

# Water Mist Performance for Electric Vehicle Fires in Parking Garages: A CFD-Based Assessment

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## **ABSTRACT**

*[Background]* The rapid growth of electromobility has led to an increasing number of parking garages being adapted for electric vehicle (EV) use. The introduction of EVs presents new challenges for both facilities and occupants due to the fire behavior and combustion products associated with lithium-ion battery packs. Considering the geometry and constraints of existing parking structures, this study evaluates the feasibility of using an automatic water mist system as an alternative to conventional sprinkler protection. *[Objective]* This study aims to assess the performance of a water mist system in controlling or suppressing a fire involving an electric vehicle in an existing parking garage. *[Method]* A series of CFD simulations using Fire Dynamics Simulator (FDS) were conducted to evaluate four scenarios: (1) no fire protection, (2) sprinkler protection according to NFPA 13 and (3) a manufacturer-specific water mist system for EV fires. The simulations represent the worst credible scenario: a fire originating in a single parked electric vehicle. Net heat transfer was analyzed to estimate the probability of fire spread to adjacent vehicles. Hot gas temperatures, toxic gas concentrations, water discharge characteristics, and visibility were evaluated to compare system performance. *[Results]* The CFD simulations indicate that both sprinkler and water mist systems are capable of controlling the fire. However, the water mist system achieves control with significantly lower water demand, resulting in a reduced volume of contaminated runoff containing toxic fire by-products. *[Main conclusions and recommendations]* Active fire protection systems are effective in controlling—though not fully extinguishing—EV fires, while maintaining tenable conditions for occupants, structural integrity, and firefighter operations. As fire protection technologies continue to evolve alongside EV development, this study provides evidence supporting the adoption of water mist systems as a viable and environmentally advantageous solution for EV fire protection in parking garages.

**Keywords:** Water mist systems, Electric Vehicle, EV Fires, FDS, Sprinkler system, Parking Garage, CFD.

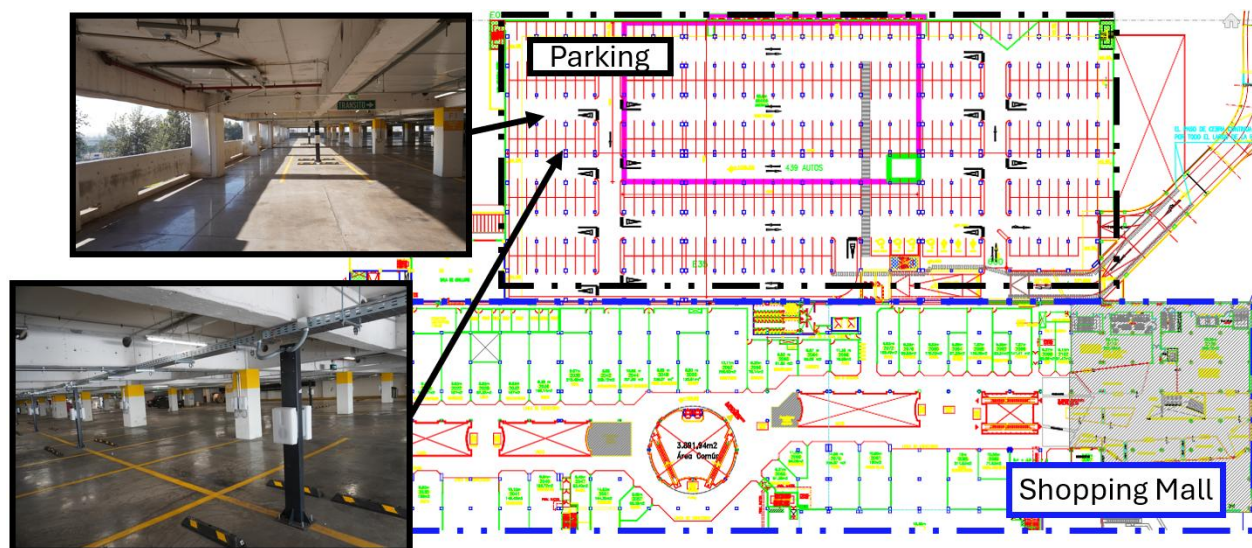
## **INTRODUCTION**

The rapid increase of electric vehicle (EV) charging stations in Chile and around the world is transforming traditional fire safety criteria for parking facilities and buildings. Public-access facilities present a new type of risk: the coexistence of high-power electrical infrastructure and a growing number of vehicles equipped with lithium-ion batteries, which can release thermal energy and toxic gases in the event of failure.

EVs can produce "thermal runaway," a phenomenon in which a defective cell overheats and propagates an exothermic reaction to the rest of the battery pack. This process releases flammable and toxic gases - including hydrogen fluoride (HF), carbon monoxide (CO), and hydrogen chloride (HCl) - presenting severe risks to occupants and emergency responders.

In enclosed or semi-open parking facilities, the accumulation of these gases and limited ventilation aggravate the situation, rapidly compromising safety conditions and delaying firefighting efforts.

In the current study, a public access existing enclosed parking garage (belonging to a shopping mall) with no active fire protection system has been adapted to allow the charge and parking of EV. Due to free access to the premises, the management of the shopping mall has decided to analyze the impact of an EV fire on the actual parking conditions and how to mitigate it through active fire protection systems.



*Figure 1: Current Facilities for EV Parking Space*

## **METHODOLOGY**

The general methodology to assess the present study is described in the Figure 2.

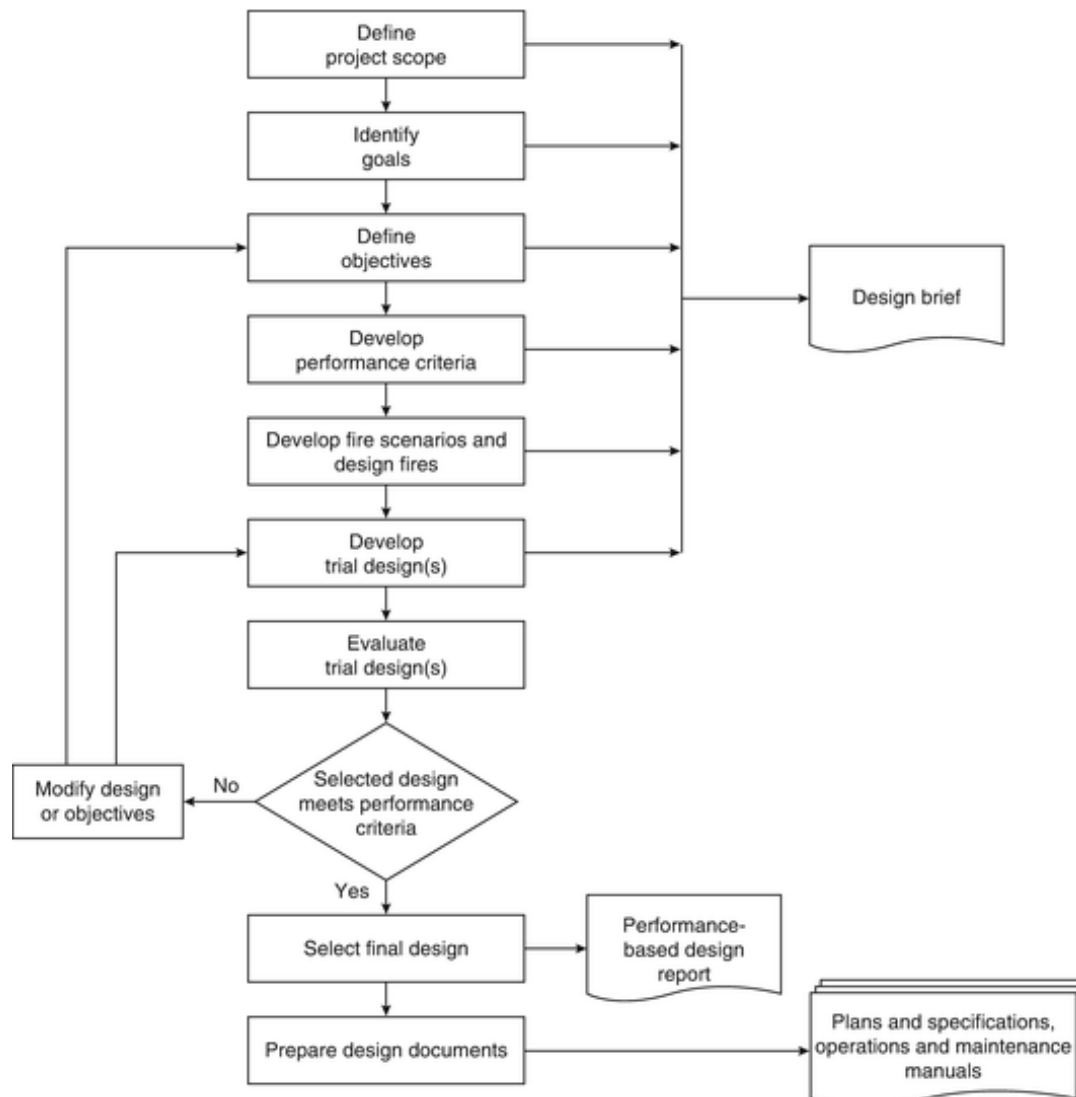


Figure 2: General methodology for PBD according SFPE Handbook [1]

## **Scope**

The scope of the study corresponds to the parking space indicated in the Figure 1

## **Goals**

The goals correspond to:

- Provide an environment reasonably safe from fire for occupants that are not closely related to the initial development of the fire and improve the survival capacity of the occupants closely related to the initial development of the fire.
- Provide an environment reasonably safe for firefighter interventions.
- Provide an environment for the protection of property and operational continuity in the event of a fire, considering minimal environmental impact, especially related to water contamination and containment.

## **Objectives**

- 1) Protection of the occupants: evaluate a fire protection system that protects the occupants who are not familiar with the initial development of the fire during the time necessary to evacuate. Allow occupants who are closely related to the fire to evacuate in sustainable conditions for life safety.
- 2) Operational continuity: Evaluate a fire protection system that minimizes the impact of fire in the facilities, considering the fire propagation, heat release rate, among others.
- 3) Minimize the water discharge: evaluate a fire protection system that allows compliance with objectives 1 and 2 before mentioned and that also fulfils the environmental requirements of minimize the water containment.

## **Performance Criteria**

The performance criteria considered in the current analysis correspond to the following:

- Visibility & Extinction Coefficient
- Fire spread and Hot Gases
- Time to Control and Extinguish the Fire.
- Water discharged.

## **Fire Scenarios**

Three fire scenarios will be modelled according to the following:

- Scenario 01 will consider the actual situation, to obtain results of the actual impact of an EV fire with no active fire protection system
- Scenario 02 will analyze the impact of sprinkler system according NFPA 88A
- Scenario 03 will analyze the impact of a Watermist system

## **Trial Designs**

Trial designs correspond to the fire protection strategies that are intended to fulfil the project objectives. To be considered acceptable, the trial designs must fulfil the performance criteria when fire scenarios are analyzed.

## **Evaluation of Trial Designs**

The evaluation of the trial designs is intended to analyze, compare and review the results regarding if the performance criteria are fulfilled or not and if the objectives of the study are also fulfilled.

## **PERFORMANCE CRITERIA**

### ***Fire Water Discharged***

Using water as the primary agent for electric vehicle fires is essential for cooling battery packs and presents an additional challenge: the quality of the runoff water. Numerous studies (RISE 2023:22, RISE 2020:90, among others) show that fire-extinguishing water from BEVs contains significantly higher concentrations of contaminants compared to that from conventional vehicles (ICEVs).

#### Composition of fire-extinguishing water

- Fluorides (dissolved HF, fluoride salts): very high levels resulting from the decomposition of the electrolyte (LiPF<sub>6</sub>). These fluorides are highly toxic to aquatic organisms, even at low concentrations.
- Heavy and transition metals: Ni, Co, Mn, Li, Cu, Al, Fe, Zn, among others, released from both cells and structural components.
- Solids: fragments of charred electrolyte, plastics, and metal particles. RISE (2023:22) found that fire-extinguishing water from BEVs had significantly higher concentrations of metals and fluoride than that from ICEVs, with measurable toxicity to aquatic species.

#### Volumes and management

- Large water volumes: an EV fire can require many times more water than an ICEV fire (up to 10 times, according to DVRPC 2024), thereby increasing the volume of contaminated fire-extinguishing wastewater.
- Underground or enclosed scenarios: the accumulation of contaminated water in pits or sumps poses an immediate risk to drainage networks and treatment plants.

#### Containment

- Where drainage systems exist provide means for temporary closure (shut-off valves, sealable grates, containment basins) to prevent direct discharge into the environment.
- Many underground parking facilities lack drainage systems designed to contain firefighting water. In such cases, water tends to pool on the floor slab and seep through cracks or joints to other levels.
- The containment must be anticipated in emergency plans by providing portable barriers (absorbents, inflatable dikes, sandbags) to limit the spread of contaminated water.
- The facility must notify the environmental authority and coordinate the removal of accumulated water using authorized hazardous liquid waste managers, in accordance with local regulations

#### Management

- All contaminated water must be treated as hazardous liquid waste, not as ordinary firefighting water.
- The volume can be substantial, making it crucial to plan for temporary storage sites (tanks, flexible containers).

**Therefore, the quantity of water discharged by the active fire protection system will be analyzed as criteria to evaluate the performance of the solution.**

## Visibility

The presence of smoke in an occupied space obscures light from windows and other sources, often forcing evacuating occupants to navigate in low-light conditions. Furthermore, smoke directly impairs a person's ability to see surrounding objects and signage through it.

Visibility tests for illuminated and reflective signs viewed through smoke were conducted at the Fire Research Institute; the results indicated that the relationship between visibility and smoke obscuration can be expressed as [2]:

$$V = \frac{B}{K} \quad \text{Equation 1}$$

Where V is the sign visibility at the obscuration threshold (m), K is the smoke density expressed by the extinction coefficient (1/m), and B is a constant that varies depending on whether the sign emits light or reflects it. The visibility value expressed above represents the distance at which the sign begins to be recognizable as an object. For light-emitting signs: B = 5 to 10 (typical value: 8). For reflective signs: B = 2 to 4 (typical value: 3). The value of B depends on whether the signs are reflective or non-reflective, whether they emit light, and their illumination level. For objects such as walls, floors, and doors: B = 2.

The minimum visibility for evacuating occupants shall be 4 meters (Figure 3), given their familiarity with the premises (e.g., workers, shift personnel, or staff who have undergone site induction). Furthermore, when visibility values fall below certain levels, it is assumed that occupants do not continue along their evacuation route and/or return to their previous location.

| Degree of familiarity<br>with inside the building | Smoke density<br>(extinction<br>coefficient) | Visibility |
|---------------------------------------------------|----------------------------------------------|------------|
| Unfamiliar                                        | 0.15 1/m                                     | 13m        |
| Familiar                                          | 0.5 1/m                                      | 4m         |

Figure 3: Minimum Visibility according to type of occupant [3]

Additionally, it must be considered that occupant movement speed decreases as the quantity and obscuration of smoke increase, as shown in Figure 7.11. Therefore, the smoke obscuration values considered for the reduction in occupant movement speed range from 0.4 to 0.9 1/m (Figure 4).

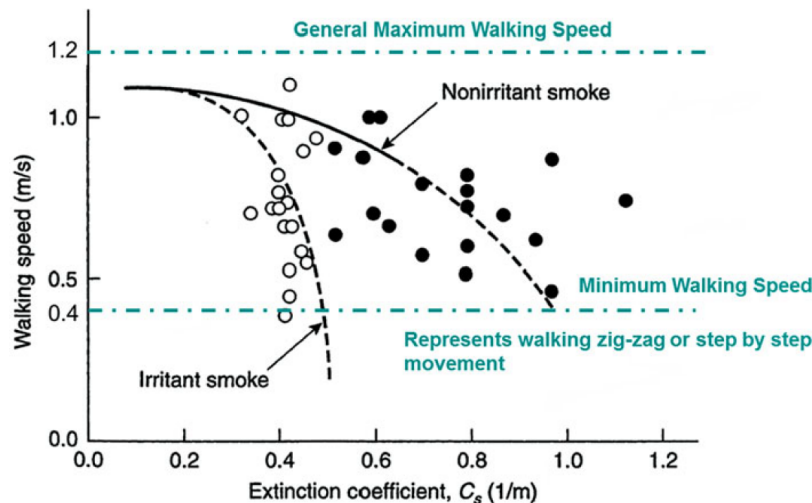


Figure 4: Decreasing speed according to visibility [4]

## ***Fire Propagation and Hot Gases***

Three studies have been identified as the most detailed and reliable [Joyeux, 1997; Steinert, 2000; and BRE, 2010]. These studies were conducted with vehicles spaced between 0.4 and 0.8 m apart and stated that ignition of the second vehicle occurred between 5 and 28 minutes after that of the first, generally due to radiative heating of the adjacent vehicle's rubber components. As can be seen from the dates of these tests, most of the vehicles used were older models, indicating a need for more up-to-date testing using modern vehicles.

Most flammable materials in a car will ignite upon exposure to a heat flux of  $25 \text{ kW/m}^2$  [Tewarson, 2016]. Tests conducted by the BRE in the UK on flammable vehicle exterior materials found a critical heat flux range of  $11\text{--}18.5 \text{ kW/m}^2$ , with most plastic components falling at the upper end of the range: bumpers at  $17.5 \text{ kW/m}^2$ , fuel tanks at  $16.5 \text{ kW/m}^2$ , and tires near the lower end at  $11 \text{ kW/m}^2$ .

An upper-layer temperature of  $500\text{--}600^\circ\text{C}$  is typically associated with the  $20\text{--}25 \text{ kW/m}^2$  heat flux levels at which most ordinary flammable materials ignite [Karlsson and Quintiere, 2000]. Parking garages often have limited ceiling heights due to cost and space constraints, or to align with the ceiling heights of apartments or shops in mixed-use buildings. Therefore, the accumulation and entrapment of hot gases are of critical importance when considering fire spread.

## ***Fire Control and Extinction***

Full-scale vehicle tests show that, although sprinklers do not “extinguish” a sealed pack, they control fire growth, reduce gas temperatures, and lower gas-phase toxic concentrations compared to free-burning fires, thereby limiting spread to neighboring vehicles and improving conditions for emergency response and evacuation [5].

Even after visible flames are extinguished, the battery pack may remain hot and release gas; consequently, EVs are more prone to reignition and require prolonged water cooling [6]. In battery pack suppression tests, discharging an agent onto the exterior of the pack reduces flames but provides minimum cooling to the active modules. Applying water to the battery thermal runaway event was not enough to extinguish the fire, but it did control the rate of spread and, consequently, the intensity of the fire.

In FDS, a prescribed HRR (e.g., via HRRPUA or HRRPUV) cannot be extinguished because it bypasses the combustion and pyrolysis models. The solver treats the HRR as a fixed heat source, independent of oxygen concentration, mixture fraction, temperature, or strain rate. Extinction mechanisms—such as oxygen depletion, excessive cooling, or flame stretch—only apply when the HRR is computed from pyrolysis and combustion chemistry. Therefore, a user-imposed HRR will continue indefinitely, even under conditions where a physical flame would be extinguished.

Because a prescribed HRR in FDS does not respond to suppression mechanisms, a fixed-value fire cannot be extinguished within the model. To represent realistic EV fire behavior, the HRR must therefore be controlled rather than imposed. As previously discussed, a user-defined HRR does not decrease when water is applied, since it bypasses the combustion and pyrolysis models. For this reason, a logical *freeze* function is implemented in FDS: once the number of sprinklers or water-mist nozzles required to control an EV fire (according to applicable codes or manufacturer specifications) has activated, the HRR is held constant. This approach prevents the artificial increase of HRR beyond the point where suppression should limit fire growth, while acknowledging that a prescribed HRR cannot self-extinguish in FDS.

## **FIRE SCENARIOS**

### **Fire Scenario 01 – Parking without Protection (Current Status)**

#### ***Statistical Information***

Electric vehicle (EV) fires data from 2020–2024 indicate that they are not more frequent than internal combustion engine vehicles (ICE) when normalized by distance traveled; in fact, Tesla data and rescue records from Sweden and Norway show lower incident rates per kilometer, and cases involving the traction battery are rare within the overall scope of EV fires (Table 1).

*Table 1: Statistics of Vehicle Fires*

| <b>Likelihood of fire claims/car/year (%)</b> | <b>Type of car</b> |
|-----------------------------------------------|--------------------|
| 0.001                                         | EV                 |
| 0.003                                         | PHEV/REEV          |
| 0.007                                         | Petrol             |
| 0.011                                         | Diesel             |

*T0194 – Covered car parks – fire safety guidance for electric vehicles, ARUP, July 2023.*

According to ARUP (2023), the annual fire probability for electric vehicles is on the order of 0.001%, compared to 0.003% for plug-in hybrids (PHEV/REEV), 0.007% for gasoline vehicles, and 0.011% for diesel vehicles. Regarding conventional vehicles, the U.S. Fire Administration (2020) found that approximately 38% of internal combustion vehicle fires occur while the vehicles are parked, while the NFPA (2021) places this proportion in the 30–40% range, allowing for the adoption of a mean value of 35%. In contrast, the EV FireSafe database (2024), which compiles global incidents of traction battery fires, indicates that only between 10% and 15% of electric vehicle fires occur during charging or within the hour following disconnection.

When these proportions are combined with global fire rates by vehicle type, the estimated annual fire probability for a parked internal combustion vehicle reaches approximately 0.035% (3.5 per 10,000 vehicles), whereas for an electric vehicle undergoing charging, it drops to nearly 0.00094% annually (0.09 per 10,000 vehicles). Therefore, the expected incidence of fires in charging electric vehicles is between 30 and 40 times lower than that of a parked conventional vehicle.

Therefore, the main problem of an EV fire corresponds to the battery pack (encapsulated modules and cells) making it difficult for water to reach the heated material. Thus, for an external active fire protection system will be more difficult to extinguish an EV fire than in an ICE fire.

## ***Ignition***

A car lithium battery consists of thousands of cells grouped into modules within a sealed pack. When a cell undergoes abuse (impact, defect, overcharge, overheating), it can enter thermal runaway (TR); a chain of internal exothermic reactions that cause a rapid rise in temperature and degrade the separator, electrolyte, and cathode. The cell vents flammable gases that can form "blowtorch-like" flames, and if the heat is not dissipated, the event can propagate to neighboring cells and the module.

Because the chemical reaction pathways and thermal-runaway mechanisms are too complex to be represented within the computational model, the simulation does not include the onset of ignition. Instead, the analysis begins with the vehicle already in a burning state.

## ***Combustible***

When the battery pack start to burn, a white vapor expelled from the battery indicating that there are present the thermal runaway phenomena, discharging most of the toxic gases such as SO<sub>2</sub> and some of them heavier than air. The quantity and type of gases released depend on the cell's chemical composition, energy capacity, and the battery's state of charge. Gases released by lithium-ion batteries include HF, CO<sub>2</sub>, CO, H<sub>2</sub>, HCN, C<sub>2</sub>H<sub>4</sub>, SO<sub>2</sub>, and components such as ethyl methyl carbonate and dimethyl carbonate.

When comparing emissions from an EV fire and ICE fire, certain gases are emitted by both at similar levels. However, the concentration of HF released during an electric vehicle fire is significantly higher. The HF originates from fluorine sources within the battery, such as the electrolyte and the binder material used in the electrodes. Toxicity analysis of electric vehicle fires in enclosed spaces revealed that HF and SO<sub>2</sub> concentrations were more critical with a greater impact on toxicity levels than CO.

The quantity of gases emitted during an EV fire is determined through full-scale tests using a cone calorimeter equipped for gas measurement (Table 2), according to the study conducted by RISE [7]. Thus, the values indicated in the experiment BEV B (Table 2) have been considered for the computational simulation.

*Table 2: Gases emitted by EV fire & ICE fire*

| Gas measurements                    | ICEV A         | BEV A          | BEV B          |
|-------------------------------------|----------------|----------------|----------------|
| CO <sub>2</sub> , [kg] / [g/lost g] | 344 / (1.4)    | 335 / (1.4)    | 438 / (1.1)    |
| CO, [g] / [mg/lost g]               | 6 420 / (25.5) | 7 790 / (31.5) | 9 510 / (23.8) |
| THC, [g] / [mg/lost g]              | 2 370 / (9.4)  | 3 130 / (12.7) | 2750 / (6.9)   |
| HF, [g] / [mg/lost g]               | 11 / (0.04)    | 573 / (2.3)    | 859 / (2.1)    |
| HCl, [g] / [mg/lost g]              | 1100 / (4.4)   | 1590 / (6.4)   | 1800 / (4.5)   |
| HBr, [g] / [mg/lost g]              | 18 / (0.1)     | 115 / (0.5)    | 88 / (0.2)     |
| HCN, [g] / [mg/lost g]              | -              | -              | 155 / (0.4)    |
| SO <sub>2</sub> , [g] / [mg/lost g] | 479 / (1.9)    | 575 / (2.3)    | 645 / (1.6)    |
| NO, [g] / [mg/lost g]               | 452 / (1.8)    | 371 / (1.5)    | 617 / (1.5)    |
| NO <sub>2</sub> , [g] / [mg/lost g] | 44 / (0.2)     | 25 / (0.1)     | 76 / (0.2)     |
| PAH, [g] / [mg/lost g]              | 112 / (0.4)    | 29 / (0.1)     | 334 / (0.8)    |

## Heat Release Rate

A traction battery consists of thousands of cells grouped into modules within a sealed pack. When a cell undergoes abuse (impact, defect, overcharge, or overheating), it can enter thermal runaway (TR): a chain of internal exothermic reactions that cause a rapid rise in temperature and degrade the separator, electrolyte, and cathode. The cell vents flammable gases that can produce "Jet fires" flames, and if the heat is not dissipated, the event can propagate to neighboring cells and the module.

Lithium-ion (or similar) vehicle batteries fail and burn in a very different way than internal combustion engine (ICE) vehicles. When they fail, they undergo a process known as thermal runaway, in which the failure of a single cell can trigger the generation of heat and oxygen, as well as flammable and toxic gases. This spreads to adjacent cells, potentially causing a fire or an explosion. The curve selected to represent the EV fire corresponds to the curve at the right in the Figure 5, which represents an EV fire with no delay regarding the thermal runaway.

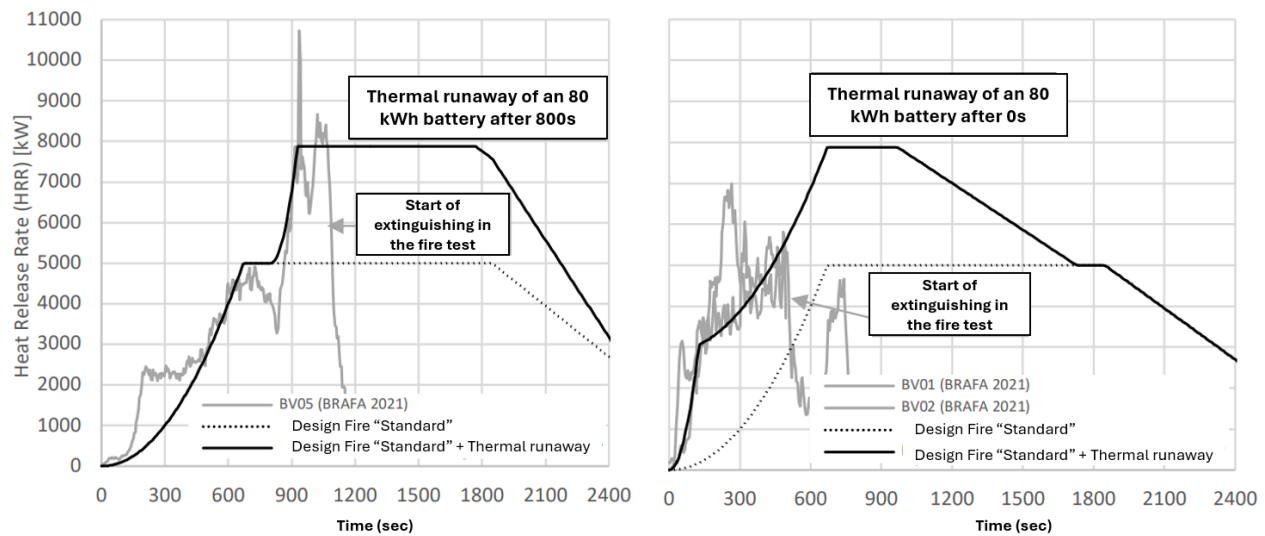
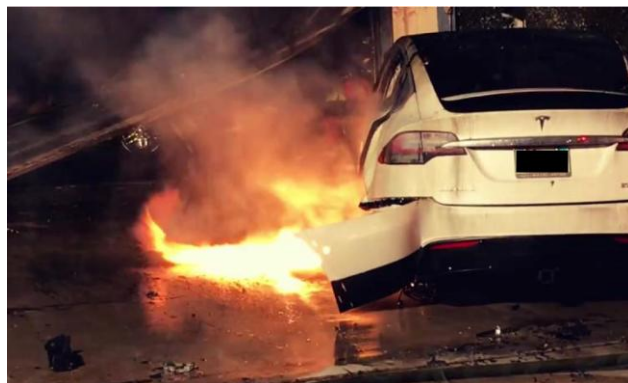


Figure 5: HRR Curves for EV [8]

## Jet Fires

In EVs, venting flame jets can occur, but their reach and duration are typically limited compared to other jets (e.g., from CNG tanks), according to observations by RISE [4]. Ignition of the flammable and toxic battery vent gases emitted from the battery pack can result in a jet fire (Figure 6). Ignition of the vent gases could be caused by an external ignition source, friction between the vent gases and the opening, or an electric arc.

The length of the battery flame jet typically ranges from 2 to 3 m, depending on its capacity. Huang et al. conducted experiments with large-scale lithium-ion battery (LIB) cells with a capacity of 50 Ah. Based on several experiments, it was determined that the flame temperature of an LIB cell can range from 700 to 900 °C [9]. Despite this phenomenon is present in EV, it is not considered in the fire modelling.



*Figure 6: Jet Fire on EV*

### ***Explosions***

Depending on the vehicle's construction, a cloud of flammable vapors and gases may accumulate inside the vehicle; if exposed to an ignition source, the vehicle could explode—a scenario highlighted by Patrick Durham in his presentation for the SFPE (Progress with LI-ION Battery Fire Safety: Engineering Solutions to Mobility and Storage Hazard) titled "Electric Vehicle & Micro-mobility Firefighting Considerations." Figure 7 illustrates the accumulation of vapors inside the vehicle and the vehicle's explosion sequence. An analysis of all electric vehicle battery fire incidents worldwide revealed that flammable vapor clouds occurred in only 5% of the incidents. The remaining 95% of incidents resulted in the rapid ignition of battery venting gases, leading to jet fires. Therefore, the explosion phenomena in EV is not considered in the computational simulation.



*Figure 7: Explosion in EV*

### ***Fire Propagation***

Tests conducted by the BRE in the United Kingdom on flammable vehicle exterior materials revealed a critical heat flux range of 11–18.5 kW/m<sup>2</sup>, with most plastic components falling at the upper end of the range: bumpers at 17.5 kW/m<sup>2</sup>, fuel tanks at 16.5 kW/m<sup>2</sup>, and tires near the lower end at 11 kW/m<sup>2</sup>. An upper-layer temperature of 500–600°C is typically associated with the 20–25 kW/m<sup>2</sup> threshold at which most common flammable materials will ignite [Karlsson and Quintiere, 2000].

### Fire Location and Geometry

The current premises where the study has been carried out correspond to a parking space adjacent to a shopping mall center (Figure 8), with general dimensions of 170m x 79m. The parking garage contains 3 exit/access and opening to the exterior as shown in the Figure 9. According to NFPA 88A to classify the parking space as open and therefore avoid the sprinklers installation, the total area of openings on each level in the exterior walls must be at least 20% of the total wall area around that level and the combined width of all openings (the total length of gaps along the perimeter) must be at least 40% of the perimeter length of that level. Therefore, the current facility does not fulfill the NFPA opening requirement, consequently a sprinkler system must be installed (Figure 9).

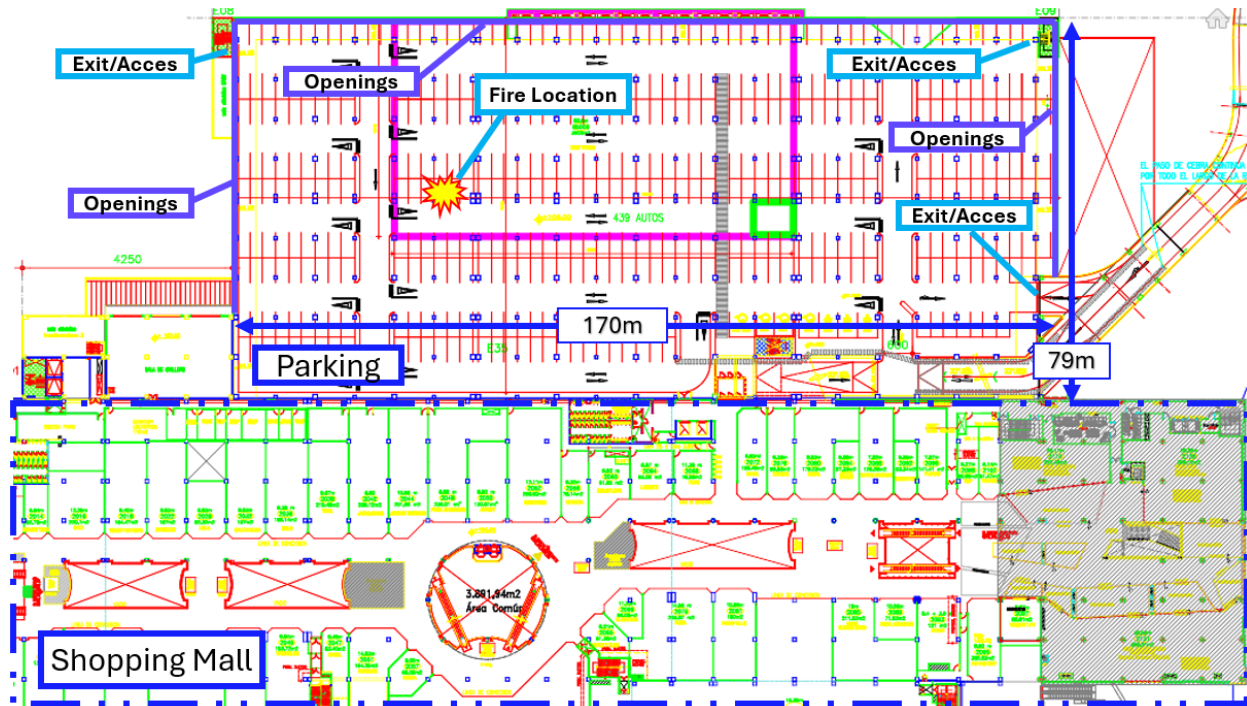


Figure 8: Floor plan of the Parking



Figure 9: Openings Dimensions

The construction of the parking corresponds to reinforced concrete without passive protection, with a ceiling height of 2.83m and distance between floor and beam of 2.2m (Figure 10). To examine the fire propagation, adjacent cars have been positioned next to the EV fire in order to measure the net incident heat and evaluate the fire propagation (Figure 11).

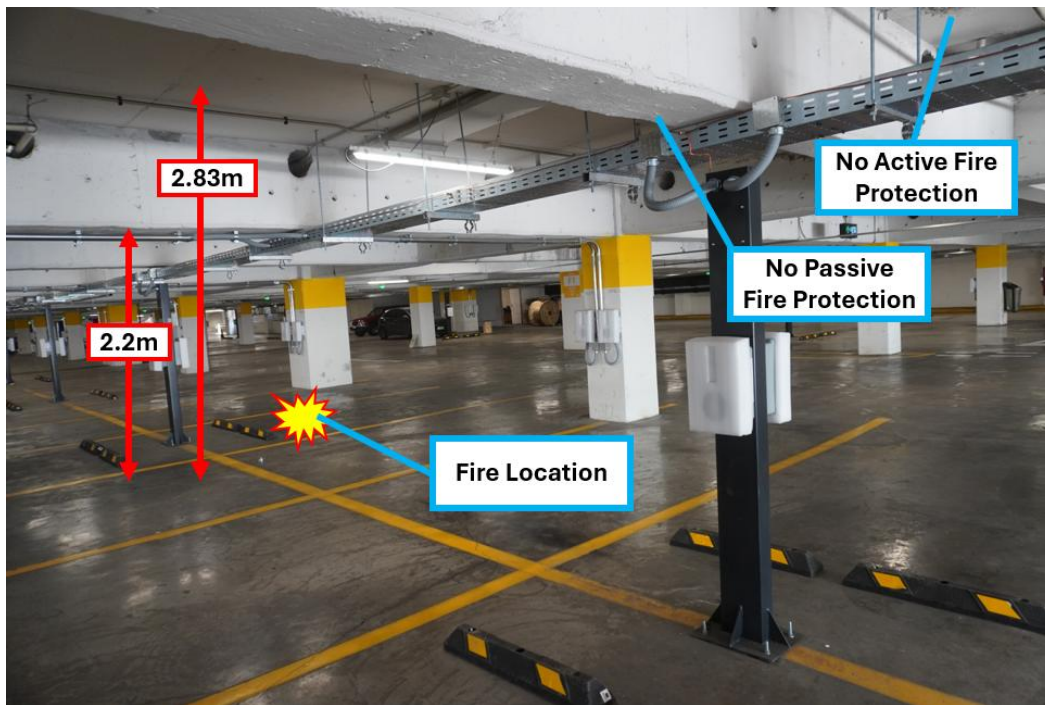


Figure 10: Actual parking situation

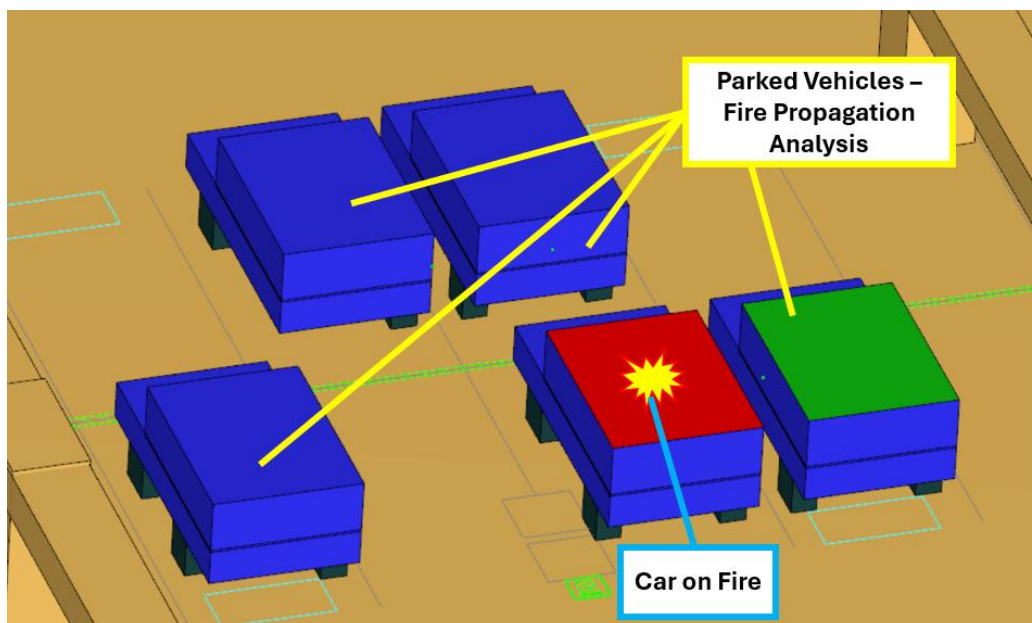


Figure 11: Car on fire and adjacent vehicles parked

## Fire Scenario 02 – Parking Protected by Sprinklers System

A new requirement in the 2023 edition of NFPA 88A mandates that all parking structures be equipped with sprinkler systems installed in accordance with NFPA 13. Prior to this edition, sprinkler installation was not required for open parking structures.

The 2022 edition of NFPA 13 - *Standard for the Installation of Sprinkler Systems*, has revised the recommended hazard classification for parking structures from Ordinary Hazard Group 1 to Ordinary Hazard Group 2. This results in a 33% increase in design density, rising from 0.15 gpm/ft<sup>2</sup> to 0.2 gpm/ft<sup>2</sup>. Consequently, as shown in Figure 12, the system design will utilize the Ordinary Hazard Group 2 curve, with a density of 0.2 gpm/ft<sup>2</sup> over an area of 1,500 ft<sup>2</sup> (140 m<sup>2</sup>).

Sprinkler layout is determined according the Figure 13 and the sprinkler selected to satisfy the water discharge requirements is shown in the Figure 14, considering an operating pressure of 11 psi and a discharge factor of K=8.

This configuration requires the operation of 12 sprinklers, each discharging 26 gpm (92 lpm). Additionally, it is important to consider the average droplet diameter produced by the sprinkler, which depends on its construction and operating pressure. Therefore, an average diameter of 2557 µm has been estimated for 50% of the discharged water (Table 7).

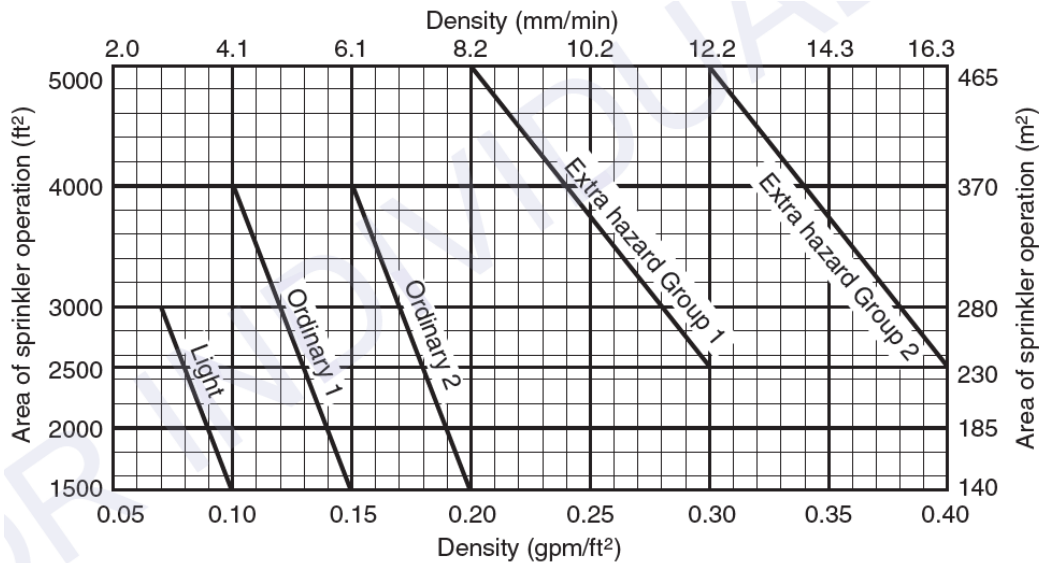


Figure 12: Density-Area curves by NFPA 13

### Protection Areas and Maximum Spacing of Standard Pendent and Upright Spray Sprinklers for Ordinary Hazard

| Construction<br>Type | System<br>Type | Protection<br>Area |                | Maximum<br>Spacing |     |
|----------------------|----------------|--------------------|----------------|--------------------|-----|
|                      |                | ft <sup>2</sup>    | m <sup>2</sup> | ft                 | m   |
| All                  | All            | 130                | 12.1           | 15                 | 4.6 |

Figure 13: Sprinkler layout according NFPA 13

## 1. PRODUCT IDENTIFICATION

This document covers the following product, hereafter referred to as “sprinkler”:

VK2021: Standard Response, Standard Coverage, Pendent, K8.0 (115) Sprinkler.

## 2. INTENDED USE

The sprinkler is intended to be used in automatic fire sprinkler systems as allowed by applicable approval authorities. The sprinkler must be used in accordance with:

1. the sprinkler’s Listings, Approvals, and associated design requirements.
2. the recognized design and installations standards issued, for example NFPA, FM, EN, VdS, or LPCB.
3. the latest revisions of all applicable manufacturer’s documentation.



| Parameter                               | Value                  |
|-----------------------------------------|------------------------|
| Minimum operating pressure              | 7 PSI (0.5 bar)        |
| Maximum rated pressure                  | 175 PSI (12 bar)       |
| Factory tested pressure                 | 500 PSI (35 bar)       |
| Thread size                             | 3/4" NPT or 20 mm BSPT |
| Nominal K-factor                        | 8.0 U.S. (115)         |
| Minimum temperature rating (glass bulb) | –65 °F (–55 °C)        |

Figure 14: Sprinkler Selected

## Number of Droplets

According to test and analysis assessed by the WPI [10], it is concluded that run FDS with more particles than the default (5000), will not improve the prediction of the water bucket test for a sprinkler K=8.0. Therefore, it is considered 5000 droplets.

## Droplets Size Estimation

According to David Sheppard’s investigation [11], several sprinkles with similar features than the sprinklers considered in the current study has been tested, presenting droplets sizes  $Dv_{50}$  between 700 to 1000  $\mu\text{m}$ . There is a mathematical correlation to estimate the sprinkler droplet size [12] and is described following.

$$\frac{Dv_{50}}{D_n} = C W_e^{-1/3} \quad \text{Equation 1}$$

Where  $Dv_{50}$  correspond to the mean value of droplets discharged by the sprinkler,  $D_n$  correspond to the sprinkler diameter, C is a constant sprinkler dependent with values between 1.74 - 3.21, and  $W_e$  correspond to the Weber number, which one is calculated as following.

$$W_e = \frac{\rho_l * U_j^2 * D_n}{\sigma} \quad \text{Equation 2}$$

Where  $\rho_l$  corresponds to the density of water,  $\sigma$  corresponds to the surface tension, U corresponds to the velocity of the discharged water by the sprinkler. Therefore, the droplet size ( $Dv_{50}$ ) will be estimated for the sprinklers to be used in the computer simulations.

### ***Droplet Initial Velocity***

The droplet initial velocity can be computed based on mean flow velocity, which depends on the injection pressure and the discharge coefficient, according to the following equation.

$$V_0 = C * \sqrt{\frac{\Delta P}{\rho}} \quad \text{Equation 3}$$

Where  $V_0$  is the initial velocity in m/s,  $\rho$  is the density of water in kg/m<sup>3</sup> and  $\Delta P$  is the relative pressure at the nozzle in Pascals. Parameter  $C$  is a factor used to consider friction losses in the nozzle. It has not been determined experimentally and typically that the value of  $C$  varies between 0.5 and 1, which corresponds to initial velocity values between 22 and 45 m/s [13].

### ***Discharge Coefficient***

The discharge coefficient ( $K$ ) relates to the physical and geometrical features of the nozzle and the operation pressure of the device. Besides, the  $K$  factor considers the behavior of the vena contracta of the flow and the flow that is discharging through the nozzle. The  $K$  factor can be computed according to the following equation.

$$K = \frac{Q}{\sqrt{P}} \quad \text{Equation 4}$$

Where the flow  $Q$  is measured in liter per minute, the relative pressure  $P$  at the nozzle is in Bar or MPa and the discharge coefficient  $K$  is in L/m/bar<sup>1/2</sup>.

## **Fire Scenario 03 – Parking Protected by Watermist System**

### ***Number of Droplets***

The default number of particles per second used in sprinkler modeling in the FDS package corresponds to 5000. Most research and studies in simulations were achieved with 1.0, 1.5 and 2, 0 x 10<sup>5</sup> particles per second for watermist discharge nozzles [14]. Counting small particles caused numerical instability when the particles hit the hot surface and the higher flows aggravated the phenomenon. Therefore, the number of particles that has been chosen to simulate the watermist nozzle will correspond to 100,000, according to the results obtained in sensitivity analysis [15].

### ***Droplets Size***

There are different quantities to characterize the size of the droplets in the sprinkler discharge. In fact, sprinkler discharge consists of millions of droplets with a certain size distribution. One quantity is the volume median diameter  $Dv_{50}$ , which is the diameter defined such that half the volume of the water is contained in droplets with a diameter less than  $Dv_{50}$  (and therefore half the water is contained in droplets with a diameter greater than  $Dv_{50}$ ). According to what is indicated by the average manufacturers of water mist systems, a droplet size of 260  $\mu\text{m}$  is considered.

### ***Technical Watermist Specification***

The watermist system has been tested in accordance FM5560:2021 Appendix P Fire Tests for Water mist systems for the protection of non-storage occupancies, Hazard Category 2 (HC-2) and Hazard Category 3 (HC-3) with an increased height at 12 meters in an ISO 17025 accredited laboratory, HC3 Test Report No: 230313-327.

According to the manufacturer, normally not more than 5 nozzles are required to control single car fire. The DBI test with EV car used 6 open nozzles for marine systems. In real life projects are designed for water supply over 144m<sup>2</sup> area of operation, considering 9 upright nozzles (Figure 15) considering safety margin.

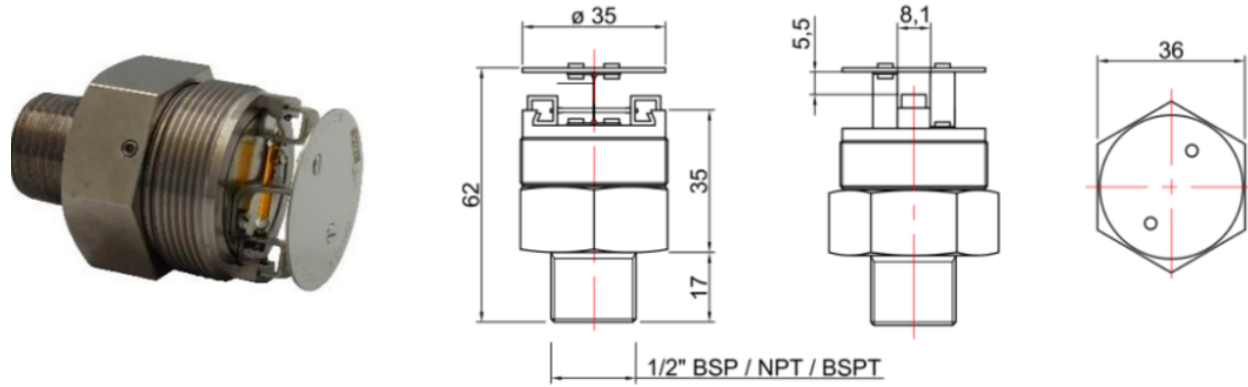


Figure 15: Nozzle selected

### **Mesh and Cell Size**

For the initial grid resolution, the expression stated in the FDS User Guide has been considered. For simulations involving buoyant plumes, a measure of how well the flow field is resolved is given by the non-dimensional expression  $\frac{D^*}{\delta x}$ , where  $D^*$  is a characteristic fire diameter and  $\delta x$  is the nominal size of a mesh cell.

$$D^* = \left( \frac{\dot{Q}}{\rho C T \sqrt{g}} \right)^{\frac{2}{5}} \quad \text{Equation 5}$$

Where  $\dot{Q}$  is heat release rate of the fire is,  $\rho$  is the air density at ambient temperature, C correspond to the air specific heat, T is the ambient temperature and g is the acceleration due to gravity. In a sensitivity analysis (Hill et al., 2007), sponsored by the U.S. Nuclear Regulatory Commission, the  $D^* / \Delta x$  value ranges between 4 and 16.

As a cell size criterion, the following relationship of numerical intervals will be used, where 4 will correspond to a poor resolution without affecting the values of the results and 16 will correspond to the greatest resolution without demanding a high cost of computational resources.

$$4 < \frac{D^*}{\delta x} < 16 \quad \text{Equation 6}$$

Thus, by applying the before mentioned criteria and considering the values shown in the Table 3 it is possible to obtain the flow resolution quality indicator values for the combustion zone, and the plume zone of the hot gases produced by the fire.

Table 3: Parameters considered.

|                      |      |                   |
|----------------------|------|-------------------|
| Ambient Temperature  | 1.2  | kg/m <sup>3</sup> |
| Cp Ambient Air       | 1    | kJ/kg °K          |
| Ambient Temperature  | 293  | °K                |
| Gravity Acceleration | 9.81 | m/s <sup>2</sup>  |

The mesh geometry will be built considering cubic cells with a symmetrical configuration. The entire computational domain will be divided into different meshes with different cell sizes, allowing to cover the computational domain without overusing cells.

The sensitivity analysis for the cell size according to the to the Equation 5 and Equation 6 is indicated in the Table 4 and Table 5, where an indicator of a great flow resolution is shown.

*Table 4: Cellsize Combustion Zone*

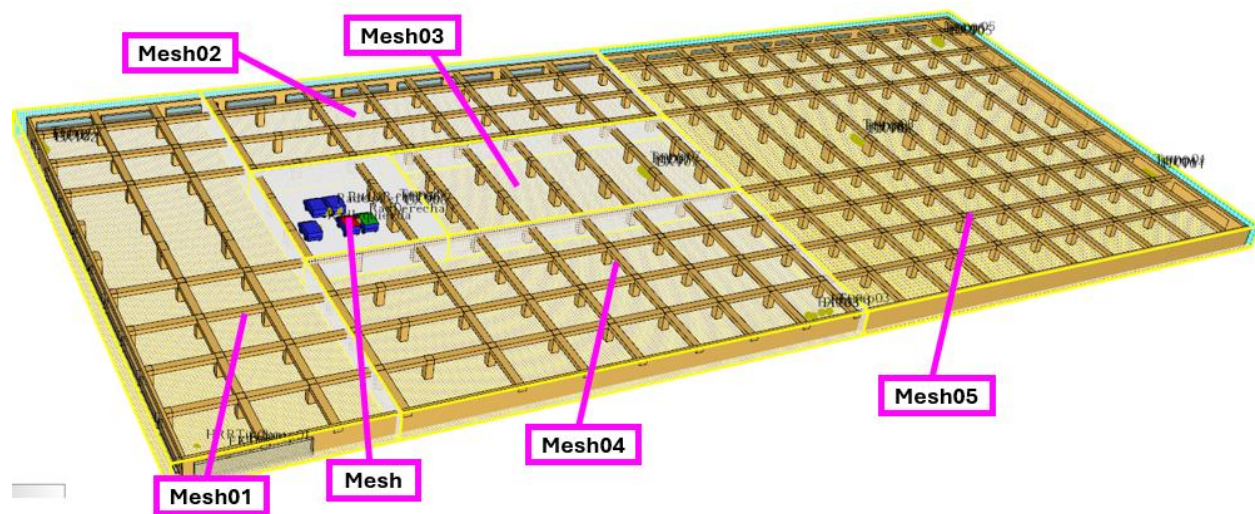
| Scenario              | HRR  |    | D*     | Cellsize (m) | D*/Cellsize |
|-----------------------|------|----|--------|--------------|-------------|
| 01 - No System        | 8000 | kW | 1.4001 | 0.20         | 7           |
| 02 - Sprinkler System | 4000 | kW | 1.0611 | 0.20         | 5           |
| 03 - WM System        | 4000 | kW | 1.0611 | 0.20         | 5           |

*Table 5: Near fire zone*

| Scenario              | HRR  |    | D*     | Cellsize (m) | D*/Cellsize |
|-----------------------|------|----|--------|--------------|-------------|
| 01 - No System        | 8000 | kW | 1.4001 | 0.4          | 4           |
| 02 - Sprinkler System | 4000 | kW | 1.0611 | 0.4          | 3           |
| 03 - WM System        | 4000 | kW | 1.0611 | 0.4          | 3           |

The mesh geometry will be constructed using cubic cells in a symmetrical configuration. The entire computational domain will be divided into several meshes, allowing the geometric requirements of the enclosure to be met without the need for excessive cell usage.

Figure 16 illustrates the mesh layout for the sections of the enclosure under analysis. Additionally, Figure 17 shows the dimensions and number of cells used for each mesh.



*Figure 16: Mesh Organization*

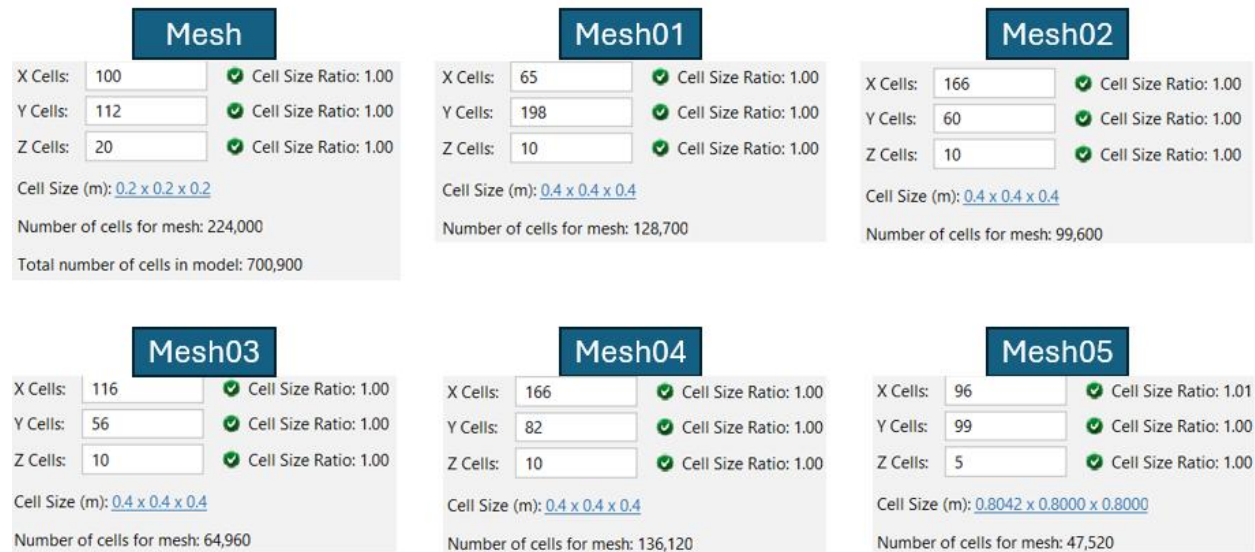


Figure 17: Mesh Dimensions

## TRIAL DESIGNS

The following trial designs contemplate the fire protection strategy that is intended to fulfill the goals and objectives of the study. To be considered acceptable, the trials designs must achieve the performance criteria indicated earlier. The following described trial designs are grouped in the following categories,

- Ignition and spreading of fire, due to the methods are used to reduce the probability of ignition and/or reduce the heat release rate of a fire.
- Fire suppression, including automatic and/or manual fire protection systems.

The trial designs are evaluated in the fire scenario 01 described earlier in the current document.

## Sprinkler System

The current scenario presents the following considerations.

- Sprinklers that correspond to FM approved standard response with a K factor of 8.0 (115) and a temperature rating of 68°C.
- Operating pressure = 11 PSI.
- The RTI corresponds to 100 m<sup>1/2</sup>\*s<sup>1/2</sup> (standard response sprinkler).
- According to the sprinkler's manufacturer [16], the discharge pattern for the operating pressure (11 PSI) corresponds to an angle of 55°.

Table 6: Sprinkler flow and pressure

| Sprinkler Operation |          |                        |
|---------------------|----------|------------------------|
| Q                   | 99       | Lpm                    |
| K                   | 115      | L/m/bar <sup>1/2</sup> |
| P                   | 11       | PSI                    |
|                     | 0.758621 | Bar                    |

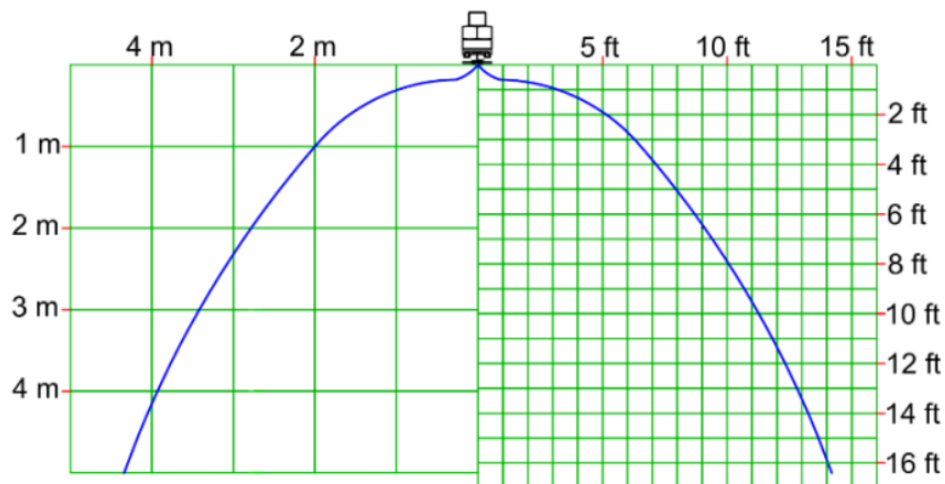
*Table 7: Sprinkler's parameters and droplet size for modelling*

|                     |             |                   |
|---------------------|-------------|-------------------|
| Density             | 1000        | kg/m <sup>3</sup> |
| Superficial Tension | 0.0728      | N/m               |
| Dn                  | 20          | mm                |
|                     | 0.02        | mm                |
| Sprinkler Area      | 0.00031415  | m <sup>2</sup>    |
| Sprinkler Flow      | 26          | gpm               |
|                     | 1.638       | l/s               |
|                     | 98.28       | lpm               |
|                     | 0.001638    | m <sup>3</sup> /s |
| Water flow speed    | 5.214070    | m/s               |
| Weber Number        | 7469        |                   |
| Dv50                | 0.002557914 | m                 |
|                     | 2.55791383  | mm                |
|                     | 2557.91383  | um                |

## **Watermist System**

The specifications for the system are the following:

- Activation Temperature: 57°C
- Water Pressure: 8 Bar
- K-factor metric: 19 (l/min 1bar)
- Flow rate: 53.74 lpm
- RTI: <50 (Fast Response)
- Drop Size DV90: <300um
- Drop Size DV50: <260um
- The montage will be pendent at 0.15m under the roof
- Maximum distance of 3,60 m between the nozzles and a maximum of 1,80 m to any walls
- Minimum distance between nozzles, 2,45 meters
- Spray pattern indicated in the Figure 18

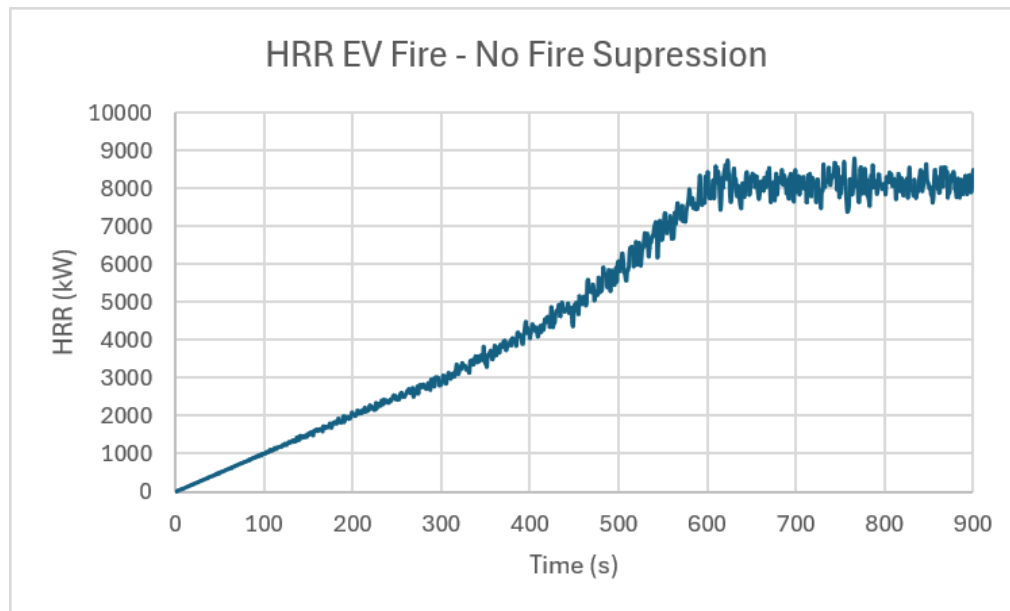


*Figure 18: Spray pattern*

## **EVALUATION OF CURRENT SITUATION & TRIAL DESIGNS**

### **Fire Scenario 01**

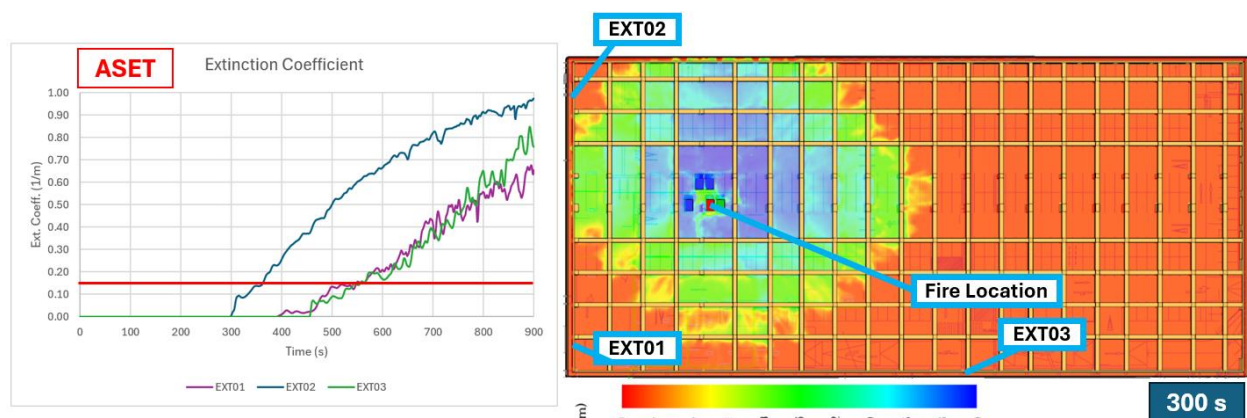
The Figure 19 contains the HRR developed for the fire with no active fire protection system active (actual parking conditions), where it is observed that the maximum HRR is reached at 600 seconds with a value of 8.2MW approximately.



*Figure 19: HRR of the fire with no fire protection system*

The extinction coefficient evolution and the visibility at the occupant's height it shown in the Figure 20, where is presented with a red line the minimum extinction coefficient for the occupants and therefore, identify the time interval at which the exit cannot be used anymore.

The Figure 21 contains the net heat flux at several intervals, where the incident heat flux in the adjacent cars present levels above 20 kW/m<sup>2</sup>. The Figure 22 contains the temperature of the hot gases around the parked cars adjacent to the car fire.



*Figure 20: Visibility of occupants*

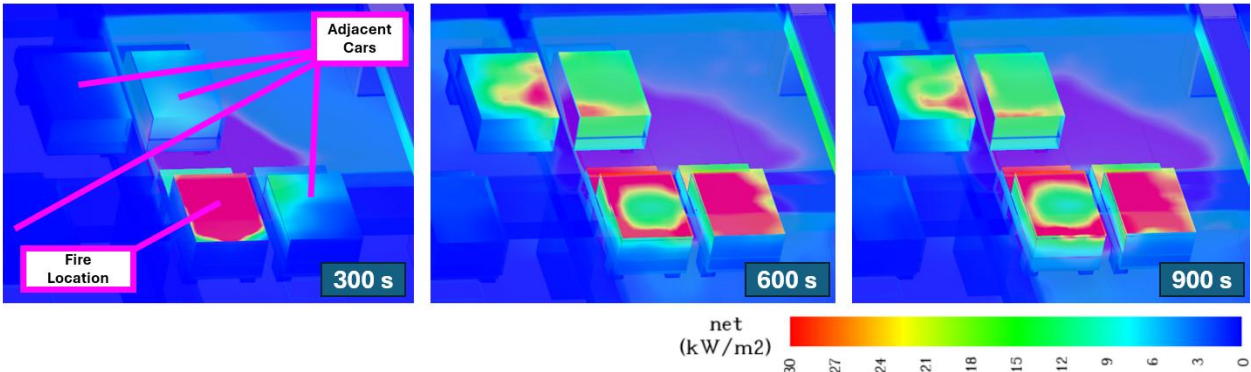


Figure 21: Net heat flux

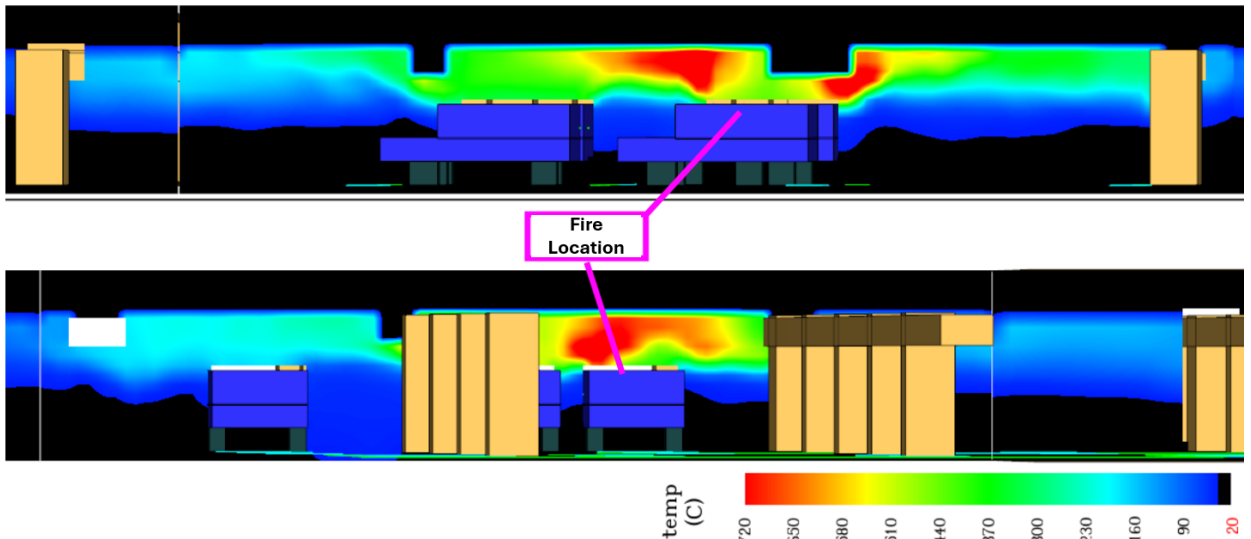


Figure 22: Temperature of hot gases around cars

## Fire Scenario 02

The Figure 23 presents the HRR for the fire with no sprinklers system and with the sprinkler system operating. As is described earlier in the present document, the sprinkler system controls the fire and it's able to contain the HRR around 386 seconds after the fire ignition. The HRR its contained and maintained at value of 4.2 MW approximately. The number of sprinklers that operated due to the fire its expressed in the Figure 24, where a total of 22 sprinklers operated.

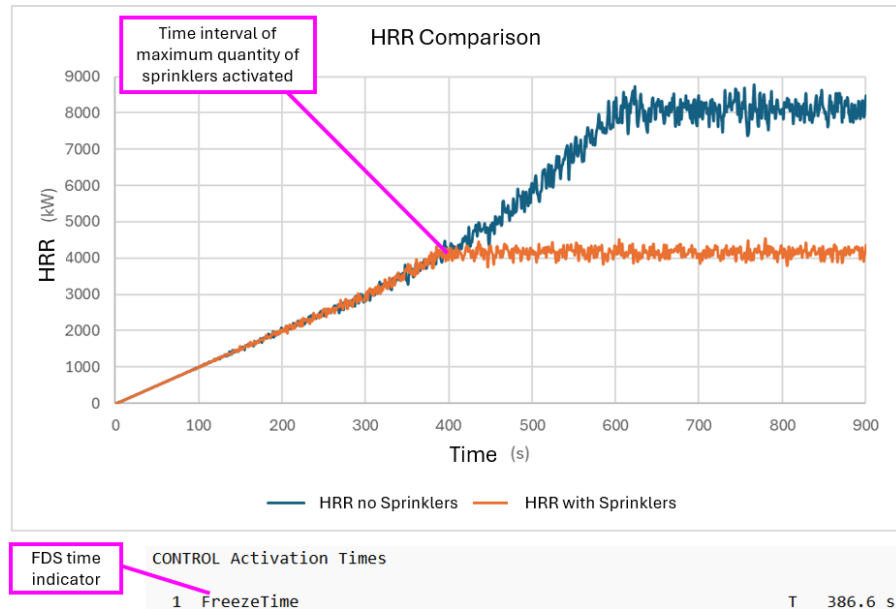


Figure 23: HRR Comparison

| DEVICE Activation Times |        |         |
|-------------------------|--------|---------|
| 37                      | SPK1   | 99.2 s  |
| 38                      | SPK2   | 89.8 s  |
| 39                      | SPK3   | 119.4 s |
| 40                      | SPK4   | 121.6 s |
| 41                      | SPK01  | 290.1 s |
| 42                      | SPK02  | 392.2 s |
| 43                      | SPK03  | 322.3 s |
| 44                      | SPK04  | 355.3 s |
| 55                      | SPK15  | 184.4 s |
| 56                      | SPK16  | 245.9 s |
| 57                      | SPK17  | 297.5 s |
| 58                      | SPK18  | 343.6 s |
| 151                     | SPK111 | 307.0 s |
| 152                     | SPK112 | 350.8 s |
| 153                     | SPK113 | 361.1 s |
| 154                     | SPK114 | 391.0 s |
| 76                      | SPK36  | 346.5 s |
| 77                      | SPK37  | 386.6 s |
| 78                      | SPK38  | 245.5 s |
| 79                      | SPK39  | 285.6 s |
| 82                      | SPK42  | 575.7 s |
| 97                      | SPK57  | 521.9 s |

Figure 24: Number of sprinklers operating

The extinction coefficient evolution and the visibility at the occupant's height it shown in the Figure 25, where is presented with a red line the minimum extinction coefficient for the occupants and therefore, identify the time interval at which the exit cannot be used anymore.

The Figure 26 contains the net heat flux at several intervals, where the incident heat flux in the adjacent cars present levels around 15-20 kW/m<sup>2</sup>. The Figure 27 contains the temperature of the hot gases around the parked cars adjacent to the car fire.

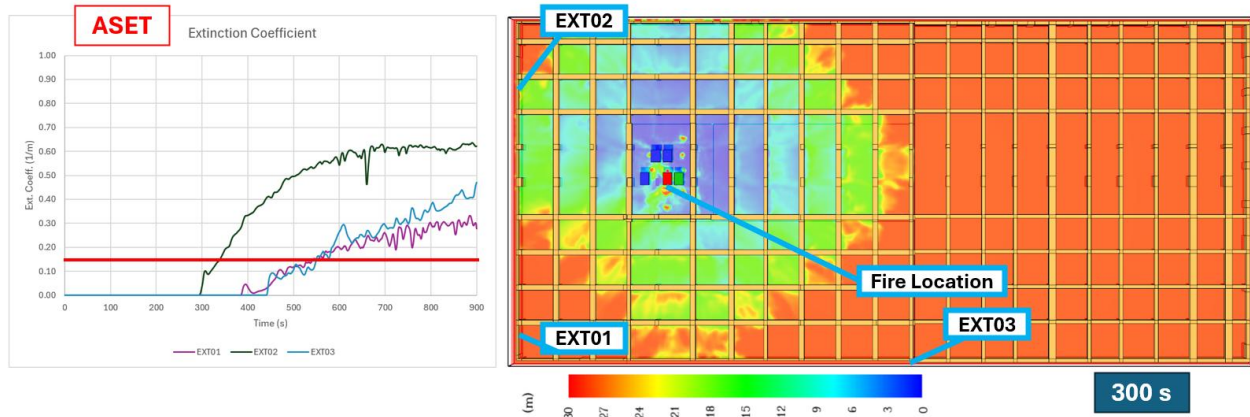


Figure 25: Visibility of occupants

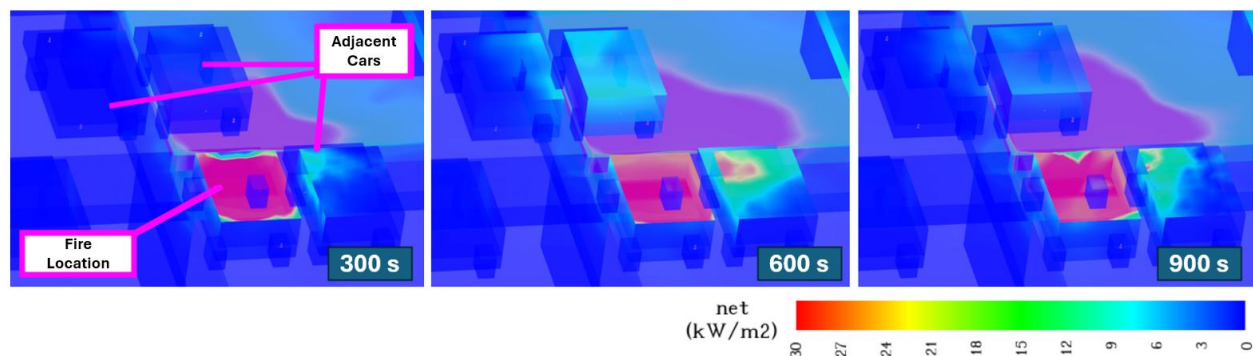


Figure 26: Net heat flux

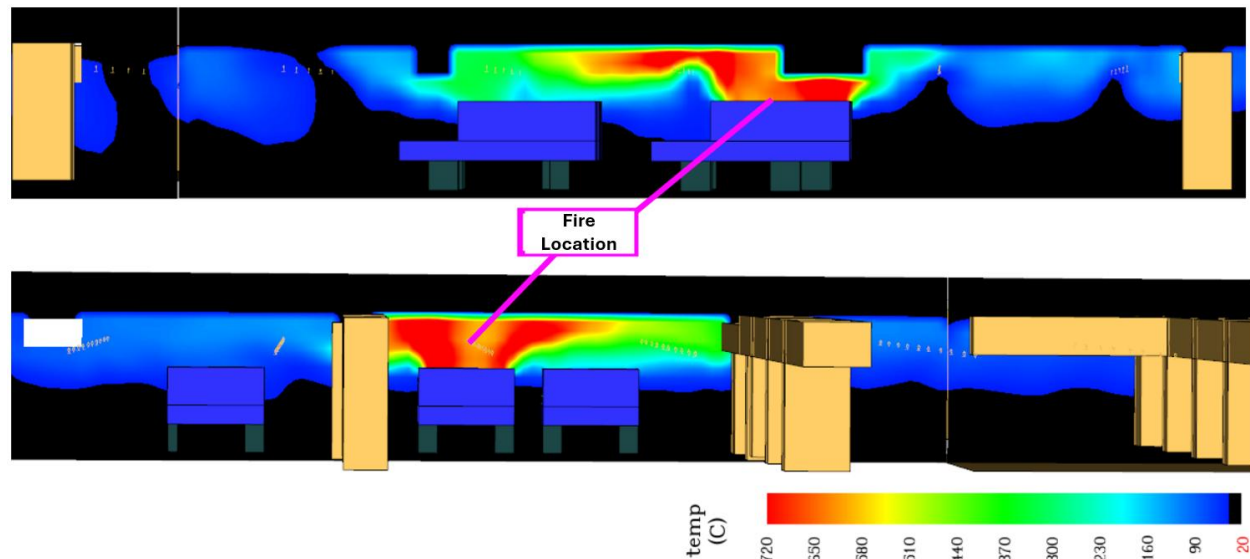


Figure 27: Temperature of hot gases around cars

The Table 8 contains the total sprinkler operated and therefore, the total amount of water discharged for the system.

Table 8: Total flow discharged

|                     |      |     |
|---------------------|------|-----|
| Operated Sprinklers | 22   |     |
| Flow per Sprinklers | 99   | lpm |
| Total Flow          | 2178 | lpm |
|                     | 575  | gpm |

### Fire Scenario 03

The Figure 28 presents the HRR for the fire with no sprinklers system and with the sprinkler system operating. As is described earlier in the present document, the sprinkler system controls the fire and it's able to contain the HRR around 386 seconds after the fire ignition. The HRR is contained and maintained at value of 4.2 MW approximately. The number of sprinklers that operated due to the fire it expressed in the Figure 29, where a total of 10 nozzles operated.

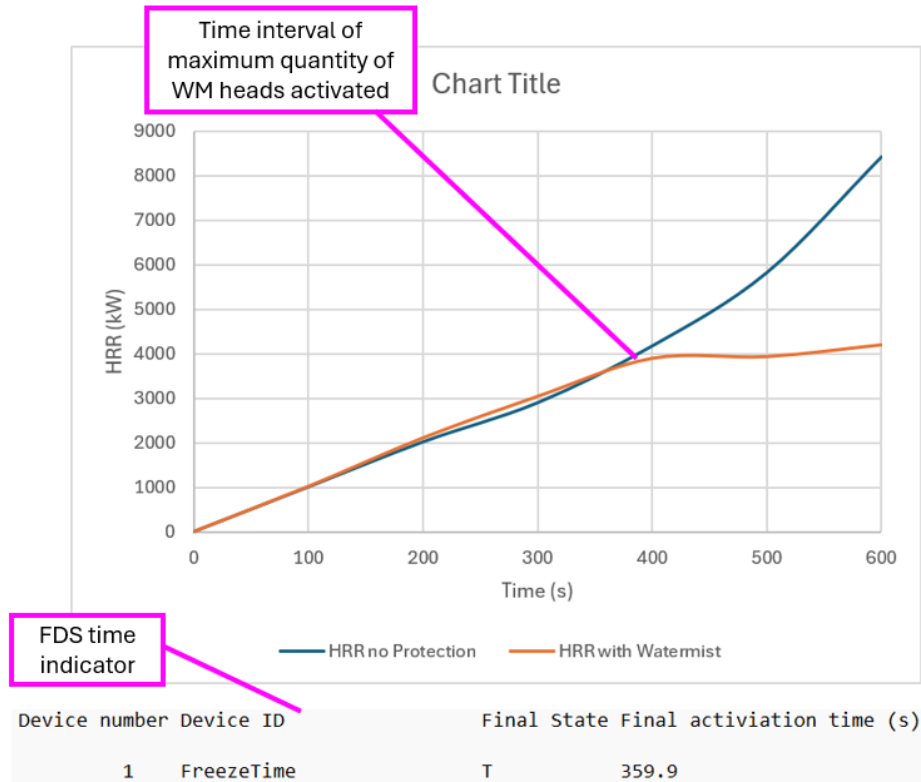


Figure 28: HRR Comparison

| DEVICE Activation Times |       |   |               |
|-------------------------|-------|---|---------------|
| 37                      | SPK1  | T | 150.6         |
| 38                      | SPK2  | T | 31.524        |
| 39                      | SPK3  | T | 265.4         |
| 40                      | SPK4  | T | 98.487        |
| 41                      | SPK01 | T | 441.3         |
| 55                      | SPK15 | T | 174.3         |
| 56                      | SPK16 | F | No Activation |
| 57                      | SPK17 | T | 359.9         |
| 76                      | SPK36 | T | 343.8         |
| 77                      | SPK37 | F | No Activation |
| 78                      | SPK38 | T | 353.3         |
| 79                      | SPK39 | T | 316.4         |

Figure 29: Number of nozzles operating

The extinction coefficient evolution and the visibility at the occupant's height it shown in the Figure 25, where is presented with a red line the minimum extinction coefficient for the occupants and therefore, identify the time interval at which the exit cannot be used anymore.

The Figure 30 contains the net heat flux at several intervals, where the incident heat flux in the adjacent cars present levels around 9-12 kW/m2. The Figure 27 contains the temperature of the hot gases around the parked cars adjacent to the car fire.

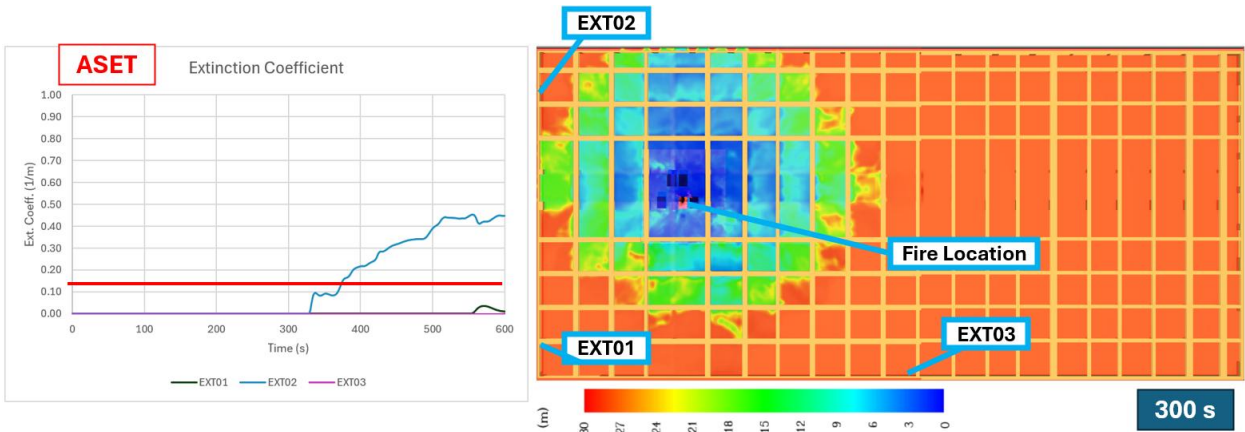


Figure 30: Heat Release Rate Evolution

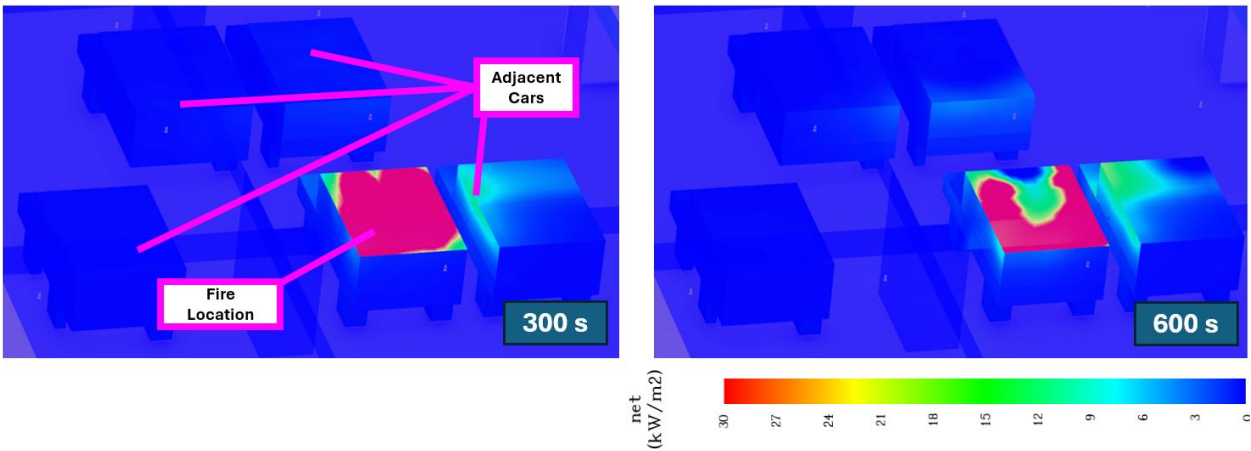


Table 9: Net heat flux

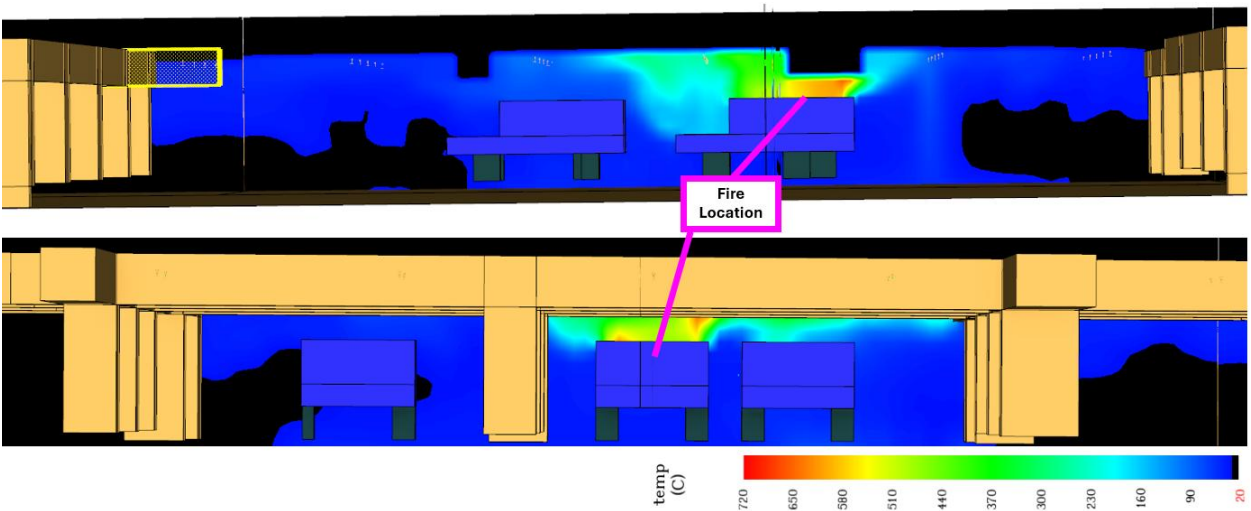


Figure 31: Temperature of hot gases around cars

## RESULTS AND DISCUSSION

The Figure 32 demonstrate the control of the fire for the sprinklers system and the water mist system. Both arrangements control the fire and restrict the fire to an HRR developed of 4MW approximately. The Table 10 shows the average and peak values for HRR, where it is possible to affirm that both extinction systems control the fire and decrease the HRR up to the half of the value.

The Table 11 contain a comparison between the sprinklers system and watermist system, where the amount of water discharged by the watermist system is 24.67% of the water discharged by the sprinklers system.



Figure 32: HRR Comparison

Table 10: HRR Average and Peak

|                 | HRR (kW)  |      |      |
|-----------------|-----------|------|------|
|                 | No System | Spkr | WM   |
| Average @ 600 s | 3323      | 2733 | 2607 |
| Max. Peak       | 8781      | 4540 | 4354 |

Table 11: Water flow comparison

| Sprinklers System   |        |     | Water Mist System |        |     |
|---------------------|--------|-----|-------------------|--------|-----|
| Operated Sprinklers | 22     |     | Operated Nozzles  | 10     |     |
| Flow per Sprinklers | 99     | lpm | Flow per Nozzle   | 53.74  | lpm |
| Total Flow          | 2178   | lpm | Total Flow        | 537.4  | lpm |
|                     | 575    | gpm |                   | 142    | gpm |
| Water Discharged    | 100    | %   | Water Discharged  | 24.67  | %   |
| Application Time    | 60     | min | Application Time  | 60     | min |
| Total Volume        | 130680 | L   | Total Volume      | 32244  | L   |
|                     | 130.68 | m3  |                   | 32.244 | m3  |

The Figure 33 presents a comparison of the incident net heat flux over the adjacent cars parked to the car fire. In the current situation, the adjacent cars to the fire receive a net heat flux of 30 kW/m<sup>2</sup> and above, increasing the probability of fire spreading. On the other hand, both fire protection systems decrease the heat flux on the nearby parked cars.

The operation of the sprinkler system decreases the net heat flux received by the parked cars to a level of 15-20 kW/m<sup>2</sup>, decreasing dramatically the probability of fire propagation. There are still zones and regions on the closest car parked where a flux of 30 kW/m<sup>2</sup> is presented.

Lastly, it is possible to see that the watermist system develops the lowest levels of heat flux on the adjacent cars, developing values 9-12 kW/m<sup>2</sup>. These levels are under the critical heat flux levels where nearby car's materials start ignition; therefore, the probability of fire propagation is very low.

The Figure 34 shows the radiation heat flux measured on the adjacent car, where it is possible to see that the watermist system blocks more radiation than sprinkler system and therefore reduces the incident radiation heat flux on the nearby car.

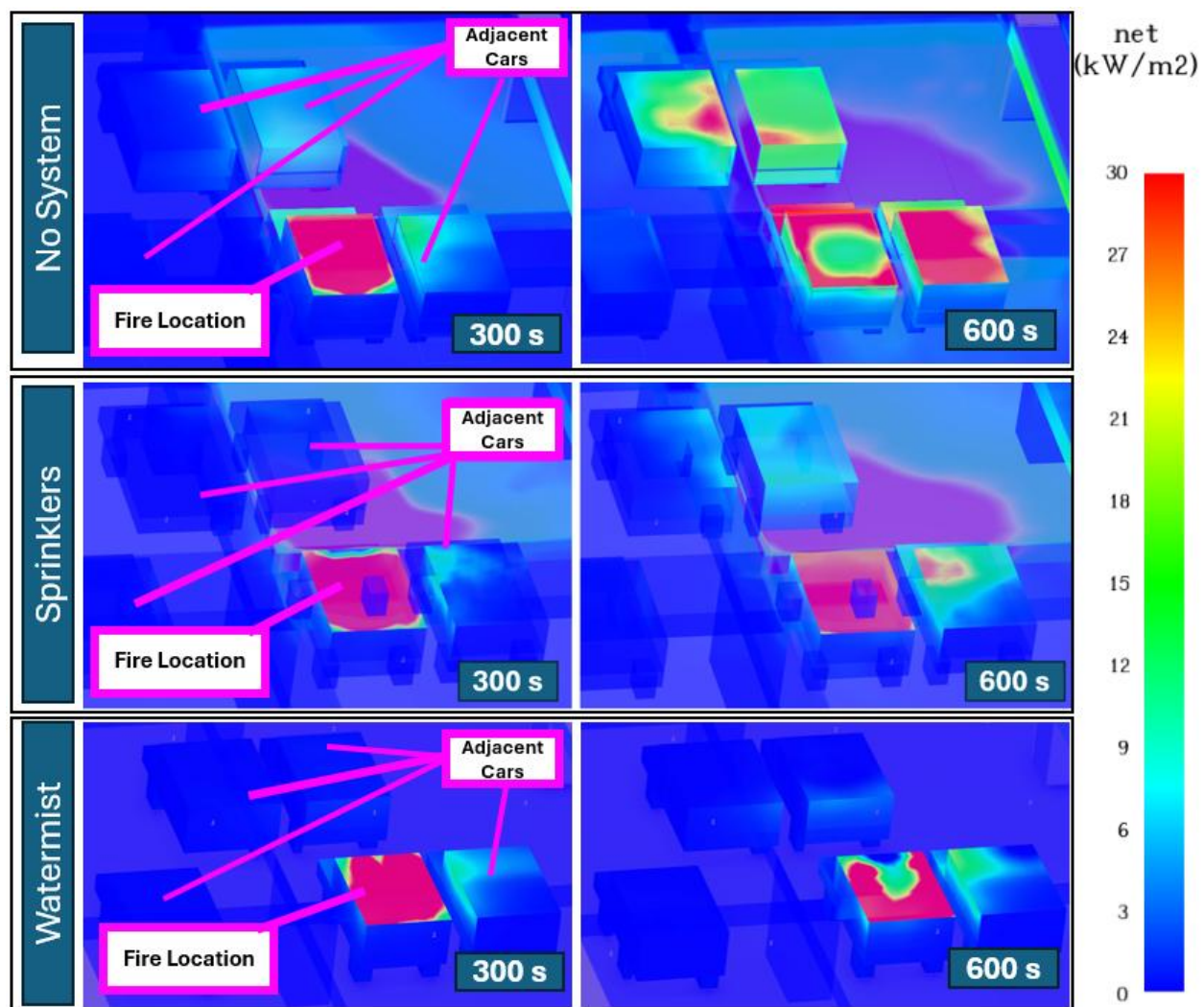


Figure 33: Net heat flux comparison

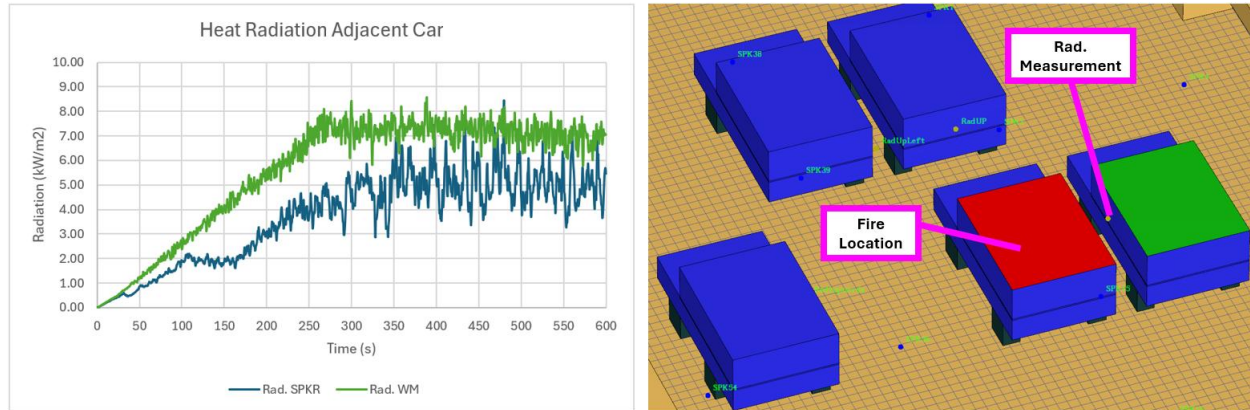


Figure 34: Radiation Heat Measurement

The Figure 35 shows a comparison of the hot gases' temperature between the three fire scenarios. It is possible to observe that the watermist system is capable to reduce temperature much more than the sprinklers system, generating a more suitable environment for firefighter intervention and occupant evacuation. A hot gases' measurement 6m away from the fire is presented in the Figure 36 and the Table 12 contains a comparison of average and max. temperature measured at the Figure 36.

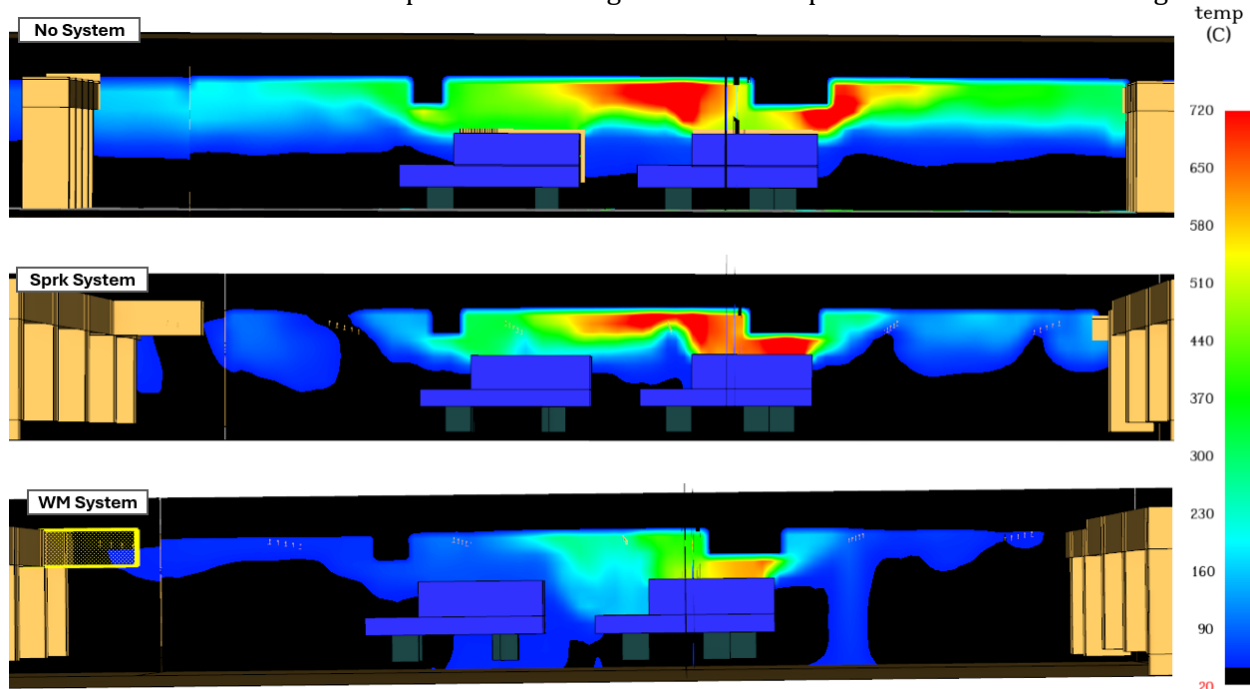


Figure 35: Hot Gases Comparison at 600 seconds – Elevation view

Table 12: Average and Max. Temperature Measurement

|         | Temperature (°C) |       |           |
|---------|------------------|-------|-----------|
|         | WM               | Sprk  | No System |
| Average | 35.50            | 44.82 | 56.65     |
| Max.    | 63.55            | 72.24 | 120.92    |

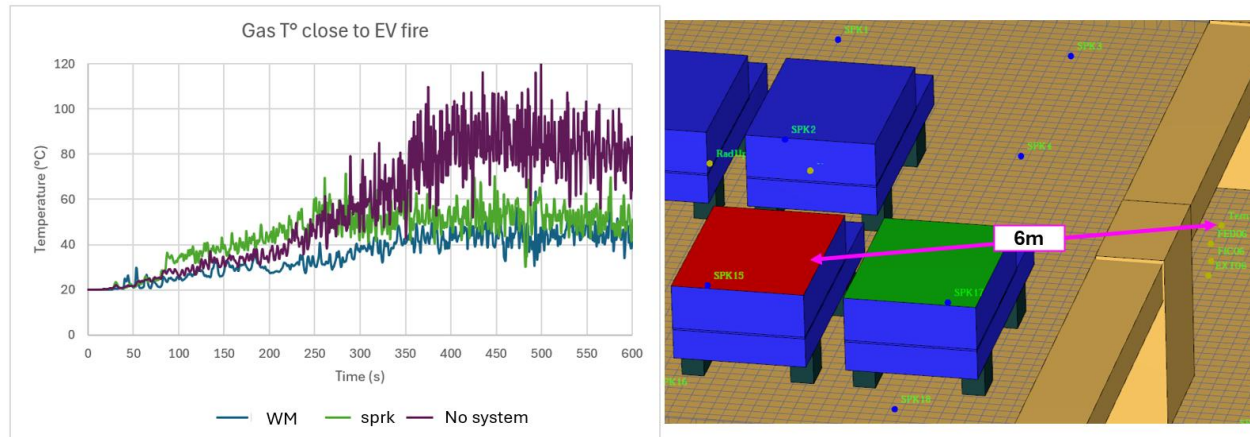


Figure 36: Hot Gases Measurement

The Figure 37 provides a comparison of the extinction coefficient present at the three exits of the car park, indicating by a red line the minimum value for the ext. coeff. The values of visibility conditions with sprinklers improve slightly compared with the fire scenario without sprinklers. On the other hand, the watermist system increases considerably the visibility on 2 of the 3 exits, allowing visibility for firefighter operations and occupant evacuation.

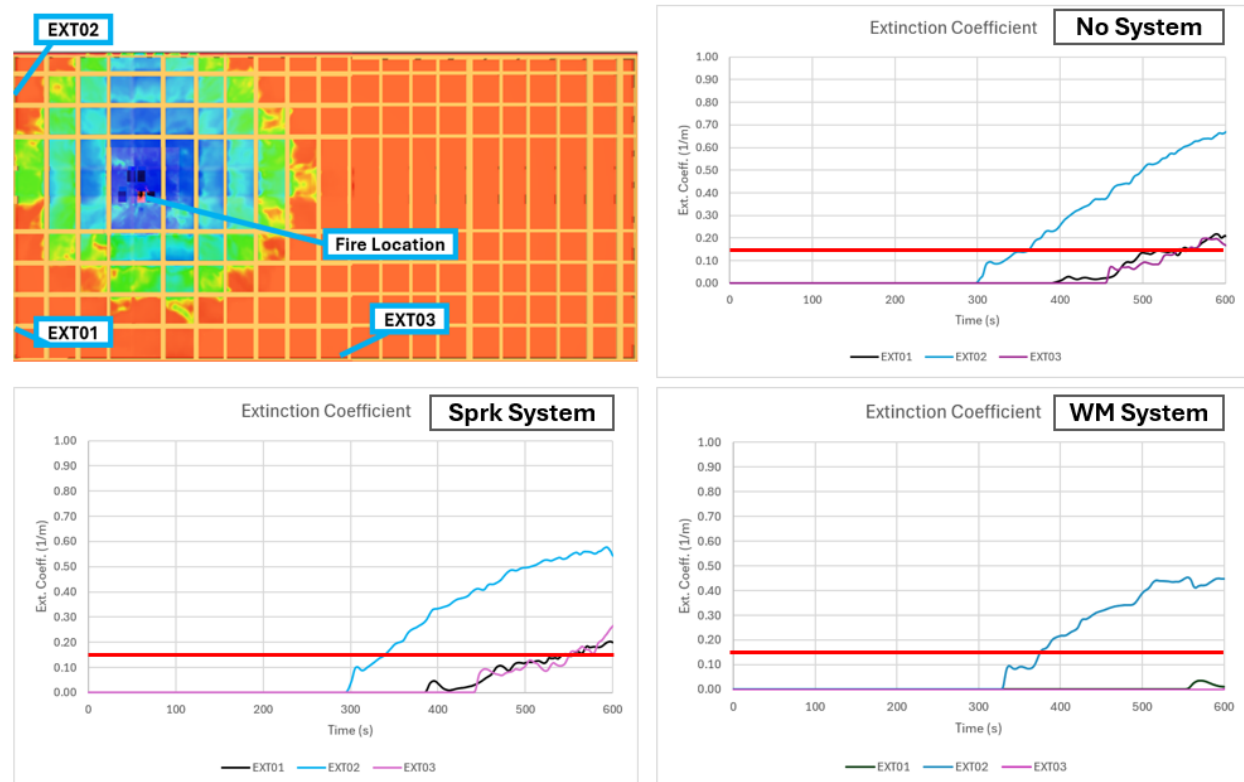


Figure 37: Ext. Coeff. & Visibility Comparison

## **CONCLUSIONS**

From the present study is possible to conclude that:

- EV fires exhibit critical characteristics that differ significantly from internal combustion engine (ICE) vehicle fires, particularly in the generation of HF, SO<sub>2</sub>, and other toxic gases associated with electrolyte decomposition. These emissions increase the severity of the event and highlight the need for fire protection systems capable of reducing temperatures and limiting gas release.
- Both conventional sprinklers and the water mist system successfully control the EV fire, substantially reducing upper-layer temperatures, radiative heat fluxes toward adjacent vehicles, and toxic gas concentrations. In all protected scenarios, conditions for evacuation and firefighter intervention are markedly improved compared to the unprotected case.
- The water mist system demonstrates superior efficiency in terms of water demand, achieving comparable levels of fire control with significantly less water than the sprinkler system. This reduction is particularly relevant in underground parking facilities, where the management of contaminated runoff presents operational and environmental challenges.
- Lower water discharge from the water mist system reduces the volume of contaminated firefighting water, mitigating environmental impacts associated with fluorides, heavy metals, and solid residues originating from the battery pack. This supports a more sustainable fire protection strategy and simplifies post-incident water handling as hazardous waste.
- The probability of fire spread to adjacent vehicles is significantly reduced when either protection system is used, due to lower net heat fluxes and reduced upper-layer temperatures. In the unprotected scenario, radiative heat fluxes reach levels consistent with ignition thresholds reported in the literature (11–18 kW/m<sup>2</sup>).
- From a design and operational perspective, water mist systems represent a viable alternative for existing parking garages that do not meet NFPA 88A opening requirements and face hydraulic or storage limitations. Their lower water demand and effective thermal control position them as an efficient and environmentally favorable solution.

## **Overall Conclusion**

The results of this study demonstrate that water mist systems are a technically effective and environmentally advantageous option for controlling EV fires in existing parking garages. Although neither sprinklers nor water mist systems fully extinguish a battery fire—consistent with experimental evidence—both reduce fire severity, improve tenability conditions, and support safer firefighter operations. The reduced water discharge and strong cooling performance of the water mist system make it a robust alternative to conventional sprinklers, particularly in facilities where contaminated water management is critical.

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