b) before the fire test are shown below, allowing for conclusions to be drawn after the test.

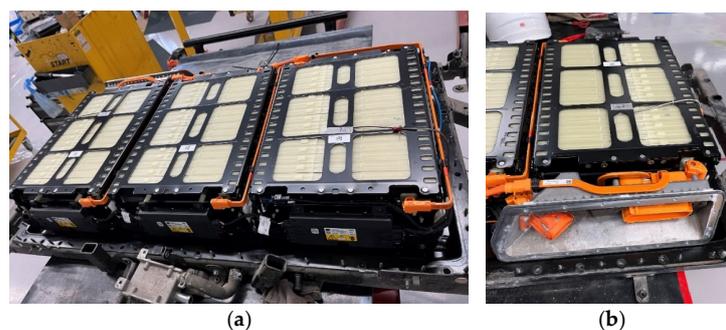


Figure 32. (a) Smart EQ ForFour vehicle battery pack before the fire test. (b) Details of a module of this battery built with a 32-cell configuration.

Due to the risk of fire in electric vehicles after a major accident, or the risk of a fire restarting after it has been extinguished, a 48 h quarantine period must be carried out in these cases. The vehicle must be parked in a location where there is no risk to people or the surrounding environment and must remain unused for at least 48 h. Currently, vehicles must remain quarantined in locations far removed from population centers, making it unfeasible for workshops or assistance services. The fire blanket is a very effective solution in these cases, as it allows the vehicle to be easily isolated without the need for a specific area for this purpose; it would be a good containment method. This test aims to demonstrate that this containment method is useful for the quarantine period.

Below are images of the Smart EQ ForFour vehicle after the fire blanket was applied to control the fire (Figure 33).



Figure 33. Images of the first responders placing the fire blanket during the vehicle’s fire test.

The following images show the state of the vehicle after the fire test (Figure 34).



Figure 34. Images of the final state of the Smart EQ ForFour vehicle after the fire test.

In the images above (Figure 34), you can check the final state of the Smart EQ ForFour vehicle and see that in the front part there is no cover, since it has melted due to being made of plastic, as verified in the fire test. On the other hand, in the lower part of the battery, there is a melted area of the metal cover, but the fire has not perforated it completely.

The following table (Table 6) details the fire test specifications, and the wind speed was higher than the wind speed in the previous fire test carried out with the Nissan Leaf vehicle.

Table 6. Controlled fire test specifications performed on the Smart EQ ForFour vehicle.

Vehicle	Electric Battery
Test specifications	
Fire	Ignition burners (fossil fuel)
Method of extinguishing the fire	Fire blanket for vehicles
Temperature monitoring	Infrared thermal imaging camera: FLIR T640
Distance of infrared thermal imaging camera	10 m
Ambient temperature	20 °C
Average wind speed	7.8 m/s
Maximum wind speed	18.9 m/s
Maximum temperature reached	~800 °C
Start time of thermal runaway	~6 min (estimated)

During the fire test of the Smart EQ ForFour vehicle, no temperatures were recorded because a correct temperature range was not established in the thermographic camera, so the temperature recorded was out of range and incorrect, which does not allow us to obtain quantitative conclusions regarding the temperature during the fire test. Once the problem was detected, it was corrected, but it was already at the time of placing the fire blanket, so there is a correct temperature record for once the fire blanket was placed.

Following ignition via the fossil fuel burner, the fire propagated through the vehicle’s chassis and body. Although the initial two-jet flame was not captured due to its position at the rear, flames were subsequently observed developing around the left rear wheel. Hot smoke infiltrated the passenger compartment via the rear seat cavity and door gaps (Figure 35). The fire progressed from the rear wheel area to the trunk, ultimately engulfing the rear section of the vehicle. In this test, with the windows kept closed, a pronounced temperature rise occurred inside the cabin. During this phase, the maximum exterior surface temperature recorded was approximately 120 °C. In the early stages of an electric vehicle fire, combustion dynamics tend to have minimal influence on the interior and immediate surroundings. Nonetheless, jet flames present a significant hazard and warrant particular attention. In this test, it is also necessary to consider the influence of the wind speed that caused the flame to go towards the rear of the vehicle, making it difficult to heat the battery directly by means of the fossil fuel burner.



Figure 35. Flame and smoke propagation (red arrows) (at the beginning of the fire test) in the case of the Smart EQ For Four vehicle.

3.2.2. Jet Flares (Smart EQ ForFour Fire Test)

Below are images of different moments of the Smart EQ ForFour electric vehicle fire (Figure 36), to analyze the height of the flame at various moments of the test and identify the highest flame.



Figure 36. Flame height at various times during the fire test (Smart EQ ForFour).

Two primary heat sources contribute to the peak intensity of an electric vehicle fire. One is the thermal energy released during battery thermal runaway, along with the combustion of flammable gases generated in the vehicle’s trunk and chassis. The other part is due to the burning of materials inside the passenger compartment, which generates flammable gases that escape through cracks in the doors and cause a fire column on the roof of the vehicle (see Figure 37).



Figure 37. Smoke and flame propagation (red arrows and white lines) (at the end of the fire test before putting on the fire blanket) in the case of the Smart EQ ForFour vehicle.

The height of the fire column was measured using an image processing tool taking the height of the car as a reference (see Figure 38). The maximum height observed was 2.5 m above the ground (Figure 39). Based on Heskestad’s empirical correlation [40], the heat release rate of the flame can be inferred from its height. For this scenario, the passenger compartment—given the vehicle’s smaller size—was modeled as a square fire source with a side length of 1.5 m. When considering a square fire source, D is equal to the diameter of the fire; therefore, it is equal to the side of the square, i.e., D is equal to 1.5 m. Using this assumption, the flame’s heat release rate was estimated at approximately 1.22 MW.

Below are images of the moments in the fire test when the flame is highest. In Figure 38, the height of the flame is 2.3 m (time elapsed 3.24 min), while in Figure 39, the height of the flame is the maximum it reaches, which is 2.5 m (time elapsed 6.01 min).



Figure 38. Image of an instant of the fire test of the Smart EQ ForFour vehicle in which the height of the flame is measured (time elapsed 3.24 min).



Figure 39. Image of an instant of the fire test of the Smart EQ ForFour vehicle in which the height of the flame is at its maximum (2.5 m) (time elapsed 6.01 min).

If we compare the maximum flame height reached in the fire test of the Smart EQ ForFour vehicle (2.5 m) with the maximum flame height reached in the fire test of the Nissan Leaf vehicle (2.7 m), it is observed that the flame is higher in the case of the Nissan Leaf fire and, consequently, that the heat release rate of the flame is higher in the case of the Nissan leaf vehicle fire (1.55 MW) than in the case of the Smart EQ ForFour vehicle fire (1.22 MW). It should be noted that the energy that can be supplied by the Nissan Leaf battery (24 kWh) is higher than the energy that can be supplied by the Smart EQ ForFour battery (17.6 kWh). Moreover, the SoC of the Nissan Leaf battery at the time of the fire test was 68%, while the SoC of the Smart EQ ForFour battery was 50%. Therefore, the result obtained is as expected.

3.2.3. Data Recorded Using the Gas Detectors

As indicated above, two gas detectors were placed during the fire test of the Smart EQ ForFour vehicle; images are shown below (Figure 40) to indicate the position of each of these detectors.

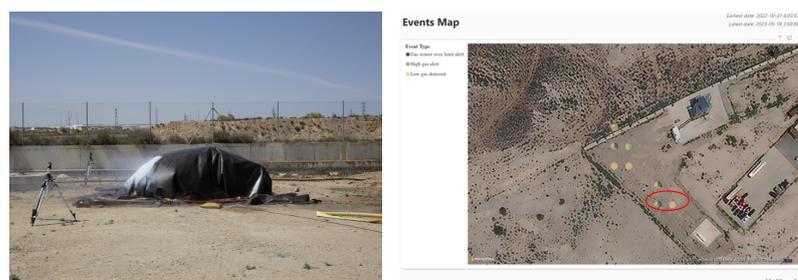


Figure 40. Image of the location of the gas detectors during the fire test of the Smart EQ ForFour vehicle (left) and image of the location of the gas detectors (red circle) according to their geolocation provided by the output data post-processing program (outputs).

Below is an image of a standard Blackline Safety portable multi-gas G7 detector (Figure 41) used for the measurement of gases emitted during the fire test.



Figure 41. Detailed image of a standard portable G7 multi-gas detector from Blackline Safety, used to measure the gases emitted during the fire test.

Once the location and designation of the gas detectors used during the test have been analyzed, it is concluded that the detector located at the right rear is the unit 3570205973, and that the one located at the left rear is the unit 3570205979.

Once the detectors have been identified, the alerts and gases detected will be analyzed according to the detector (Figure 42).

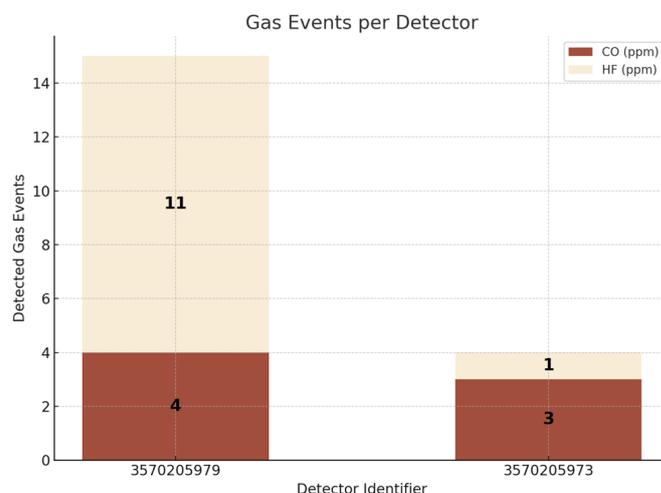


Figure 42. Detected gases (ppm) as a function of the detector during the fire test of the Smart EQ ForFour vehicle.

The previous figure shows that the detector located in the rear left zone (unit 3570205979) is the one that detects the highest amount of gas, but detects both hydrofluoric acid (HF) and carbon monoxide (CO).

On the other hand, Figure 43 shows the number of events per detector according to the type of event, and it is concluded that only the detector located at the rear left (unit 3570205979) presents alerts for elevated gas (3 events) and for exceeding the limit (3 events).

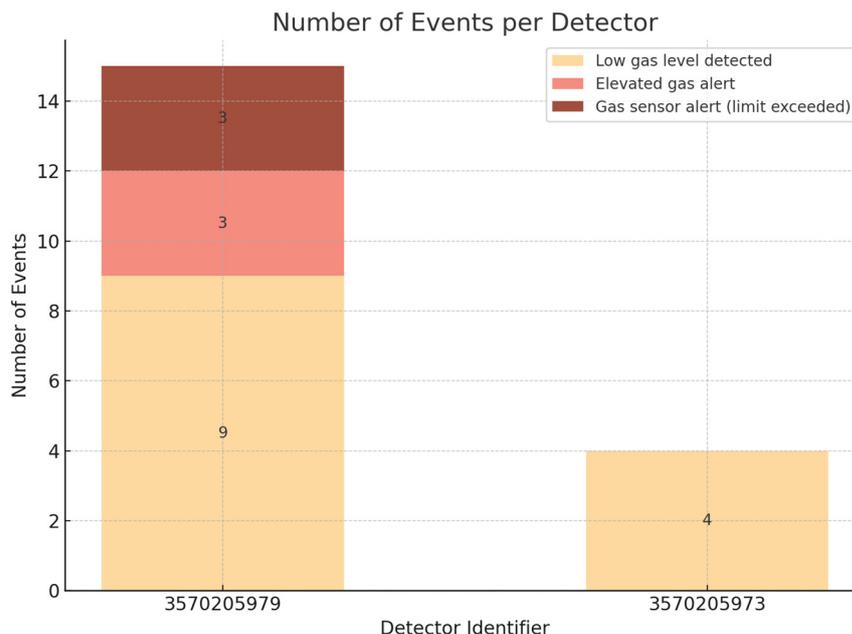


Figure 43. Number of events detected depending on the detector and type of event during the fire test of the Smart EQ ForFour vehicle.

The following graph (Figure 44) shows the events by type of gas recorded; therefore, considering the graphs shown in Figures 42 and 43, it can be concluded that the three events detected by the detector located at the back left, because they exceed the established limits, correspond to hydrofluoric acid.

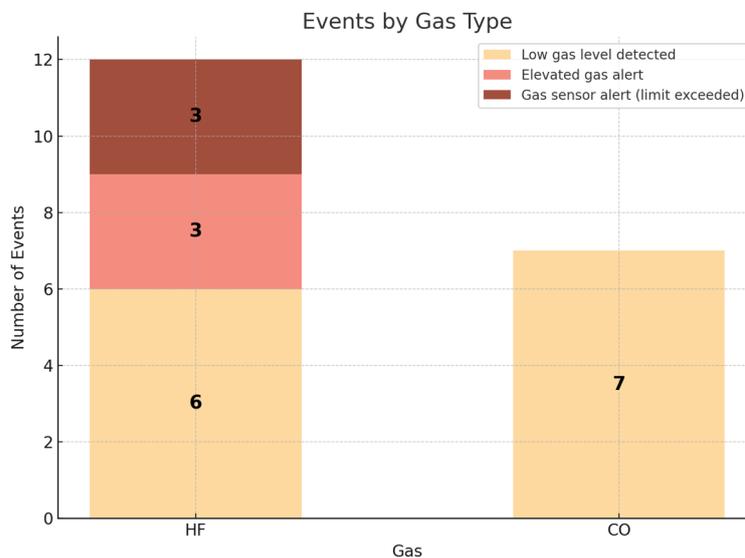


Figure 44. Events detected depending on the type of gas during the fire test carried out with the Smart EQ ForFour vehicle.

If we consider that ppm is equivalent to mg/L, we can observe that the detected amount of HF is very low in relation to the amount of HF produced in the fire of an electric vehicle, between 120 and 859 g [43]. Therefore, it is concluded that in this test, the lithium-ion battery does not burn at TR, as it will be verified by disassembling the battery of the Smart EQ ForFour vehicle on fire.

3.2.4. Use of Fire Blanket in Smart EQ ForFour Fire Test

A fire blanket works as a protective layer that limits the transfer of flames to adjacent combustible elements. In most fires, preventing the supply of air, i.e., oxygen, can prevent the spread of combustion. But avoiding oxygen supply cannot extinguish the chemical reactions of lithium-ion batteries. Therefore, fire blankets can effectively isolate electric vehicles from their surroundings and contain the spread of fire.

The blanket used during this test is a standard blanket; it has dimensions of 6×8 m and is not reusable, and the manufacturer indicates that it is usable in a small fire. It weighs about 28 kg. The material is pyroxene 380 gsm (grams per square meter) coated with a silicone polymer (120 gsm), and it is intended for workshops, shopping center parking lots, and preventive use in the quarantine vehicle, etc.

In the test at hand, a fire blanket was placed only 6 min after the start of the test. Upon placement of the fire blanket, the temperature surrounding the vehicle quickly decreased to near ambient levels as the flames were effectively extinguished by the fire blanket, as was the case in the previous test. After covering with the fire blanket, the temperature inside the vehicle did not suddenly increase because the fire blanket did not change the hot smoke output from the interior of the vehicle because it was no longer coming out initially due to the windows being up. If the windows had been down during the test, this increase in temperature inside the passenger compartment would have been noticeable, as the smoke would not have escaped through the windows when the fire blanket was put in place. Immediately after covering the vehicle with the blanket, its surface temperature decreased to around 200 °C. From that point onward, the blanket acted as a thermal insulator, shielding the vehicle from fire-induced radiation, preventing the release of materials into the surrounding environment, and simultaneously promoting vehicle cooling.

It was observed that the temperature in the trunk area was higher than in the passenger compartment (Figure 45). This phenomenon was also noted in the previous test, where a distinct temperature stratification was observed—suggesting that turbulent combustion did not take place within the vehicle interior.

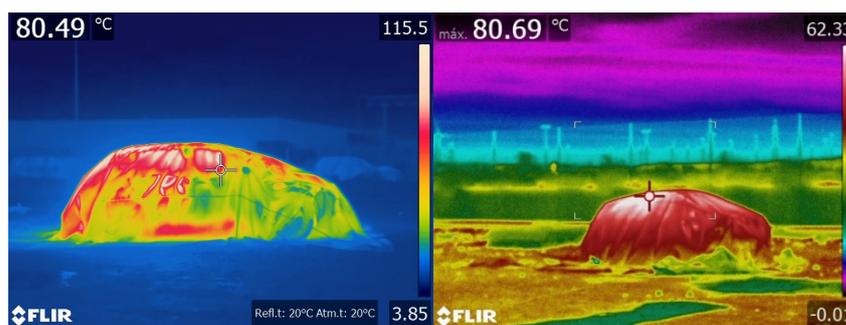


Figure 45. Comparison of the two tests carried out, Nissan Leaf (left) and Smart EQ ForFour (right).

Once the test had been completed, the fireproof blanket was left in place until the following day, monitoring the temperature with a manual thermographic camera.

3.2.5. Identification of the Battery Status of the Smart EQ ForFour Vehicle After the Fire Test

Once the test had been concluded and the mandatory cooling/quarantine interval had ended, the cells were disassembled (Figure 46) to analyze their behavior and their integrity according to the position in which they were located. The objective was to analyze how the cells showed damage patterns influenced by the position of individual cells within the battery casing. As a result, the condition of these cells has been perfectly documented.



Figure 46. Images of the condition of the battery pack, the module, and the lithium-ion cells inside the battery pack.

Once the burnt battery of the Smart EQ ForFour vehicle had been disassembled, the damage was visually identified. When performing the relevant measurement, it was observed that in each module, there was 116 V, so it was deduced that it had the full voltage (348 V). On the other hand, it was verified that the heater used to cause the thermal failure was still working.

When the battery was disassembled, it was observed that the fire did not affect the battery. It was disassembled and it was observed that it had the total voltage and was whole. On being measured cell to cell, it was observed that there was a derivation, but as for its physical state, it was whole.

If it is analyzed why the fire did not affect the battery, it is concluded that it is due to two factors: firstly, due to the wind that forced the flame to go towards the rear of the vehicle, and secondly, it was not left to act enough (in previous published tests, the fire acts on the battery for approximately 20 min before the thermal runaway occurs).

Furthermore, it should be noted that, as indicated above, the energy that the Nissan Leaf battery can supply (24 kWh) is greater than the energy that the Smart EQ ForFour battery can supply (17.6 kWh). In addition, the SoC of the Nissan Leaf battery at the time of the fire test was 68%, while the SoC of the Smart EQ ForFour battery was 50%. Therefore, the fact that the Smart EQ ForFour battery did not experience TR was expected, since studies indicate that TR tends to occur only when the SoC exceeds 50% [44–46]. Furthermore, a thermal runaway with flame is more likely to occur if the state of charge of an electric vehicle's battery is above 50%; below that percentage, a runaway without flame is more common.

As a future line of research, we propose conducting the test at the module level, utilizing the vehicle's battery modules. Initially, this test caused a short-circuit failure in one of the modules and caused a failure in another module due to the overheating of the heater. These tests on the day of the full-vehicle test went well, but there were some issues, such as the cable cross-section in the case of a short circuit and the heater's activation time. These issues will be resolved in future tests.

The following graphs (Figures 47–49) show the temperature recorded by each of the thermocouples placed on the Smart EQ ForFour vehicle's battery. As indicated in the explanation of the test, type K thermocouples (Type K Thermocouple AISI 310 Stainless

Steel Sheath), which support temperature values of up to 1100 °C punctually and 1050 °C sustained, were placed inside the battery to measure the temperature in different modules; the orange one (T_1) was placed on the right side, the red one (T_2) was placed on the left side, and to measure the temperature in the battery casing, the green thermocouple (T_3) was placed on the battery casing. To measure the temperature in different points of the battery, in addition to the type K thermocouples, a Keysight 970 A Datalogger was used, which measures, records, and stores the temperature values, and a connection panel to which the thermocouples are connected to take the measurement through the datalogger.

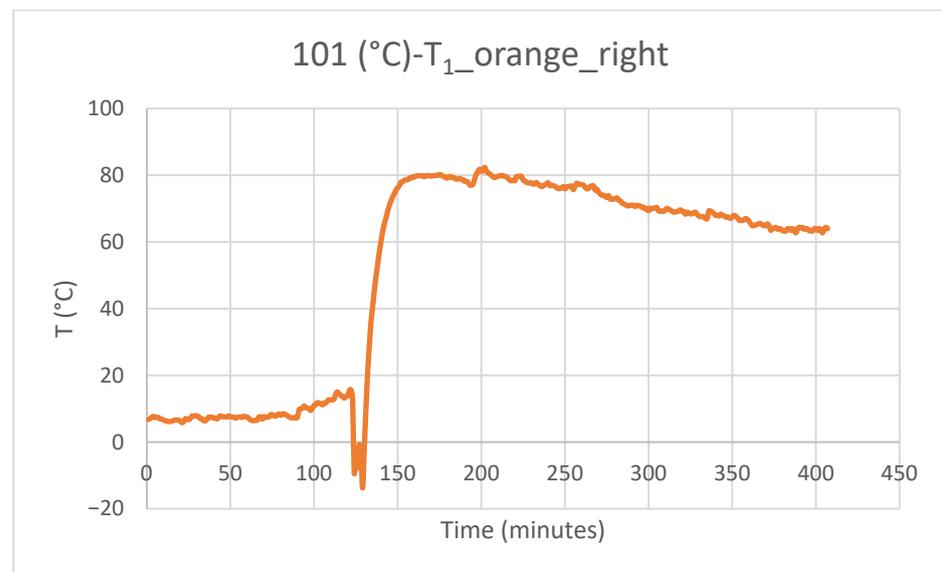


Figure 47. Temperature recorded using the orange K-type thermocouple placed inside the battery on the right side.

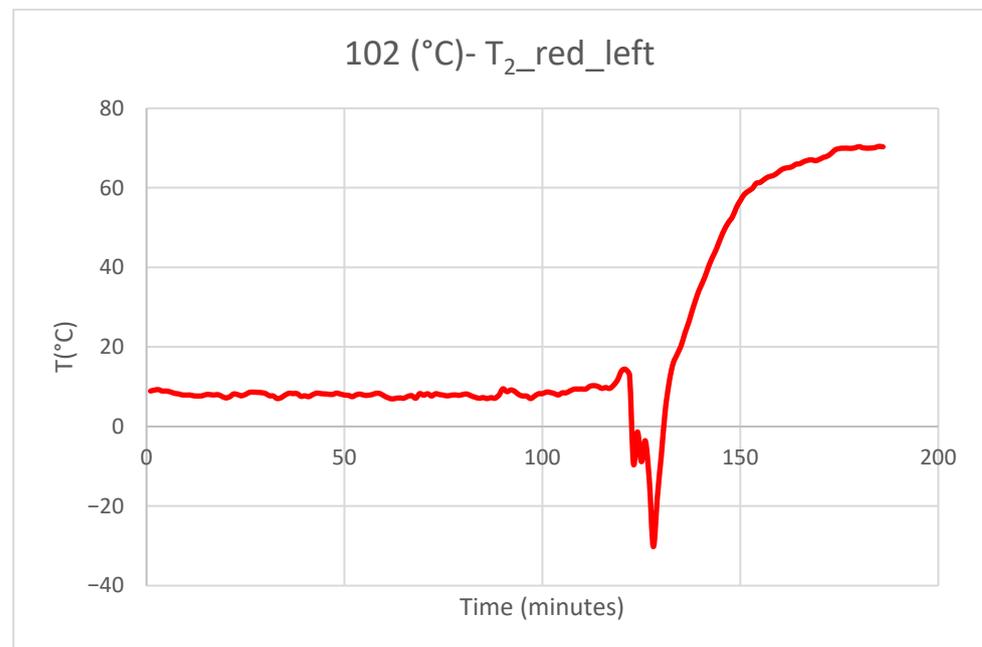


Figure 48. Temperature recorded using the red K-type thermocouple placed inside the battery on the left side.

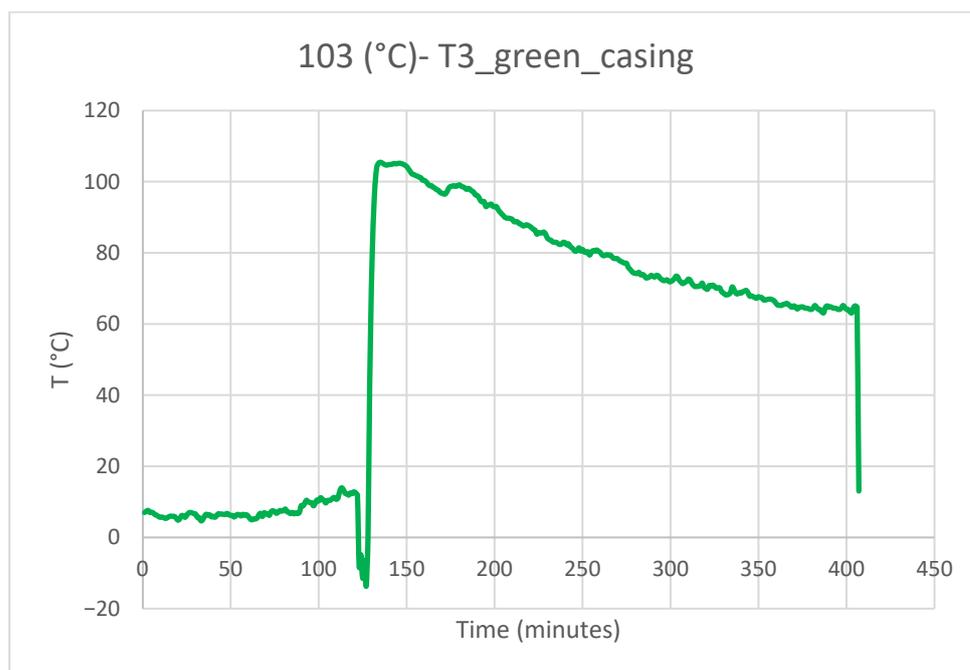


Figure 49. Temperature recorded using the red K-type thermocouple placed on the outside of the battery on the casing.

First, the temperature reached by the orange thermocouple (T_1) placed on the right side is indicated, then the temperature reached by the red thermocouple (T_2) placed on the left side, and finally, the temperature reached by the green thermocouple (T_3) that has been placed in the casing. It is observed that the highest temperature is reached by the thermocouple located on the outside of the casing ($T_{3\max} = 104.97\text{ }^\circ\text{C}$), and inside the battery, the thermocouple that reaches the highest temperature is the orange one placed on the right ($T_{1\max} = 81.16\text{ }^\circ\text{C}$), an expected result since it is in that part (right zone) where the different components melt first, and the right tire explodes first, which indicates that the concentration of the fire is on the right side. On the other hand, it is logical that the temperature reached on the outside is higher, since it is the one that is first exposed to fire. The behavior of the battery with temperature is observed, and if it had continued heating, the TR would have been reached, but in this case, the fire was stopped earlier with the fire blanket, and the battery's TR was not reached.

Furthermore, after the fire blanket was placed, the temperature reached on the surface of the burning electric vehicle continued to be controlled and monitored. The following graph (Figure 50) shows the temperature evolution (measured with a handheld thermal imaging camera) on the vehicle once the fire blanket was placed over it as a containment method, measured from 1:30 p.m. to 4:30 p.m. the following day (the fire started at 12:30 p.m.). The ambient temperature is also indicated (orange graph).

A peak in temperature is observed at first, and then it drops to $6.80\text{ }^\circ\text{C}$ (minimum temperature measured at 3:30 a.m.). This temperature then rises as the ambient temperature begins to rise. Furthermore, it can also be seen that the measurement was not taken in the battery area but at a midpoint; the temperature in the battery area is even lower. This measurement was taken on the right side of the vehicle, facing the direction of travel. The temperature was also recorded on the left side, facing the direction of travel.

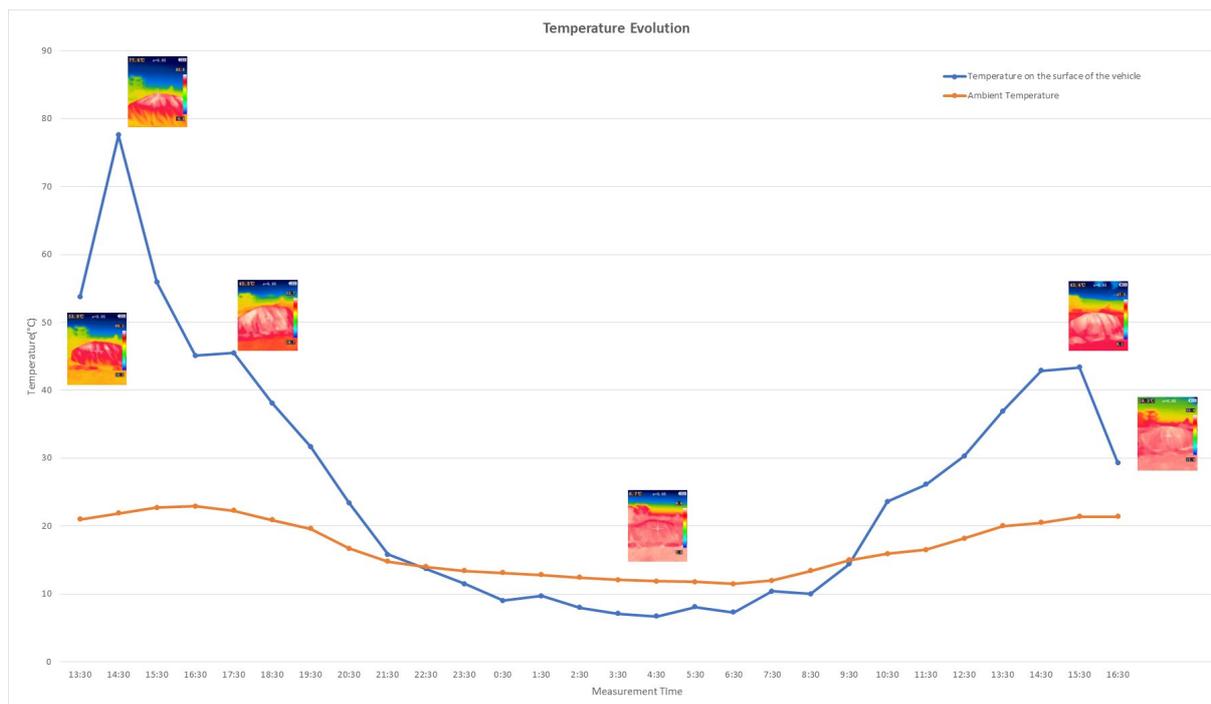


Figure 50. Temperature evolution of the vehicle covered with the fire blanket after the fire test, recorded every half hour.

In the figure (Figure 51) above, you can see how the most damaged area of the fire blanket is at the rear, which is the direction in which the fire was traveling due to the prevailing wind. The structural integrity of the fire blanket 24 h after the start of the fire test is shown below. The most damaged area of the fire blanket is in the area located on the rear left side of the vehicle. This corresponds to the area where the gas detector recorded the greatest amount of HF gas (three events exceeding the limits). However, the fire blanket functioned correctly as a containment method, so it could be considered a suitable method for quarantining damaged electric vehicles at risk of fire. It should be noted that this fire blanket is for single use only; it cannot be reused.



Figure 51. State of the fire blanket hours after the test, from different perspectives of the vehicle.

4. Conclusions

Thermocouples were not installed in the controlled fire test on the Nissan Leaf. Furthermore, the images were taken from the side of the Nissan Leaf, so the flame height could be measured, but not its length, resulting in the loss of critical data. However, some conclusions can be drawn, as detailed below:

- The fire was relatively small before spreading to the passenger compartment. In the early stages, the jetting fire is concerning;
- Once the fire reaches the passenger compartment, it intensifies. The peak of the fire was therefore dominated by combustion in the passenger compartment. Therefore, it is concluded that, as a matter of good practice, the fire should be controlled before it reaches the passenger compartment. This way, its environmental impact can be significantly reduced. Since the battery pack and passenger compartment are areas where combustible materials are concentrated, they are prone to catching fire. Proper fire separation can slow the spread of the fire and save time in the fire response;
- The fire blanket can effectively extinguish the flames and control the spread of the fire in the early stages, but it cannot stop the battery's thermal runaway, i.e., the chemical reaction that continues to occur. Furthermore, the fire blanket insulates the radiation emitted by the flames, significantly reducing the temperature on the other side of the blanket. Another aspect to consider is that the gas produced by the battery accumulates in the vehicle. Therefore, when removing the fire blanket, this must be considered. When removing it, do so in such a way that the flammable gas can escape through the area where personnel are not present, i.e., on the side opposite to where the blanket is being removed;
- After removing the fire blanket, the fire quickly re-ignited. Therefore, it is concluded that the fire blanket is a good containment solution to effectively stop the spread of a disaster. However, it must be noted that the application of Heskestad's formula to estimate flame height has significant limitations in this context. The formula assumes a steady-state pool fire and may not be accurate for transient fire events like vehicle re-ignitions. Furthermore, in vehicle fires, the flame plume consists of distinct regions—the flame zone, transitional zone, and smoke zone—making it difficult to determine flame height precisely through visual estimation. These factors should be considered when interpreting calculated flame heights and associated heat release rates;
- If the fire were to break out in an enclosed space, after removing the blanket, the facility should be ventilated quickly to allow the gas to disperse as quickly as possible;
- Adding water can help reduce the temperature in the traction battery and reduce the rate of heat release from the flame, stopping thermal runaway from the battery. It is noted that the perforation in the casing means that a smaller volume of water needed to extinguish the fire, and cools the battery more quickly;

On the other hand, the early termination of the test with the Smart EQ ForFour, and the fact that it was very windy on the day of the test, were the reasons why the battery did not experience thermal runaway. This led to the loss of essential data. Nevertheless, it is still possible to draw certain conclusions, as detailed below:

- Before spreading to the passenger compartment, the fire was relatively contained. However, the appearance of a jet flame in the early moments is noteworthy;
- Once the fire reaches the passenger compartment, it intensifies. The peak of the fire was therefore dominated by combustion in the passenger compartment. Therefore, it is concluded that, as a matter of good practice, the fire should be controlled prior to its spread into the passenger compartment, thereby substantially reducing its environmental impact. Since both the battery pack and passenger compartment

contain high concentrations of flammable materials and are susceptible to ignition, effective fire compartmentalization can delay fire propagation and provide valuable time for emergency response;

- In the early stages of ignition, the fire blanket can efficiently control flame development and limit fire propagation, but it cannot stop the thermal runaway of the battery, i.e., the chemical reaction that continues to occur. Furthermore, the fire blanket insulates the radiation emitted by the flames, significantly reducing the temperature on the other side of the blanket. Another aspect to consider is that the gas produced by the battery accumulates in the vehicle, so when removing the fire blanket, this must be considered. When removing it, do so in such a way that the flammable gas can escape through the area where there are no personnel, i.e., on the opposite side from where the blanket is being removed;
- The fire blanket is an effective fire containment system, allowing the vehicle to be quarantined more safely and without the need for special areas;
- The use of the fire blanket in both open and closed spaces and its role as a preventative method in post-fire situations is highlighted.

After the two tests carried out, the following are the main conclusions on good practices for extinguishing fires in electric vehicles and in their batteries:

1. Effective extinguishing with fire blankets:
 - Fire blankets were effective in containing the spread of fire in the initial phase;
 - They reduce thermal radiation, dissipate the surface temperature of the vehicle, and block oxygen intake, facilitating the containment of the fire without the need for immediate direct intervention.
2. Risk of re-ignition after blanket removal:
 - Even if the visible flame has been extinguished, the chemical process in the battery (thermal runaway) may continue;
 - Removing the blanket may cause violent re-ignition if there are accumulated gases. It is recommended to do it from the opposite side and with pre-ventilation if it is in closed spaces, and following an established protocol.
3. Use of fireman's access and pressurized water orifice:
 - Allows for the direct cooling of the battery with less water and greater effectiveness;
 - Reduces the time needed to control the fire and reduces the risk of spreading.
4. Mandatory quarantine:
 - After extinguishing a fire in an electric vehicle, it is essential to keep it under observation for 48 h;
 - It avoids the risk of re-ignition and allows gases and the temperature to be safely controlled.
5. Importance of intervening before the fire reaches the passenger compartment:
 - The highest peak heat release occurs when the fire spreads to the passenger compartment, so early intervention drastically reduces the impact.
6. Training of civilian and emergency personnel:
 - The placement of the blanket must be carried out by trained and equipped people, never improvised;
 - The use of Personal Protective Equipment, knowledge of the environment, and recognition of the type of vehicle are essential for a safe intervention.
7. Applicability of the method in real scenarios:

- Fire blankets and the use of Fireman Access are shown to be viable solutions in urban environments, workshops, parking lots, or roadside assistance, even without the need for special quarantine areas.
8. Protective equipment:
- To protect against combustion products, including ashes, sharp edges, and potentially active cells, the necessary equipment is as follows:
- Coveralls, safety screens, masks with an appropriate filter, dielectric gloves, mechanical protection gloves, insulating helmets, and dielectric footwear, depending on the type of work to be performed;
 - If necessary, the use of dielectric equipment to avoid possible electric shocks;
 - Lithium-ion battery cells are to be inspected on site before being placed on the ground, and checked for active cells that could cause secondary ignition;
 - Once the inspection has been carried out, change clothes and wash face, wrists, and neck, i.e., all exposed parts;
 - At the end of the dismantling, the whole area is cleaned, and all waste is properly managed with the waste manager.

According to research data, secondary ignition only occurs in about 5–10% of incidents. Delayed ignition is also possible, although it is unlikely and difficult to verify.

Another conclusion that can be drawn is that when thermal runaway occurs, fire activity is usually observed on the underside of the vehicle, which often results in tires and wheel arches catching fire before other combustible parts of the burning vehicle.

5. Future Work

This study has some limitations that will be addressed in future work. Performing the fire tests with an external ignition source limits the conclusions on the intrinsic ignition behavior of the battery, as ignition inside the battery represents a critical failure mode. Furthermore, the results showed that fire blankets successfully extinguished flames by cutting off the oxygen supply, although there is a high risk of re-ignition after the fire blankets are removed.

Given the scope and constraints of the current experimental setup—as well as the safety limitations when conducting full-scale vehicle fire tests—it was not possible to initiate ignition directly inside the battery pack or to isolate battery-induced combustion from external fire sources. Therefore, future experiments should explore alternative ignition positions to better isolate and analyze thermal runaway phenomena.

Consequently, for future lines of work, it is necessary to carry out the following:

- Experiments where the fire is initiated directly on the battery to better capture the unique characteristics of BEV fires;
- Improved thermal imaging protocols to more accurately distinguish heat sources (between the battery surface and the initial ignition point);
- Consideration of more advanced HRR quantification methods (e.g., cone calorimetry or mass loss rate);
- Tailored extinguishing strategies and suppression techniques that reflect the specific behavior of battery fires, beyond what standard fire blankets and water streams can achieve.

Author Contributions: Conceptualization, A.O. and L.C.; data curation, A.O. and L.C.; formal analysis, A.O. and L.C.; funding acquisition, A.O. and L.C.; investigation, A.O. and L.C.; methodology, A.O. and L.C.; project administration, L.C.; resources, A.O. and L.C.; supervision, L.C.; writing—original draft, A.O. and L.C.; writing—review and editing, A.O. All authors have read and agreed to the published version of the manuscript.

Funding: University of Zaragoza: Industrial Doctorate (DI 4/2020).

Institutional Review Board Statement: This statement must be excluded, given that the study did not require ethical approval.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy restrictions.

Acknowledgments: The authors are grateful for the support received through the Industrial Doctorate financed by the University of Zaragoza (DI 4/2020) and Instituto de Investigacion sobre Vehículos, S.A. (Centro Zaragoza), through which the work presented in this article was framed.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

EV	Electric Vehicles
TR	Thermal Runaway
HEV	Hybrid Electric Vehicle
LIB	Lithium-Ion Battery
ICEV	Internal Combustion Engine Vehicle
NFPA	National Fire Protection Association's
MSB	Swedish Civil Contingencies Agency
DSB	Norwegian Directorate for Civil Protection
SOC	State of Charge
GSM	Grams per Square Meter

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