Pre-normative research for safety of hydrogen driven vehicles and transport through tunnels and similar confined spaces

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Recommendations for RCS

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Summary

This report is the synthesis of practical outputs from the research-intensive Work Packages 2, 3, 4 and 5 on hydrogen dispersion, fires and explosions and its interaction with enclosed transportation systems. The recommendations contained within include developed and validated hydrogen incident/accident prevention and possible mitigation strategies for road, rail and other hydrogen powered transport applications – for easy reference by stakeholders from tunnel and hydrogen transport sectors.

The objective of this D6.10 deliverable report is to study the findings of the HyTunnel-CS project and to identify and categorize recommendations on regulations, codes and standards (RCS) concerning requirements for use of hydrogen systems in tunnels / enclosed spaces to achieve an acceptable level of risk, life safety and property protection and to propose a roadmap for bringing these recommendations to international bodies. The report represents the consensus of the HyTunnel-CS group regarding RCS recommendations.

Important topics addressed in the recommendations concern:

- Thermal and pressure hazards associated with hydrogen fuel cell electrical vehicle incidents;
- Unique for hydrogen pressure peaking phenomena (PPP);
- Effect of hydrogen release direction and TPRD sizes on hazards and hazard distances;
- Prevention of tank rupture; and
- Analytical tools, correlations and CFD models to be used for safety design.

The recommendations presented in this report are based on research conclusions of FCH-JU funded project “HyTunnel-CS”, which are summarised in the deliverable D6.9 “Recommendations for inherently safer use of hydrogen vehicles in underground traffic systems” available at the project website (hytunnel.net). The references to the deliverable D6.9 are essential for understanding background and specificities of the recommendations made in this document, thus it is strongly recommended to read both documents in conjunction.

Keywords

Good Practice Guidelines, Recommendations, Safety Strategies, Hydrogen Safety, Tunnels, Underground Traffic Structures, Confined Spaces, QRA Methodology

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Nomenclature and abbreviation

CEN	European Committee for Standardization
CFD	Computational fluid dynamics
CS	Confined Spaces
FCEV	Fuel Cell Electric Vehicle
H2	Hydrogen
HDV	Heavy Duty Vehicle
HRR	Heat Release Rate
ISO	International Standardization Organization
JTC	Joint Technical Committee
LDV	Light Duty Vehicle
M	Milestone
NEN	Dutch Standardization Organization
PPP	Pressure Peaking Phenomenon
PRD	Pressure Relief Device
QRA	Quantitative Risk Assessment
RCS	Regulations, Codes, Standards
SDO	Standards Developing Organization
TC	Technical Committee
TPRD	Thermally Activated Pressure Relief Device

Definitions

Accident is an unforeseen and unplanned event or circumstance causing loss or injury.

1. Introduction

1.1 Safety strategy

The findings of the HyTunnel-CS project suggest that most of the safety issues associated with hydrogen transport incidents in underground infrastructure may be resolved via a “safety by design” strategy. The strategy is based on the following general principles:

- Foreseeable hydrogen releases should not lead to violation of current regulations and their requirements;
- Hydrogen combustion contribution to the total heat release rate (HRR) of a vehicle fire should be negligible;
- In the case of unintended hydrogen releases in tunnels, carparks etc. it is recommended to use high ventilation rates.

In many cases minimisation of hydrogen release rate through a Thermally Activated Pressure Relief Device (TPRD) onboard a vehicle by selection of a sufficiently small orifice is sufficient to comply with the existing Regulations Codes and Standards (RCS).

However, a small TPRD orifice leads to long hydrogen discharge (blowdown) time, which could result in a tank rupture when the tank is exposed to a fire if the tank is still pressurised by the time the tank wall burns through. The project proposes measures to prevent such a tank rupture by design of tank-TPRD assembly as a system and also by employment of innovative leak-no-burst tank technology. This will prevent hazards such as blast wave, fireball and projectiles.

The recommendations below present in a concise way implementations of the strategy for incident scenarios with hydrogen transport in tunnels, carparks and similar confined spaces. Recommendations on engineering and modelling tools to perform safety design and hazards assessment are also given where possible.

1.2 Structure of recommendations

This deliverable D6.10 categorises the recommendations for regulations, codes and standards (RCS) based on the findings of HyTunnel-CS project work packages 2 to 5.

The recommendations for RCS are structured as follows:

Each recommendation has been given a number, followed by the recommendation itself. Next, a short explanation of the recommendation is given, followed by a reference to a specific section in deliverable D6.9 “Recommendations for inherently safer use of hydrogen vehicles in underground traffic systems” (available at HyTunnel-CS project website “hytunnel.net”) where the recommendation is discussed in more detail.

Finally, the RCS body for which the recommendation is most relevant is named. Most of the recommendations are made for the general content of specific RCS. For some recommendations, particular sections of RCS are specified.

2. Recommendations for RCS to deal with unignited hydrogen releases (WP2) and jet fires (WP3), and how they could be implemented

2.1.1 ***Recommendation 1:*** *Recommendation to minimise TPRD orifice to reduce hazards of unignited and ignited hydrogen releases*

TPRD orifice diameter should be designed to prevent formation of flammable hydrogen-air clouds under tunnel or carpark ceilings in cases of unignited releases. In cases of ignited release, the hydrogen jet fire should not prevent self-evacuation from the vehicle or pose a threat to members of the public or first responders.

A TPRD diameter should be designed to minimise the effect of a hydrogen jet fire on the smoke extraction system and to comply with current ventilation requirements (see BS 7346-7:2013). Mechanical ventilation shall be active and designed as per current standards to ensure the clearance of smoke during a fire and to comply with the performance recommendations for the equipment, i.e. the requirement for extraction fans to operate at 300 °C for a period of not less than 60 minutes (class F300), see (BS 7346-7:2013).

Hydrogen release and hydrogen jet fire from a TPRD onboard a Light Duty Vehicle (LDV) in a carpark with ceilings as low as 2.1 m may be considered as a conservative incident scenario. CFD simulations and experiments demonstrated that for a TPRD orifice diameter of 0.5 mm, the hydrogen jet fire thermal hazards were reduced to the immediate vicinity of the vehicle chassis and did not prevent self-evacuation from a vehicle when the TPRD release was directed downward at 45° to vertical. Hot gases (>300°C) did not reach elements of the ventilation system. Additionally, for the same TPRD orifice diameter of 0.5 mm, the jet fire impact on structures was only localised. Combustion of hydrogen release through a 0.5 mm TPRD orifice will have negligible contribution to the LDV fire, reducing hazards and associated risks to the level of fossil fuel vehicles. Increase of carpark or tunnel ceiling height will lead to a further reduction of hazards and risks. Experimental evidence also indicates that the jet fire from such a TPRD will not interfere with the work of the rescue services.

For more information on this recommendation, please see HyTunnel-CS deliverable D6.9: Section 3.2 “Hydrogen release and dispersion in tunnels”, Section 3.3 “Hydrogen release in underground parking, garages and maintenance shops” (3.3.1 “Underground parking”, 3.3.1.1 “Requirements for ventilation and TPRD sizing and orientation of release”, 3.3.3.3 “Experimental studies of ignited releases”), Section 3.5 “Contribution of hydrogen to the heat release rate of a vehicle fire”. More information is also available in HyTunnel-CS project deliverables D2.3 and D3.3.

This recommendation could be of relevance for:

- ISO/AWI TR 15916 Basic considerations for the safety of hydrogen systems.

- ISO 23273:2013 Fuel cell road vehicles.
- ISO/AWI 19882 Gaseous hydrogen - Thermally activated pressure relief devices for compressed hydrogen vehicle fuel containers.
- EN 1991-1-2:2002 Eurocode 1: Actions on structures - Part 1-2: General actions - Actions on structures exposed to fire.
- EN 1993-1-2+C2:2011 Eurocode 3: Design of steel structures - Part 1-2: General rules - Structural fire design.

2.1.2 ***Recommendation 2**: Recommendation to use validated engineering model for assessing the possibility of PPP overpressure by unignited and ignited hydrogen releases in confined spaces*

The pressure peaking phenomenon (PPP) may result from both unignited and ignited hydrogen releases in confined areas with poor ventilation and may generate pressures hazardous to human life and property. The PPP from ignited hydrogen releases is more dangerous than that from unignited releases. Theoretical, numerical and experimental analysis has proved the existence of PPP and demonstrated that minimisation of hydrogen release rate is an effective PPP mitigation measure. An engineering model for predicting PPP overpressure was further validated by the project and can be used to assess the overpressure generated by ignited and unignited releases in confined spaces, such as mechanically ventilated buildings and structures and non-mechanically ventilated residential garages, storage compartments on ships and other marine applications, in trains, aviation etc.

For more information on this recommendation, please see HyTunnel-CS deliverable D6.9: Section 3.3.3.1 “The pressure peaking phenomenon” and Appendix 3, Section A3.1.5 “The pressure peaking phenomena model”.

This recommendation could be of relevance for:

- ISO 23273 Fuel cell road vehicles — Safety specifications - Part 2: Protection against hydrogen hazards for vehicles fuelled with compressed hydrogen, Section 5.4 “Discharges”.
- Input for adoption by CEN/CLC/JTC6/WG3 Hydrogen Safety.

2.1.3 ***Recommendation 3:** Recommendation for design in case of upward release from a TPRD*

TPRD release orifice for each vehicle type should be engineered to allow them to safely enter tunnels and underground carparks. In contrast to LDVs, which typically have a downward TPRD release direction, Heavy Duty Vehicles (HDV) may have an upward direction of hydrogen release from their TPRD(s).

It is recommended that the TPRD design - number and diameter of TPRD orifices, their release direction, etc. – is based on the requirement to prevent the possibility of flammable cloud formation under the ceiling. The similarity law for concentration decay in a circular momentum dominated jet, which was validated down to cryogenic temperatures, is available as a design tool (Molkov, 2012).

For more information on this recommendation, please see HyTunnel-CS deliverable D6.9: Section 3.3 “Hydrogen release in underground parking, garages and maintenance shops”. The similarity law and its implementation as an online tool of the e-Laboratory of Hydrogen Safety are described in Appendix 3.1.1 of HyTunnel-CS deliverable D6.9.

This recommendation could be of relevance for:

- BS 7346 -7:2013 “Components for heat and smoke control systems – Part 7: Code of practice on functional recommendations and calculation methods for smoke and heat control systems for covered car parks”, Annex B “Computer based models”.
- Informative Annex for ISO/AWI TR 15916 “Basic considerations for the safety of hydrogen systems” (or input in section 7.5.8 “Considerations for facilities - Ventilation”).
- Input for adoption by CEN/CLC/JTC6/WG3 Hydrogen Safety.
- UNECE GTR#13 IWG Hydrogen and fuel cell vehicles.
- IEC 63341-2 ED1 Railway applications – Rolling stock – Fuel cell systems for propulsion - Part 2: Hydrogen storage system.

2.1.4 ***Recommendation 4:*** *Recommendation to use 45° direction in case of downward release from a TPRD*

LDVs typically have TPRD release direction downward. Downward release at an angle of 45° to the vertical provides an optimum balance between minimal flammable cloud size, short jet flame length, opportunity to self-evacuate from the vehicle and avoidance of flammable mixture accumulation under a typical tunnel ceiling. CFD simulations and results of large-scale experimental campaigns demonstrated that release from a TPRD with a diameter of 0.5 mm at an angle of 45° to the vertical does not obstruct evacuation from the vehicle and does not lead to temperatures exceeding 300℃ at the intake to the ventilation system in underground carparks with ceiling heights of 2.1-3.0 m. Ignited releases vertically downward may obstruct self-evacuation and rescue operations from the vehicle.

For more information on this recommendation, please see HyTunnel-CS deliverable D6.9: Section 3.2.3 “Large-scale experiments on unignited releases in a real tunnel”, Section 3.2.4 “Hydrogen releases in tunnels”, Section 3.3 “Hydrogen release in underground parking, garages and maintenance shops”.

This recommendation could be of relevance for:

- UNECE GTR#13 IWG Hydrogen and fuel cell vehicles.
- ISO/AWI TR 15916 Basic considerations for the safety of hydrogen systems.
- ISO 23273:2013 Fuel cell road vehicles.

- ISO/AWI 19882 Gaseous hydrogen - Thermally activated pressure relief devices for compressed hydrogen vehicle fuel containers.

2.1.5 **Recommendation 5:** *Recommendation for no need of special treatment of FCEV in tunnels with slope up to 5% in case of high-pressure hydrogen dispersion through TPRD*

CFD analysis (HyTunnel-CS deliverable D2.3) performed to study high-pressure hydrogen dispersion through a TPRD inside a sloped tunnel suggests that there is no need for special treatment in sloped tunnels with up to 5% inclination. The presence or not of ventilation does not affect this recommendation.

For more information on this recommendation, please see HyTunnel-CS deliverable D6.9, Section 3.2.1 “Effect of tunnel slope” and (HyTunnel-CS deliverable D2.3).

This recommendation could be of relevance for:

- ISO/AWI TR 15916 Basic considerations for the safety of hydrogen systems.
- ISO 23273:2013 Fuel cell road vehicles — Safety specifications — Protection against hydrogen hazards for vehicles fuelled with compressed hydrogen.
- ISO/AWI TR 24488 Road Tunnel Fire Safety — A general overview of regulatory frameworks and research.

2.1.6 **Recommendation 6**: *Recommendation to use high ventilation rates in case of unintended hydrogen releases to decrease duration of flammability for unignited releases and to reduce thermal exposure in case of ignited releases.*

The use of high ventilation rates is recommended in the case of unintended hydrogen releases. In large-scale hydrogen release experiments and CFD simulations, the ventilation rate did not have a significant impact on the maximum hydrogen concentration level. However, an increased ventilation rate decreased the duration of time when the hydrogen-air mixture was flammable for unignited releases and also reduced the degree of thermal exposure in the case of ignited releases.

For more information on this recommendation, please see HyTunnel-CS deliverable D6.9: Section 3.2.3 “Large-scale experiments on unignited releases in a real tunnel”, Section 3.3.1 “Underground parking”.

This recommendation could be of relevance for:

- BS 7346 -7:2013 “Components for heat and smoke control systems – Part 7: Code of practice on functional recommendations and calculation methods for smoke and heat control systems for covered car parks”, Annex B “Computer based models”.
- Informative Annex for ISO/AWI TR 15916 “Basic considerations for the safety of hydrogen systems” (section 7.5.8 “Considerations for facilities - Ventilation”).

2.1.7 **Recommendation 7**: *Recommendation to use a high rebar cover of more than 5cm in the structural design of car parks and tunnels*

Building structures may be impacted by hydrogen jet flames in the event of TPRD activation. The degree of heat transfer to structures caused by impinging jet flames will depend strongly upon TPRD orifice sizes and the duration of release. The TPRD orifice size should be chosen to prevent damage to structures which could result in reduction of their strength. TPRD diameters below 1 mm appear to be appropriate for LDVs in this regard.[1]

Due to the large heat flux produced by an impinging hydrogen jet fire, local spalling of the concrete parts exposed to the flame is still probable. Spalling can reduce the fire resistance of the concrete elements by reducing the amount of concrete protecting the steel reinforcement. For this reason, a reinforcement cover of more than 5 cm is recommended.

For more information on this recommendation, please see HyTunnel-CS deliverable D6.9: Section 5 "Impact of hydrogen vehicle incidents on structures".

This recommendation could be of relevance for:

- NEN 2443:2013 Design standards and recommendations on parking facilities for passenger cars.
- EN 1991-1-2:2002 Eurocode 1: Actions on structures - Part 1-2: General actions - Actions on structures exposed to fire.
- EN 1993-1-2+C2:2011 Eurocode 3: Design of steel structures - Part 1-2: General rules - Structural fire design.

2.1.8 **Recommendation 8**: *Recommendation to account for realistic heat transfer between a high-pressure tank and its environment when assessing tank performance in a fire*

Calculation of high-pressure hydrogen storage tank parameters, like pressure and temperature, based on the assumption of an adiabatic process is an idealisation applicable only to relatively short hydrogen release durations, e.g., in case of large orifice and/or small tank volume. Accounting for realistic heat exchange between a high-pressure tank and the environment is required for accurate prediction of pressure and temperature in storage tanks in case of releases from large tank volumes, small release orifices, large intensity of heat transfer etc. This is particularly important for the scenario of a tank in a fire, where ambient temperatures, intensity of heat exchange and exposure time are substantial. Thus, a blowdown model accounting for heat exchange between the tank and fire environment was used to

[1] Smaller TPRD diameters, e.g. diameter 0.5 mm recommended in Section 2.1.1 and 2.1.4, would result in lesser thermal damage and lesser potential for concrete spalling.

determine the load-bearing ability of hydrogen storage tanks in the modelling approaches described in Section 3.1.1 and Section 3.1.2 of present recommendations.

For more information on this recommendation, please see HyTunnel-CS deliverable D6.9: Section 4.2 “Hydrogen tank rupture in a fire: consequences and prevention” (sub-section 4.2.2. “The model to design an inherently safer tank-TPRD system”) and Appendix A3.1.4 “Model for non-adiabatic compressed gaseous hydrogen tank blowdown”.

This recommendation could be of relevance for:

- EN ISO 11439:2013 Gas cylinders — High pressure cylinders for the on-board storage of natural gas.
- ISO 19880 1:2020 Gaseous hydrogen — Fuelling stations.
- ISO/AWI 19881 Gaseous hydrogen — Land vehicle fuel containers.
- Input for adoption by CEN/CLC/JTC6/WG3 Hydrogen Safety.
- UNECE GTR#13 IWG Hydrogen and fuel cell vehicles.
- UNECE Regulation No. 134 Uniform provisions concerning the approval of motor vehicles and their components with regard to the safety-related performance of hydrogen fuelled vehicles (HFCV).
- Commission Regulation (EU) No 406/2010 on type-approval of hydrogen-powered motor vehicles.
- IEC 63341-2 ED1 Railway applications – Rolling stock – Fuel cell systems for propulsion - Part 2: Hydrogen storage system.

2.1.9 ***Recommendation 9****: Recommendation to use the dimensionless flame length correlation tool for hydrogen jet fires*

The dimensionless flame length correlation tool (Molkov, 2012)-can be used to assess flame length and thermal hazards of hydrogen jet fires not impinging on a surface. The dimensionless correlation was seen to be valid also for releases from cryo-compressed gas stores.

For more information on this recommendation, please see HyTunnel-CS deliverable D6.9: Section 3.3.1. “Underground parking”, Section 3.6.1 “Flame length” and Appendix 3, Section A3.1.7 “Hydrogen flame length correlation and three jet fire hazard distances”, for a tool description.

This recommendation could be of relevance for:

- ISO/AWI TR 15916 Basic considerations for the safety of hydrogen systems.
- ISO 23273:2013 Fuel cell road vehicles — Safety specifications — Protection against hydrogen hazards for vehicles fuelled with compressed hydrogen.
- ISO/AWI 19882 Gaseous hydrogen - Thermally activated pressure relief devices for compressed hydrogen vehicle fuel containers.

- ISO 16730-1:2015 Fire safety engineering — Procedures and requirements for verification and validation of calculation methods — Part 1: General.

2.1.10 **Recommendation 10:** *Recommendation to use validated CFD models for assessment of hydrogen release and jet fire hazards*

Work undertaken by the project produced a high level of confidence in the predictive capabilities of validated CFD modelling tools when dealing with analysis of hydrogen distribution and fires resulting from hydrogen incidents. In contrast to reduced models (e.g. lumped parameters, 1D, etc.) and correlations, CFD models also account for interaction with walls and obstacles, such as neighbouring vehicles.

In the course of the project, CFD models were successfully validated and recommended as a predictive method for, e.g.:

- design of smoke and heat control systems to mitigate the effects of hydrogen releases in confined spaces;
- defining hazard distances and safe interval distances between neighbouring FCEVs in tunnels and other confined spaces;
- assessing the pressure peaking phenomenon and thermal effects from jet fires in enclosures;
- assessment of thermal hazards from high-pressure hydrogen jet fires in confined ventilated spaces.

For more information on this recommendation, please see HyTunnel-CS deliverable D6.9: Section 3.2.2 “Effect of counter-, co- and cross-flow on the flammable envelope”, Section 3.3.1.1 “Requirements for ventilation and TPRD sizing and orientation of release”, Section 3.3.3.1 “The pressure peaking phenomenon”, HyTunnel-CS deliverables D2.3 and D3.3.

This recommendation could be of relevance for:

- Informative Annex for ISO/AWI TR 15916 “Basic considerations for the safety of hydrogen systems” (or input in section 7.5.8 “Considerations for facilities - Ventilation”).
- Input for adoption by CEN/CLC/JTC6/WG3 Hydrogen Safety.
- ISO 23932-1:2018 “Fire safety engineering — General principles — Part 1: General”.
- BS 7346 -7:2013 “Components for heat and smoke control systems – Part 7: Code of practice on functional recommendations and calculation methods for smoke and heat control systems for covered car parks”, Annex B “Computer based models”.
- ISO 23273:2013 Fuel cell road vehicles — Safety specifications — Protection against hydrogen hazards for vehicles fuelled with compressed hydrogen.

- ISO/AWI 19882 Gaseous hydrogen — Thermally activated pressure relief devices for compressed hydrogen vehicle fuel containers.
- ISO/AWI TR 24488 Road Tunnel Fire Safety — A general overview of regulatory frameworks and research.
- NEN 2443:2013 Design standards and recommendations on parking facilities for passenger cars.

*2.1.11 **Recommendation 11**: Recommendation to disclose TPRD data by car manufacturers on limiting release area (or diameter) and response time to fires of different specific heat release rates, HRR/A*

In order to facilitate safety analysis and safety design of underground structures, rescue plans for firefighters and safety guidance for the public, TPRD diameter data should be provided by car manufacturers as a condition for the sale of hydrogen-driven vehicles in Europe. Currently, this data is confidential, which has a detrimental impact on safety. The engineering tools used for analysis of hydrogen vehicle accidents are based on the mass-flow rates resulting from TPRD releases. To ensure the quality of the results from the safety engineering tools and RCS, it is recommended that manufacturers be compelled to disclose TPRD data for the vehicles they wish to sell in Europe. Only then can a proper assessment be made of the safety of such vehicles.

For more information on this recommendation, please see HyTunnel-CS deliverable D6.9: Section 3.3.1 “Underground parking”, Section 3.3.2. “Example of hydrogen release effect on car fire in the underground parking” and Section 3.3.3 “Garages, maintenance shops, CHSS enclosures””.

This recommendation could be of relevance for:

- ISO 23273:2013 Fuel cell road vehicles.
- UNECE GTR#13 IWG Hydrogen and fuel cell vehicles.
- UNECE Regulation No. 134 Uniform provisions concerning the approval of motor vehicles and their components with regard to the safety-related performance of hydrogen fuelled vehicles (HFCV).
- Commission Regulation (EU) No 406/2010 on type-approval of hydrogen-powered motor vehicles.

3. Recommendations for RCS related to prevention and mitigation of hydrogen explosions in confined spaces (WP4) and how they could be implemented

3.1.1 ***Recommendation 12***: *Recommendation to use tank-TPRD system design approach preventing tank rupture in a fire, therewith excluding blast wave, fireball and projectiles, in case TPRD installation is mandatory*

The largest risk associated with use of hydrogen transport is insufficient fire resistance of the high-pressure hydrogen storage system, which may lead to tank rupture followed by blast wave, fireball and generation of projectiles. Research undertaken by the HyTunnel-CS project has led to the conclusion that a blast wave in a tunnel (contrary to the blast wave in open space) decays very slowly. The general recommendation is therefore to prevent hydrogen tank rupture in a tunnel by all means, since the low rate of decay results in a potentially very large zone where serious injury or even fatality is a likelihood.

The recommended approach of designing the tank-TPRD assembly as a system was developed within the HyTunnel-CS project to prevent the long blowdown time of a high-pressure hydrogen tank with inadequate fire performance through a small TPRD orifice, leading to tank rupture in a fire. The overall engineering model is described in the paper by Molkov et al. (2021). The design approach relies on defined TPRD activation time and is applicable to storage tanks of any size, volume and pressure, tank wall thickness, thermal properties and TPRD orifice size. The previously described sub-model for non-adiabatic tank blowdown (see section 2.1.3) is an integral part of this modelling process.

For more information on this recommendation, please see HyTunnel-CS deliverable D6.9, Section 4.2.3 “System approach to the choice of onboard storage TPRD”. More model details and references to validation framework may be found in Appendix 3, Section A3.3.1 “Model to design a tank-TPRD system that excludes rupture in engulfing fire”.

This recommendation could be of relevance for:

- EN ISO 11439:2013 Gas cylinders — High pressure cylinders for the on-board storage of natural gas.
- ISO 19880 1:2020 Gaseous hydrogen — Fuelling stations.
- ISO/AWI 19881 Gaseous hydrogen — Land vehicle fuel containers.
- ISO/DIS 11119-3 Gas cylinders — Refillable composite gas cylinders and tubes — Design, construction and testing — Part 3: Fully wrapped fibre reinforced composite gas cylinders and tubes up to 450 l with non-load-sharing metallic or non-metallic liners or without liners.
- Documents being developed by CEN/CLC/JTC6/WG3 Hydrogen Safety.

- UNECE GTR#13 IWG Hydrogen and fuel cell vehicles.
- UNECE Regulation No. 134 Uniform provisions concerning the approval of motor vehicles and their components with regard to the safety-related performance of hydrogen fuelled vehicles (HFCV).
- Commission Regulation (EU) No 406/2010 on type-approval of hydrogen-powered motor vehicles.
- IEC 63341-2 ED1 Railway applications – Rolling stock – Fuel cell systems for propulsion - Part 2: Hydrogen storage system.

3.1.2 ***Recommendation 13****: Recommendation to use safety technology of explosion free in a fire self-venting (TPRD-less) tank*

Innovative explosion-free-in-a-fire self-venting (TPRD-less) safety technology (Molkov et al., 2018) permits safe Type 4 tank blowdown even when the TPRD fails to activate, or in absence of a TPRD at all. The technology prevents rupture of the high-pressure hydrogen storage tank by allowing the tank to vent hydrogen via the formation of micro-channels in the wall material when exposed to fire. If TPRD installation on the storage tank(s) is mandatory, the technology permits the reduction of TPRD orifice diameter, which would decrease the risk of PPP occurring, as well as long-duration jet fires.

For more information on this recommendation and technology description, please see HyTunnel-CS deliverable D6.9: sub-section 4.2.3. “Safety technology of explosion free in fire self-venting (TPRD-less) tank”, Appendix 3, Section A3.3.2 “Model to design a tank-TPRD system that excludes rupture in engulfing fire” and HyTunnel-CS deliverable D4.3.

This recommendation could be of relevance for:

- UNECE GTR#13 IWG Hydrogen and fuel cell vehicles.
- UNECE Regulation No. 134 Uniform provisions concerning the approval of motor vehicles and their components with regard to the safety-related performance of hydrogen fuelled vehicles (HFCV).
- Commission Regulation (EU) No 406/2010 on type-approval of hydrogen-powered motor vehicles.
- ISO/DIS 11119-3 Gas cylinders — Refillable composite gas cylinders and tubes — Design, construction and testing — Part 3: Fully wrapped fibre reinforced composite gas cylinders and tubes up to 450 l with non-load-sharing metallic or non-metallic liners or without liners.
- ISO 19880 1:2020 Gaseous hydrogen — Fuelling stations.
- EN ISO 11439:2013 Gas cylinders — High pressure cylinders for the on-board storage of natural gas.
- ISO/AWI 19881 Gaseous hydrogen — Land vehicle fuel containers.
- Input for adoption by CEN/CLC/JTC6/WG3 Hydrogen Safety.

- IEC 63341-2 ED1 Railway applications – Rolling stock – Fuel cell systems for propulsion - Part 2: Hydrogen storage system.

3.1.3 **Recommendation 14**: *Recommendation to use engineering correlation to assess potential for hydrogen flame acceleration and DDT in tunnels*

The methodology for evaluation of critical hydrogen concentrations for flame acceleration (FA) and deflagration-to-detonation transition (DDT) was developed by the project for hydrogen-air mixtures in channel and layer geometries, in particular for tunnels. The method takes into account the blockage of tunnel cross-section, stratification of the mixture, and extension (elongation) of hydrogen cloud. The methodology was validated against large-scale experiments and reproduced by CFD simulations. Critical upper limits of hydrogen concentrations are proposed to eliminate supersonic fast flames and detonation, and to avoid catastrophic combustion pressures in the case of a late hydrogen ignition.

The correlation application example presented in Deliverable D6.9 demonstrates that for the scenario of a train in a tunnel, the uniformly distributed in the tunnel cross section of an inventory of 2-10 kg is unlikely to lead to detonation. Detonation of a 10 kg inventory is possible when the maximum hydrogen concentration in a stratified (non-uniform) layer is above 20% vol. Transition to detonation is still possible if the maximum hydrogen concentration is above 15%, the rail tunnel blockage ratio is 40% or higher and hydrogen inventory is 100 kg.

For more information on this recommendation, please see HyTunnel-CS deliverable D6.9: Section 4.1.3 “Prevention of hydrogen-air flame acceleration and DDT in train tunnels”.

This recommendation could be of relevance for:

- ISO/PRF 20710-1 “Fire safety engineering — Active fire protection systems”.

3.1.4 **Recommendation 15**: *Recommendation to use correlation and validated CFD model for hazard assessment of blast wave and fireball from hydrogen tank rupture in a tunnel*

Universal best-fit and conservative correlations to assess blast wave overpressure resulting from hydrogen high-pressure tank rupture in an empty tunnel was developed in (Molkov, Dery, 2020). The correlation is applicable to tunnels of any cross-sectional area and length, tanks of any volume and storage pressure. In the HyTunnel-CS project the correlation was expanded to the modelled scenario of a tunnel containing vehicles. The model provided good agreement with experimental data on blast wave propagation in a real tunnel performed within the project. The correlation may be used for the analysis of consequences of any tank rupture in a tunnel of any cross-section area, aspect ratio and length, allowing inherently safer design and use of hydrogen vehicles in tunnels.

Due to complicated fireball behaviour in a tunnel, it is recommended to use validated CFD models, e.g. (Molkov et al., 2021) for the assessment of fireball thermal hazards.

For more information on this recommendation, please see HyTunnel-CS deliverable D6.9: Section 4.2.1 "Blast wave and fireball after hydrogen tank rupture in a fire" (sub-section 4.2.1.1 "Blast wave and fireball after hydrogen tank rupture in a fire"), Appendix 3, Section A3.3.2 "Dimensionless correlation for blast wave decay in a tunnel".

This recommendation could be of relevance for:

- ISO/AWI TR 15916 Basic considerations for the safety of hydrogen systems.
- Proposal for the new Appendix E (informative) "Road tunnels and confined spaces" for ISO/AWI TR 15916 – to address blast wave propagation in tunnels (with corresponding correlation and graphical materials).

3.1.5 ***Recommendation 16**: Recommendation to use conservative correlation and validated CFD model for assessment of hazards generated by delayed ignition of hydrogen jets*

Delayed ignition of a highly turbulent under-expanded hydrogen jet may cause a strong deflagration, which can harm people and damage civil structures. The validated semi-empirical correlation can be applied for predicting the maximum overpressure that may be generated by delayed ignition of a hydrogen jet at an arbitrary location for known storage pressure and release diameter. The TPRD diameter should be designed so as to minimise the generated overpressure effects in the event of delayed ignition of the hydrogen jet.

CFD modelling can be used as a complementary tool to the recommended conservative correlation for predicting the overpressure generated by delayed ignition of a hydrogen jet and the associated thermal hazards. CFD modelling can be used in the scenarios beyond the validity assumptions of the correlation.

For more information on this recommendation, please see HyTunnel-CS deliverable D6.9: Section 4.1.2 "Deflagrations of ignited spurious hydrogen releases"; Appendix 3, Section A3.2.2 "Correlation for deflagration from a spurious hydrogen release".

This recommendation could be of relevance for:

- ISO/AWI TR 15916 Basic considerations for the safety of hydrogen systems.
- ISO/AWI 19882 Gaseous hydrogen — Thermally activated pressure relief devices for compressed hydrogen vehicle fuel containers.

3.1.6 ***Recommendation 17**: Recommendation to use thermodynamic model for calculation of allowable hydrogen inventory in confined spaces without ventilation*

The thermodynamic model can be used to provide a conservative estimate of maximum possible overpressure which may be developed in a confined space (garage, workshop, etc.) without ventilation after hydrogen release and ignition. The overpressure is calculated based on assumptions of complete hydrogen-air mixture combustion and a perfectly sealed enclosure.

For more information on this recommendation, please see HyTunnel-CS deliverable D6.9: Appendix 3, Section A3.2.1 “Upper limit of hydrogen inventory in closed space without ventilation”.

This recommendation could be of relevance for:

- Proposal for the new Appendix E (informative) “Road tunnels and confined spaces” for ISO/AWI TR 15916 – the proposed text will have section on allowable hydrogen inventory.

*3.1.7 **Recommendation 18**: Recommendation to include calculation examples of typical tank rupture blast waves demonstrating failure of the tunnel ceiling slab is unlikely to have significant effects on the tunnel main structure*

The simulation of a car hydrogen tank explosion (tank volume 62.4 L, storage pressure 700 bar) in a tunnel has been performed by the project and has indicated that a peak overpressure of 152 kN/m^2 is recorded on the surface of the tunnel ceiling.

Such a pressure is about 10 times larger than the static load-bearing capacity of a typical tunnel ceiling slab in either the positive or negative moment. As such, the slab would immediately fail, if such a pressure would be applied in a quasi-static way. However, the duration of such overpressure is so short compared to the natural period of vibration of the slab that the action is felt as “impulsive” and leads to a dynamic de-amplification of the slab response.

Nonlinear dynamic FE analyses carried out on a 2D slice of the slab, considered as simply-supported, indicate that the overpressure cause very large permanent deflection of slab mid span (up to 40 cm, in case of a linear decay of the overpressure), but do not highlight a collapse of the slab. A more refined calculation of the pressure wave (variation along the slab and duration of the decay phase) and a 3D model of the slab would be recommended though, in order to exclude the failure of the slab. In particular, the assessment of the duration of the overpressure is paramount, in order to ensure a de-amplified impulsive response of the slab.

It should be noted that, even if the slab does not collapse, the large mid-span deflection would likely affect the integrity and stability of the ventilation system supported by the slab and consequent risk of falling debris and injury.

For more information on this recommendation, please see HyTunnel-CS deliverable D6.9: Section 5.4 “Effect of blast wave after hydrogen tank rupture on tunnel structure”.

This recommendation could be of relevance for:

- the new Appendix E (informative) “Road tunnels and confined spaces” for ISO/AWI TR 15916 - to have examples of a typical tank rupture blast wave calculation concluding that it does not lead to structural damage.

3.1.8 *Recommendation 19: Recommendation to use validated CFD models for assessment of deflagration hazards and design of deflagration mitigation systems*

CFD models can be effectively used to simulate hydrogen deflagration in tunnels and confined spaces. If proper modelling strategy and best practice guidelines are followed, CFD results can be reliably used to assess pressure and thermal hazards of hydrogen deflagration scenarios.

There is also growing evidence of CFD simulations being successfully used for the assessment of water spray/mist system efficiency in suppressing deflagration pressure and thermal hazards. Validated CFD models can correctly predict the effects of different droplet sizes and water concentrations on hydrogen explosion.

For more information on this recommendation, please see HyTunnel-CS deliverable D6.9: Section 3.4 “Mitigation of hydrogen jet fire with water sprays and mist systems”, Section 4.1.4 “Blast wave attenuation by water sprays, mist and absorbing materials” and HyTunnel-CS deliverable D4.3.

This recommendation could be of relevance for:

- ISO/AWI TR 15916 Basic considerations for the safety of hydrogen systems.
- ISO/PRF 20710-1 “Fire safety engineering — Active fire protection systems”.
- ISO 19880-1:2020 Gaseous hydrogen — Fuelling stations — Part 1: General requirements.
- ISO 23273:2013 Fuel cell road vehicles — Safety specifications — Protection against hydrogen hazards for vehicles fuelled with compressed hydrogen.
- ISO 17840-1,2,3:2015 Road vehicles — Information for first and second responders — Part 1,2,3: Rescue sheet for passenger cars and light commercial vehicles.
- NEN 2443:2013 Design standards and recommendations on parking facilities for passenger cars.

4. Recommendations for RCS related to QRA methodology and intervention strategies and tactics for accidents in tunnels and parking (WP5) and how they could be implemented

*4.1.1 **Recommendation 20**: Recommendation to supplement quantitative risk assessment for road and railway tunnel design with the more hydrogen specific event tree to minimise risks*

It is recommended that the common Quantitative Risk Assessment methodologies, e.g., QRAM from PIARC, be supplemented with the more hydrogen specific event tree based QRA method developed by the HyTunnel-CS project, using the specific worst case QRA method to estimate the consequences of tank rupture scenario developed by the project. The methods have been applied for calculation of individual and societal risk measures and costs for both road and railway tunnels. This QRA method can also be used for calculation of risk in car parks and other confined spaces. The main risk is related to a fire scenario causing tank rupture followed by a blast wave and a fireball. The influential event is identified as a malfunctioning (non-activated) TPRD. The TPRD failure rate is only estimated by rough expert judgments in the literature, which is a major difficulty for any QRA method.

It is therefore recommended that risks be minimised by adoption of the following measures:

- Increase of TPRD activation reliability in case of localised fires by means of improved technology.
- Increase of the fire resistance rating of high-pressure hydrogen tanks to beyond 90 min.
- Use of self-venting (TPRD-less) tank safety technology.

It is also recommended that the present bonfire test procedure be further developed to mandate mock-up vehicle testing and incorporation of more realistic fire scenarios for hydrogen vehicles concerning both external and in-vehicle fires. These enhanced test procedures will be greatly beneficial in supporting better performance-based fire safety assessments, generating statistical data on the failure behaviour of all safety critical components.

For railway applications, it is finally recommended that requirements for running capability under fire conditions applicable to hydrogen-fuelled trains be defined, so that a train would be able to reach a "safe area". Such a safe area will ideally be in the open, permitting safe and rapid evacuation of passengers and train staff, whilst providing suitable access to enable emergency first responders to deal with the situation safely.

For more information on this recommendation, please see HyTunnel-CS deliverable D6.9: Chapter 6 “Quantitative risk assessment methodology”, and the respective Section 6.2 “Examples of QRA methodology application to hydrogen vehicles”.

In the deliverable D6.9 it was possible to a evaluate the associated risk in terms of human fatality per vehicle per year and in terms of monetary losses of human lives per accident. It was demonstrated that the risks obtained for the current FRR of state-of-the-art standard hydrogen storage tanks of 6-8 min is unacceptable. In order to decrease the level of risk (fatality/vehicle/year) to an ‘acceptable’ value (10^{-5}), it was demonstrated that the hydrogen tank FRR must be increased to more than 80 min (1 hour 20 min). From another risk standpoint (£/accident), in order to decrease the accident cost from £ millions to only £ hundreds, the tank FRR should be increased even more, i.e. to above 96 min (1 hour 36 min).

This recommendation could be of relevance for:

- UNECE GTR#13 IWG Hydrogen and fuel cell vehicles.
- UNECE Regulation No. 134 Uniform provisions concerning the approval of motor vehicles and their components with regard to the safety-related performance of hydrogen fuelled vehicles (HFCV).
- Commission Regulation (EU) No 406/2010 on type-approval of hydrogen-powered motor vehicles.
- ISO/DIS 11119-3 Gas cylinders — Refillable composite gas cylinders and tubes — Design, construction and testing — Part 3: Fully wrapped fibre reinforced composite gas cylinders and tubes up to 450 l with non-load-sharing metallic or non-metallic liners or without liners.
- ISO 19880 1:2020 Gaseous hydrogen — Fuelling stations.
- EN ISO 11439:2013 Gas cylinders — High pressure cylinders for the on-board storage of natural gas.
- ISO/AWI 19881 Gaseous hydrogen — Land vehicle fuel containers.
- Input for adoption by CEN/CLC/JTC6/WG3 Hydrogen Safety.
- EN 50553 Railway applications - Requirements for running capability in case of fire on board of rolling stock.
- IEC 63341-2 ED1 Railway applications – Rolling stock – Fuel cell systems for propulsion - Part 2: Hydrogen storage system.

4.1.2 ***Recommendation 21****: Recommendation to introduce telemetry / data transmission technology for optimizing road vehicles-information for emergency responders*

Emergency services intervening in incidents in tunnels must be able to obtain the correct rescue information as quickly as possible. In the case of 'normal' interventions, this would be part of 'the reconnaissance phase', with the commander determining his response strategy on the basis of the information obtained. In particular with regard to hydrogen, it is a huge advantage to know from the start which energy source(s) are involved. This knowledge will shorten the intervention time and reduce risk to personnel.

It is therefore recommended to integrate a suitable telemetry or data communication system during the construction of a tunnel, via which information can be transferred from the vehicle(s) involved for use by emergency service personnel. This will obviously also require the development of suitable on-vehicle data transmission technology to be fitted to hydrogen vehicles, standardised across all manufacturers. Such equipment would also be usefully applied to other vehicle types such as those powered by batteries or fossil fuels.

For more information on this recommendation, please see HyTunnel-CS deliverable D5.4 “Harmonised recommendations for response and intervention strategies for first responders”.

This recommendation could be of relevance for:

- ISO 17840 - Road Vehicles-Information for emergency responders.
- CEN/TC 278 - Road transport and traffic telematics.
- ISO/TC 204 - Intelligent transport systems.

5. International RCS bodies

This section of the report describes where the recommendations will be forwarded to, i.e. the leadership of the relevant (CEN and ISO) technical committees where the RCS recommendations will be proposed to be assessed and possibly implemented into existing or new RCS.

Only after the respective technical committees have accepted the recommendations and the standards have been revised should efforts be made to have them referred to in EU/national regulations.

5.1 Recommendations to be forwarded to the Secretariat of ISO/TC 22 Road vehicles

Recommendations #1-5, #9-11, #15, #19, #21 of this report shall be forwarded to:
Secretariat: AFNOR
Secretary: Mme. Valérie Maupin
Chairperson: Mr. Fabien Duboc

Recommendations #1, #15, #19 and #21 of this report shall be forwarded to:
Secretariat SC36: AFNOR
Secretary: Mme. Dyhia Siali
Chairperson: Dr. Annette L. Irwin

Recommendations #1, #3-5, #10, #1, #2, #9-11, and #19 of this report shall be forwarded to:
Secretariat SC37: DIN
Secretary: Mr. Daniel Pacner
Chairperson: Mr. Dr.-Ing Michael Herz

5.2 Recommendations to be forwarded to the Secretariat of ISO/TC 58 Gas cylinders

Recommendations #12, #13, and #20 of this report shall be forwarded to:
Secretariat: BSI
Secretary: Mr. Stephen Read
Chairperson: Dr. Warren Hepples

5.3 Recommendations to be forwarded to the Secretariat of ISO/TC 92 Fire safety

Recommendations #5, #9, #10, #14, #15 and #19 of this report shall be forwarded to:
Secretariat: BSI
Secretary: Mr. Christopher Smith-Wong
Chairperson: Mr. Patrick van Hees

5.4 Recommendations to be forwarded to the Secretariat of ISO/TC 197 Hydrogen technologies

Recommendations #1, #3-5, #8-10, #12-13, #15-19 and #20 of this report shall be forwarded to:
Secretariat: SCC
Secretary: Ms. Anne-Louise Fortin
Chairperson: Mr. Ikeda-san

5.5 Recommendations to be forwarded to the Secretariat of ISO/TC 204 Intelligent transport systems

Recommendation #21 of this report shall be forwarded to:
Secretariat: ANSI
Secretary: Mr. Adrian Guan
Chairperson: Mr. Dick Schnacke

5.6 Recommendations to be forwarded to the Secretariat of IEC TC9 Electrical equipment and systems for railways

Recommendations #3, #8, #12-13, #20 of this report shall be forwarded to:
Secretariat: AFNOR
Secretary: Mr. Denis Miglianico;
Chairperson: Mr. Gianosvaldo Piana Fadin; and
Project 63341-2 Leader: Mr. Enrico Morelli

5.7 Recommendations to be forwarded to the Secretariat of CEN/CLC/JTC6 Hydrogen in Energy Systems

Recommendations #2-3, #8, #10, #12-13 and #20 of this report shall be forwarded to:
Secretariat: NEN
Secretary: Ms. Françoise van den Brink / Mr. Janwillem van den Berg
Chairperson: Mr. Bernard Gindroz

5.8 Recommendations to be forwarded to the Secretariat of CEN/TC 23 Transportable gas cylinders

Recommendations #8, #12-13, and #20 of this report shall be forwarded to:
Secretariat: BSI
Secretary: Mr. Denis Miglianico
Chairperson: Mr. Stephen Read

5.9 Recommendations to be forwarded to the Secretariat of CEN/TC 250 Structural Eurocodes

Recommendations #1, and #7 of this report shall be forwarded to:
Secretariat: BSI
Secretary: Ms. Tracey Wilkins
Chairperson: Mr. Steve Denton

5.10 Recommendations to be forwarded to the Secretariat of CEN/TC 278 Intelligent Transport Systems

Recommendation #21 of this report shall be forwarded to:
Secretariat: NEN
Secretary: Ms. Astrid de Haes
Chairperson: Mr. Hans Nobbe

5.11 Recommendations to be forwarded to the Secretariat of CLC/TC 9X Electrical and electronic applications for railways

Recommendations #3, #8, #12-13, and #20 of this report shall be forwarded to:
Secretariat: BSI
Secretary: Mr. Stephen Read

5.12 Recommendations to be forwarded to the Secretariat of UNECE GTR No. 13 - Hydrogen and fuel cell vehicles

Recommendations #3-4, #8, #11-13 and #20 of this report shall be forwarded to:
Secretariat GTR #13: Toyota
Secretary: Mr. Yoshio Fujimoto

6. References

Giannissi, S.G., Tolias, I.C., Abbasi, H.E., Makarov, D., Grune, J., Sempert, K. (2021). Modelling of ventilated hydrogen dispersion in presence of co-flow and counter-flow, 9th International Conference on Hydrogen Safety, 21-24 September 2021, on-line conference

HyTunnel-CS deliverable D2.3 'Deliverable D2.3 Final Report on analytical, numerical and experimental Studies on hydrogen dispersion in tunnels, including Innovative Prevention and Mitigation Strategies', February 2022. Available at: https://hytunnel.net/.

HyTunnel-CS deliverable D3.3 'Deliverable 3.3 Final report on analytical, numerical and experimental studies on fires, including innovative prevention and mitigation strategies', February 2022. Available at: https://hytunnel.net/.

HyTunnel-CS deliverable D4.3, 'Deliverable D4.3 Final report on analytical, numerical and experimental studies on explosions, including innovative prevention and mitigation strategies, February 2022. Available at: https://hytunnel.net/.

HyTunnel-CS deliverable D6.9 'Recommendations for inherently safer use of hydrogen vehicles in underground traffic systems', April 2022. Available at: https://hytunnel.net/.

Molkov, V. (2012). Fundamentals of hydrogen safety engineering, Bookboon.com. Available from: https://bookboon.com/en/author/0908031c-ce02-9b86-11e6-6dd9714a99d1 [Accessed 29.01.2022].

Molkov, V., Makarov, D., Kashkarov, S. (2018). Composite Pressure Vessel for Hydrogen Storage. PCT International Application P119851PC00, WO 2018/149772 A1.

Molkov, V., Dery, W. (2020). The blast wave decay correlation for hydrogen tank rupture in a tunnel fire, International Journal of Hydrogen Energy, V.45, pp. 31289-31302. https://doi.org/10.1016/j.ijhydene.2020.08.062.

Molkov, V.V., Cirrone, D.M.C., Shentsov, V.V., Dery, W., Kim, W., Makarov, D.V. (2021). Dynamics of blast wave and fireball after hydrogen tank rupture in a fire in the open atmosphere. International Journal of Hydrogen Energy, V.46, pp.4644-4665. https://doi.org/10.1016/j.ijhydene.2020.10.211.

Appendices

Appendix 1. List of international RCS

ISO/TR 15916:2015 (will be replaced by ISO/AWI TR 15916)	Basic considerations for the safety of hydrogen systems
ISO 19880-1:2020	Gaseous hydrogen — Fuelling stations — Part 1: General requirements
ISO 26142:2010	Hydrogen detection apparatus — Stationary applications;
ISO 19882:2018 (Will be replaced by ISO/AWI 19882)	Gaseous hydrogen — Thermally activated pressure relief devices for compressed hydrogen vehicle fuel containers
ISO 23273:2013	Fuel cell road vehicles — Safety specifications — Protection against hydrogen hazards for vehicles fuelled with compressed hydrogen
ISO 17840-1:2015	Road vehicles — Information for first and second responders — Part 1: Rescue sheet for passenger cars and light commercial vehicles
ISO 17840-2:2019	Road vehicles — Information for first and second responders — Part 2: Rescue sheet for buses, coaches and heavy commercial vehicles
ISO 17840-3:2019	Road vehicles — Information for first and second responders — Part 3: Emergency response guide template
ISO 17840-4:2018	Road vehicles — Information for first and second responders — Part 4: Propulsion energy identification
ISO 22899-1:2007	Determination of the resistance to jet fires of passive fire protection materials — Part 1: General requirements
ISO/TR 22899-2:2013	Determination of the resistance to jet fires of passive fire protection — Part 2: Guidance on classification and implementation methods
ISO 6944-1:2008	Fire containment — Elements of building construction — Part 1: Ventilation ducts;

ISO 21925-1:2018	Fire resistance tests — Fire dampers for air distribution systems — Part 1: Mechanical dampers
ISO/DIS 23693-1	Determination of the resistance to gas explosions of passive fire protection materials — Part 1: General Requirements
ISO/TR 16576:2017	Fire safety engineering — Examples of fire safety objectives, functional requirements and safety criteria
ISO 16732-1:2012	Fire safety engineering — Fire risk assessment
ISO 10961:2019	Gas cylinders — Cylinder bundles — Design, manufacture, testing and inspection;
ISO 11625:2007	Gas cylinders — Safe handling
ISO 2685:1998	Aircraft — Environmental test procedure for airborne equipment — Resistance to fire in designated fire zones
EN 1846-1:2011	Firefighting and rescue service vehicles - Part 1: Nomenclature and designation
EN 1846-2:2009+A1:2013	Firefighting and rescue service vehicles - Part 2: Common requirements - Safety and performance;
EN 1846-3:2013	Firefighting and rescue service vehicles - Part 3: Permanently installed equipment - Safety and performance
EN 1366-1:2014	Fire resistance tests for service installations - Part 1: Ventilation ducts
EN 1797:2001	Cryogenic vessels - Gas/material compatibility
ISO 834-1:1999	Fire-resistance tests — Elements of building construction — Part 1: General requirements
ISO/TR 834-3:2012	Fire-resistance tests — Elements of building construction — Part 3: Commentary on test method and guide to the application of the outputs from the fire-resistance test
ISO 834-4:2000	Fire-resistance tests — Elements of building construction — Part 4: Specific requirements for loadbearing vertical separating elements
ISO 834-5:2000	Fire-resistance tests — Elements of building construction — Part 5: Specific requirements for loadbearing horizontal separating elements

ISO 834-6:2000	Fire-resistance tests — Elements of building construction — Part 6: Specific requirements for beams
ISO 834-7:2000	Fire-resistance tests — Elements of building construction — Part 7: Specific requirements for columns
ISO 834-8:2002	Fire-resistance tests — Elements of building construction — Part 8: Specific requirements for non-loadbearing vertical separating elements
ISO 834-9:2003	Fire-resistance tests — Elements of building construction — Part 9: Specific requirements for non-loadbearing ceiling elements
ISO 834-10:2014	Fire resistance tests — Elements of building construction — Part 10: Specific requirements to determine the contribution of applied fire protection materials to structural steel elements
ISO 834-11:2014	Fire resistance tests — Elements of building construction — Part 11: Specific requirements for the assessment of fire protection to structural steel elements
ISO 834-13:2019	Fire-resistance tests — Elements of building construction — Part 13: Requirements for the testing and assessment of applied fire protection to steel beams with web openings
ISO/TR 16738:2009	Fire-safety engineering — Technical information on methods for evaluating behaviour and movement of people
ISO 16111:2018	Transportable gas storage devices — Hydrogen absorbed in reversible metal hydride
ISO 17081:2014	Method of measurement of hydrogen permeation and determination of hydrogen uptake and transport in metals by an electrochemical technique
ISO 19881:2018 (Will be replaced by ISO/AWI 19881)	Gaseous hydrogen — Land vehicle fuel containers
ISO 16733-1:2015	Fire safety engineering — Selection of design fire scenarios and design fires — Part 1: Selection of design fire scenarios
ISO 24679-1:2019	Fire safety engineering — Performance of structures in fire — Part 1: General
ISO/TS 13447:2013	Fire safety engineering — Guidance for use of fire zone models

ISO 16730-1:2015	Fire safety engineering — Procedures and requirements for verification and validation of calculation methods — Part 1: General
ISO/TR 16730-2:2013	Fire safety engineering — Assessment, verification and validation of calculation methods — Part 2: Example of a fire zone model
ISO 16736:2006	Fire safety engineering — Requirements governing algebraic equations — Ceiling jet flows
ISO 16737:2012	Fire safety engineering — Requirements governing algebraic equations — Vent flows
ISO 10294-5:2005	Fire resistance tests — Fire dampers for air distribution systems — Part 5: Intumescent fire dampers
ISO 3008-1:2019	Fire resistance tests — Door and shutter assemblies — Part 1: General requirements
ISO 23932-1:2018	Fire safety engineering — General principles — Part 1: General
ISO/TR 12471:2004	Computational structural fire design — Review of calculation models, fire tests for determining input material data and needs for further development
ISO/TR 15655:2020	Fire resistance — Tests for thermo-physical and mechanical properties of structural materials at elevated temperatures for fire engineering design
ISO/TR 15656:2003	Fire resistance — Guidelines for evaluating the predictive capability of calculation models for structural fire behaviour
EN 17339:2020	Transportable gas cylinders - Fully wrapped carbon composite cylinders and tubes for hydrogen
CEN/TR 14473:2014	Transportable gas cylinders - Porous materials for acetylene cylinders
CEN/TR 15444:2006	Transportable gas cylinders - Gas cylinders conforming to the TPED to be used for PED applications - Applicability and justifications
EN 1089-3:2011	Transportable gas cylinders - Gas cylinder identification (excluding LPG) - Part 3: Colour coding
EN 12257:2002	Transportable gas cylinders - Seamless, hoop-wrapped composite cylinders

EN 12862:2000	Transportable gas cylinders - Specification for the design and construction of refillable transportable welded aluminium alloy gas cylinders
EN 13322-1:2003	Transportable gas cylinders - Refillable welded steel gas cylinders - Design and construction - Part 1: Carbon steel
EN 13322-2:2003	Transportable gas cylinders - Refillable welded steel gas cylinders - Design and construction - Part 2: Stainless steel
EN 14208:2004	Transportable gas cylinders - Specification for welded pressure drums up to 1000 litre capacity for the transport of gases - Design and construction
EN 14513:2005	Transportable gas cylinders - Bursting disc pressure relief devices (excluding acetylene gas cylinders)
EN 1964-3:2000	Transportable gas cylinders - Specification for the design and construction of refillable transportable seamless steel gas cylinders of water capacities from 0,5 litre up to and including 150 litres - Part 3: Cylinders made of seamless stainless steel with an Rm value of less than 1100 MPa
EN 720-1:1999	Transportable gas cylinders - Gases and gas mixtures - Part 1: Properties of pure gases
ISO/AWI TR 24488	Road Tunnel Fire Safety — A general overview of regulatory frameworks and research (under development)
EN NWIP TR JTC6	Technical Report on the Safe use of hydrogen in built constructions
ISO/CD TR 17886	Technical Report on Fire safety engineering — Design of evacuation experiments
ISO/CD 20710	Fire safety engineering — Active fire protection systems
IEC 62282-5-100:2018	Fuel cell technologies – Part 5-100: Portable fuel cell power systems – Safety
EN ISO 11439:2013/prA1	Gas cylinders - High pressure cylinders for the on-board storage of natural gas as a fuel for automotive vehicles
FprEN ISO 19884	Gaseous hydrogen - Cylinders and tubes for stationary storage
ISO/CD 11114-2	Gas cylinders — Compatibility of cylinder and valve materials with gas contents — Part 2: Non-metallic

EN-ISO 11114-1:2020	Gas cylinders - Compatibility of cylinder and valve materials with gas contents - Part 1: Metallic materials
BS 7346-7:2013	Components for smoke and heat control systems. Code of practice on functional recommendations and calculation methods for smoke and heat control systems for covered car parks
NPR 6095-1:2012	Smoke and heat control systems - Part 1: Guidelines on design and installation of smoke and heat exhaust installations and smoke control systems in car parks
NEN 2443:2013	Design standards and recommendations on parking facilities for passenger cars
NEN 6098:2012	Smoke control systems for powered smoke exhaust ventilators in car parks
EN 1990:2002	Eurocode - Basis of structural design
EN 1991-1-2:2002	Eurocode 1: Actions on structures - Part 1-2: General actions - Actions on structures exposed to fire
EN 1993:2005	Eurocode 3: Design of steel structures - Part 1-2: General rules - Structural fire design
EN 2:1992/A1:2004	Classification of fires
EN 50553	Railway applications - Requirements for running capability in case of fire on board of rolling stock
ISO/TS 16976-5:2020	"Respiratory protective devices — Human factors — Part 5: Thermal effects"
ISO/DIS 11119-3	Gas cylinders — Refillable composite gas cylinders and tubes — Design, construction and testing — Part 3: Fully wrapped fibre reinforced composite gas cylinders and tubes up to 450 l with non-load-sharing metallic or non-metallic liners or without liners