The present work was submitted to the Faculty of Mechanical and Electrical Engineering

Design of the Fire Extinguishing System for Electric Vehicles.

Bachelor Thesis

by

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Statutory Declaration

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I hereby affirm in lieu of an oath that I provided the submitted bachelor thesis

Design of the Fire Extinguishing System for Electric Vehicles.

I did not use any sources other than those stated. In case that the work is additionally submitted on a data medium, I declare that the written and the electronic form are completely identical. The work was not submitted in the same or similar form to any examination authority.

Nalaikh, 2025.05.02	
Place, Date	Signature

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I am immensely grateful for the support and guidance I have received through the journey of completing this thesis. I extend my deepest appreciation to my first supervisor, Prof. Sungchil Lee who has never lost his faith in me. His mentorship made me believe in myself and encouraged me to finalize this thesis, providing me with knowledge and confidence required to navigate complex challenges.

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Abstract

As man kind develops social life, everyone interests in urban life. This term urban life is simply to be near with new innovations and technologies by living in dense city. With demand for technologies increase globally, the adoption of more environmental and economical friendly technology is more likely to be chosen.

This thesis will focus on risk hazard of both traditional Internal Combustion Vehicles and lately developed Electric Vehicles. This thesis investigates the primary causes and characteristics of EV fire incidents, emphasizing why, despite lower incident rates compared to internal combustion vehicles, battery fires demand specialized suppression systems due to their prolonged burn time, risk of re-ignition, and emission of toxic gases.

Through analysis and comparison between existing fire extinguishing systems, cherry-pick the advantageous and efficient factors. This system design is guided by environmental conditions in Mongolia, focusing on parking standards and arena.

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List of Abbreviation

EV	Electric Vehicle
ICEV	Internal Combustion Engine Vehicle
BEV	Battery Electric Vehicle
PHEV	Plug in Hybrid Electric Vehicle
HEV	Hybrid Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
LIB	Lithium Ion Battery
CO	Carbon Monoxide
HF	Hydrogen Fluoride
$Pb+PbO_2+H_2SO_4$	Lead Acid Battery
Ni - Cd	Nickel - Cadmium Battery
Ni - Mh	Nickel - Metal Hydride Battery
LiX	Lithium Ion Battery
TR	Thermal Runaway
SEI	Solid Electrolyte Interphase
AC	Alternating Current
DC	Direct Current
SC	Short Circuit
BEST	Battery Extinguisher System Technology
AVD	Aqueous Vermiculite Dispersion
NFPA	National Fire Protection Association
HRR	Heat Release Rate
FRS	Fire and Rescue Services
FSS	Fire Suspension System
CO_2	Carbon Dioxide
ISO	International Organization for Standardization
CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
FEM	Finite Element Method

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1. Introduction

1.1 Background of the Study

In recent years, the number of Electric Vehicle users across the world has increased due to its environment friendly and economical efficient aspects. As more people adopt Electric Vehicles, the issue of its safety becomes critical. (1)

Table 1. The number of fire incidents reported by vehicle type in 2023-2024

Vehicle types	Fire accident cases
ICE Vehicles	1530 fire cases per 100000 vehicles sold
Electric Vehicles	25 fire case per 100000 vehicles sold
Hybrid Vehicles	3475 fire case per 100000 vehicles sold

Statistically, there are more cases of Internal Combustion Engine Vehicle's incident compared to cases of Electric Vehicle's incident. Even though an Electric Vehicle is safer, its fire gets rapidly hot and it's contained within a metal container, thus if the firefighters can't get to the fire and suppress the heat effectively. (1)

Table 2. Comparison between Internal Combustion Engine vehicles and Electric vehicles

Vehicle types	Primary Cause	Burn Duration	Emissions
ICE Vehicles	Fuel leaks, Engine mal-functions, Electrical shorts	Shorter, with lower risks of reignition	CO and Hydrocarbons
Electric Vehicles	Battery related issues, Charging faults	Prolonged, With reignition risks	HF and other toxic gases

There are many possible sources for Electric Vehicles While it's difficult to find concrete data on the breakdown of Electric Vehicle fire causes, the most widely known causes of the fire incidents are:

- **Thermal Runaway** Overheating in battery cells leads to a self-sustaining chain reaction.
- **Charging Issues** Faulty charging equipment or user error causes overheating or electrical faults.
- **Collisions** Physical damage compromises battery integrity, leading to internal short circuit.
- **Manufacturing Defects** Faulty batteries or wiring flaws increase fire risks.
- **Other Environmental Factors** Extreme temperatures or flooding disrupt battery stability.

1.2 Problem Statement

Since the innovation of the technology at astronomical speed, people have the same favors of shifting from common to excessive. With modern urban life, urgent using electronics and technologies (mostly transportations) is becoming daily life requirement. But, on the other hand, these many vehicles could require a massive square for parking. To save up space, many parking lot is way denser and have a capacity of:

- Small to Medium-Sized Facilities: Typically accommodate between 100 to 300 vehicles.
- Large Urban Garages: In major cities, parking structures can hold 500 to over 1,000 vehicles, especially in commercial or high-density residential areas.

With that many vehicles, one simple ignition could lead to massive property damage. In particular, indoor parked Electric Vehicles lead to even more serious consequences than those outside operating vehicles.

The traditional fire extinguishing systems are more likely suitable for Internal Combustion Engine Vehicles. Thus, the Fire Extinguisher itself needs to be specific for this purpose. There are many variants of Fire Extinguisher with different substances, mixture and even textures. Bur for Electric Vehicle, water is the most suitable substance to distinguish fire.

Lastly, for future development for Mongolia, the working environment is suitable and acceptable to Mongolian's harsh and unexpected conditions.

1.3 Research Questions

- What are the Primary causes and Characteristics of fire incidents in Electric Vehicles?
- If fire risk is relatively lower by statistics, then why is the Fire Risk is critically considered?
- What are the Limitations of conventional fire suppression systems when applied to Electric Vehicle fires?
- What materials and extinguishing agents are most effective in suppressing battery related fires while ensuring safety and environmental compliance?
- How can a fire extinguishing system be designed to detect, penetrate and suppress fires within sealed Electric Vehicles Battery compartment efficiency?

1.4 Scope and Limitation

This thesis focuses on the conceptual and technical design of a fire extinguishing system specifically tailored for Electric Vehicle, with an emphasis on addressing the Thermal Runaway phenomenon in Lithium Ion Battery packs. The system is intended for use in passenger and commercial EVs operating under the environmental and infrastructural conditions prevalent in Mongolia.

The study includes the following:

- Analysis of thermal runaway triggers and propagation in EV battery systems.
- Review of existing fire suppression technologies and their adaptation to EVs.
- Consideration of fire suppression agents that are effective, affordable, and safe for use in enclosed vehicle compartments.

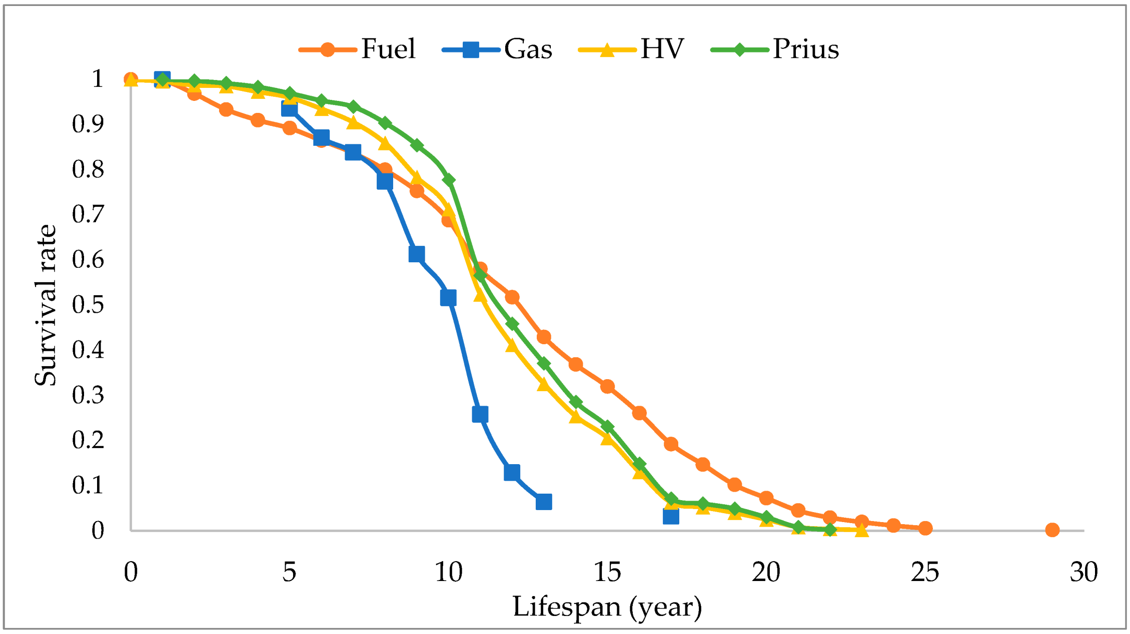


Figure 1. Cumulative Survival rate of the Vehicles in Mongolia

Above Figure.1 indicates that Mongolia is not that much suitable for adaptation of Electric Vehicles.

2. Literature Review

2.1 Overview of the Electric Vehicles

In 2023, Electric Vehicles accounted for approximately 18% of new car sales worldwide. With the rapid global shift toward Electric Vehicle, it will continue grow in the future. Countries like China, Norway, and the Netherlands are leading in EV adoption, supported by robust infrastructure and favorable policies. The expansion of model offerings and improvements in battery technology continue to make EVs more accessible and appealing to a broader consumer base.

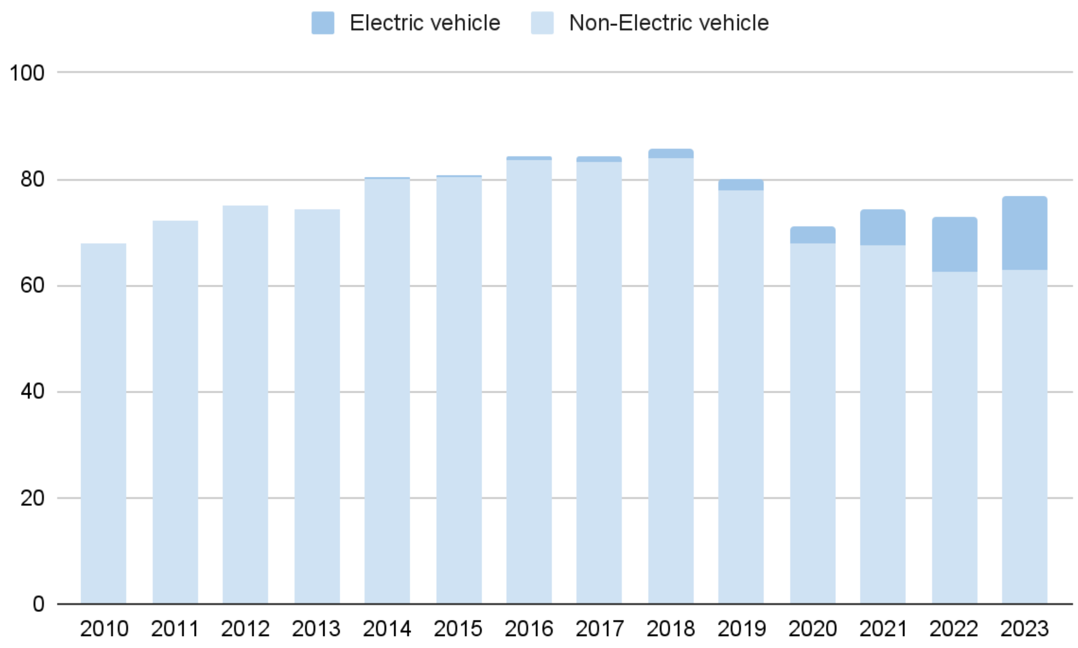


Figure 2. Overall sell of the Electric and Non-Electric vehicle in 2010 to 2023

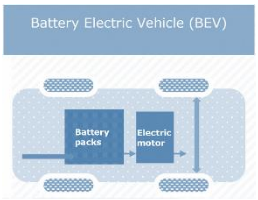
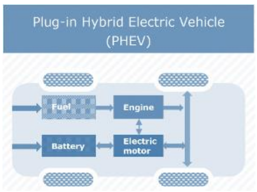
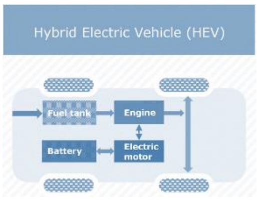
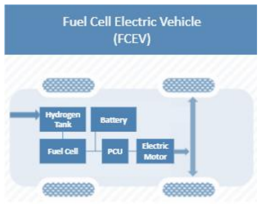
Above graph shows that sell of Non-Electric vehicle has dominated, almost entire sales. Sales volume steadily increased during first period, peaking around 2016–2018. After that, the overall vehicle sales volume slightly decreased compared to the peak years, but the share of Electric Vehicles visibly increased every year. EVs began to take up a bigger share of the total market, especially after 2020.

Key factors influencing the increase in Electric Vehicles would be:

- Environmental Concerns
- Government Incentives
- Rising Fuel Cost
- Urbanization

EVs can be categorized into several types based on their power sources and design.

Table 3. Types of Electric Vehicles

Types of Electric Vehicles			
Battery Electric Vehicles (BEVs):	Plug-in Hybrid Electric Vehicles (PHEVs):	Hybrid Electric Vehicles (HEVs):	Fuel Cell Electric Vehicles (FCEVs):
			

Battery Electric Vehicles (BEVs) have no gasoline engine and rely completely on charging from external electric sources, offering zero tailpipe emissions.
Plug-in Hybrid Electric Vehicles (PHEVs) can switch between electric power and gasoline, giving them longer driving ranges when charging stations are unavailable.
Hybrid Electric Vehicles (HEVs) primarily use gasoline but enhance efficiency with small electric motors that are charged internally, not by plugging in.
Fuel Cell Electric Vehicles (FCEVs) differ by generating their own electricity using hydrogen fuel, emitting only water vapor as a byproduct.

2.2 Key Components of the Battery Electric Vehicle

Among mentioned types of Electric Vehicles, this thesis will focus on Battery Electric Vehicle. Below figure contains main key components of Battery Electric Vehicle.

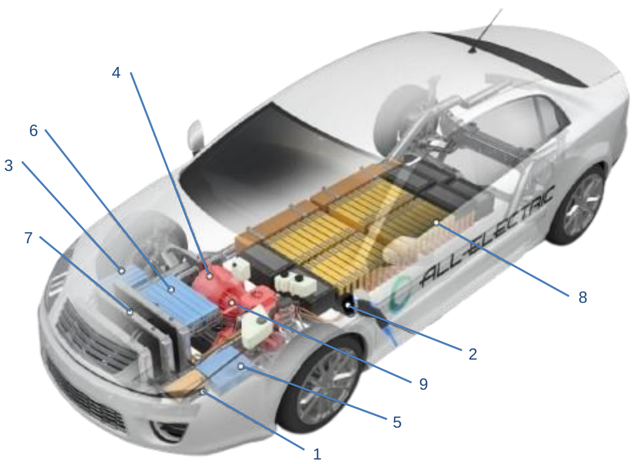


Figure 3. Main components of Electric Battery Vehicle

1. Battery (all-electric auxiliary): In an electric drive vehicle, the auxiliary battery provides electricity to power vehicle accessories.
2. Charge port: The charge port allows the vehicle to connect to an external power supply in order to charge the traction battery pack.
3. DC/DC converter: This device converts higher-voltage DC power from the traction battery pack to the lower-voltage DC power needed to run vehicle accessories and recharge the auxiliary battery.
4. Electric traction motor: Using power from the traction battery pack, this motor drives the vehicle's wheels. Some vehicles use motor generators that perform both the drive and regeneration functions.
5. Onboard charger: Takes the incoming AC electricity supplied via the charge port and converts it to DC power for charging the traction battery. It also communicates with the charging equipment and monitors battery characteristics such as voltage, current, temperature, and state of charge while charging the pack.
6. Power electronics controller: This unit manages the flow of electrical energy delivered by the traction battery, controlling the speed of the electric traction motor and the torque it produces.
7. Thermal system (cooling): This system maintains a proper operating temperature range of the engine, electric motor, power electronics, and other components.
8. Traction battery pack: Stores electricity for use by the electric traction motor.
9. Transmission (electric): The transmission transfers mechanical power from the electric traction motor to drive the wheels.

Electric Vehicle burning accidents most likely start from its Battery source, it is most efficient to place the Fire Extinguisher under the Battery source. The overall system will be placed within floor of the Indoor Garage, parallel to the Battery. The flow and the capacity of the extinguisher will be calculated accordingly to the battery properties.

2.2.1 Lithium Ion Battery

Lithium is the lightest element to make a battery. It is also a highly reactive alkali metal that readily loses its electron to become an ion, because it has only 1 electron in its outermost shell. Since it can produce more ions, higher energy can be stored with a lesser amount of lithium. This is called the Energy Density. A Singular Lithium-Ion cell can produce about 3.7 V voltage which is relatively higher than other alkalines, which produce only 1.5 V at most. This high energy density made the possibility of making smaller battery packs with a large amount of energy and less mass. (2)

Lithium Ion Battery goes through 2 cycles, which are charging and discharging cycles. It consists of multiple Lithium Ion Cells in series connection, along with a protective circuit board. Inside the Ion Cells:

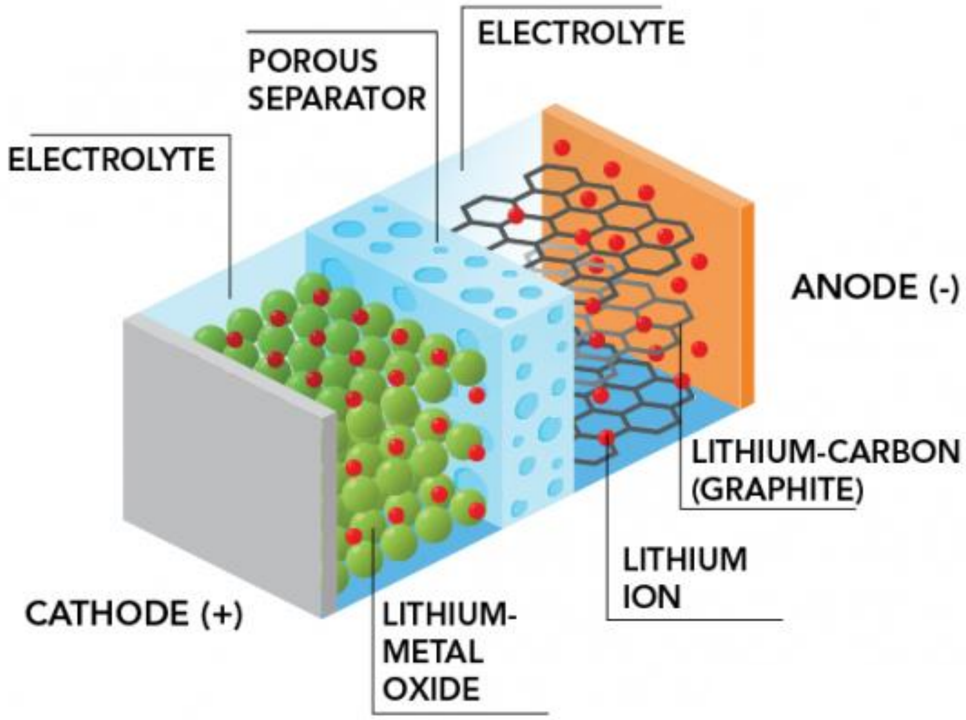
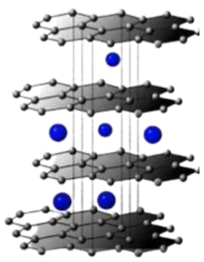


Figure 4. Components of Lithium Ion Cell

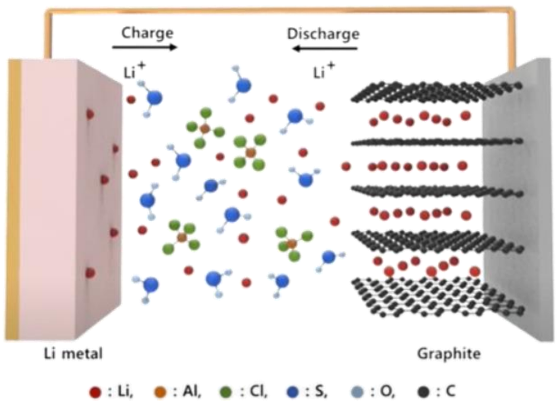
- **Cathode Materials:** The positive electrode, where Lithium Ions are stored during charge. Common cathode materials include Lithium Cobalt Oxide ($LiCoO_2$), Lithium Iron Phosphate ($LiFePO_4$), and Lithium Nickel Manganese Cobalt Oxide ($LiNiMnCoO_2$). Each material presents a balance between energy density, safety, cost, and lifespan.
- **Anode Materials:** The negative electrode, where Lithium Ions are stored during discharge. Traditionally, Graphite C_6 has been the predominant anode material due to its stability and favorable electrochemical properties.
- **Separator:** A porous polymeric film (Polyethylene or Polypropylene) that separates the electrodes while enabling the exchange of Lithium Ions from one side to the other. Separator allows only the Lithium Ions to pass through, because they are electron phobic.
- **Electrolytes:** A liquid or gel that conducts electricity (conducting Lithium salt solution), which transports Ions between the anode and cathode. While conventional LIBs use liquid electrolytes, research into solid-state electrolytes seeks to improve safety and energy density by mitigating issues like leakage and flammability.

The Anode and Cathode store the Lithium. The Electrolyte carries positively charged Lithium Ions from the Anode to the Cathode vice versa through the Separator. The Movement of the Lithium Ions creates free electrons in the Anode which creates a charge at the positive current collector.



During the charging cycle, the battery is connected to an external charging source. electrons run from the Cathode to the Anode. This causes Lithium Ions to move from the Cathode, then pass through the electrolyte to the Anode. When ions reach the Anode, they occupy the spaces between the Graphite atoms, thus the graphite gets loaded or charged with the Lithium Ions.

Figure 5. Graphite loaded with Lithium Ions



During the discharging cycle, the battery supplies the power to the external load for instance the electric motor. Ions loaded in the Graphite Anode move through the separator and reach the Cathode.

Figure 6. Illustration of the Charging and Discharging process

Lithium Ion Battery fires are complex due to the potential for thermal runaway, where an increase in temperature leads to self-sustaining exothermic reactions. This process can result in the release of flammable and toxic gases, posing significant challenges for fire suppression. Effective extinguishing agents must address high temperatures, rapid flame propagation, and hazardous emissions associated with Lithium Ion Battery fires.

2.3 Thermal Runaway

Thermal Runaway is commonly occurred by physical damage to battery cells, overcharging, exposure to excessive heat, or manufacturing defects. These initiators increase the initial temperature, leading to decomposition of the electrolyte and other components. Causes of chemical decomposition would be: (4)

- Solid Electrolyte Interphase starts to break down
- Electrolyte and Electrode materials begin to decompose

These reactions generate heat, which results thermal expansion inside the cell. Another dangerous substance form inside the cell is Flammable Gas. When this gas builds up, and create enough difference between inside and outside, the Safety Valve opens to vent gases. The gases burst the battery and almost always ignite. This fire then rapidly propagates across all the cells in the battery, causing thermal runaway in otherwise undamaged cells. The explosive nature of the molten metal and the degree of collateral fires it causes is huge, causing peripheral fires to spread to surrounding areas.

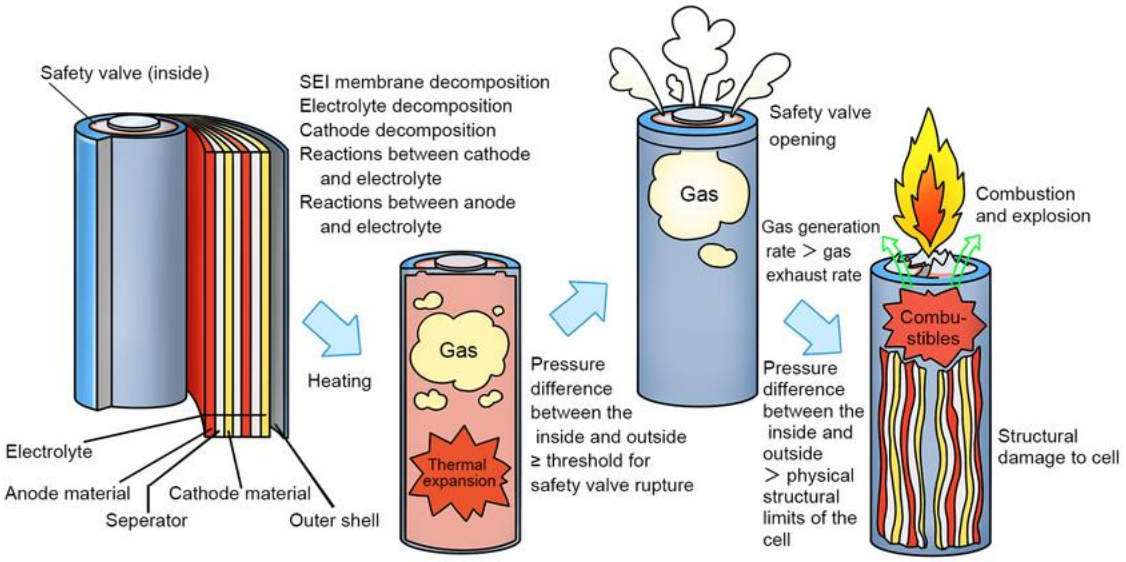
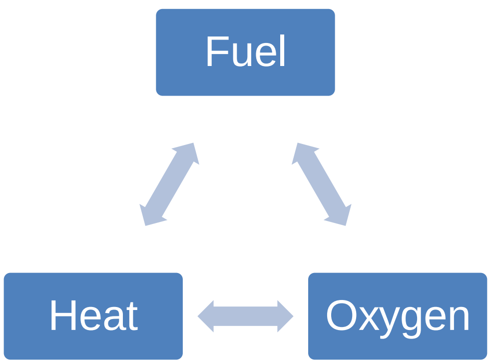


Figure 7. Mechanical diagram of the Thermal Runaway

Lithium Ion Batteries contain oxidizing materials, especially in the cathode that can release oxygen atoms during decomposition. This internal oxygen feeds combustion reactions inside the battery, without any air. On the other hand, The electrolyte in the battery (typically a flammable organic solvent like ethylene carbonate) acts as fuel. So, when thermal runaway starts, the battery has its own oxidizer and fuel, also able to generate its own heat.



Thus, unlike other fires which can be extinguished by just cutting down oxygen, to extinguish this fire, cutting down heat by cooling with water.

Figure 8. Fire Triangle

Thermal runaway in Lithium Ion Batteries remains a significant safety concern. Continued advancements in materials science, battery design, and monitoring technologies are pivotal in addressing the challenges posed by thermal runaway.

2.4 Indoor Parking

Ulaanbaatar, Mongolia's capital, is experiencing rapid urbanization, leading to increased demand for structured parking solutions. While comprehensive data on all indoor parking facilities is limited, notable examples provide insight into the city's current infrastructure.

2.4.1 Structural Design

Most indoor parking garages in Ulaanbaatar are reinforced concrete structures, designed to support multiple levels of vehicle load while providing durability against harsh winter conditions.

- Structural System:
  - Cast-in-place reinforced concrete for slabs, columns, and beams.
  - Post-tensioned concrete for longer spans in larger garages (reduces the number of support columns, improving vehicle maneuverability).
- Foundation:
  - Raft or mat foundations are common due to variable soil conditions and the need for seismic resistance.
  - Pile foundations are used for larger structures or where soil bearing capacity is low.
- Seismic Design:
  - Mongolia, including Ulaanbaatar, is in a seismic zone. Therefore, structures include shear walls, braced frames, and ductile detailing as per local or international seismic design codes.

3. Methodology

The methodology of this thesis focuses on the conceptualization, comparative analysis, and simulation-based design of a fire extinguishing system specifically tailored to Electric Vehicle Battery fires. Given the absence of physical prototyping due to safety and resource constraints, the approach combines qualitative and quantitative analyses to arrive at an optimized design solution that is environmentally adaptable, economically viable, and technically effective.

3.1 Research Design and Approach

With various types of Fire Extinguisher, all beneficial aspects from each extinguisher are included in this Extinguisher System. In Mechanical Engineering, designing new system starts from listing all functions. After listing all functions, proper parts and techs are selected for action. Sometimes, one mechanism could be used for two or more application. It takes great wisdom from Mechanical Engineers to decide on this.

3.1.1 List of Functions

- Detect Fire
- Activate Extinguisher
- Transport Extinguisher
- Release Extinguisher into fire
- Supporting functions
  - Connect System to the Transporter
  - Connect Transporter into Frame
- Remote Monitoring
  - Pressure Monitoring
  - Flow Rate Monitoring
  - Temperature Monitoring
- Extinguisher pressurizer

Those listed function's technology or parts will be explained with details in section 4.1. After deciding all mechanisms, dimensioning takes step. It takes quite a few redoing to finalized the design, before passing all simulations, tests, and analysis.

3.1.2 Data Sources and Literature Review

All technical and statistical data are valid data provided by formal sources. Special focus is given to localization, adapting international best practices to the Mongolian context, including cost-effectiveness, ease of deployment in remote areas, and compatibility with locally available firefighting equipment. Figure.1 shows that more than 50% of the total Vehicles are located in the capital Ulaanbaatar.

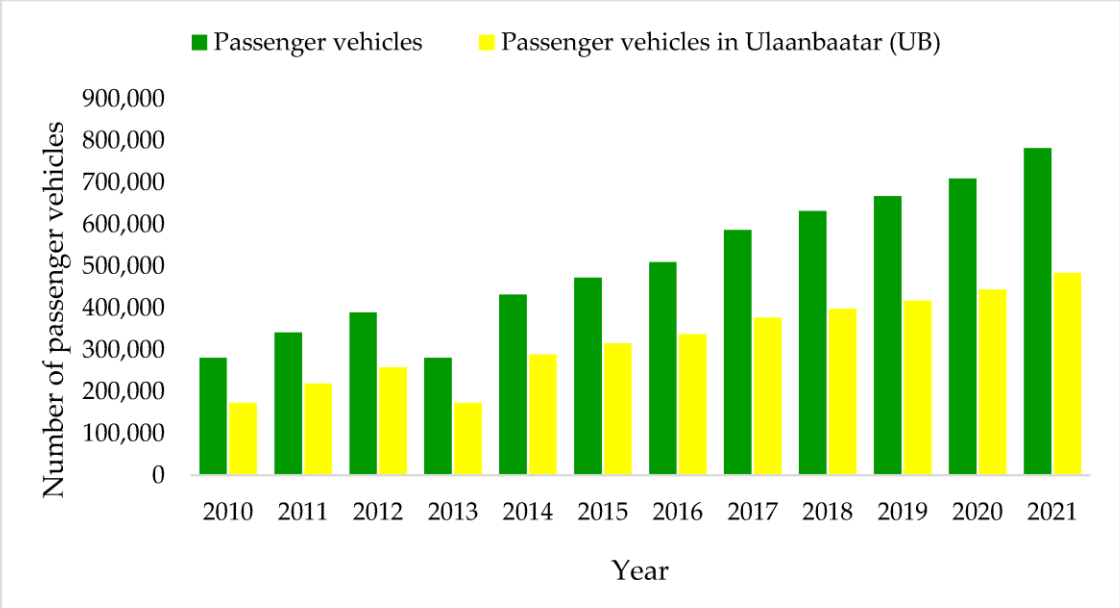


Figure 9. Number of Passenger Vehicles in Mongolia between 2010 and 2021

- The design is conceptual and simulation based, physical prototyping and full-scale fire testing are beyond the current research scope due to resource and safety constraints.
- The system is not tested across all Electric Vehicle makes and models; assumptions are made based on standard lithium-ion battery configurations.
- The research focuses primarily on thermal incidents originating from the battery pack and does not address fires from other sources such as electric motors, wiring, or charging systems.
- The environmental focus is specific to Mongolian conditions; findings may not be directly generalizable to other countries with significantly different climates or infrastructure.
- Regulatory and legal considerations, including national safety standards and Electric Vehicle certification requirements, are mentioned but not exhaustively explored.

3.2 Existing Fire Extinguisher for Electric Vehicle

Several fire suppression agents have been assessed for their efficacy against LIB fires:

- **Water and Water-Based Agents:** Water's high heat capacity and cooling effect make it effective in suppressing LIB fires. Water mist systems, in particular, have shown promise by providing rapid cooling and gas absorption, thereby mitigating thermal runaway and preventing re-ignition.
- **Foam Suppressants:** Foam agents can smother flames and provide cooling effects. However, their effectiveness may be limited due to the potential for re-ignition if the battery remains at high temperatures.
- **Dry Chemical Agents:** Dry powders can interrupt the chemical reactions of a fire. While they may suppress surface flames, they often lack sufficient cooling capacity to prevent re-ignition in LIB fires.
- **Clean Agent Systems:** These systems use gaseous agents to suppress fires without leaving residue, making them suitable for environments with sensitive equipment. However, their effectiveness in cooling and preventing re-ignition in LIB fires may be limited.

Several companies have developed specialized fire suppression systems tailored for electric vehicles. These systems are designed to address the unique challenges posed by lithium-ion battery fires. Each solution varies in technology, application, and effectiveness depending on the vehicle type and fire risk level.

3.2.1 Aqueous Vermiculite Dispersion

AVD is an aqueous dispersion of chemically exfoliated Vermiculite. Vermiculite is the name given to a group of hydrated laminar Aluminum Iron Magnesium Silicates. Raw Vermiculite consists of thin, flat flakes containing microscopic layers of water.

When Vermiculite is exfoliated, either thermally or chemically, the microscopic layers of water are removed and this either causes expansion (thermally exfoliated) or creates microscopic, individual platelets that are freely suspended in water (chemically exfoliated). AVD is approximately 20% Vermiculite / 80% Water with a viscosity of 3000 cPs and a D90 of 180 microns (0.18mm). AVD is nonflammable and has excellent insulation properties.

Working Principle of the AVD

Due to the reactivity between a flammable metal fire and water, AVD is applied in the form of a 'mist' or 'foam'. The Vermiculite particles within the mist or foam are deposited on the surface of the burning fuel to create a film over the top of the fire. This film instantly dries and because the high aspect ratio platelet particles overlap and bind together, they produce a nonflammable oxygen barrier between the fire and the atmosphere.

This process offers cooling to the surface of the fire and as the AVD platelets begin to build up they form an oxygen barrier over the fuel source, the fire is gradually cooled and brought under control. Unlike other Class D Extinguishing Agents where the fire has to be left for long periods of time before the fire is truly under control and completely burnt out, AVD offers quicker control to the fire.

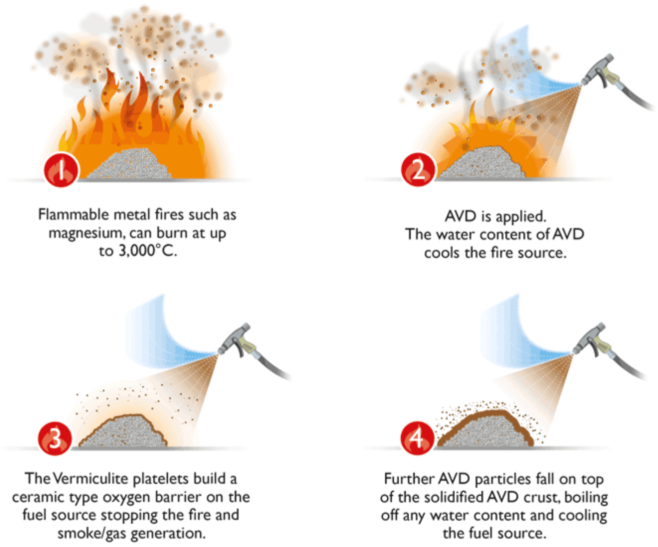


Figure 10. Application of the Aquerous Vermiculite Dispersion

The Aqueous Vermiculite Dispersion (AVD) system is an effective fire suppression solution specifically designed for Lithium Ion Battery fires.

Table 4. SWOT analysis of the Aquerous Vermiculite Dispersion

Strength	Weakness
• Specialized for Lithium Ion Fires • Dual Action Suppression • Non Toxic and Environmentally Friendly • Non Conductive After Application	• Limited Penetration into Enclosed Battery Packs • Residue Management • Storage and Shelf Life • Higher Initial Cost
Opportunities	**Threats**
• Growing EV Market • Integration in Smart Systems • Policy and Regulation • Diversified Use Cases	• Emerging Alternatives • Adoption Barriers • Technical Limitations in Extreme Conditions • Regulatory Uncertainty

3.2.2 Rosenbauer Battery Extinguisher System Technology

The Rosenbauer BEST is an extinguishing system for high-voltage LIB in electric vehicles. Tried and tested since 2018, it is the safest, most efficient, and fastest extinguishing option on the market to cool batteries and quickly stop Thermal Runaways.

Working Principle of the BEST

The Rosenbauer BEST is designed to effectively cool and suppress fires in high-voltage Lithium Ion Battery systems. Its operation involves the following steps:

- Detection: Identification of thermal runaway or fire within the battery pack.
- Penetration: The system employs a specially designed lance or nozzle capable of penetrating the battery housing without causing additional damage or risk.
- Agent Delivery: Once penetration is achieved, a cooling agent is directly injected into the battery modules to absorb heat and halt the thermal runaway process.
- Cooling and Suppression: The agent works to lower the temperature of the battery cells, preventing the spread of fire to adjacent cells and modules.

Figure 11. Rosenbauer Battery Extinguisher System Technology

Rosenbauer BEST offers a rapid, direct water injection method to effectively suppress electric vehicle battery fires at their source. Its remote-controlled, piercing nozzle design ensures firefighter safety while significantly reducing water usage and extinguishing time.

Table 5. SWOT Analysis of Rosenbauer Battery Extinguisher System Technology

Strength	Weakness
Specialized Technology Innovative Design Brand Reputation Portability	High Initial Cost Complex Training Requirements Limited Market Reach Reliance on Specific Scenarios
Opportunities	**Threats**
Market Growth in EVs Partnerships with EV Manufacturers Regulatory Support Global Expansion	Competition Evolving Battery Technology Economic Downturns Regulatory and Legal Risks

3.2.3 Water Sprinkler

Water sprinkler systems are among the most prevalent and effective fire suppression methods used in residential, commercial, and industrial settings. Their primary function is to detect and suppress fires in their early stages, thereby minimizing property damage and enhancing occupant safety. (4)

Working Principle of the Water Sprinkler System

An automatic fire sprinkler system head is a valve, in broad terms there are two types of sprinkler heads. All valve type sprinkler heads contain a heat-sensitive element and plug to control the flow of water: (5)

- A glass bulb sprinkler heads include a temperature sensitive glass bulb. The liquid in the glass bulb is color coded to indicate its operating temperature. When the liquid in the glass bulb expands and reaches its predetermined fixed temperature, the glass bulb breaks and then allows the free flow of water on to the source of heat that caused it to operate.
- A fusible link fire sprinkler head includes a two-part metal element that is fused by a heat-sensitive alloy that holds the valve plug in place. The heat-sensitive alloy acts as the heat-sensitive element of a fusible link sprinkler. When it reaches its' designated temperature, it melts, and the two metal plates detach from each other.

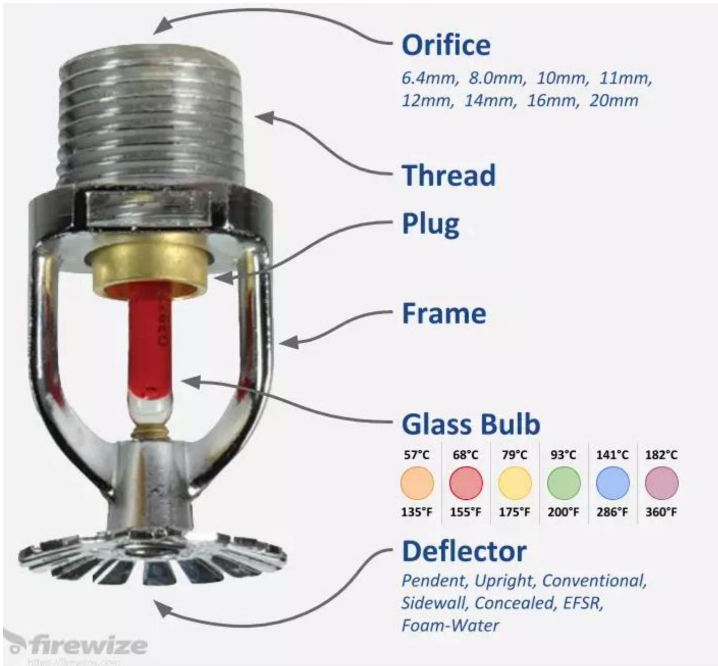


Figure 12. Components of the Head of Water Sprinkler

The Glass Bulb or Fusible Link in an automatic Water Sprinkler system is calibrated to operate at designated temperature. Sprinkler heads are selected and installed taking into consideration the use, location and typical ambient operating temperatures.

The Australian Standard AS 2118.1 states that the temperature rating chosen shall be not less than 30ºC above the highest anticipated temperature conditions except under specific conditions:

- Under glazing, translucent plastics and uninsulated metal roofs, in unventilated concealed spaces and show windows on external walls, and in other locations that are directly exposed to the sun, it may be necessary to install sprinklers with a temperature rating between 79°C and 100°C.

- High Hazard systems protecting high piled storage, sprinklers having a nominal temperature rating of 141°C shall be used at the roof or ceiling roof or ceiling, except where in the case of special sprinklers, the listing, manufacturers published data sheets and codes and standards referenced herein, recommend an alternative temperature rating.

- Where high-temperature sprinklers are installed within drying ovens or hoods over papermaking machines and the like (see Clauses 5.6.14 and 5.7.6), sprinklers at the ceiling or roof immediately over and to a distance of 3 m beyond the boundary of such structures shall be of the same temperature rating, subject to a maximum of 141°C.

The fluid in the bulb is typically a colored alcohol or another heat sensitive liquid that expands with heat, causing the glass to shatter and activate the sprinkler. This expansion of the liquid is what triggers the release of water. Also, to prevent false Glass Bulb shattering, there is small amount of air is sealed with it.

According to system's water supply pipe, it can also be categorized into two main types.

- **Wet Pipe**, the pipes are always filled with pressurized water. When a sprinkler head is activated, the water immediately flows out to extinguish the fire, providing fast reaction time. This type is used in areas, where temperatures do not drop below freezing as the water in the pipes could freeze.

- **Dry Type**, the pipes store pressurized air or nitrogen instead of water. When the sprinkler head is activated, the air pressure drops. A valve opens and release water into the pipes. The water then flows through the open sprinkler head onto to the fire. Dry pipe system has slower reaction times and typically used in areas prone to freezing, such as parking garages or warehouse.

Table 6. SWOT Analysis of Water Sprinkler System

Strength	Weakness
Proven Effectiveness Broad Applicability Cost-Effective Established Standards Automatic Activation	Limited Versatility Water Damage Installation Challenges Maintenance Requirements Over-Activation Risks
Opportunities	**Threats**
Growing Demand for Safety Integration with Smart Systems Customization Options Emerging Markets Sustainability Features	Competition from Advanced Systems Environmental Concerns Regulatory Variations Economic Factors Technological Obsolescence/ Outdated

3.2.4 Fire Blanket

A fire blanket is a protective film that prevents the expansion of combustion from spreading into surrounding combustibles. In most fire scenarios, cutting off air entry can prevent combustion propagation.

As cutting off air cannot extinguish Lithium Ion Battery fires, fire blankets can isolate Electric Vehicles from the outside world and prevent fires from spreading. The effectiveness of fire blankets has been demonstrated in automobile fire experiments conducted by various manufacturers.

Table 7. SWOT Analysis of Fire Blanket

Strength	Weakness
Oxygen Deprivation Chemical Free Easy Deployment Reusable	Limited Penetration Physical Handling Difficulty No Cooling Effect Storage and Size
Opportunities	**Threats**
Integration in EV facilities Supplementary Tool Green Buildings and Tech Clean Zones Emergency Kits for EVs	Thermal Runaway Escalation Market Competition Misuse or Delayed Deployment Durability Limitations

Fire blankets offer a low-tech, fast-deployment solution for surface fire suppression, especially in early stages of combustion or in conjunction with more advanced extinguishing technologies. While they provide certain strategic benefits in confined spaces and chemical-sensitive environments, their inability to actively cool or penetrate EV battery modules limits their standalone effectiveness in managing electric vehicle fires. Proper integration into a larger fire safety strategy is essential for maximizing their utility.

3.3 Electric Vehicle Fire Properties

Fire hazards pose a growing concern for electric vehicles, particularly when thermal runaway occurs in environments with a high concentration of Electric Vehicles. Such scenarios can escalate rapidly and lead to severe consequences. In this study, a large-scale fire simulation involving a full-sized electric vehicle was carried out to explore how different suppression strategies perform in response to battery initiated fires.

The research also examined how fires originating from thermal runaway propagate within an Electric Vehicle. Several fire suppression methods were tested namely fire blankets, water mist systems, and compressed air foam during the early ignition stages. Thermal data collected from various parts of the vehicle revealed intense heat, with peak temperatures in the cabin area reaching nearly 920 °C. Visual analysis showed flame jets extending as far as 2.5 meters.

Among the suppression methods, fire blankets smothered flames and gradually reduced the internal temperature by isolating Electric Vehicle from environment. This method reduces fire's hazard but not much effective for putting down fire. Water mist systems effectively cooled the area and helped extinguish flames. The compressed air foam not only suppressed the fire but also achieved a cooling effect, reducing temperatures at an average rate of almost 10 °C per second.

Due to the significant expense involved in full-scale EV fire testing, such experiments remain limited. Nevertheless, this study provides valuable insights into fire behavior in electric vehicles and evaluates the effectiveness of multiple suppression tactics, offering practical guidance for emergency response planning in EV-related incidents.

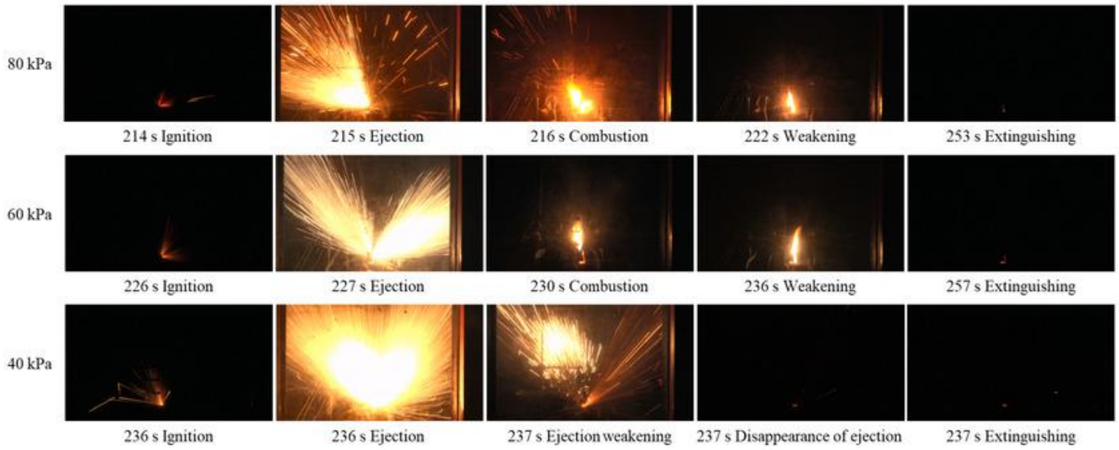


Figure 13. Thermal Runaway Phenomena of cells at 75% SOC under Different Pressures

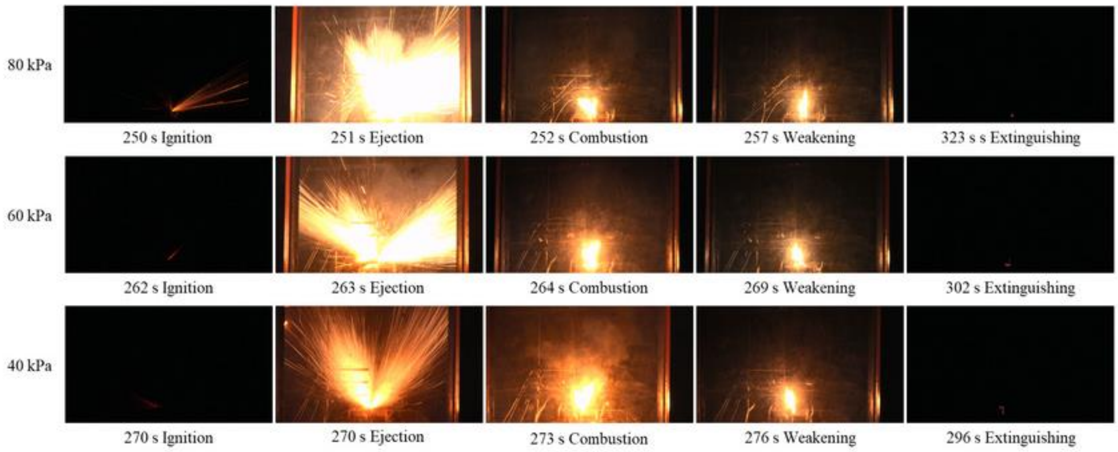


Figure 14. Thermal Runaway Phenomena of cell at 100% SOC under Different Pressures

3.3.1 Combustion Behavior of Electric Vehicle fire process

The timing of the event was recorded from the moment the electric heater was switched on. A minor explosive noise followed by a rapid increase in the battery pack's temperature signaled the onset of thermal runaway at around 2,368 seconds. The delay in triggering this event was likely due to the battery pack's cooling system, which reduced the heater's overall effectiveness. After this point, the thermal runaway process continued in succession. During this phase, the battery released dense white smoke. At approximately 2,773 seconds, visible flames emerged from beneath the vehicle, accompanied by a significant volume of smoke.

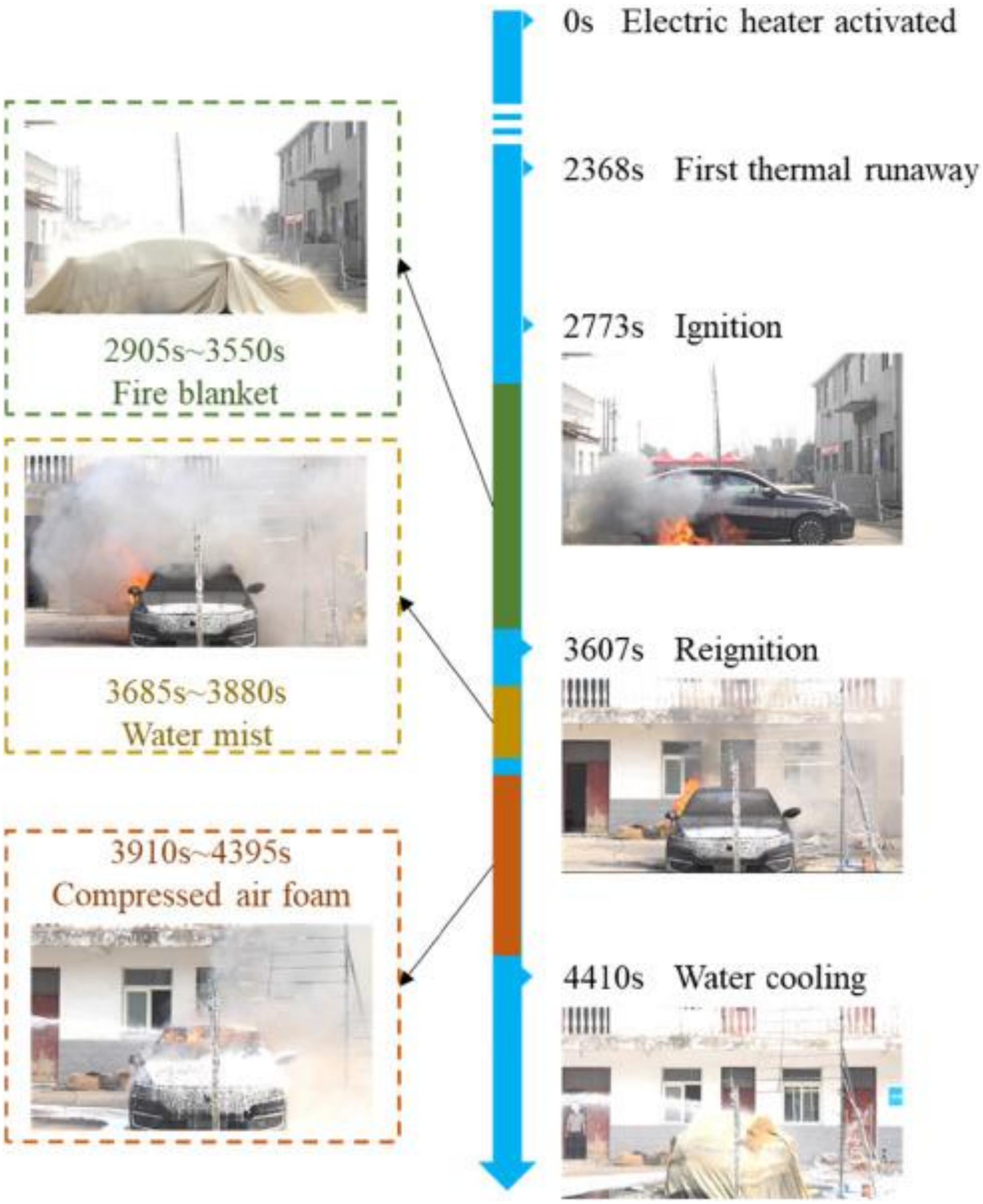


Figure 15. Timeline of the Experimental Procedure

As the fire advanced, it engulfed the car's exterior in flames. When the fire blanket previously applied was removed, the flames reignited almost immediately, confirming its role in temporarily suppressing the fire. Once the blanket was taken off, temperatures inside the vehicle began to rise again. A fine water mist system was then activated to evaluate its impact on both heat and smoke reduction. While it helped cool the area and visibly reduced smoke, it was not sufficient to fully extinguish the flames.

The water mist was withdrawn at approximately 3,900 seconds into the event, at which point compressed air foam was deployed. This method proved effective in putting out the fire, after which water was used to cool the battery pack and surrounding components. As noted in related studies, the early stages of thermal runaway in EV batteries are often marked by white smoke, sparks, and concentrated jets of flame. The ignition source was traced to a crack near the rear of the battery, close to the heating pad.

For analytical purposes, the vehicle was divided into four zones: the battery section, engine bay, trunk, and passenger cabin (refer to Figure 16). Among these, the passenger area is particularly prone to ignition. The fire began in the battery and spread along the chassis and body panels. After three distinct jet flame events, a sustained flame appeared near the right rear wheel. Heat and smoke migrated into the passenger compartment through structural gaps, including those in the rear seat and door seals (see Figure 17).

The fire then advanced from the right rear wheel into the trunk, eventually surrounding the vehicle's back half. Because the windows remained open during the experiment, the interior cabin experienced limited temperature rise. The highest external temperature recorded during this phase was 155.2°C. These findings suggest that in the early moments of an EV fire, the thermal effects on the passenger compartment and surrounding areas are contained—however, the presence of jet flames introduces significant safety concerns that demand focused mitigation strategies.

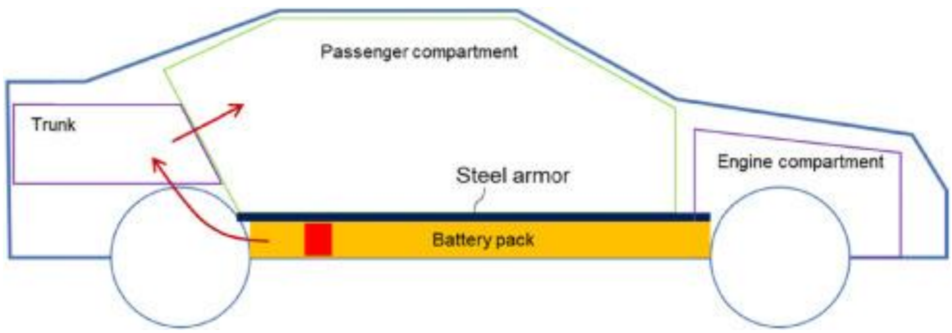


Figure 16. Paths of Flame and Smoke Propagation

Figure 17. Flame and Smoke expanded around the right rear of the car

3.4 Requirements for the Design

After comparing all existing extinguisher, most suitable and yet both Environmentally and Economically friendly extinguisher is water. In indoor garage, water supply can connect to the Extinguisher system by dry pipe, since Mongolia has harsh and unpredictable weather condition. It will prevent the risk of water freezing in piping system. (7)

To be fully automatic system, the Extinguisher system doesn't demand technological advanced sensors (Thermal Proximity Sensor). It could easily use the Glass Bulb. By recalling Figure.12 for this Extinguisher System mostly operate with Green or Blue Glass Bulb, since Electric Vehicle fire starts around 100℃.

3.4.1 Calculation of the Capacity of Water Sprinkler Head

To maintain the efficiency of the Extinguisher System, one system is designated per Electric Vehicle. Thus, the working area of the Extinguisher System is can be calculated by using equation (3.1).

Figure 18. Dimension of the Basic Electrical Vehicle

Dimension of typical Electrical Vehicle consists that:

width: $w \approx 2\,m$

length: $l \approx 5\,m$

$$\boldsymbol{A = w * l} \tag{3.1}$$

$$A = 2\,m * 5\,m = 10\,m^2$$

Design density in fire sprinkler systems refers to the amount of water flow rate that must be applied per floor area to effectively control or suppress a fire. It is a key parameter used in the hydraulic design of fire sprinkler systems.

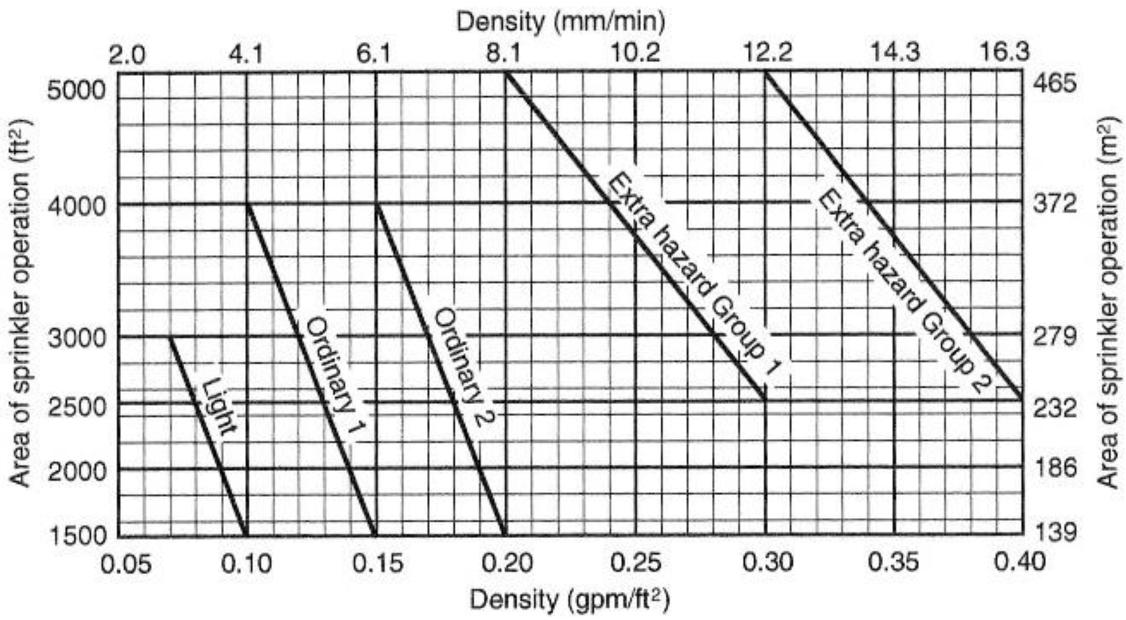


Figure 19. Design Density chart according to the National Fire Protection Association (NFPA)

By using above figure, the required Water Design Density can be found as around 6mm/min. Using equation (3.2) minimum required the water flow rate will be calculated.

$$\boldsymbol{q = d * A} \qquad (3.2)$$

$$q = 6\frac{mm}{min} * \frac{10^{-3}\,m}{1\,mm} * \frac{1\,min}{60\,s} * 10\,m^2 = 10^{-3}\frac{m^3}{s} = 60\frac{l}{min}$$

The second step is to calculate the minimum flow from the sprinkler given the K-Factor and the minimum head pressure by using the standard K-Factor formula:

$$\boldsymbol{q = k * p^{0.5}} \qquad (3.3)$$

Where:

p = the required pressure [bar]

q = the required flow from the first sprinkler [l/min]

k = the discharge coefficient of the sprinkler (k-factor) [l/min/bar^{½}]

The table below shows the conversion of some typical imperil sprinkler head k-factor conventions to the metric equivalent. (8)

Table 8. K-factor

Imperial [gpm/psi½]	2.8	4.2	5.6	8.0	11.2	14.0	25.2
Metric [l/min/bar½]	40.0	60.0	80.0	114.0	160.0	200.0	360.0

From equation (3.3) the required pressure can be calculated as:

$$p = \left[\frac{q}{k}\right]^2 = \left[\frac{60\ l/min}{40\ \ l/min/bar½}\right]^2 = 2.25\ bar = 0.225\ MPa$$

The Fire Sprinkle's head should withstand this pressure.

3.4.2 Accounting for Sprinkler water Pressure Loss due to Turbulance and Valves

Pipe fittings (tees, elbows, etc.) create turbulence in the water flow that causes pressure loss. These losses are not *friction* losses *per se*. However, they are calculated in terms of the equivalent friction loss of a length of pipe. NFPA 13 (**27.2.3.1.1**) says that losses due to certain fittings and valves should be understood in terms of Schedule 40 steel pipe based on the table below:

Table 9. Equivalent Schedule 40 Steel Pipe Length Chart

Fittings and Valves	Fittings and Valves Expressed in Equivalent Feet (Meters) of Pipe														
	½ in. (15 mm)	¾ in. (20 mm)	1 in. (25 mm)	1¼ in. (32 mm)	1½ in. (40 mm)	2 in. (50 mm)	2½ in. (65 mm)	3 in. (80 mm)	3½ in. (90 mm)	4 in. (100 mm)	5 in. (125 mm)	6 in. (150 mm)	8 in. (200 mm)	10 in. (250 mm)	12 in. (300 mm)
45° elbow	—	1 (0.3)	1 (0.3)	1 (0.3)	2 (0.6)	2 (0.6)	3 (0.9)	3 (0.9)	3 (0.9)	4 (1.2)	5 (1.5)	7 (2.1)	9 (2.7)	11 (3.3)	13 (4)
90° standard elbow	1 (0.3)	2 (0.6)	2 (0.6)	3 (0.9)	4 (1.2)	5 (1.5)	6 (1.8)	7 (2.1)	8 (2.4)	10 (3)	12 (3.7)	14 (4.3)	18 (5.5)	22 (6.7)	27 (8.2)
90° long-turn elbow	0.5 (0.2)	1 (0.3)	2 (0.6)	2 (0.6)	2 (0.6)	3 (0.9)	4 (1.2)	5 (1.5)	5 (1.5)	6 (1.8)	8 (2.4)	9 (2.7)	13 (4)	16 (4.9)	18 (5.5)
Tee or cross (flow turned 90°)	3 (0.9)	4 (1.2)	5 (1.5)	6 (1.8)	8 (2.4)	10 (3)	12 (3.7)	15 (4.6)	17 (5.2)	20 (6.1)	25 (7.6)	30 (9.1)	35 (10.7)	50 (15.2)	60 (18.3)
Butterfly valve	—	—	—	—	—	6 (1.8)	7 (2.1)	10 (3)	—	12 (3.7)	9 (2.7)	10 (3)	12 (3.7)	19 (5.8)	21 (6.4)
Gate valve	—	—	—	—	—	1 (0.3)	1 (0.3)	1 (0.3)	1 (0.3)	2 (0.6)	2 (0.6)	3 (0.9)	4 (1.2)	5 (1.5)	6 (1.8)
Vane type flow switch			6 (1.8)	9 (2.7)	10 (3)	14 (4.3)	17 (5.2)	22 (6.7)	—	30 (9.1)	—	16 (4.9)	22 (6.7)	29 (8.8)	36 (11)
Swing check*	—	—	5 (1.5)	7 (2.1)	9 (2.7)	11 (3.3)	14 (4.3)	16 (4.9)	19 (5.8)	22 (6.7)	27 (8.2)	32 (10)	45 (14)	55 (17)	65 (20)

3.4.3 Sprinkler water Pressure loss from Gravity

When water has to travel vertically upward in a pipe, the force of gravity counteracts the pressure that conducts it (pressure also increases when water moves vertically down). The head loss due to gravity for water is 0.433 psi for every foot of vertical elevation. Besides the friction losses, our example with the 100-ft. riser would lose 43.3 PSI simply because of height.

Pressure-wise, things aren't looking good for the Extra-Hazard room in our example. Combined head losses are up to 58.3 psi (43.3 psi + 15 psi) without counting any devices, cross-mains, or branch lines. With the actual demand (21.97 psi), the water supply needs to deliver over 80 psi at the riser. Water pressures above 80 psi can cause plumbing problems, so it's unlikely that a municipal water supply will meet this demand. The system will need a pump!

3.5 Selection

The normal Water Sprinkler System hangs upside down. This movement supports the spaying pressure, resulting large area covering and high flow output.

The overall system is pretty similar to the garden sprinkler irrigation. Sprinkler irrigation is a method of applying water to the land in a manner that mimics natural rainfall. Water is distributed through a system of pipes, usually by pumping, and is then sprayed into the air through sprinklers that break up the water into small drops. The water drops then uniformly fall to the ground.

4. System Design and Development

The proposed fire extinguishing system is designed for indoor parking facilities housing Electric Vehicles, where the risk of thermal runaway in Lithium Ion Batteries necessitates targeted and rapid suppression. This system uses a dry pipe water sprinkler network with thermally activated glass bulb sprinkler heads, optimized for installation beneath Electric Vehicle Battery packs.

4.1 System Overview

The core concept is a localized suppression unit assigned to each Electric Vehicle Parking spot. When a battery fire initiates and reaches ignition temperatures (typically 90–110°C), the heat-sensitive sprinkler activates, releasing water directly onto the battery compartment from below.

Typical Ulaanbaatar’s indoor parking garage consists around 120 to 150 vehicles. As of December 2023, there were 1061 Electric Vehicle checked in Mongolia. Also, there is around 1800 individual indoor parking garage in Ulaanbaatar. Statistacally, there would be 2 to 3 fire extinguisher is enough for one indoor parking garage.

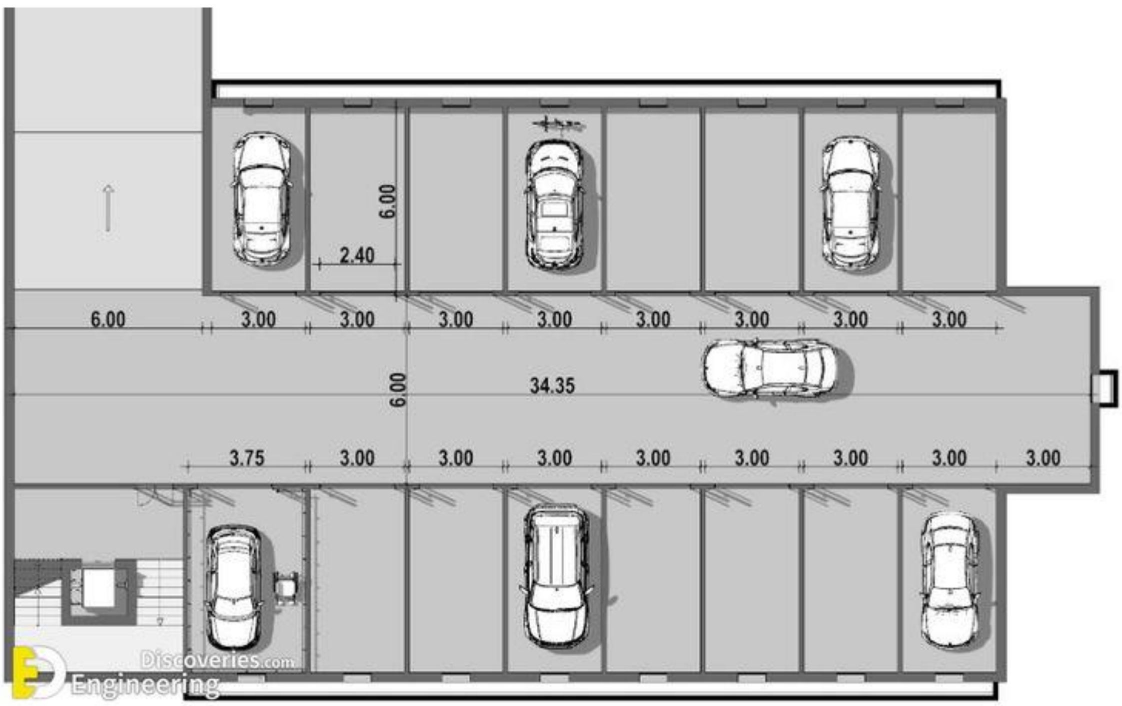


Figure 20. Standard of the Indoor Parking Garage

If all three parking placed in parallel with each other, piping system would simple.

4.1.1 Sprinkler Pump

A sprinkler pump plays a crucial role in delivering water from a storage reservoir or direct supply line to a connected sprinkler system during a fire emergency. Its function is to ensure a consistent and adequate water flow throughout the network. Typically, systems are equipped with two main pumps: one serves as the primary pump while the other remains on standby to ensure operational reliability. Additionally, a jockey pump is included to maintain system pressure under normal, non-emergency conditions.

The selection of a sprinkler pump depends on multiple factors, including the type and level of fire risk in the protected area. Pump capacity and performance must align with the specific fire hazard classification and the structure's vertical requirements. Buildings with greater height or classified as high-risk zones demand higher pressure and flow rates, which influences both pump sizing and system configuration.

Figure 21. Sprinkler Pump

4.1.2 Pump Starter Panels & Controls

Pump starter panels and control units serve as the electrical backbone for managing the operation of fire sprinkler pumps. These panels are designed to automatically initiate or shut down the pumps based on specific conditions, such as changes in water pressure, tank levels, or flow rates. For optimal reliability and organization, the control panel should have separate compartments for each pump: main (duty), standby, and jockey. Indicator lights must be included to show the operational status of each pump. To enhance safety and prevent equipment contamination, the enclosure should include ventilation slots fitted with insect-proof mesh.

The system's electrical wiring must use fire-resistant materials—preferably mineral-insulated copper cable (MICC)—and should be routed through areas with minimal fire exposure risk. For system safety and coordination, electrical interlocks are necessary to ensure that multiple pumps do not activate at the same time unless specifically required. In addition, a warning buzzer should be triggered if the pump isolator switch is set to "manual" or turned off.

While the sprinkler pump sets are designed to start automatically during a fire event, manual intervention is required to stop the system, ensuring that suppression efforts are not halted prematurely.

Figure 22. Pump Starter Panels & Controls

4.1.3 Sprinkler Tanks

Sprinkler tanks are large tanks designed to hold and store water specifically for use in fire protection systems. They can be made of various materials, including pressed steel, fibre-reinforced polyester (FRP) and concrete. Pressed steel tanks should be galvanized and coated with bituminous paint.

They should also be compartmentalized, and equipment like ball float valves, overflow pipes, and water level indicators should be provided. The minimum effective capacity of a sprinkler storage tank that does not depend on inflow should be determined based on the hazard classification and the height range between the lowest and highest sprinkler.

In addition, sprinkler tanks not dependent on inflow can be installed anywhere and together with hose reel tanks. The tank capacity should be the total water storage for both systems, and the hose reel tap-off level should be more than the sprinkler tap-off level to maintain water for the sprinkler system.

Figure 23. Sprinkler Tanks

4.1.4 Breeching Inlet

Breeching inlets are openings or connections installed on a fire sprinkler system for firefighters to access water to extinguish fires. They are typically located outside of a building and are connected to the fire sprinkler system riser.

These inlets should be of the 4-way type and meet the standards outlined in M.S.120: Part 3. If enclosed, the inlets should adhere to the regulations in M.S.120: Part 5 and be labelled 'Sprinkler Inlet'. Additionally, a drain must be installed at the bottom of the riser to empty the system after use.

Figure 24. Breeching Inlet

4.2 Design

The design and development of a fire extinguishing system for Electric Vehicles require a multidisciplinary approach that integrates fire dynamics, hydraulic engineering, environmental adaptation, and cost-effective deployment. This section outlines the complete system architecture, design parameters, and development rationale based on the findings of previous chapters and aligned with the specific needs of indoor EV parking facilities in cold-climate regions such as Mongolia.

4.3 Technical Drawing

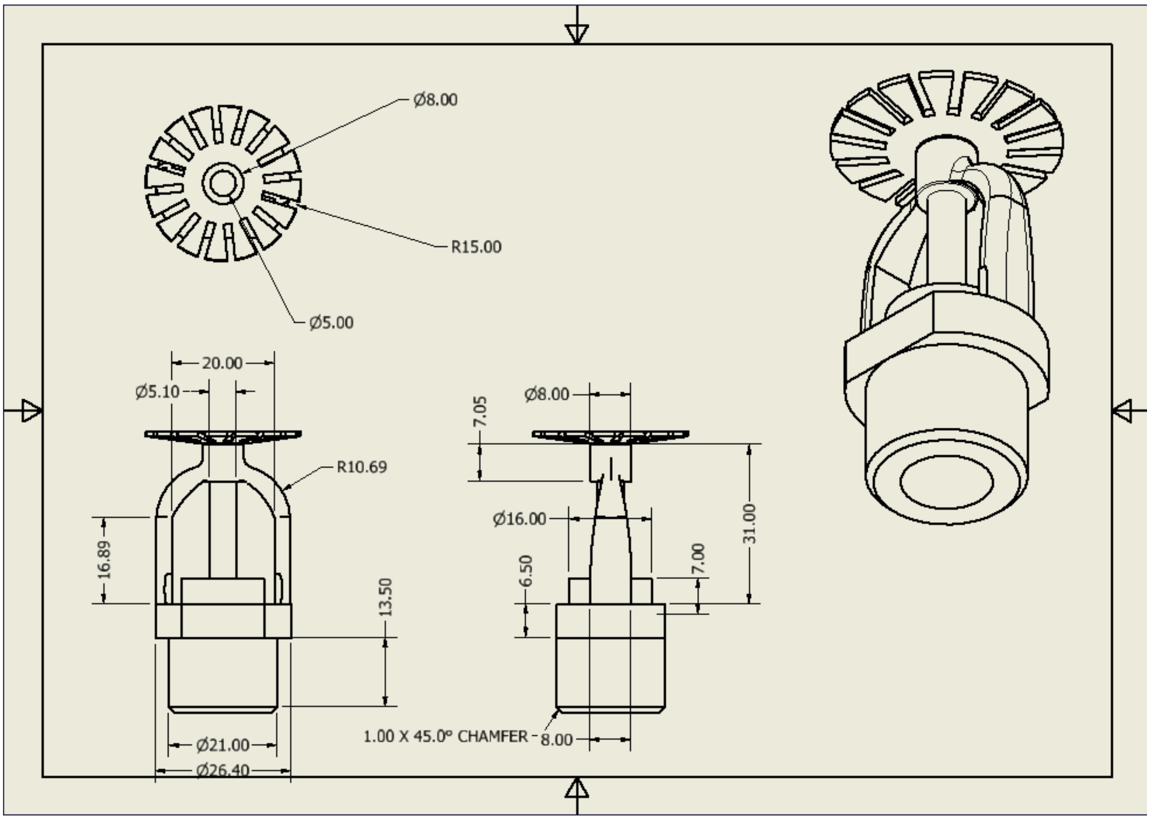


Figure 25. Technical Drawing of the Water Sprinkler Head, Installed into Piping

4.5 Parts Design

Figure 26. 3D Design of the Frame

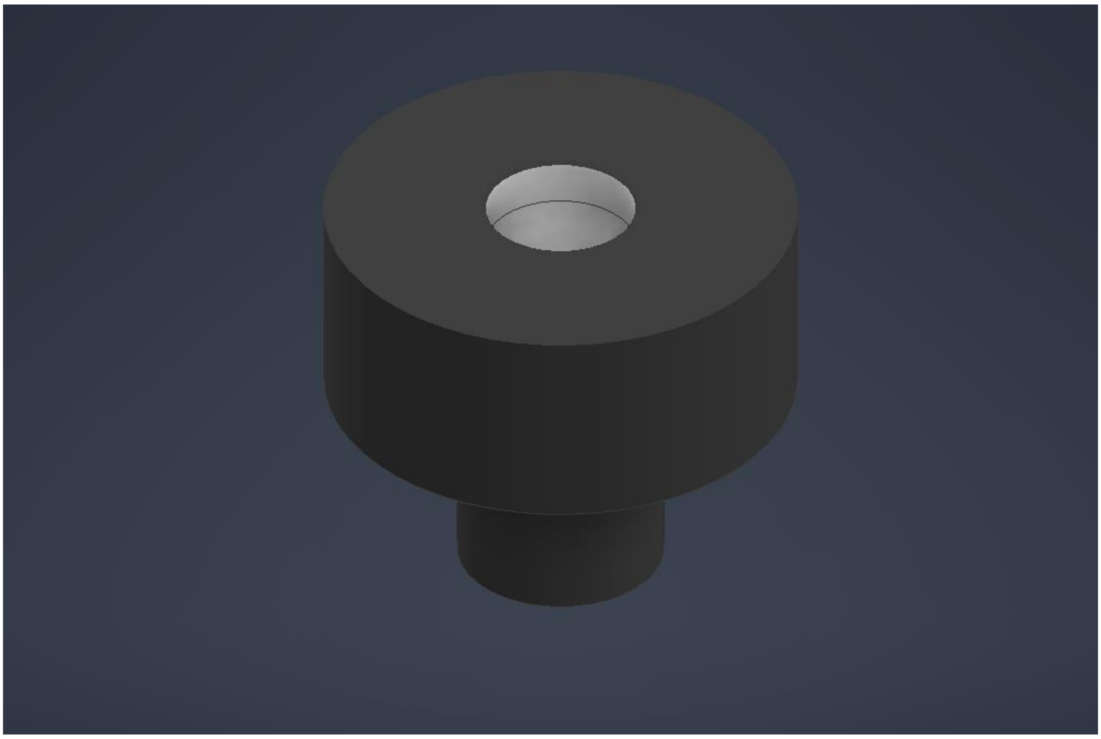


Figure 27. 3D Design of the Plug

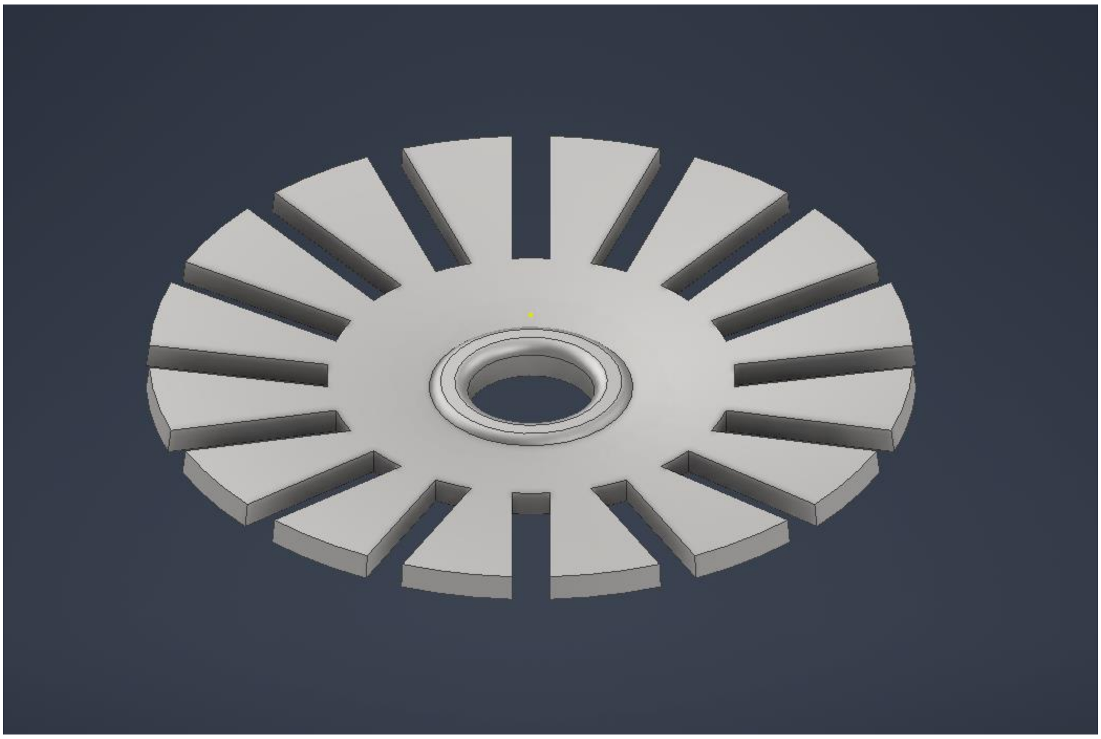


Figure 28. 3D Design of the Deflector

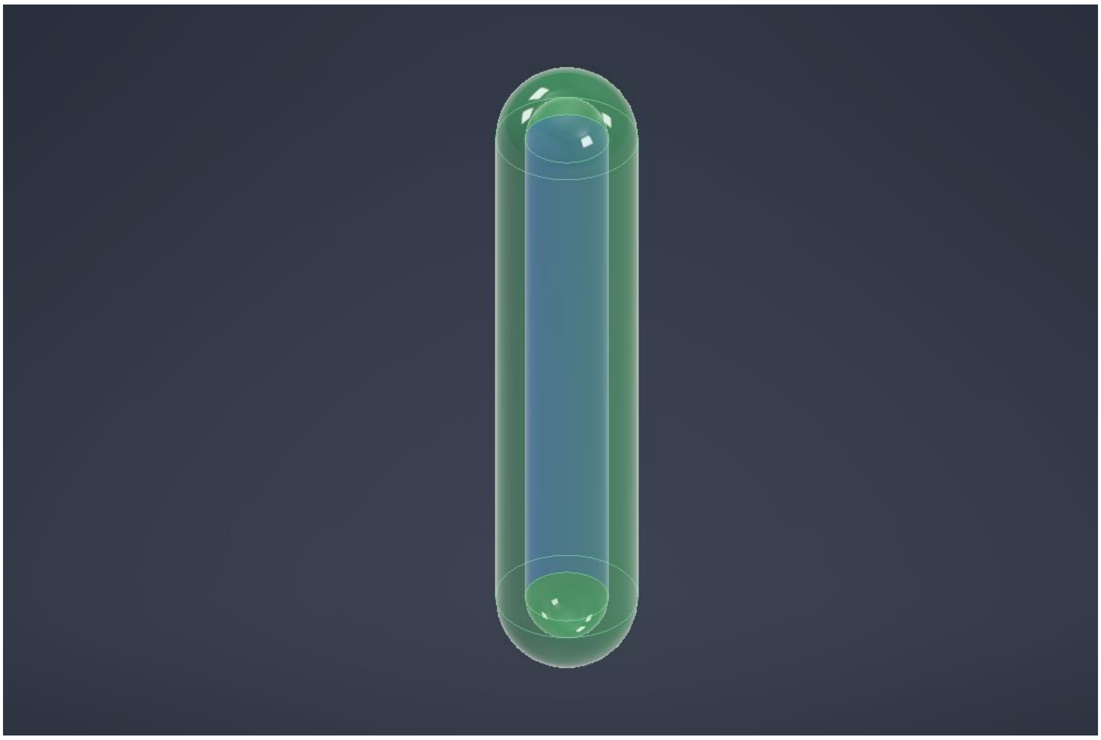


Figure 29. 3D Design of the Glass Bulb

5. Results and Discussion

5.1 Results

The conceptual design of the fire extinguishing system for electric vehicles (EVs) in indoor parking environments is based on the integration of dry-pipe water sprinkler systems equipped with thermally activated glass bulb sprinklers. The system is engineered to directly address battery-related thermal runaway incidents by ensuring effective heat suppression and re-ignition prevention.

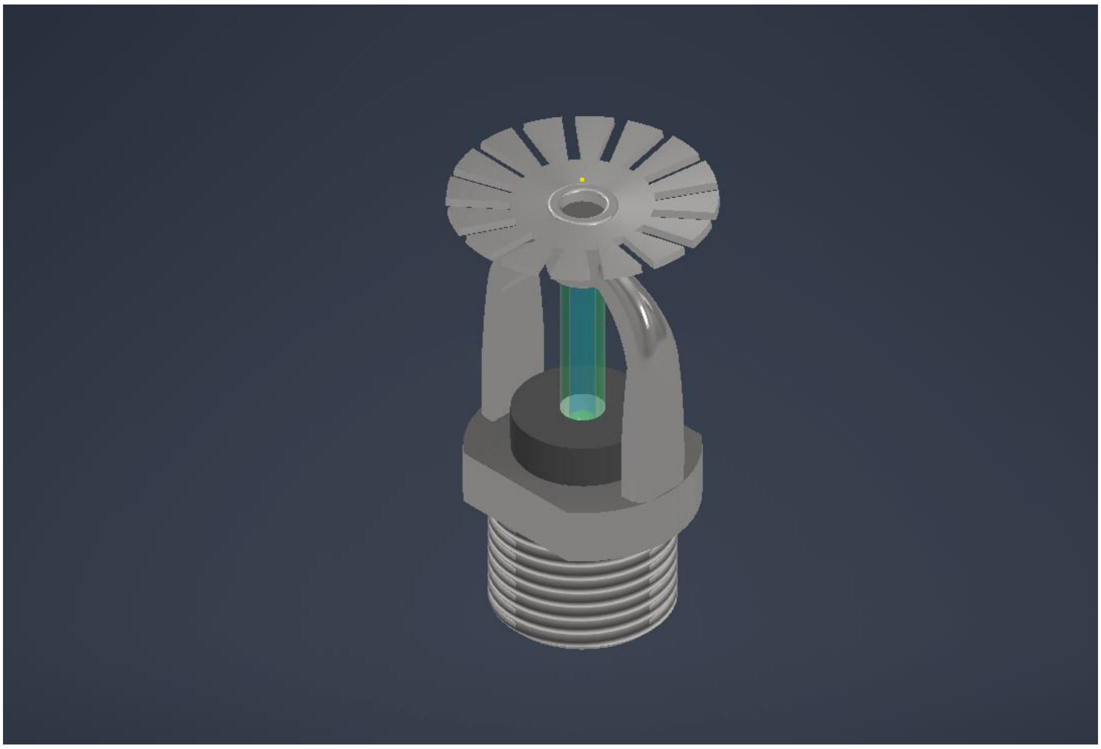


Figure 30. 3D Model of the Assembled Parts

5.1.1 Design Output

The proposed system comprises the following core elements:

- **Dry-pipe network**: Prevents freezing in Mongolia's sub-zero temperatures, holding pressurized air or nitrogen until a sprinkler head activates.
- **Glass bulb sprinklers**: Calibrated to activate at 93°C (green bulb), appropriate for typical lithium-ion battery ignition points.
- **Sprinkler layout**: One sprinkler per parking spot, positioned beneath the battery compartment, with spacing and orientation optimized via CAD simulations.

- **Activation logic**: Upon thermal activation, the sprinkler releases water directly onto the battery area, minimizing delay and maximizing cooling efficiency.

5.1.2 Compliance and Standards

The proposed design aligns with:

- **NFPA 13**: Standard for the Installation of Sprinkler Systems. (9)
- **ISO 17831-1**: Requirements for automatic fire suppression in vehicle environments.
- **IEC 62660-2**: Safety performance of lithium-ion cells for EVs.

5.1.3 System Limitations

Due to the scope of this thesis, physical testing and validation were not conducted. Simulations assumed ideal conditions; variables such as water pressure loss, obstruction, or simultaneous multi-vehicle ignition were excluded.

The Glass Bulb activator of Water Sprinklers is designed to withstand significant pressure. They can handle pressure up to 1.2 MPa (175 psi) during normal operation and are hydrostatically tested at 3 MPa (435 psi).

5.3 Discussion

The results from the conceptual and simulation stages support the viability of a water-based, thermally triggered suppression system for EV battery fires. This section evaluates the design's implications in the context of the research questions and broader fire safety considerations.

5.3.1 Limitations of Conventional Systems

Conventional fire suppression tools such as foam, dry powder, and fire blankets lack the dual ability to cool effectively and penetrate confined battery structures. As detailed in the SWOT analyses, AVD offers specialized performance but presents logistical challenges in storage and application. Fire blankets, while useful in isolation, do not actively cool or extinguish fires.

5.3.1 Adaptation to Mongolian Conditions

Mongolia’s harsh winters necessitate the use of dry-pipe systems to prevent freezing, a key consideration in the design. Additionally, indoor parking structures in urban centers like Ulaanbaatar are often multi-level and densely packed, increasing the risk of rapid fire spread. The localized, per-vehicle activation mechanism of this system ensures that suppression is targeted, reducing unnecessary water damage and conserving resources.

5.3.2 Research Question Alignment

- **What are the primary causes of EV fires?**
  The study confirms thermal runaway and charging faults as dominant causes, necessitating direct battery-targeted suppression.
- **Why is the fire risk critically considered despite lower incident rates?**
  Because of the difficulty in extinguishing battery fires and the potential for toxic emissions, even rare incidents require high-priority mitigation systems.
- **What materials and agents are most effective?**
  Water is validated as the most practical and effective agent due to its availability, cooling power, and non-conductivity when applied properly.
- **How can the system be designed for sealed battery compartments?**
  The floor-mounted positioning and system response time are modeled to address the containment and penetration challenges.

6. Conclusion and Future Work

6.1 Conclusion

This thesis has explored the unique fire risks associated with electric vehicles, particularly focusing on the phenomenon of thermal runaway in lithium-ion batteries. While EVs statistically present fewer fire incidents than traditional internal combustion engine vehicles, the nature of battery fires characterized by intense heat, toxic emissions, and potential for re-ignition necessitates specialized fire suppression solutions.

The research evaluated various existing technologies and identified the strengths and limitations of each, highlighting the need for a system that can detect, penetrate, and effectively suppress fires within sealed battery enclosures.

Through technical analysis and design consideration, a water-based sprinkler system utilizing dry-pipe infrastructure and glass bulb thermal activation was proposed. This solution offers an effective, environmentally safe, and economically feasible method tailored to the Mongolian context, where extreme weather and infrastructural constraints present additional challenges. The design accounts for NFPA standards and emphasizes localized adaptability, making it suitable for deployment in indoor parking facilities with dense EV concentrations.

While the proposed system remains at a conceptual stage due to resource and safety limitations preventing physical prototyping, the study lays a strong foundation for future development. Further research should focus on experimental validation, integration with smart detection systems, and broader applicability across various EV platforms. Ultimately, the implementation of targeted fire suppression systems will be essential in ensuring the safe coexistence of electric mobility and urban infrastructure.

6.2 Future Work

While this study presents a conceptual design for an electric vehicle fire extinguishing system tailored to indoor environments, several areas remain open for further research and development:

- **Prototype Development and Testing**: A critical next step is the physical prototyping of the proposed sprinkler system. Controlled testing under simulated thermal runaway conditions would validate the effectiveness of the design, optimize system parameters, and confirm its response time and reliability.
- **Integration of Smart Sensors**: Future iterations could incorporate advanced detection technologies such as thermal proximity sensors or gas detectors to enhance early fire detection and improve the precision of activation. This would allow for a hybrid system combining the simplicity of glass bulbs with intelligent monitoring capabilities.
- **Material Compatibility and Durability Testing**: The impact of various extinguishing agents on EV battery casings and vehicle components should be explored, ensuring long-term material compatibility, corrosion resistance, and safety, especially in cold or humid conditions.
- **Application Across EV Variants**: Expanding the research to accommodate different EV types and battery architectures would improve the generalizability of the design. This includes adapting the system for use in buses, trucks, and vehicles with newer solid-state batteries.
- **Economic Feasibility and Deployment Models**: A detailed cost-benefit analysis and implementation framework could be developed to support large-scale deployment, especially in public and commercial parking facilities. Collaboration with government and industry stakeholders would also help align the system with regulatory standards.
- **Localized Fire Safety Training and Awareness**: Successful implementation requires more than technology—it depends on human factors. Training first responders and facility personnel in the operation, limitations, and maintenance of EV fire systems will be critical for real-world efficacy.

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Appendix

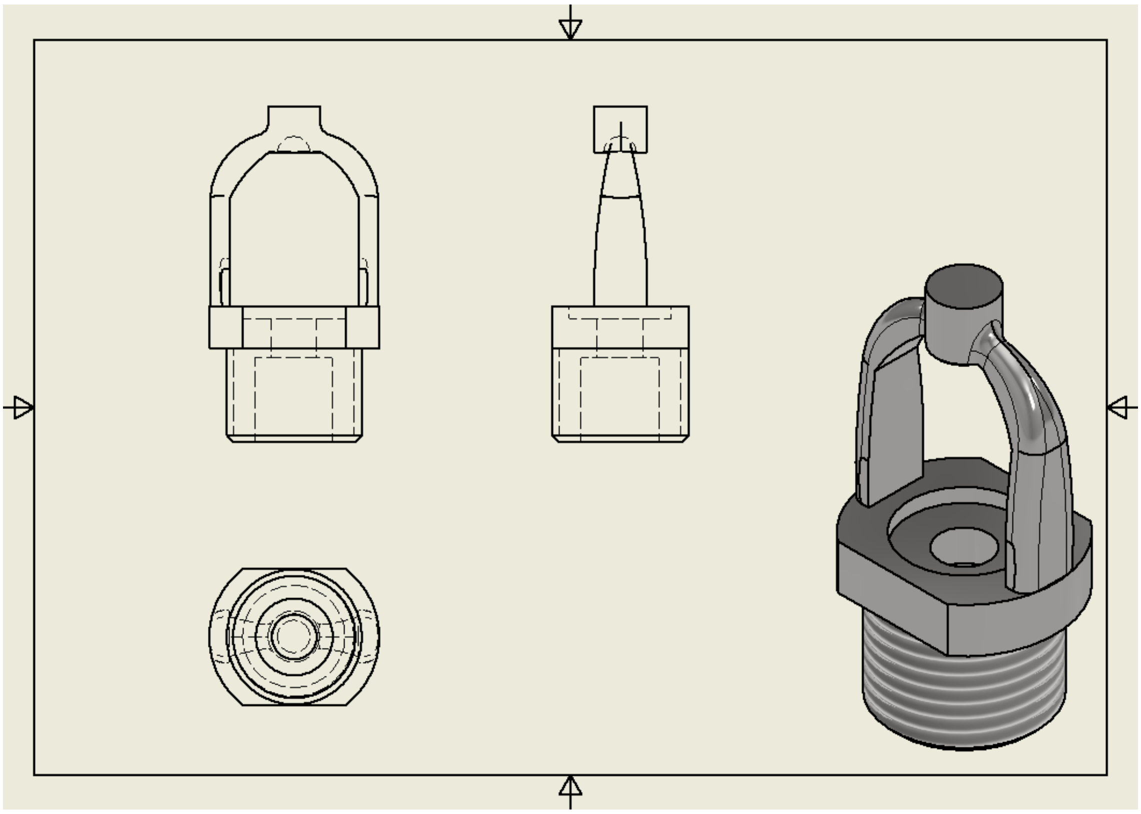

Figure 31. Technical Drawing of the Frame

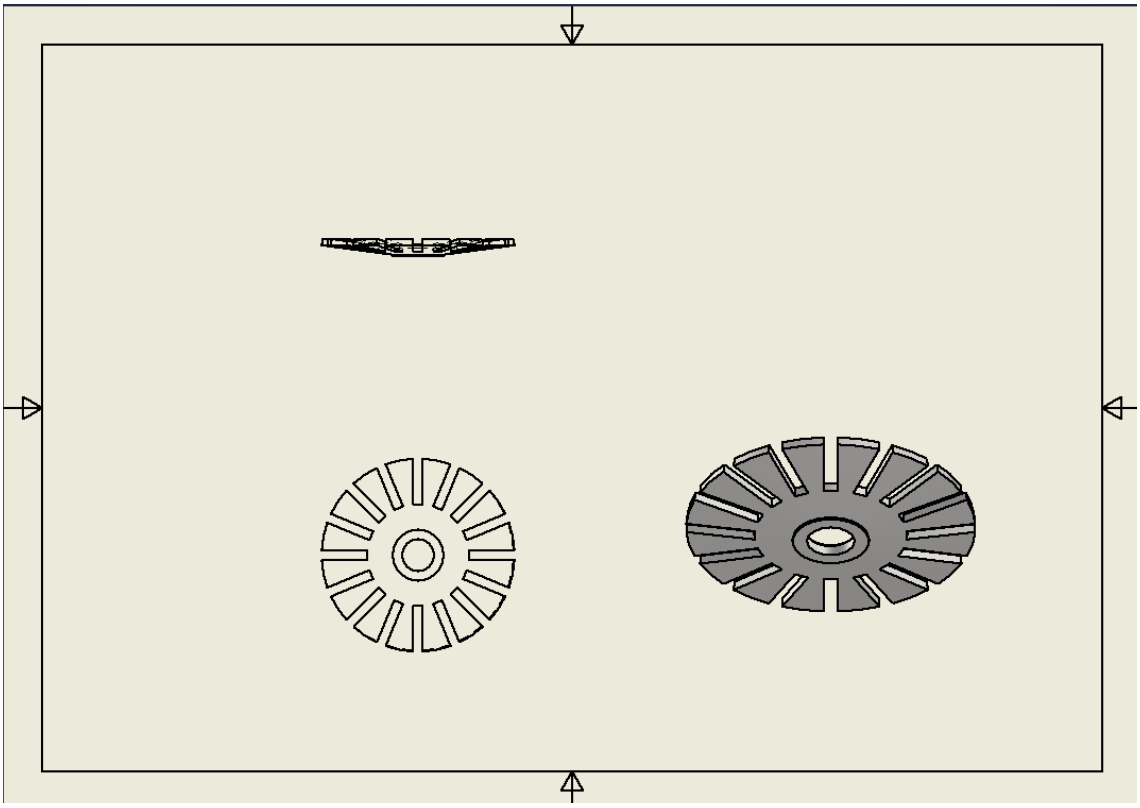

Figure 32. Technical Drawing of the Deflector

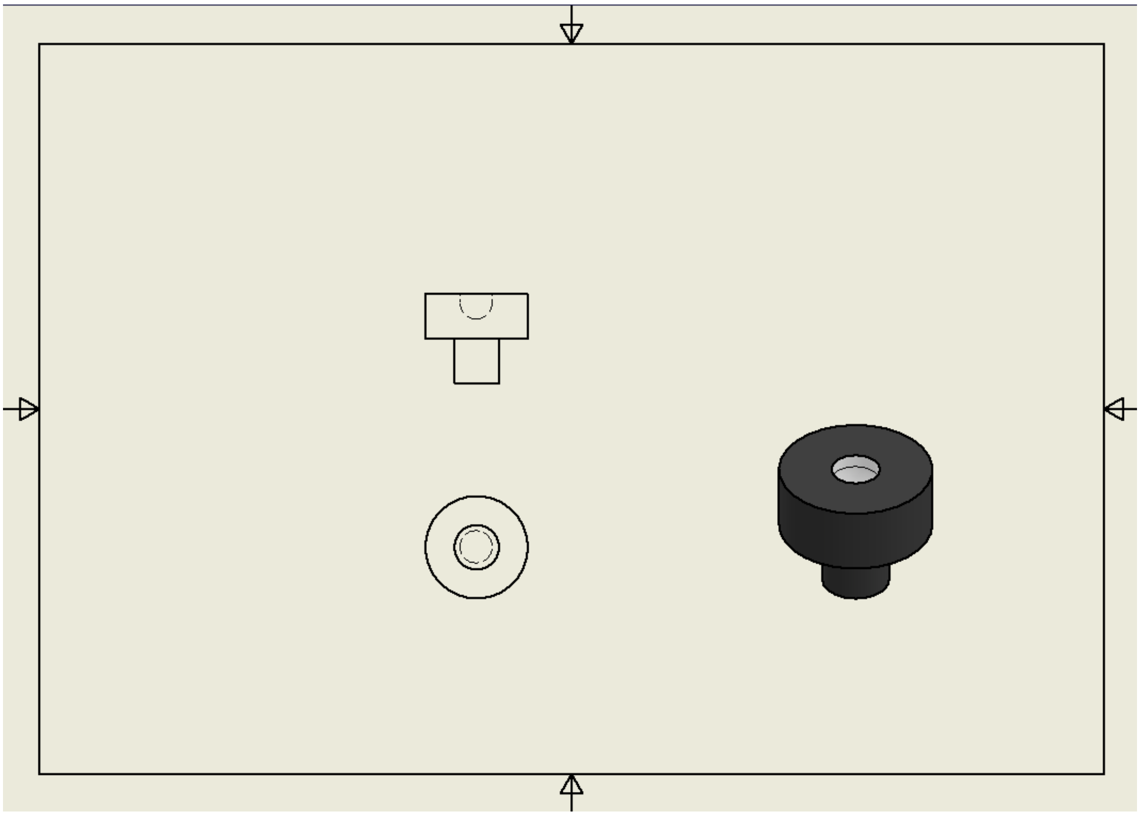

Figure 33. Technical Drawing of the Plug