Fire Test Protocol for Testing Fixed Fire Fighting Systems for Bus Depots

Version 1.0

22.01.2026

Disclaimer

This document has been prepared within the framework of the SUVEREN4Depots research project. The views and opinions expressed herein are those of the authors.

The protocol is intended as a research and performance-testing methodology. It does not constitute a design standard, approval guideline or legally binding requirement. Application of the methods and criteria described in this document shall rely on professional engineering judgement, project-specific risk assessment and compliance with all applicable laws, regulations, and standards. This document is intended for use by individuals and organisations familiar with fire safety engineering.

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SUVEREN4Depots research project:

The SUVEREN1 research project (2017 until 2020), funded by the German Federal Ministry of Education and Research (BMBF), dealt with the risks posed by new energy sources, in particular LIBs, in underground urban transport areas. While the follow-on project SUVEREN2use2 (2022 until 2025), funded by the German Federal Ministry of Economics and Climate Protection (BMWK), is investigating various areas of the LIB value chain with a particular focus on LIB production, storage and recycling as well as BESS. FOGTEC Brandschutz GmbH, University of Wuppertal, Fraunhofer Heinrich Hertz Institute, IFAB Institute for Applied Fire Safety, the STUVA e.V. and the Association of German Transport Companies (VDV) were partners in the research consortium.

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1. Introduction

1.1 General

This protocol establishes a generic full-scale fire test methodology for evaluating fixed fire fighting systems (FFFS) in bus depots. It applies to both electric buses (BEV) equipped with lithium-ion traction batteries, buses powered by internal combustion engines (ICE) and possible hybrids (HEV) combining both.

The protocol is intended as a methodological framework that defines the essential background, objectives and boundary conditions of the tests. Project-specific parameters such as nozzle type, system operating pressure and activation logic, shall be specified separately in a dedicated test plan. All full-scale tests shall adhere to the mandatory definitions, minimum requirements and boundary conditions set out in this protocol.

1.2 Objective

The objective is to assess the ability of a depot-level FFFS system to mitigate the consequences of a developing bus fire, including scenarios where battery thermal runaway contributes additional heat release, projectile hazards and prolonged burn duration.

The key safety functions evaluated are:

- Prevention or delay of fire spread from an initiating bus to adjacent buses and the depot structure, and
- Provision of a more tenable and accessible environment for manual firefighting intervention.

1.3 Scope

This protocol applies to full-scale fire tests conducted in large compartments representative of bus depots, including test halls and large tunnels used as test environments. It covers following:

- A bus mock-up representing key geometric features influencing fire growth and suppression effectiveness,
- Representative Class-A fire load replicating bus interior and technical compartments,
- Representative battery module arrangements reflecting roof-mounted and underfloor battery pack layouts.

The protocol is applicable to performance demonstration, comparative testing (system A vs system B) and research trials.

The protocol is not a design standard and does not prescribe the acceptance of a specific system for a specific depot without engineering judgement.

The protocol allows required, additional instrumentation (e.g. gas analysis, heat flux, visibility) to be included where required and documented in a project-specific annex.

1.4 Fundamental assumptions

The protocol is based on the assumption that a bus fire can develop beyond the bus interior if not controlled and that the internal progression of battery thermal runaway is not be directly accessible to the fixed fire fighting system during the early stages of the fire. Consequently, the evaluation focuses on impact mitigation and exposure reduction rather than extinguishment of battery reactions.

Some internal combustion engine (ICE) buses may be equipped with integrated engine-bay suppression systems, and future buses may also include mitigation systems for battery compartments. Their potential influence is not considered in this protocol, as fires may originate in other areas of the vehicle and such systems have not demonstrated effectiveness for electric buses (BEV). The baseline assumption is therefore that external suppression by the FFFS must address fully developed fire scenarios independent of any vehicle-integrated system.

1.5 Definitions

Acceptance criteria	Minimum performance requirements used to determine whether the tested fixed fire fighting system (FFFS) is considered acceptable under this protocol.
Activation criterion	The predefined condition used to initiate system activation. In this protocol, activation is based on visual confirmation as defined in Chapter 4 and the project-specific test plan annex.
Additive	A chemical or mixture intentionally introduced into the extinguishing water to modify performance (e.g. wetting, cooling, radiation attenuation).

Adjacent-bus target (fire target)	A replaceable target assembly representing the exterior surface of a neighbouring bus or depot wall, used to assess thermal exposure, damage and ignition.
Ambient conditions	Environmental conditions within the test facility prior to ignition, including ambient temperature, relative humidity and barometric pressure.
Authority Having Jurisdiction (AHJ)	An organisation, office, or individual responsible for enforcing regulatory requirements or approving equipment, installations or procedures.
Bus depot	A facility where buses are parked, serviced, charged or maintained. Represented by a large enclosed or semi-enclosed compartment with defined airflow and ceiling characteristics.
BEV bus	A bus propelled solely by electric motors and powered by onboard rechargeable lithium-ion traction batteries. Compared to conventional buses, there are additional-fire hazards, which are primarily associated with high-voltage electrical systems and the potential for lithium-ion battery thermal runaway. The buses operate also low-voltage systems and often fossil fuel auxiliary heating system.
Bus mock-up	A reusable test object representing the geometry and enclosure effects of a typical bus, designed to carry defined replicate fire loads and battery configurations.
Ceiling region	The upper layer of the test facility above the mock-up, instrumented to characterise hot gas layer development and thermal exposure of the depot structure.
Class A fire load	A standardised solid combustible surrogate representing typical bus interior and technical-area combustibles, primarily based on standardised Euro pallets and defined supplemental materials.
Critical failure	A malfunction preventing the FFFS from delivering extinguishing agent as intended, including loss of discharge, loss of required pressure or failure of critical system components.
Deluge system	A water-based FFFS using open nozzles supplied by a valve-controlled water source, discharging water at comparatively low pressure in spray form.
FTIR	Fourier Transform Infrared Spectroscopy multigas analyser. An analytical technique that measures infrared absorption to identify and quantify gases based on their molecular vibration signatures. In fire testing, FTIR is used as a multigas sensor to monitor combustion products and toxic effluents in real time.
GFRP	Glass Fibre Reinforced Polymer (GFRP) is a composite material consisting of a polymer matrix reinforced with glass fibres. GFRP is lightweight, strong, and corrosion-resistant, but exhibits high heat-release characteristics and can contribute to rapid fire growth when exposed to fire, making it a suitable indicator material for assessing thermal exposure and fire-spread potential in fire tests.
HEV bus	A bus that combines an internal combustion engine with an electric drive system powered by a rechargeable battery. It presents fire risks associated with both conventional fuels and high-voltage battery components.
Heat release rate (HRR)	The rate at which heat energy is generated by combustion, typically expressed in kW or MW.
ICE bus	A bus powered by an internal combustion engine that uses liquid or gaseous fuels (e.g. diesel, petrol, CNG, LNG) as its primary energy source.
Isolated temperature peak	A short-duration temperature exceedance lasting less than 10 seconds, not sustained or repeated, and not leading to ignition or loss of target integrity.
LIB	Lithium-Ion Battery, a rechargeable electrochemical energy storage device that uses lithium-ion

	movement between the anode and cathode to store and release electrical energy. LIBs offer high energy density and are widely used in electric vehicles, including battery electric buses, but can pose specific fire hazards due to the potential for thermal runaway.
LIB involvement	A condition where lithium-ion batteries exhibit sustained flaming and/or characteristic thermal runaway behaviour (e.g. venting, jet flames, projectiles).
PMMA	Polymethyl Methacrylate (PMMA) is a transparent, thermoplastic polymer commonly used as a lightweight, shatter-resistant alternative to glass. PMMA has well-defined softening, melting, and ignition characteristics, making it a suitable indicator material for assessing thermal exposure and fire spread potential in fire tests.
Post-activation duration	The minimum time for which the FFFS shall operate after activation for acceptance evaluation (≥ 60 min unless otherwise specified).
Sustained flaming	Visible flames persisting for more than 5 seconds on a target surface after system activation.
Water mist system	A water-based FFFS discharging water primarily as small droplets, with $D_{v0.90} < 1$ mm measured 1 m from the nozzle at minimum operating pressure.
Shall / Should	‘Shall’ indicates a mandatory requirement; ‘Should’ indicates a recommendation.

2. Test environment and boundary conditions

The test environment shall be documented in sufficient detail to allow third parties to understand the boundary conditions and reproduce the tests in a comparable facility.

The tests can be organized in any facility capable of accommodating the physical dimensions of the test arrangement and the fire size of the buses. The test location shall be enclosed in a manner representative of the bus depot. Tunnel-type structures may be used, provided that the cross-section is sufficiently large and the ceiling geometry and height shall replicate typical depot structures. Tests shall be carried out under indoor conditions; outdoor tests are not considered applicable. The facility shall also allow controlled, directional ventilation.

2.1 Facility geometry

The test facility shall be of sufficient size to allow reproduction of a representative bus depot segment, including realistic bus-to-bus spacing and the installation of target surfaces. The geometry of the facility shall be documented by drawings and verified by as-built measurements.

Any longitudinal or transverse floor slope shall be documented. Where such slope may influence smoke or heat transfer, appropriate compensatory measures shall be applied, such as levelling of the bus mock-up roof plane, in order to ensure defined and reproducible boundary conditions.

The ceiling within the test section shall be planar and free of geometrical irregularities that could affect fire plume development, smoke stratification or heat accumulation.

2.2 Ventilation

A controlled airflow shall be imposed to represent wind effects and conditions typical of open or semi-open bus depots. The airflow shall be directed along the longitudinal axis of the bus mock-up.

The target airflow velocity at the location of the test object shall be between 0.5 m/s and 1.0 m/s. The airflow shall be maintained throughout the test and may be adjusted in a controlled manner as the fire size develops, provided that all changes are documented.

The ventilation shall also serve to maintain adequate visibility for observation and documentation of the test, without compromising the representativeness of the fire scenario.

2.3 Ambient conditions

Ambient temperature, relative humidity, and barometric pressure within the test facility shall be recorded prior to each test. These parameters shall be measured at representative locations in the test section and documented as part of the test record.

The test facility shall be enclosed or only limitedly opened in a controlled manner such that external weather conditions do not significantly influence the fire development or smoke movement within the test section. Consequently, external wind conditions shall not be considered a governing boundary condition for the test.

No correction of measured fire-related temperatures for ambient conditions shall be applied, unless explicitly defined in a project-specific annex or required for comparative post-processing of results.

2.4 Drainage and environmental controls

The facility shall provide means to manage run-off water and contaminated fire water. Measures to prevent uncontrolled spread of burning liquid electrolyte and to capture contaminated residues shall be implemented where reasonably practicable. Waste classification and disposal routes shall be defined prior to testing. Certificates of proper disposal for all waste streams, including lithium-ion batteries, shall be produced as part of the test program.

2.5 Test object and arrangement

The test arrangement shall represent a conservative section of a bus depot. The initiating bus shall be represented by a reusable mock-up designed to carry the defined surrogate fire loads and battery modules. Adjacent buses shall be represented by target surfaces located at specified clearances. The entire arrangement shall be oriented relative to the imposed airflow in a repeatable manner.

2.6 Bus mock-up

2.6.1 General

The bus mock-up shall be constructed to represent a standard 12 m class low-floor bus. The external geometry shall provide representative enclosure effects for the passenger compartment and technical areas, while allowing repeatable installation of fire loads in accordance with the defined design fire curve.

The mock-up shall be constructed primarily from non-combustible materials, such as a steel frame and steel sheet cladding. Where required, thermal insulation or protective layers shall be applied to preserve structural integrity during repeated test exposures and to prevent premature deformation of the supporting structure.

General dimensions and concept of the bus mock-up is shown in the figure 1.

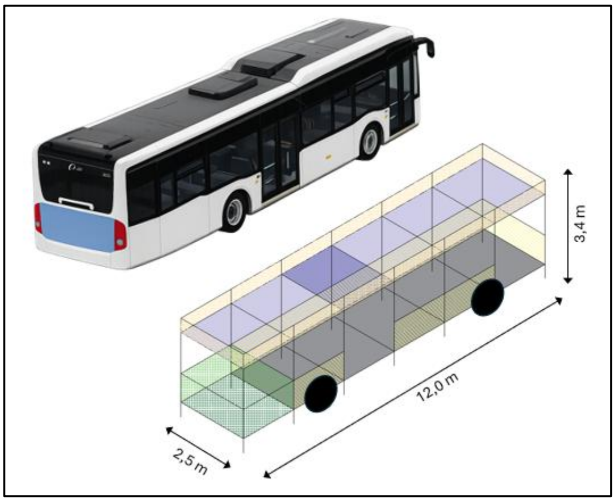

Figure 1. Bus mock-up dimensions

The passenger and technical compartment(s) of the mock-up shall be configured such that the fire load can be installed and ignited to achieve a heat release rate (HRR) approximating the design HRR curve for buses. Both HRR development and the total energy content of the fire load shall be representative of bus fires. The mock-up shall replicate the rapid fire development and the difficulty of reaching burning surfaces within the bus interior, while also allowing the fire to break out of the vehicle. This ensures that the FFFS is challenged to prevent fire spread from one vehicle to another.

The design fire curve applied in this protocol is based on published literature and experimental data, as illustrated in Figure 2. The mock-up is designed such that the selected fire load arrangement and the use of multiple ignition locations result in a fire development comparable to the typical fire behaviour observed in real buses. Results from the SUVEREN research project indicate no significant difference in the total energy content or characteristic fire development between internal combustion engine (ICE) buses and battery-electric buses (BEV).

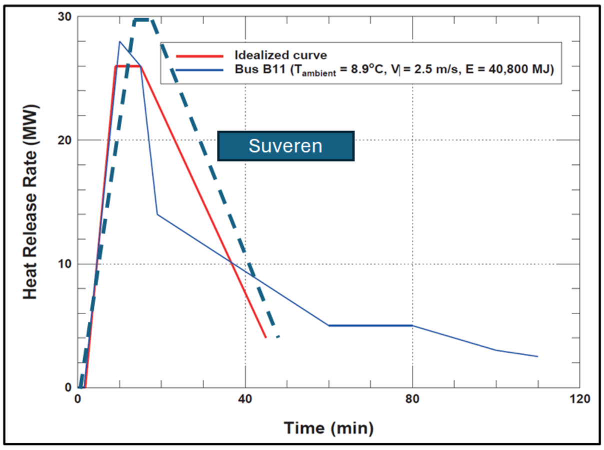

Figure 2. Design fire / HRR for buses / Suveren (Technical Committee 3.3 Road tunnels Operations, "Design Fire Charasteristics for Road Tunnels," World Road Association (PIARC), 2017.)

Standardised Euro pallets (Class A) shall be used as fire load to ensure repeatability and reproducibility. The number, positioning and ignition procedure of the pallets is defined in detail in the subsequent chapters.

The mock-up shall incorporate representative openings for doors and windows. These openings are essential to enable realistic heat radiation and convective heat transfer from the interior of the vehicle to the surroundings, thereby providing a conservative representation of real bus fire conditions.

The technical compartments of buses are typically located in several distinct areas, all of which shall be represented within the mock-up. The rear compartment may contain an internal combustion engine or an electric power drive and is commonly separated from the passenger compartment by structural elements. This separation shall be replicated in the mock-up. Traction batteries are typically installed either on the roof or within the vehicle chassis. For this test protocol, tests with both roof-mounted and underfloor battery configurations have been selected to represent a particularly challenging and conservative scenario with respect to fire exposure and accessibility.

Figure 3. Typical technical areas (power drive, batteries) in a bus

2.6.2 Rationale for using a mock-up instead of a real bus

Real buses are not used for testing under this protocol. A standardised mock-up is required to ensure safety, repeatability and comparability between tests. Using actual vehicles would introduce uncontrolled variability in materials, fire load and response behaviour and would make systematic testing impractical.

In particular:

- The combustible load, interior layout, and material mix vary strongly between bus types, preventing reproducible heat release rates and fair comparison between systems.
- By selecting a bus that is either unusually easy to ignite or, conversely, very slow to ignite, the test scenario could be manipulated, leading to non-representative or favourable results for a given system. Also the ignition location or locations with real buses can help to manipulate the results.
- Defined Class A fire loads and battery arrangements in a steel mock-up allow controlled, conservative and repeatable fire scenarios, while maintaining an acceptable safety level for personnel and equipment.
- The mock-up is reusable for multiple tests, whereas a real bus would be destroyed in each test, making a full test programme economically and logistically infeasible.

For these reasons, the mock-up is considered the only practical and technically robust solution for full-scale testing under this protocol. This approach is also common practice in large-scale fire testing, including other critical-infrastructure applications involving heavy vehicles, such as road tunnels.

2.6.3 Dimensions

The mock-up dimensions shall represent a typical 12 m class low-floor bus and shall be selected to provide representative enclosure volume, surface-to-volume ratio, and characteristic lengths governing fire dynamics.

The overall external dimensions of the mock-up shall be a length of 12.0 m, a width of 2.5 m and an overall height of 3.4 m. These dimensions are considered representative for the buses currently in service and provide an appropriate basis for evaluating fire development and fire spread under bus depot conditions.

The ceiling and internal floor of the mock-up shall be straight and continuous over the full length of the passenger compartment. The layout of technical compartments shall comply with the referenced drawings in order to provide standardised and reproducible test scenarios. The spatial separation between the passenger compartment and the rear technical compartment of the mock-up reflects realistic bus layouts and ensures that heat transfer and fire spread pathways between compartments are neither artificially restricted nor artificially enhanced by the mock-up geometry.

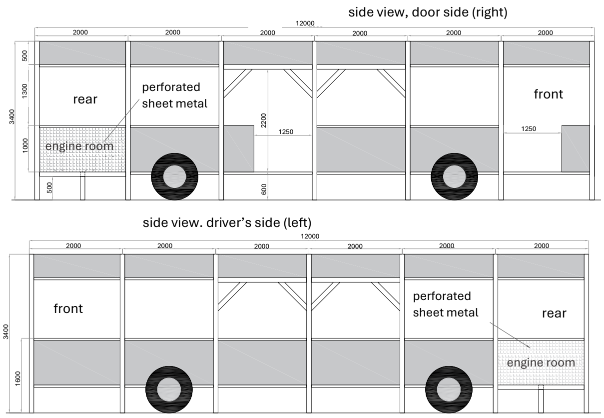

Figure 4. Side views of bus mock-up

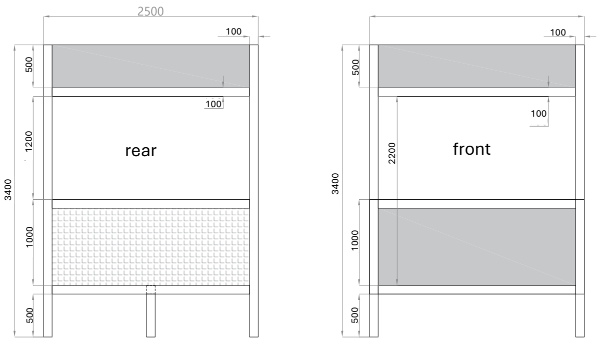

Figure 5. Rear and front views of bus-mock up

The mock-up ceiling shall consist of non-combustible steel elements combined with combustible plastic components. The material of the combustible part of the ceiling shall be glass-fibre-reinforced plastic (GFRP) panels with a thickness of 6mm.

All dimensions of the mock-up shall comply with the referenced drawings with a tolerance of ±20 mm. Any deviations from the specified dimensions shall be documented prior to testing.

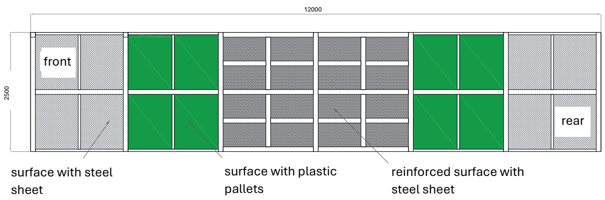

Figure 6. Roof view of bus mock-up

2.6.4 Fire load – Class A

The fire load applied in the bus mock-up shall be defined to represent the combustible materials present within the passenger compartment and technical areas of a standard bus. The fire load is defined to achieve a representative heat release rate development and total energy content in accordance with the design fire curve specified for buses in this protocol. The objective of the fire load definition is not to replicate specific vehicle materials, but to generate a reproducible and conservative fire scenario suitable for performance-based assessment of fixed fire fighting system

To ensure repeatability, comparability between tests and traceability of fire behaviour, the fire load shall be based on standardised Class A fire load. For this purpose, standard Euro pallets shall be used as the primary fire load within the passenger compartment and the back technical compartment of the mock-up.

The basic dimensions of the Euro pallet are following:

- Dimensions: 120 × 80 × 15 cm
- Weight: Approximately 20–25 kg
- Condition: Used pallets may show minor wear or light damage, but no parts may be missing.
- Moisture content: Maximum 20 %, pallet must be dry.
- Material: Untreated wooden surfaces, no paint, plastics or surface coatings.

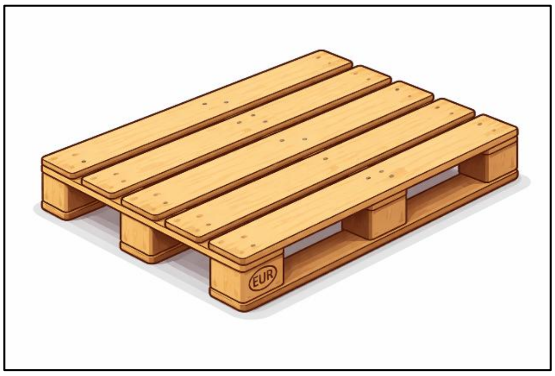

Figure 7. Euro pallet (fire load, Class A)

In total 92 pallets shall be used for the replicating the total energy load and HRR as for real buses. The pallets are to distributed following typical seat arrangements in the buses and also providing enclosed fire in the technical compartment in the back.

The following image shows the fire load arrangement.

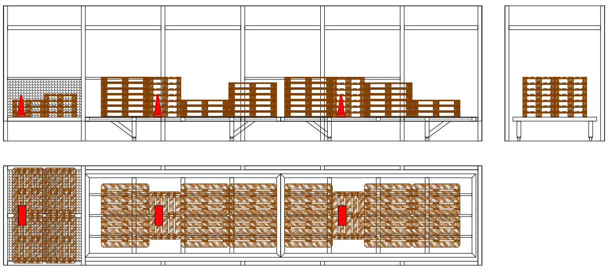

Figure 8. Fire load (Class A - pallet) arrangement in the mock-up.

In addition to the pallets, a minimum of 5 kg of polyurethane-based mattress foam shall be used. This material shall be equally divided between the two ignition pallet stacks located inside the replicated passenger compartment. The foam mattresses shall be placed between the Euro pallets to provide additional fire load representative of the passenger compartment and to enhance the fire development.

2.6.5 Fire load – LIBs

In addition to the Class A fire load representing the typical combustible materials of the passenger compartment and chassis, lithium-ion batteries (LIBs) shall be incorporated into the test setup in order to simulate the specific fire characteristics of BEVs. The inclusion of LIBs is intended to represent the influence of traction batteries on fire development, fire duration and interaction with fixed fire fighting systems.

As traction batteries in electric buses may be installed in different locations depending on vehicle design, two representative battery arrangements shall be implemented within the mock-up. These arrangements correspond to batteries installed underfloor and on the roof, respectively and are illustrated in the following figures.

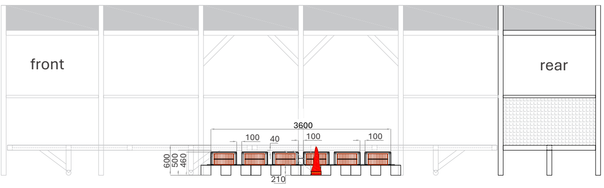

Figure 9. LIB fire load underfloor

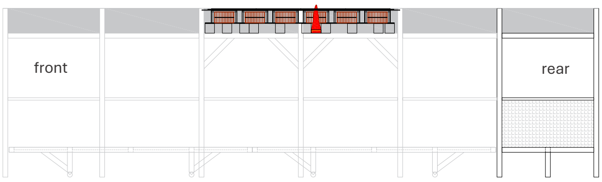

Figure 10. LIB fire load on the roof

For both configurations, the total installed battery capacity shall be minimum 300 kWh (±5 %). All lithium-ion batteries used in the tests shall have a minimum state of charge (SOC) of 95 % at the start of the test in order to represent a conservative fire scenario. The battery chemistry shall be nickel-manganese-cobalt (NMC), reflecting a widely used and comparatively energetic chemistry in current electric bus applications. The cell format shall be prismatic, and the battery type shall be representative of batteries used in the automotive industry.

The LIBs shall be installed within metallic battery boxes representing battery housings. Each housing shall be made of steel with a wall thickness of 1 mm. The battery boxes shall be arranged with a longitudinal spacing of approximately 100 mm between adjacent units.

Each individual battery box shall have a nominal capacity of approximately 50 kWh (±5 %). The external dimensions of the battery boxes shall be as specified in the referenced drawings and are illustrated in the following figure.

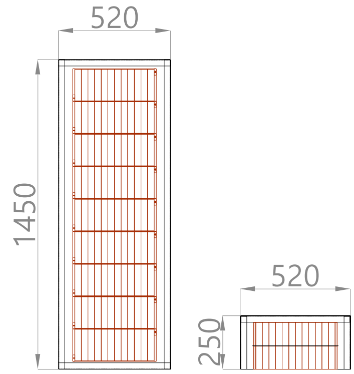

Figure 11. Battery box/case dimensions (top view left, side view right)

A total of six battery boxes shall be installed for each test configuration, resulting in the specified total capacity. The installation of the battery boxes in both the underfloor and roof configurations is illustrated in the following figure.

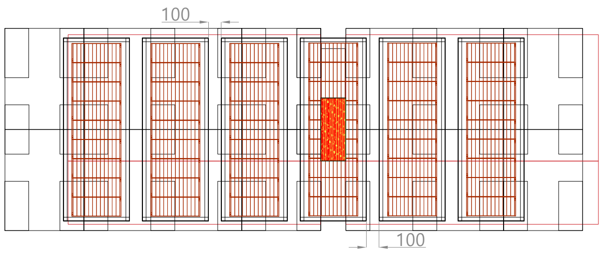

Figure 12. Installation of 6 battery boxes/cases under floor or ceiling (ignition tray indicated as solid red)

In the underfloor configuration, the battery boxes shall be installed eccentrically beneath the mock-up floor, with a maximum vertical distance of 150 mm to the platform on which the pallet fire load is placed. The arrangement shall ensure that there is no direct access of water or other fire fighting agents to the batteries during the test. Bricks or steel supports may be placed beneath the boxes to raise them to the correct height.

Both in under floor and on the roof configuration, the battery boxes shall be covered by multiple fire retardant plates as illustrated in the referenced figure 13. This shielding plate is intended to prevent direct access of fire fighting agents onto the battery modules. Bricks or steel supports may be placed beneath the boxes to raise them to the maximum height.

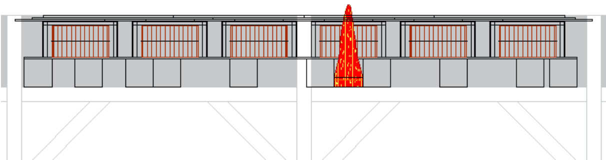

Figure 13. Shielding of the LIB fire load in the roof

In both configurations, the test objective is not to extinguish the batteries, but to allow them to undergo complete involvement during the test period. This approach ensures a conservative test scenario and enables the evaluation of the fixed fire fighting system under severe and sustained battery fire exposure conditions.

2.6.6 Ignition

The fire scenarios shall be based on the assumption that ignition of the lithium-ion batteries (LIBs) occurs as a result of thermal abuse caused by a technical defect, followed by the ignition and involvement of the remaining combustible materials of the bus. This approach reflects realistic fire initiation mechanisms observed in bus fires and provides a conservative basis for evaluating the performance of fixed fire fighting systems.

In order to achieve a defined, controlled, and reproducible heat release rate development, the ignition of the lithium-ion battery fire load and the ignition of the Class A fire load shall be carried out separately. This separation ensures that the contribution of each fire component can be controlled and that the overall fire development follows the intended design scenario without uncontrolled interactions between the battery fire and the passenger compartment fire.

Ignition shall be performed using rectangular fire trays with nominal dimensions of 20 × 70 × 7 cm (width × length × height). Each fire tray shall be filled with a fuel mixture consisting of 3 litres of diesel and 5 litres of n-heptane. All fire trays shall be ignited remotely using electrically actuated remote igniters, ensuring safe and precise ignition control.

One fire tray shall be used to ignite the lithium-ion battery fire load. The tray shall be positioned so that the flames directly impinge on and heat the underside of the battery enclosure. An appropriate opening shall be provided in the bottom of the battery boxes to enhance heat transfer to the batteries, depending on the cell type and size used. This configuration ensures reliable and repeatable thermal exposure of the battery modules.

Three fire trays shall be used for ignition of the Class A fire load. These trays shall be placed beneath the lowest layer of Euro pallets, as illustrated in the referenced figures. This arrangement ensures rapid and near-simultaneous ignition of the distributed pallet fire load.

The exact positioning of all fire trays, including the battery ignition tray and the Class A fire load ignition trays, shall be as shown in Figures 8, 9, 10, 12 and 13.

Figure 14. Pool for Class A - Euro pallet fire load with remote igniter (before sliding under the pack of pallets)

2.6.7 Fire targets

Fire targets shall be installed to represent the adjacent bus exterior and/or depot walls in order to assess the potential for fire spread from the burning bus mock-up to neighbouring vehicles or combustible structures and equipment. The targets shall be used to evaluate whether fire spread to adjacent buses could occur under the defined fire scenario and whether the fixed fire-fighting system is capable of preventing or limiting such spread.

Where a polymer sheet is used as an indicator, its softening, melting and ignition behaviour shall be documented as part of the acceptance criteria. The targets shall be constructed so that they do not contribute significantly to the fire, while still providing a clear indication of thermal exposure and ignition tendency. Target materials shall be replaceable and shall allow for damage grading.

The fire targets shall consist of rigid target frames positioned adjacent to the bus mock-up at representative bus-to-bus distances, as defined elsewhere in this protocol. The target frames shall be oriented parallel to the longitudinal axis of the bus mock-up and shall provide continuous exposed surfaces representative of the side walls of neighbouring buses. Additional target frames shall be positioned in front of and behind the bus mock-up in order to represent adjacent vehicles in the longitudinal direction. These front and rear targets shall be configured in the same manner as the side targets. The dimensions of the fire targets shall match those of the opposite surfaces of the bus mock-up.

All side target frames shall be built in an identical manner to ensure consistency and reproducibility of the test conditions. The primary exposed surface of the side targets shall consist of polymethyl methacrylate (PMMA) panels with a nominal thickness of 3 mm, installed as continuous surface coverage over the target frames. PMMA has been selected due to its well-defined thermal degradation behaviour and its relevance as a representative polymer material commonly used in vehicle body components and glazing elements.

The fire targets shall be equipped with an appropriate ceiling construction that prevents the firefighting agent from reaching their rear side and provide cooling for them. A suitable ceiling solution must be used to ensure this does not occur. The required ceiling coverage depends on the nozzle characteristics and their positioning.

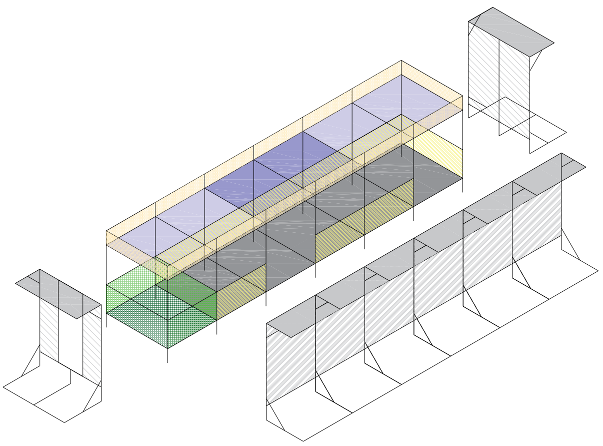

Figure 15. Fire targets and mock-up

In addition to the PMMA panels, glass-fibre-reinforced plastic (GFRP) plates shall be installed on the side target frames as secondary reference materials. Three GFRP plates shall be mounted on one side of each target frame and positioned at upper, middle, and lower elevations. This vertical distribution allows the assessment of thermal exposure and material response at different heights, reflecting the expected variation in heat flux and flame impingement along the height of adjacent vehicles.

The GFRP plates shall be attached directly to the target frame structure and shall be fully exposed to radiative and convective heat from the fire. The PMMA panels shall form the primary exposed surface of the fire targets, while the GFRP plates shall provide additional reference points for comparative evaluation of thermal damage, deformation, ignition, and delamination behaviour.

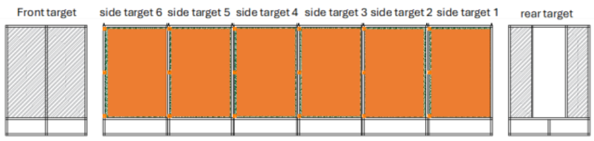

Figure 16. GFRP target plates (orange)

All fire target materials shall be installed prior to testing and shall be visually inspected to confirm correct positioning, fixation and surface condition. The arrangement of the fire targets and all installed materials shall be documented by drawings and photographs prior to test execution. Any deviations from the specified configuration shall be documented and justified. The design and layout of the fire targets are shown in the figures below. The distance between the bus mock-up and the fire targets shall be 1.0 m.

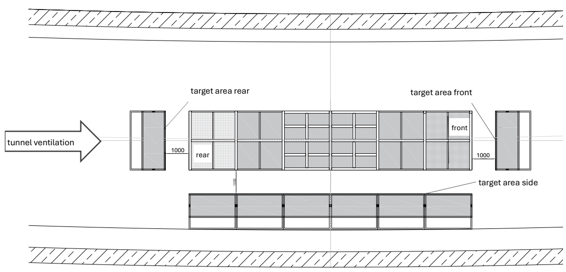

Figure 17. Arrangement of the targets

3. Instrumentation

Measurement locations shall be defined in a structured and repeatable manner in order to ensure consistency between tests and comparability of results. Each measurement point shall be assigned a unique designation reflecting the measured quantity and its physical location within the test setup.

The measurement locations shall be grouped according to functional zones, including the ceiling region of the test facility, fire target surfaces, the interior of the bus mock-up, lithium-ion battery assemblies, the fixed fire fighting system pipework and the fire gas flow downstream of the fire source.

3.1 Temperature measurements

The temperatures are used to evaluate the fire characteristics and the exposure in the tunnel. Thermocouples type K, 1.0 – 2.0 mm diameter, shall be able to measure up to 1300 °C. The accuracy shall comply with Class 1 of standard EN60584. The uncertainty shall not exceed 5%.

3.1.1 Fire targets

Fire target temperatures shall be categorised according to their position at the front, rear, or side of the mock-up.

On the front and rear fire targets, four thermocouples shall be installed at two horizontal levels. The upper row shall be positioned approximately 100 mm below the upper edge of the target surface, and the second row at approximately the mid-height of the surface. All thermocouples shall be installed 5 mm from the exposed surface, on the fire-facing side of the target, to measure representative near-surface gas temperatures.

On the side fire target surfaces, two thermocouples per target field shall be installed at heights corresponding to those used for the front and rear targets.

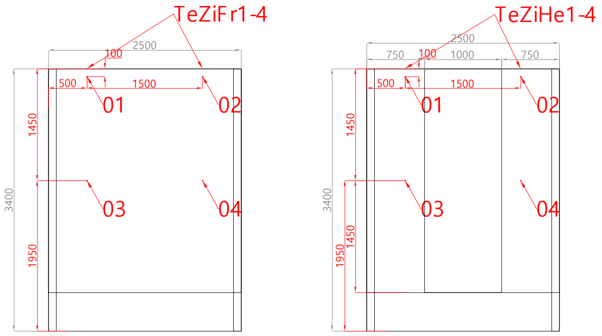

Figure 18. Thermocouple arrangement on front and rear fire targets

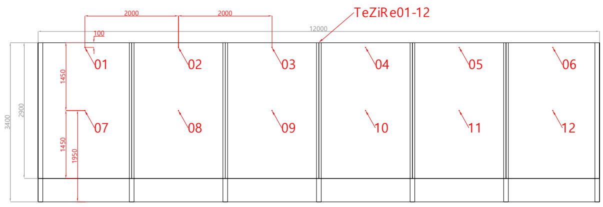

Figure 19. Thermocouple arrangement on side fire targets

3.1.2 Bus mock-up

Three thermocouples shall be installed inside the bus mock-up at a vertical distance of 75 mm below the ceiling beams. The thermocouples shall be positioned to measure representative gas temperatures beneath the ceiling structure of the passenger compartment and to allow monitoring of the internal fire development.

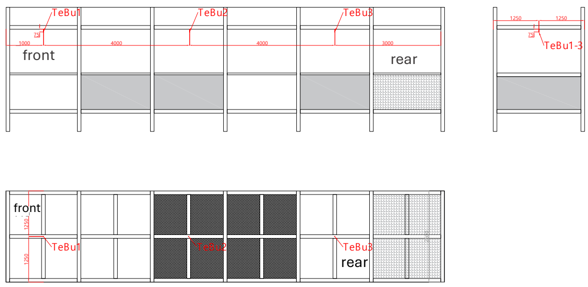

Figure 20. Thermocouple arrangement inside the bus mock-up

3.1.3 LIBs

Thermocouples installed on the lithium-ion battery assemblies shall be used to monitor the fire development within the battery arrangements. Battery temperatures shall be differentiated according to installation location, either on the roof or underfloor. These measurements shall be for documentation purposes only and shall not be used for performance evaluation of the fixed fire fighting system.

The positioning of the thermocouples may be adapted to the battery configuration and installation conditions. The measurement locations are shown in following figure.

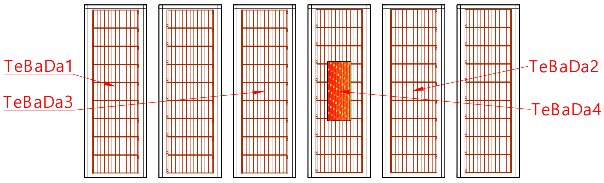

Figure 21. Thermocouple arrangement in LIBs

3.1.4 Ceiling structure

In the ceiling region, thermocouples shall be installed along the longitudinal centreline of the bus mock-up and in positions directly above the outer edges of the fire target surfaces. They shall be subdivided into right, centre, and left zones relative to the longitudinal axis of the bus mock-up. The thermocouples shall be positioned at a vertical distance of approximately 75 mm below the ceiling surface.

A ceiling height of 5.0 m (± 5%) above the floor shall be used for the test configuration. Although real depot ceilings may be higher and are determined by the authority having jurisdiction (AHJ), the reduced height introduces a conservative condition for the testing.

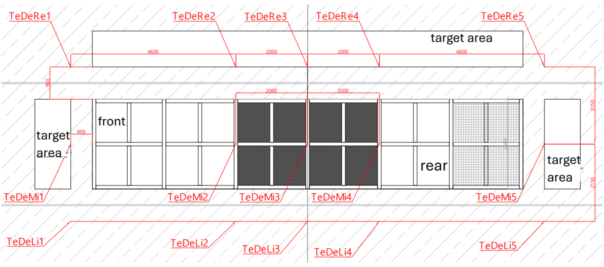

Figure 22. Arrangement of thermocouples at the ceiling, top view

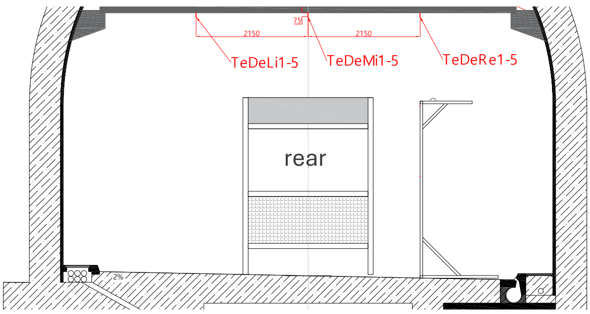

Figure 23. Arrangement of thermocouples at the ceiling, rear view

3.2 Pressure measurements

Pressure measurement points shall be installed in the piping system to verify that the required operating pressure is achieved at the hydraulically most unfavourable nozzle, i.e. the nozzle with the lowest operating pressure.

Where multiple nozzle levels or branches are present, pressure measurement points shall be installed at the end of each representative nozzle line with the lowest expected operating pressure. Pressure measurements shall be associated with the ceiling and floor sections of the fixed fire fighting system.

The pipework shall be dimensioned and arranged such that no significant pressure differences occur between individual nozzles within the protected area under the specified operating conditions. Hydraulic design shall ensure uniform water distribution and consistent nozzle performance.

The measurement shall be done with pressure transducers able to measure up to 160 bar or relevant to used pressure range. The accuracy shall be a minimum of ±0.2%, the uncertainty shall not exceed 5%. The pressure of FFFS shall be recorded as documentation of operating parameters.

3.3 Multigas analyser

A multigas analyser based on Fourier-transform infrared spectroscopy (FTIR) shall be used to assess the combustion process and gases (also from LIBs). Fire gas measurements shall be taken at a dedicated sampling point located within the smoke flow. The sampling point shall be positioned approximately 12.5 m downstream from the fire source, in the direction of the airflow, at a height of 2 m above floor level. This height is representative of conditions relevant to life safety and fire service operations.

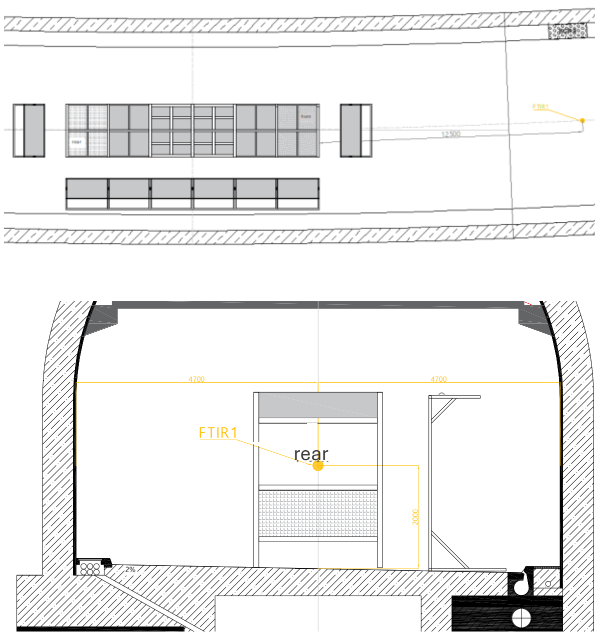

Figure 24. FTIR measurement point

3.4 Video recordings

Multiple video and camera systems shall be used to document the test execution and fire development. The number, type and positioning of the camera systems shall be adapted to the specific test scenario and test objectives. There shall be at least two optical video cameras and two infrared video cameras.

The camera systems shall be arranged to provide clear visual coverage of the fire source, fire spread, activation and performance of the fixed fire fighting system and relevant structural or target elements. The positioning shall ensure that key events can be observed and documented without interfering with the test arrangement or measurement systems.

The visual recordings shall be used for qualitative evaluation, test documentation, and correlation with measured data.

3.5 Environmental conditions

Immediately before the start of the experiment, ambient temperature, wind speed and wind direction shall be measured and recorded. Fire tests shall be conducted at an ambient temperature of approximately 20 °C (±10 °C) and the conditions shall be documented in the test report.

The humidity and air velocity shall be determined using hand-held measuring devices. The moisture content of the wooden pallets shall be determined at random using a material moisture meter and documented in the report. The moisture content shall not exceed 20%

3.6 Summary of measurement locations

The designation scheme shall be used consistently in the data acquisition system, test documentation and evaluation reports.

For the definition of the measurement locations and their designation, the test arrangement shall be subdivided in a systematic manner. The following measurement points shall be provided as a minimum:

- 44 temperature measurement points (TE)
  - 15 temperature measurement points located at the ceiling of the test tunnel
  - 20 temperature measurement points located on the fire target surfaces at the sides, front, and rear
  - 3 temperature measurement points located at the ceiling inside the bus mock-up
  - 6 temperature measurement points installed at each lithium-ion battery fire load configuration
- Pressure measurement points for the fixed fire fighting system
- 1 FTIR measurement point located in the fire gas flow downstream of the test arrangement
- Multiple video and camera systems, with positioning adapted depending on the specific test scenario

Each measurement point shall be assigned a unique designation. The designation scheme shall be defined in accordance with Table 1 and shall be documented in a project-specific instrument list. This list shall link each sensor to its inventory number and to the corresponding measurement channel in the data acquisition system.

Table 1. Definition of measurement points

Measured variable	Designation
Gas temperature, ceiling, right [°C]	TeDeRe1…5
Gas temperature, ceiling, center [°C]	TeDeMi1…5
Gas temperature, ceiling, left [°C]	TeDeLi1…5
Surface temperature, target, front [°C]	TeZiFr1…4

Surface temperature, target, rear [°C]	TeZiHe1…4
Surface temperature, target, right [°C]	TeZiRe1…12
Gas temperature, mock-up, ceiling [°C]	TeBu1…3
Temperature, LIB, ceiling, [°C]	TeBaDa1…6
Temperature, LIB, floor, [°C]	TeBaBo1…6
Nozzle pressure, HPWM-FFS, ceiling-system [bar]	PrWN1
Nozzle pressure, HPWM-FFS, floor-system [bar]	PrWN2
Multigas measurement in fire gas flow [ppm or Vol.-%	FTIR1

3.7 Accreditation and quality assurance

All measurements, testing activities, and data evaluation shall be performed by an accredited testing laboratory operating in accordance with EN ISO/IEC 17025. The laboratory shall be accredited for the relevant measurement disciplines or shall otherwise demonstrate technical competence through validated procedures and traceable calibration.

All measurement systems and data acquisition equipment shall be subject to traceability to national or international standards. Calibration shall be done before the fire tests. Calibration records shall be maintained and made available upon request.

4. Test procedure

4.1 General principles

All fire tests shall be conducted in accordance with a uniform, controlled, and reproducible test procedure. The procedure shall ensure that fire development, detection and activation of the fixed fire fighting system occur under clearly defined and conservative conditions. The sequence of events shall be identical for all tests unless a deviation is explicitly defined in the test plan and documented.

The fire scenario shall be designed to represent a late-detected, severe bus fire, including lithium-ion battery involvement and followed by full vehicle fire development. The procedure shall intentionally avoid early intervention or automatic detection in order to evaluate the fixed fire fighting system under demanding conditions.

4.2 Pre-test preparation

Prior to each test, the bus mock-up and all fire target structures shall be installed and aligned in accordance with the defined geometry. The fixed fire fighting system shall be installed, checked for functionality, pressure tested/flushed and set to standby condition. All measurement systems, data acquisition equipment and camera systems shall be installed, checked for functionality and activated.

The Class A fire load shall be positioned on the designated platforms in accordance with the fire load definition. The lithium-ion battery assemblies shall be installed either in the underfloor or roof configuration, as specified for the test. Ignition systems for both the batteries and the Class A fire load shall be prepared and verified.

Before ignition, a final safety check shall be performed and all non-essential personnel shall withdraw to designated safe locations.

4.3 Ignition and fire development

Each test shall commence with ignition of the lithium-ion batteries. The battery fire shall be allowed to develop freely without intervention. Battery involvement shall be considered established once sustained visible flames and characteristic battery reaction events (e.g. venting, jet flames or explosions) are observed.

Only after clear battery involvement has been achieved shall the ignition of the Class A fire load be initiated. All ignition sources for the Class A fire load shall be activated simultaneously, ensuring a rapid and reproducible transition from a battery-started fire to a fully developed vehicle fire scenario.

Figure 25. Fire before FFFS start (IFAB)

4.4 System activation and test duration

No automatic fire detection shall be used for system activation. Activation shall be intentionally delayed and based on a combination of quantitative temperature criteria and qualitative flame observations. The intent is to challenge the system under a late activation scenario representative of severe real-world bus depot fires.

Activation shall occur when:

- Temperatures inside the mock-up have reached 200 °C,
- Flames are visibly emerging beyond the lateral boundaries of the mock-up, and
- Ceiling temperatures have exceeded 100 °C and are increasing.

These quantitative values, complemented by qualitative flame behaviour, define a conservative late-detection condition.

Once the criteria are met, the fixed fire-fighting system shall be manually activated. From the moment of activation, the test shall continue for a minimum of 60 minutes, unless early termination is required for safety reasons.

During this time, the system shall operate continuously or according to its pre-defined operating mode. No manual suppression is permitted. All lithium-ion batteries shall burn during the test, the objective is not to extinguish the batteries, but to evaluate system performance under prolonged and severe fire exposure.

4.5 Test termination and post-test actions

The test shall be terminated after the minimum post-activation duration has elapsed. Following test termination, all remaining fires shall be manually extinguished in a controlled manner.

Damaged or partially reacted lithium-ion batteries shall be secured and handled in accordance with established safety procedures. Measurement data shall be saved, backed up and archived. Fire damage to the mock-up, fire targets and system components shall be documented.

Residual fire load materials shall be removed and the bus mock-up shall be cleaned and repaired as necessary. Measurement equipment shall be inspected and any damaged sensors shall be replaced prior to preparation for any additional tests.

4.6 Safety and risk management

Full-scale bus fire tests with lithium-ion batteries involve hazards such as projectiles, jet flames, toxic gases, contaminated fire extinguishing water and delayed re-ignition. A controlled exclusion zone shall be maintained until the test leader declares the area safe. Personnel entering the zone shall wear appropriate PPE. Emergency stop and termination criteria shall be defined in advance and adequate firefighting resources shall remain on standby throughout the test.

After test termination, all LIBs shall be treated as unstable and potentially re-ignitable. Batteries shall be cooled, monitored, and where required, placed in a designated quarantine area for an appropriate observation period. Handling, transport and disposal of damaged or reacted batteries shall follow applicable hazardous-waste and battery-safety regulations and the test facility’s safety management procedures.

5. Acceptance criteria

5.1 Purpose and principle

This chapter defines the minimum performance requirements for the fixed fire fighting system (FFFS) tested in accordance with Chapter 4.

The acceptance criteria are based on a deliberately severe bus fire scenario with late system activation and lithium-ion battery involvement.

The evaluation focuses on:

- Prevention of fire spread to adjacent buses,
- Limitation of thermal exposure, and
- Support of safe manual firefighting intervention.

Unless otherwise stated in the project-specific test plan annex and additional requirements by AHJ, these criteria apply to all tests conducted under this protocol.

5.2 Preconditions for acceptance

Test results shall be considered valid for acceptance evaluation only if all of the following conditions are met:

- The test is executed in accordance with Chapter 4, without unplanned deviations affecting fire development, ventilation, ignition sequence or activation timing.
- All mandatory instrumentation defined in Chapter 3 is operational and provides usable data for the test duration (or until justified later termination).
- The FFFS activates and operates as intended, with extinguishing agent delivered to the designated areas and without critical system failure.
- Boundary conditions (geometry, ventilation, and ambient conditions) are met and properly documented.

If these conditions are not met, the test shall be considered invalid for acceptance, unless explicitly justified in the test report and approved by AHJ.

5.3 Acceptance criteria

5.3.1 Acceptance

The FFFS shall be considered acceptable if all of the following conditions are fulfilled:

- No flaming combustion occurs on any target representing adjacent buses during the evaluation period following system activation.
- No sustained flaming ignition occurs on PMMA or GFRP indicator materials. Local melting, softening, charring, blistering or delamination is permitted, provided no sustained flaming is observed.
- Thermal exposure limits at monitored locations are not exceeded during system operation:
    - Targets: Sustained temperatures shall not exceed 100 °C. Short-duration, isolated temperature peaks at individual thermocouples may be accepted if:
        - The exceedance lasts no more than 5 seconds,
        - It occurs as an isolated peak (not sustained or recurring), and no ignition, sustained flaming, or loss of target integrity occurs.
    - Ceiling region: Sustained ceiling gas temperatures shall not exceed 250 °C. Short-duration, localized exceedances may be accepted (single thermocouple), provided no structural damage is observed.
    - The FFFS operates continuously for at least the minimum required post-activation duration without critical malfunction.
    - All LIBs in the test are deemed to have burned fully by the end of the test, as the intention is not to extinguish the batteries but to evaluate the system's ability to prevent fire spread and limit thermal exposure.

Lithium-ion battery flaming, jet flames, venting, explosions, or continued thermal runaway do not constitute failure, as the objective is to prevent fire spread, not to extinguish the batteries.

All short-duration thermal peaks accepted under the above criteria shall be documented in the test report and clearly identified as transient effects.

5.3.2 Failure

Failure is deemed to have occurred if any acceptance criterion defined in Section 5.3.1 is not fulfilled. In addition, any of the following conditions explicitly constitute failure:

- Sustained flaming ignition on any adjacent-bus target surface.

- Sustained flaming ignition of PMMA or GFRP indicator materials.
- Failure of the FFFS to deliver water as intended, including loss of pressure, blocked flow or critical component malfunction.
- Exceedance of the mandatory temperature limits defined in Section 5.3.1, unless explicitly permitted as short-duration peaks.
- Premature termination of system operation before the minimum required post-activation duration due to system-related causes.
- Premature activation of the system or any other procedural mistake

5.4 Documentation requirements

The test report shall include as a minimum:

- Activation time and activation criterion,
- Time-resolved temperature plots (ceiling, targets, bus interior),
- Pressure recordings at defined locations,
- Photographic documentation of targets before and after testing,
- Video time stamps of key events (ignition, activation, battery involvement, any target damage).
- Documented fire damages including LIBs.
- Confirmation of the nozzle k-factor, including retention of at least two sample nozzles used in the tests.

A. Annexes

A.1 Information of bus depot fire safety

A.1.1 Background

Bus depots represent important infrastructure for public transport systems and are characterised by a high concentration of vehicles, significant combustible loads and increasing electrification. In recent years, the transition from diesel-powered buses to battery-electric buses has introduced new fire safety challenges related to lithium-ion battery systems, charging infrastructure and other technologies.

Bus depots typically operate with vehicles parked in close proximity, often for extended periods and frequently outside of active supervision. Fire events in such facilities have repeatedly demonstrated the potential for rapid fire spread, large-scale property damage and long operational disruptions. In several documented cases, single-vehicle fires have escalated into multi-vehicle depot fires within minutes, leading to total loss of the fire compartment and severe structural damage.

Previous fires in bus depots, both involving conventional buses and electric buses, have shown that early fire growth, limited accessibility and delayed detection are dominant contributing factors. While lithium-ion batteries are not always the initiating cause, their presence can significantly influence fire duration and severity, re-ignition potential and firefighting complexity. These experiences underline the necessity of systematic fire risk assessment and the consideration of fixed fire protection measures for bus depots.

A.1.2 Bus depot types

Bus depots can be categorised according to their geometric configuration, enclosure, surroundings, and operational characteristics. This classification is essential for determining the fire risk level and the need for enhanced fire safety measures.

A.1.2.1 Open parking facilities

Typically characterised by:

- Open or semi-open arrangements, located at ground level
- No enclosure, or enclosure on not more than one side
- Absence of a roof or only lightweight weather protection
- Adequate separation distances to residential buildings, public spaces, or other infrastructure, demonstrated by a site-specific risk analysis

In such depots, smoke and heat can dissipate more freely and structural fire exposure is limited. Fixed fire fighting systems are strongly recommended but not necessary mandatory in all cases; however, business continuity considerations or fleet value may justify FFFS and other safety measures.

A.1.2.2 Closed parking facilities

Fully or partially enclosed volumes with a roof and at least two closed sides. Typical examples include

- underground or semi-underground depots
- depots integrated into special structures, such as mixed-use buildings or transport hubs (or above depot structures)
- proximity to residential buildings, public facilities, or sensitive occupancies, requiring detailed risk assessment

In these depots, fire and smoke accumulation can occur rapidly, structural elements may be exposed to high thermal loads and evacuation and firefighting operations can be significantly impaired.

Higher risk depots generally should require active fire protection systems and enhanced detection and alarm strategies.

A.1.3 Applicable standards

A.1.3.1 Germany

In Germany, the fire safety design of bus depots is governed by a combination of sector-specific recommendations, insurance-driven approval schemes, national and European standards, and building regulations.

The following references are commonly applied.

A.1.3.1.1 Public transport sector recommendations

- VDV (Verband Deutscher Verkehrsunternehmen)
    - VDV-Schrift 825 (02/2023): Anforderungen an Betriebshöfe und Werkstätten beim Einsatz von Linienbussen mit sauberen und/oder emissionsfreien Antrieben

A.1.3.1.2 Insurance and approval-oriented fire protection guidance

- VdS Schadenverhütung
    - VdS 0825:2023-03 (01*):* Brandschutz in Betriebshöfen für Linienbusse
    - VdS CEA 4001:2024-01 (08): VdS CEA guidelines for sprinkler systems – planning and installation
    - VdS 3188:2019-10 (02): Guidelines for high-pressure water mist sprinkler and extinguishing systems – planning and installation

A.1.3.1.3 Occupational safety and firefighting guidance

- DGUV
    - FBFHB-024 (2023): Guidance for firefighting involving lithium-ion batteries in vehicle fires

A.1.3.1.4 Standards (DIN / EN)

- DIN
    - DIN EN 14972-1:2025-07: Fixed firefighting systems – water mist systems – design, installation, inspection, and maintenance
    - DIN EN 12845:2020-11: Automatic sprinkler systems – design, installation, and maintenance
    - DIN EN 54-1:2021-08: Fire detection and fire alarm systems – introduction
    - DIN 14095:2025-07: Fire brigade plans for buildings

A.1.3.1.5 Fire engineering and fire brigade guidance

- vfdb (Vereinigung zur Förderung des Deutschen Brandschutzes)
    - vfdb guideline MB 14-02: Water mist extinguishing systems
    - vfdb guideline MB 10-17: Recommendations for fire brigade operations involving lithium cells, batteries, and accumulators

A.1.3.1.6 Building regulations

- Musterbauordnung (MBO), version November 2002, last amended by decision of the Building Ministers' Conference on 26–27 September 2024
- Applicable state building regulations (Landesbauordnungen), depending on federal state

A.1.3.2 International

For projects outside Germany, or for internationally benchmarked designs, local regulatory requirements should be applied together with recognised international standards and best practice, particularly for large vehicle facilities, alternative propulsion systems, and lithium-ion battery risks.

A.1.3.2.1 Examples – NFPA / FM

- National Fire Protection Agency (NFPA)
    - NFPA 13 (2025): Installation of sprinkler systems
    - NFPA 15 (2022): Water spray fixed systems
    - NFPA 18A (2022): Water additives for fire control and vapour mitigation
    - NFPA 72 (2025): National fire alarm and signalling code
    - NFPA 750 (2023): Water mist fire protection systems
    - NFPA 502 (2026): Road tunnels, bridges, and other limited access highways
    - NFPA 855: Installation of stationary energy storage systems
    - NFPA Project summary (10.08.2023): Lithium-ion battery transit bus fire prevention and risk management
- FM Global
    - FM 6540: Lithium-ion battery off-gas detection
    - FM 5-48: Automatic fire detection
    - FM 2-0: Installation guidelines for automatic sprinklers
    - FM 1-21: Fire resistance of building assemblies
    - FM 4-2: Water mist systems
    - FM 5-32: Data centres and related facilities
    - FM 5-33: Lithium-ion battery energy storage systems
    - FM 7-112: Lithium-ion battery manufacturing and storage

A.1.4 Fire safety systems for bus depots

A.1.4.1 Fire detection

Early fire detection is a fundamental element of fire safety in bus depots. Due to the large fire loads, rapid fire growth and limited supervision during parking periods, detection systems shall be designed to identify developing fires at the earliest practicable stage.

Detection systems in bus depots may include different technologies, depending on depot type, geometry and risk level.

Typical detection types include:

- Point-type smoke detectors
- Linear heat detection systems
- Aspirating smoke detection systems
- Flame detectors
- Different camera technologies including infrared
- Gas-based detection (e.g. CO, H_2, or battery off-gas detection)
- Systems for detection of battery anomalies

The selection of detection technology shall consider:

- High ceilings and large volumes
- Potential dilution effects in open or semi-open depots
- Contamination, dust, and environmental influences
- The need for rapid response in high-risk depots

Applicable standards for fire detection systems shall be observed, including national and international fire alarm standards. In higher risk depots, the combination of multiple detection principles is recommended to improve reliability and reduce detection time. Detection systems shall be integrated with alarm and fire fighting systems where applicable.

A.1.4.2 Fire fighting systems

Fire-fighting systems in bus depots are primarily intended to limit fire growth, reduce thermal exposure, prevent fire spread to adjacent vehicles and structures, and support safe evacuation and fire-fighting operations. This chapter summarises the main system types commonly used in depots. Regardless of the system type, all systems shall demonstrate their performance in accordance with the requirements defined in this document. As a general principle, only systems that have been tested and shown suitable for the specific risk and hazard profile shall be installed.

A.1.4.2.1 Sprinkler / deluge systems

Conventional sprinkler systems operate mainly by surface wetting and cooling, providing a predominantly two-dimensional water application from above.

In bus depots, sprinkler systems have the following characteristics and limitations:

- Effectiveness relies on direct wetting of burning surfaces
- Limited capability to block radiative heat transfer
- Reduced efficiency in shielding targets from high radiant heat flux
- No established design basis specifically addressing electric bus or large battery fires
- Limited large-scale test data for battery-driven vehicle fires in depot environments

Only deluge-type systems, with open nozzles and immediate full-system discharge upon manual or detection-based activation, shall be considered for bus depot fire protection. Their use must still be justified and supported by appropriate full-scale testing in accordance with this document.

A.1.4.2.2 Water mist systems

Water mist systems act through a combination of gas-phase cooling, surface wetting, and partial local inerting of the fire. Their fine droplet distribution provides a three-dimensional fire control mechanism that interacts with flames, hot gases and exposed target surfaces.

Systems designed and tested for heavy-vehicle applications, such as those used in tunnel, also provide effective surface wetting and thermal shielding.

Water mist systems are considered particularly suitable for bus depots due to:

- Effective reduction of gas and surface temperatures
- Significant attenuation of radiative heat transfer
- Capability to protect adjacent vehicles and structural elements
- Suitability for large volumes and complex geometries

Extensive full-scale testing has been conducted with electric vehicles (passenger vehicles), lithium-ion batteries and heavy vehicles, including buses.

These tests have demonstrated the ability of water mist systems to control fire development, reduce thermal exposure, and limit secondary damage. Data from recognised independent research programmes shall be considered when designing such systems.

Only deluge operated water mist systems, with open nozzles and immediate full-system discharge upon manual or detection-based activation, shall be considered for bus depot fire protection. Their use must still be justified and supported by appropriate full-scale testing in accordance with this document.

A.1.4.2.3 Foam systems

Foam systems apply a mixture of water, air and foaming agent to form an expanded extinguishing medium. Depending on the expansion ratio, firefighting foam is categorised as low-, medium-, or high-expansion foam. For this guideline, only systems using an extinguishing agent with an expansion ratio greater than 4 are considered and compressed-air foam systems are included.

The primary extinguishing mechanism of foam is oxygen displacement (suffocation), as the foam layer separates the burning material from ambient air. Foam also provides limited cooling, depending on its water content and therefore on the expansion ratio. Cooling, however, is critical in lithium-ion battery fires to prevent thermal runaway propagation. While foam may cover the enclosure or battery module surfaces, it does not reach or cool individual battery cells.

Compared with other water-based systems, foam has a lower capacity to cool hot gases, as gas-phase cooling depends largely on available droplet surface area. High temperatures and chemically aggressive fire effluents may also accelerate degradation of the foam blanket.

In addition to performance considerations, several operational and safety aspects must be evaluated:

- Foam additives may pose environmental and human health risks, depending on their chemical composition.
- Foam can obstruct visibility, conceal trip hazards, and hinder the location of unconscious persons.
- Foam-covered surfaces are slippery, increasing risks for evacuees and firefighters.
- Low-expansion foam used to flood a depot can reduce oxygen locally but will not stop battery thermal runaway.
- Large quantities of foam may damage vehicles or equipment and may introduce electrical conductivity risks under unfavourable conditions.
- Foam may contribute to thermal instability by insulating burning materials, potentially increasing heat release rates (as noted in NFPA 855, C.5.1).

These factors shall be taken into account when evaluating foam systems as part of a FFFS design and when developing the overall safety, evacuation, and firefighting concepts for bus depots.

If foam systems are tested, the maximum protected area, nozzle configuration, and system design parameters (also dosing and foam details) shall be justified through full-scale testing or performance-based design in accordance with this document.

A.1.4.2.4 Encapsulator Additive Systems (e.g., F-500)

Encapsulator additives such as F-500 are mixed with water to modify its physical and chemical behaviour. These additives reduce the evaporation temperature and surface tension of water, resulting in enhanced cooling performance compared with plain water. During application, the additive forms micelles capable of encapsulating flammable molecules, thereby limiting fire spread and reducing the release of combustible vapours.

Encapsulator additives are regulated under NFPA 18A. They are typically applied using low-pressure spray or flood systems operating at standard pressure. The additive is introduced into the water stream via a mixing or dosing device and therefore the overall water distribution pattern and water consumption are often comparable to those of conventional sprinkler deluge-type systems.

The reduced surface tension produces smaller droplets that penetrate more deeply into the fire load, improving cooling efficiency, particularly for Class A materials, and enhancing the thermal management of lithium-ion battery cells, thereby reducing the risk of thermal runaway propagation. Micelle formation is claimed to bind combustible gases and particulates, providing additional mitigation during battery fire scenarios.

However, several limitations and safety considerations apply:

- As referenced in NFPA 855, the electrical conductivity of the extinguishing medium must be assessed. Encapsulator additives typically increase conductivity, potentially heightening electrical hazards and increasing the risk of short circuits in high-voltage systems.

- Encapsulator agents may be chemically incompatible with foam, and foam applied manually by firefighters may rapidly degrade or become ineffective when used in combination with these additives.
- It shall therefore be clearly stated that firefighters cannot rely on foam as part of their manual firefighting strategy when encapsulator additives are installed, unless explicitly coordinated with the local fire service and supported by appropriate operational precautions.

If encapsulator additive systems are used, the maximum protected area, nozzle configuration, and system design parameters (also dosin and additive details) shall be justified through full-scale testing or performance-based design in accordance with this document.

It is also recommended to conduct a reference test using water only, without additive, to establish the baseline performance of the system and to demonstrate the specific added-value of the encapsulator agent.

A.1.4.3 Passive fire protection

Passive fire protection measures form an essential component of overall depot safety by providing structural robustness, limiting fire spread, and supporting life safety.

Typical passive measures include:

- Fire-resistant structural elements
- Fire compartmentation within buildings
- Fire-rated separations between designated depot zones

These measures contribute to maintaining structural integrity and preventing the escalation of fires across fixed building boundaries. However, passive protection cannot prevent fire propagation between closely spaced buses nor effectively manage the intense thermal radiation produced by large vehicle fires, particularly those involving lithium-ion batteries.

Furthermore, implementing fire-rated passive barriers between individual buses or parking lanes would severely compromise depot operability. Such an arrangement would restrict manoeuvring space, reduce parking capacity, hinder maintenance operations, and impose significant logistical and economic burdens. A depot configured with continuous passive separations would become operationally constrained and unable to function efficiently.

For these reasons, passive fire protection shall be considered a supplementary measure that enhances, but does not replace, active fire-fighting systems. A practical and effective depot fire safety concept requires a balanced combination of active suppression, possible passive measures and operational procedures.

A.1.5 Other standardised safety equipment

In addition to fixed fire fighting systems, bus depots are typically equipped with other fire safety measures required by regulations.

A.1.5.1 Portable fire extinguishers

Portable fire extinguishers are required for incipient fire fighting and shall be provided in accordance with applicable regulations. Their effectiveness in large vehicle fires is limited, but they may support early intervention or secondary fire control.

A.1.5.2 Wall cabinets and hose reels

Wall-mounted fire cabinets and hose reels may be required by law in certain jurisdictions. These systems support manual firefighting operations but shall not be considered a substitute for fixed fire fighting systems in higher risk depots.

A.1.5.3 Evacuation routes and markings

Evacuation concepts in bus depots differ significantly from those in public buildings. Depots are typically occupied by trained personnel, often familiar with the layout.

Minimum distances between buses and access routes shall be maintained in accordance with occupational safety and fire regulations.

For open parking facilitiesas defined in Section A.1.2.1

- Access to exits is generally unobstructed
- Evacuation distances are short
- Fire and smoke can dissipate more easily
- Risks to operators and maintenance personnel are comparatively lower

For closed parking facilities as defined in Section A.1.2.2

- Access and evacuation routes may be restricted
- Smoke accumulation can occur rapidly
- Orientation may be impaired
- Greater reliance is placed on early detection and fixed fire fighting systems to maintain tenable conditions

Evacuation routes generally shall be clearly marked, illuminated, and kept free of obstructions.

A.1.6 Smoke extraction systems

Smoke extraction systems are not typically required in open parking facilities. In closed parking facilities, smoke control measures may be necessary to

- Maintain tenable conditions during evacuation
- Support firefighting operations
- Reduce thermal exposure to structural elements

The design basis for smoke extraction in bus depots is challenging due to the rapid development of heat release rates / fire size. Where provided, smoke extraction systems shall be designed based on conservative fire scenarios and integrated with detection and fire fighting systems.

A.2 Drawings

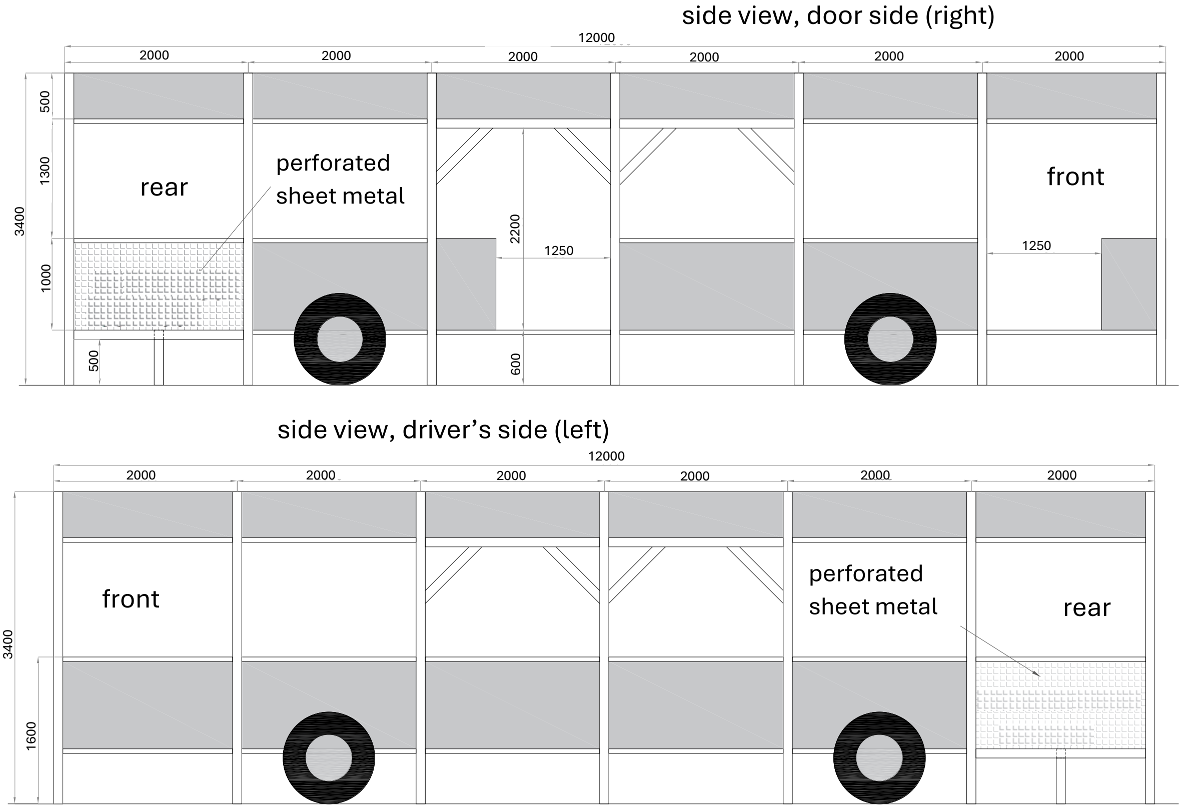

Figure 26. Side views of bus mock-up

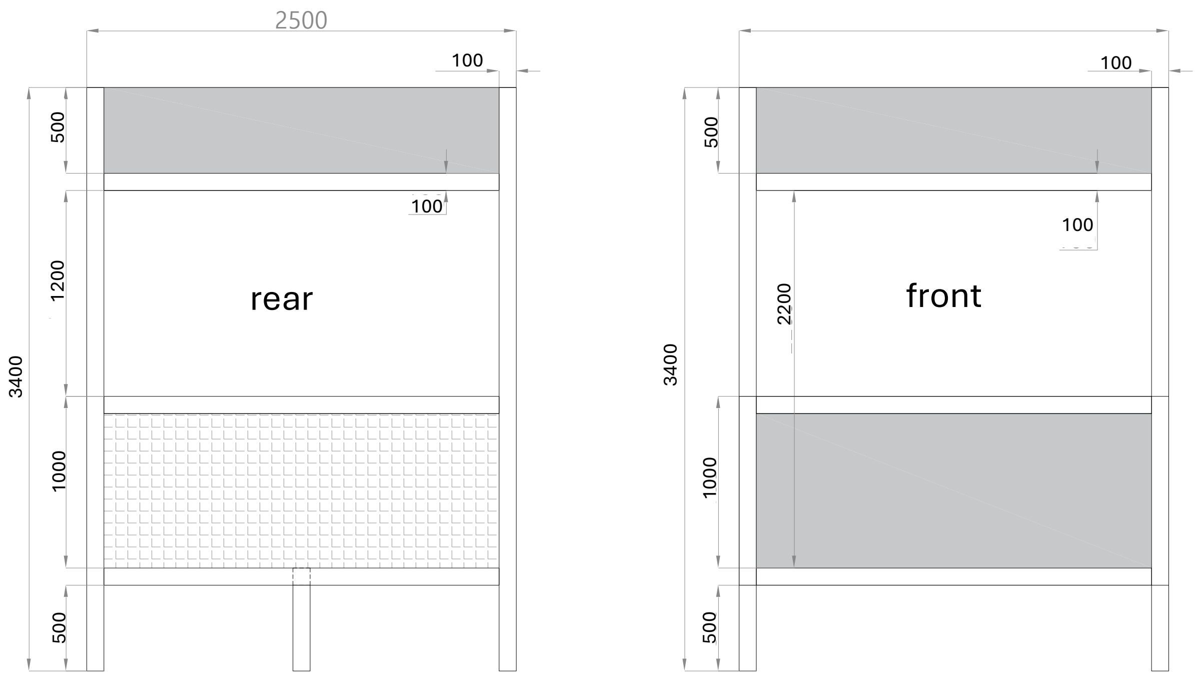

Figure 276. Rear and front views of bus-mock up

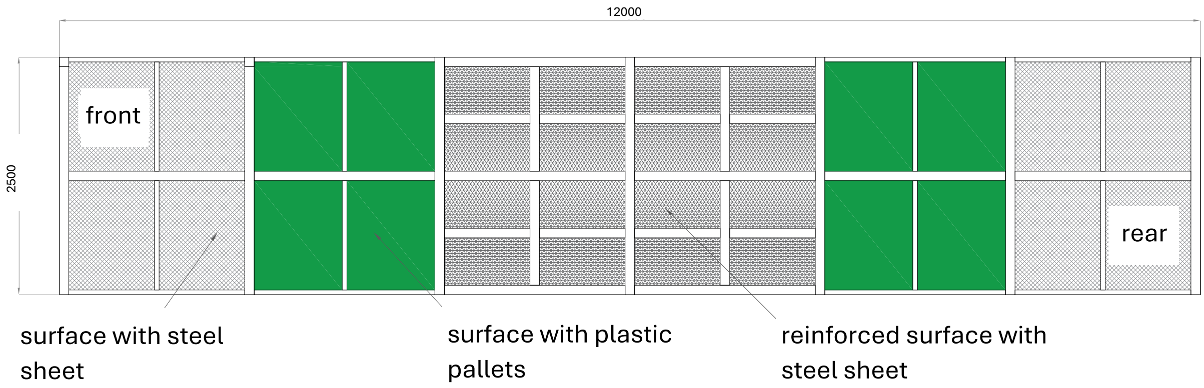

Figure 28. Roof view of bus mock-up

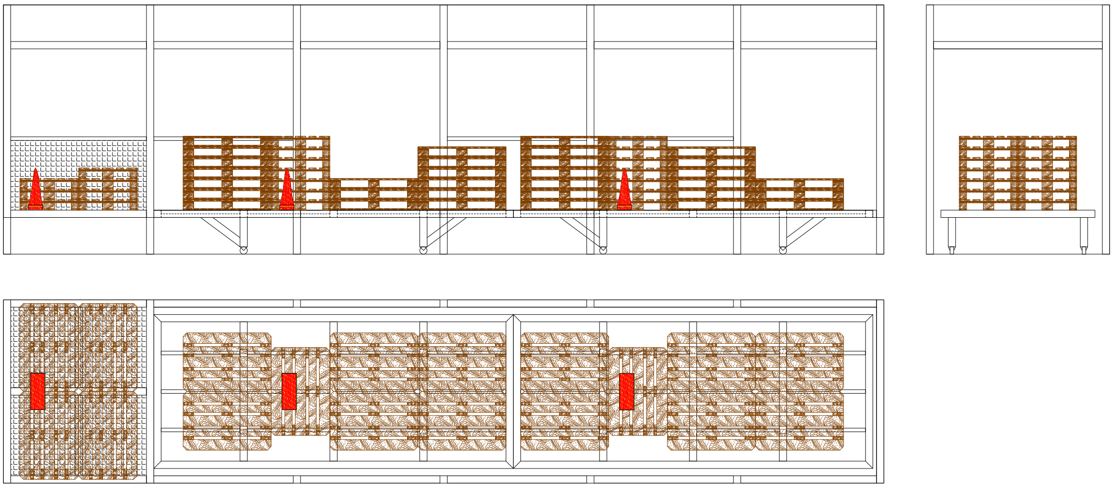

Figure 29. Fire load (Class A - pallet) arrangement in the mock-up.

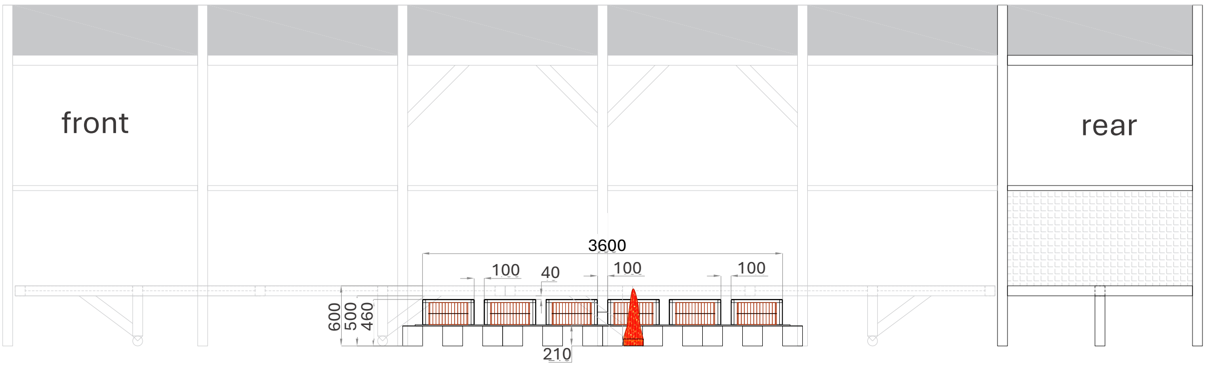

Figure 30. LIB fire load underfloor

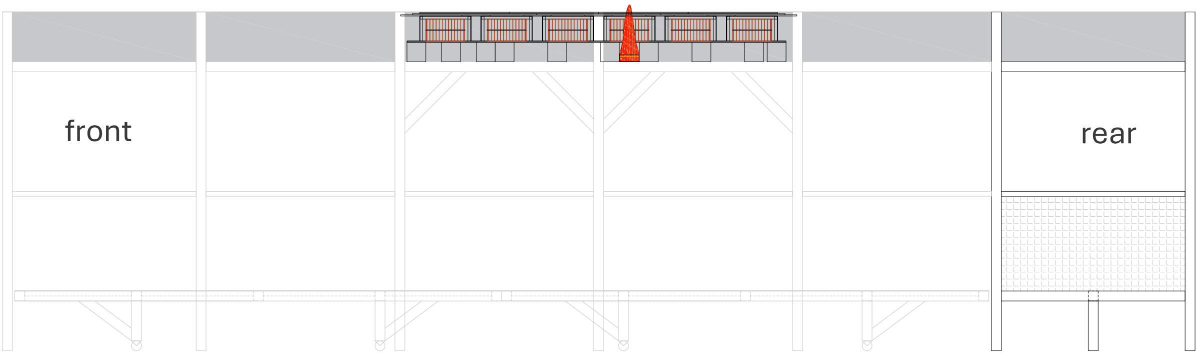

Figure 31. LIB fire load on the roof

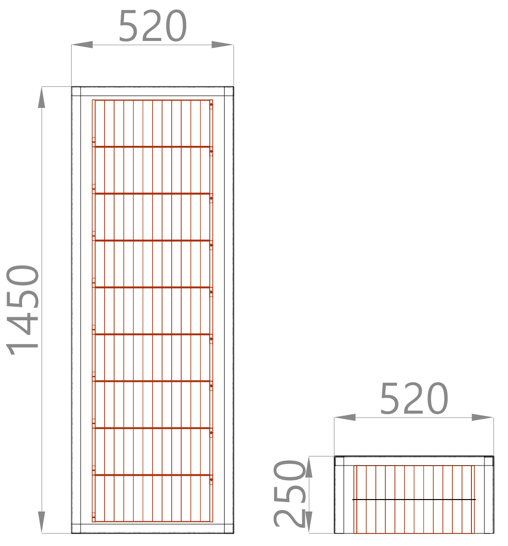

Figure 32. Battery box/case dimensions (top view left, side view right)

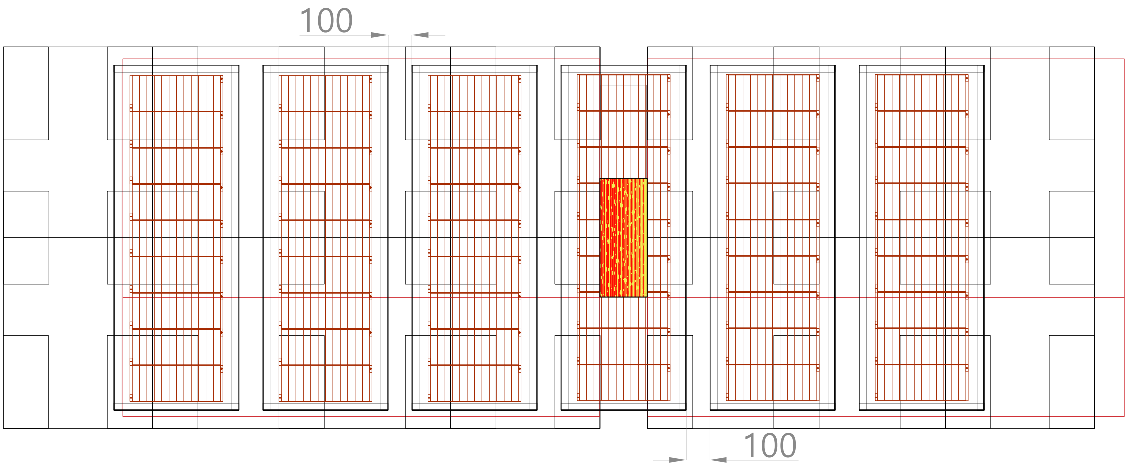

Figure 33. Installation of 6 battery boxes/cases under floor or ceiling

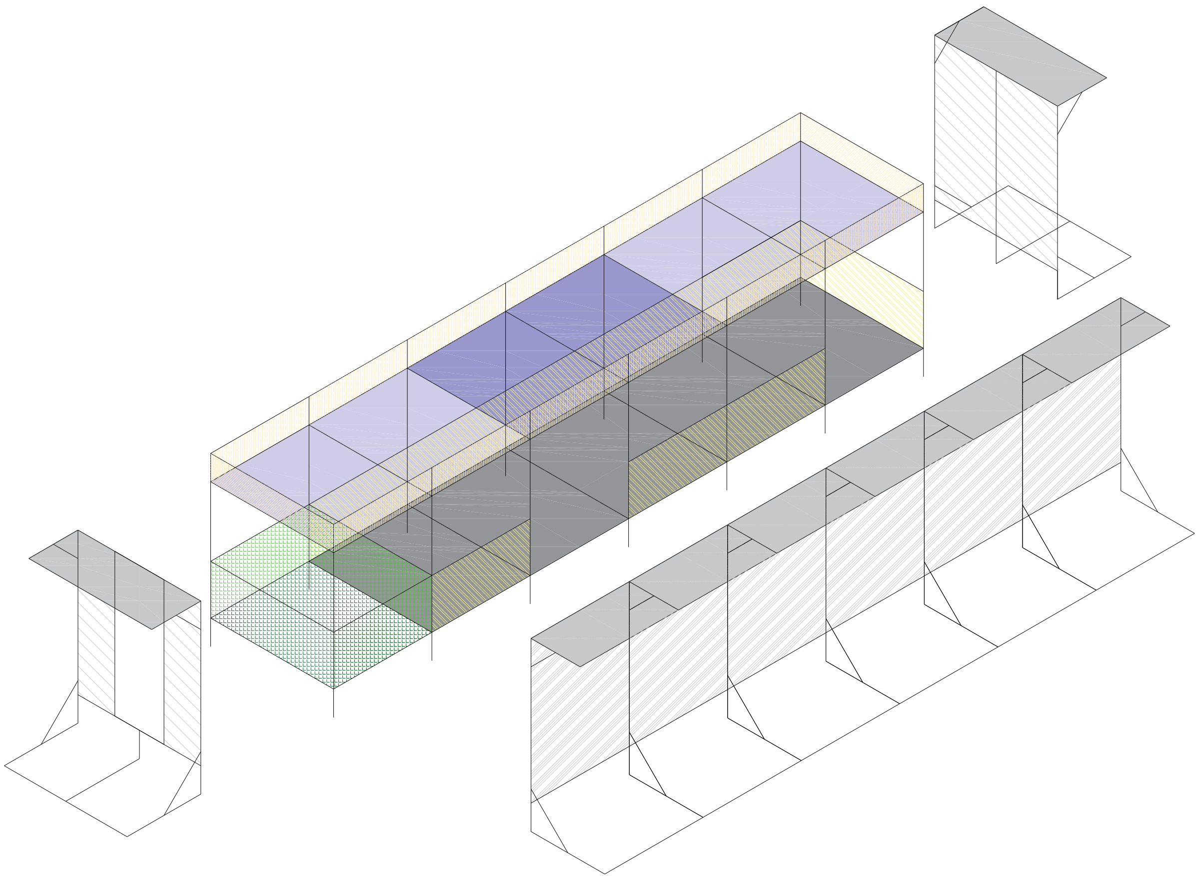

Figure 34. Fire targets and mock-up

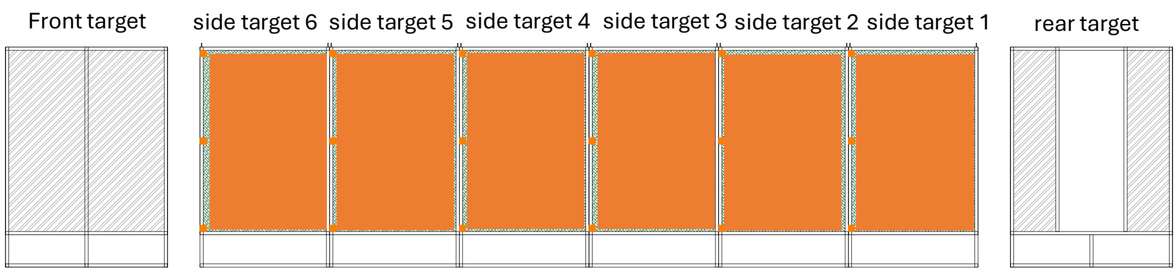

Figure 35. GFRP target plates (orange)

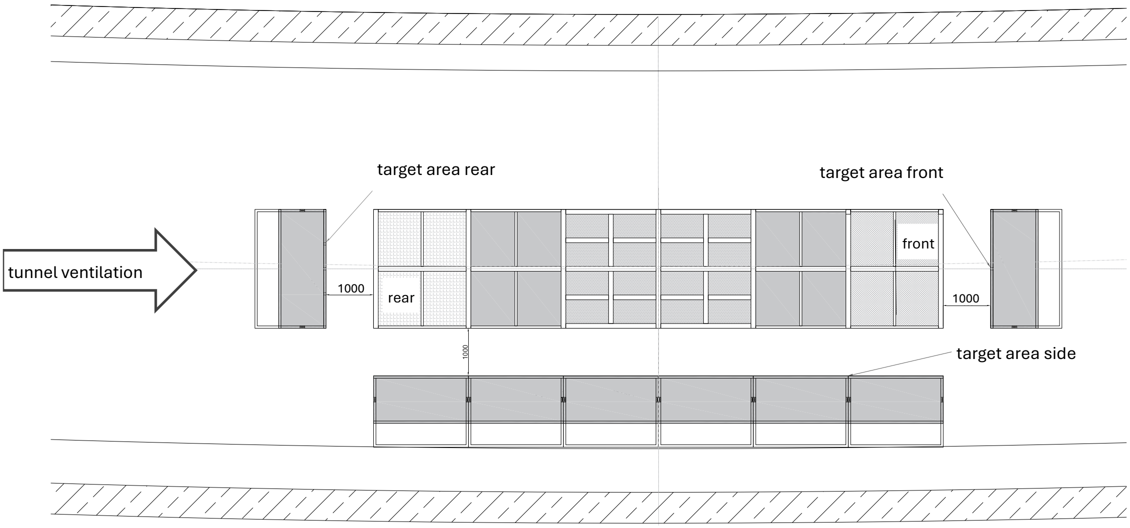

Figure 36. Arrangement of the targets

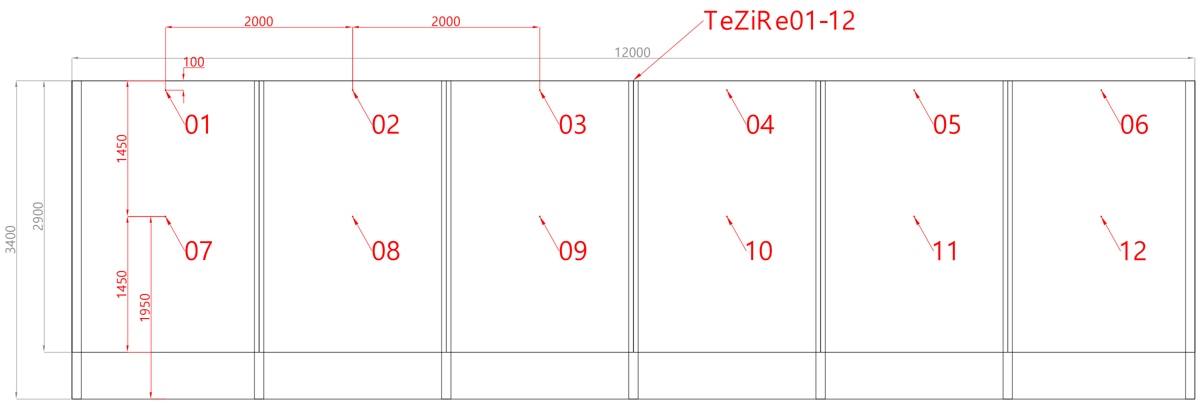

Figure 37. Thermocouple arrangement on side fire targets

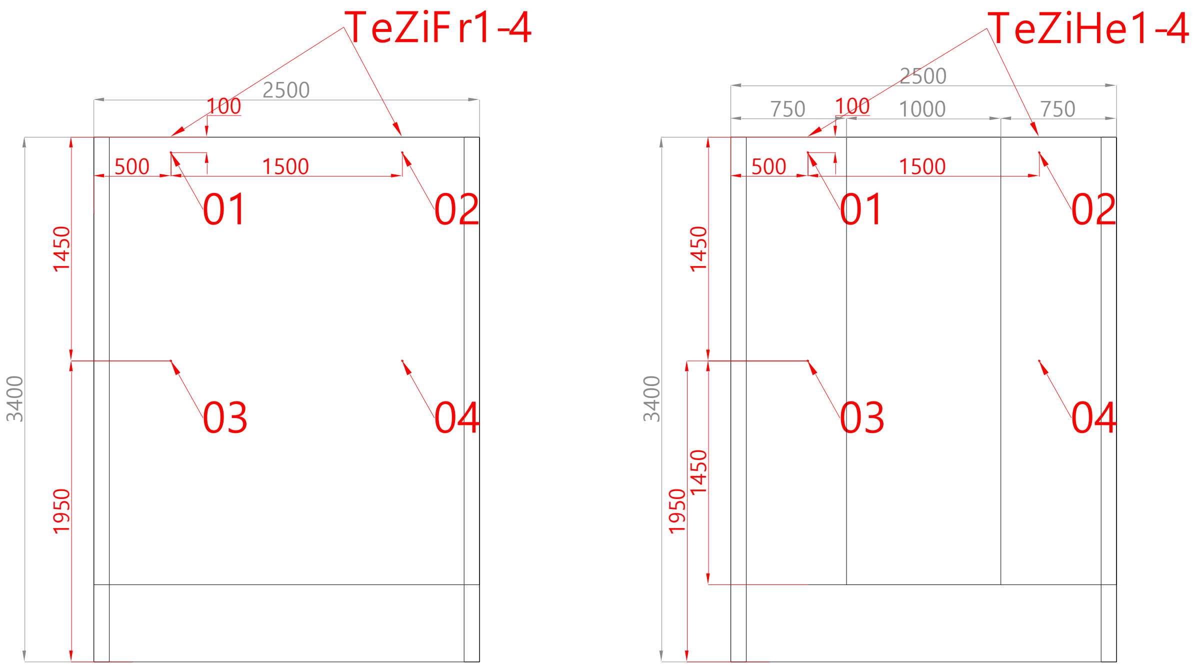

Figure 38. Thermocouple arrangement on front and rear fire targets

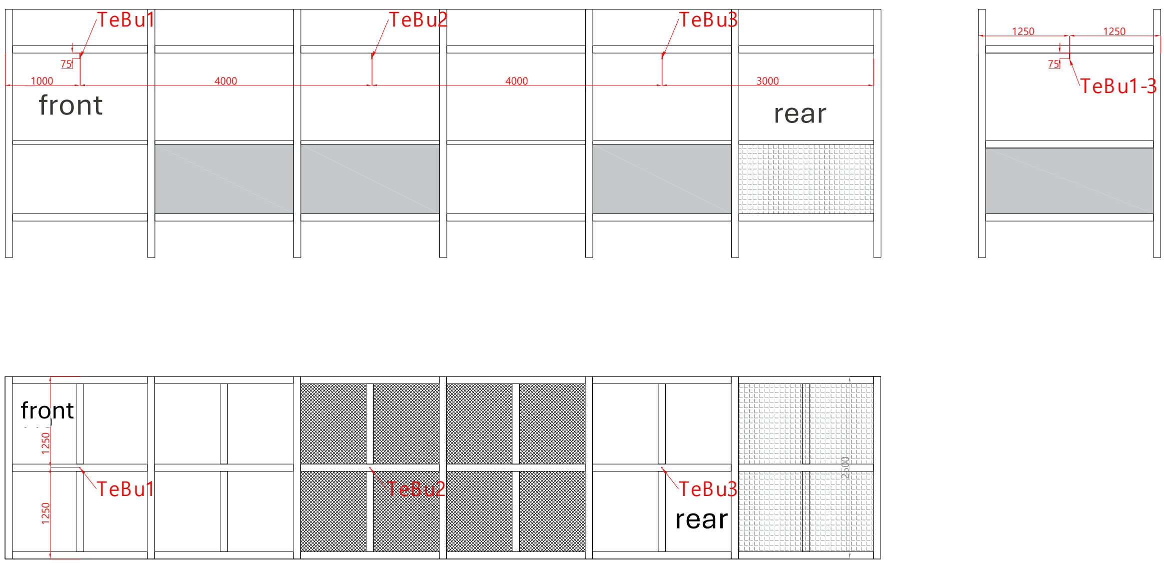

Figure 39. Thermocouple arrangement inside the bus mock-up

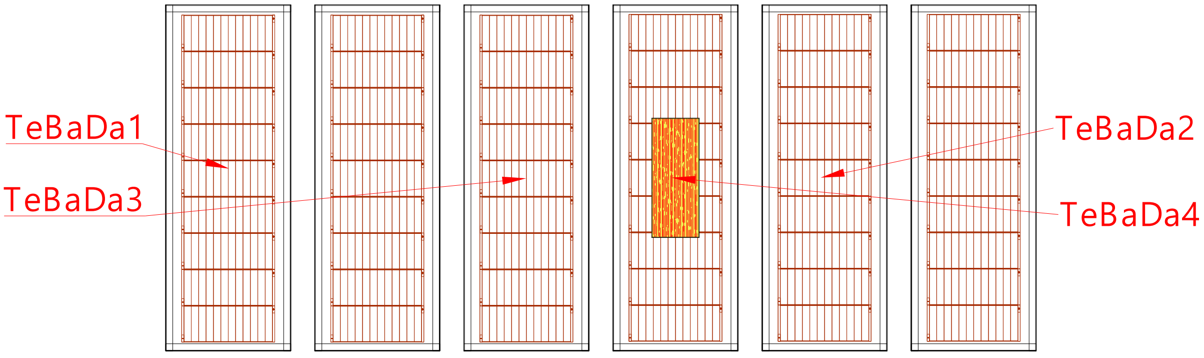

Figure 40. Thermocouple arrangement in LIBs

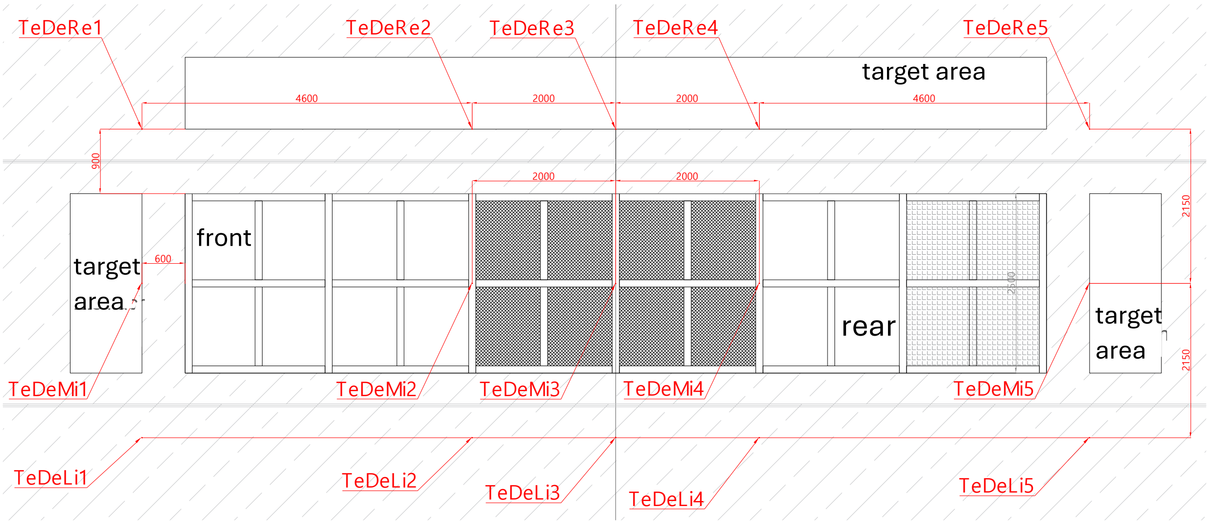

Figure 41. Arrangement of thermocouples at the ceiling, top view

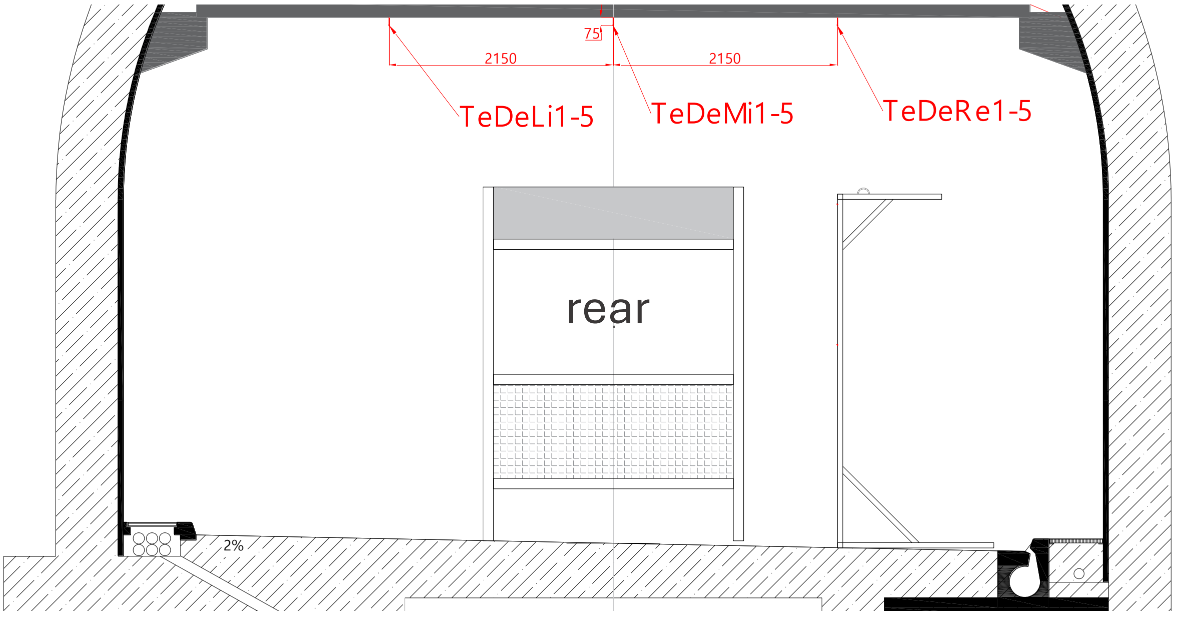

Figure 42. Arrangement of thermocouples at the ceiling, front view

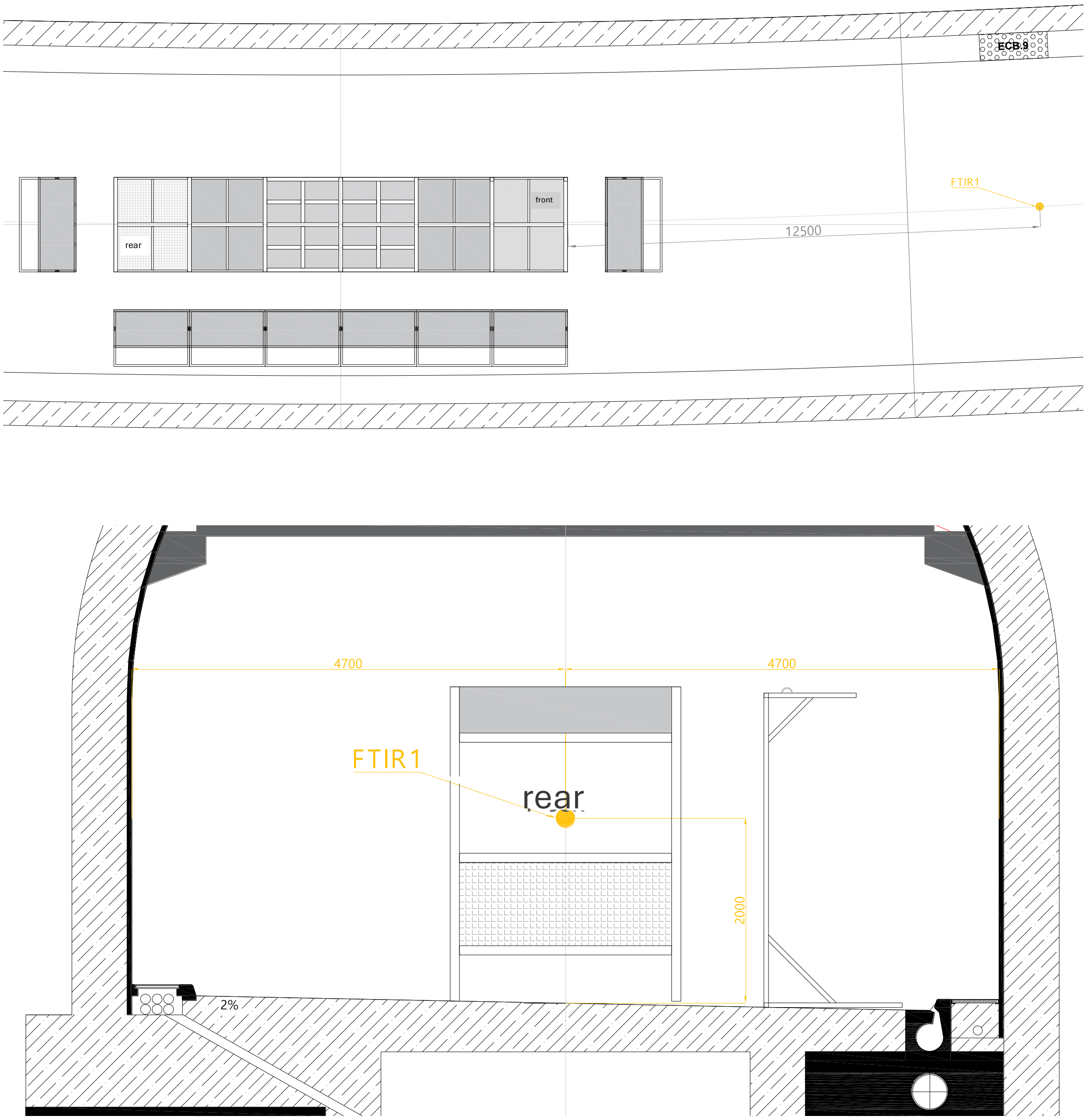

Figure 43. FTIR measurement point