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

Fuel Cells and Hydrogen Joint Undertaking (FCH JU)
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Deliverable 4.1
Detailed research programme on explosion in underground transportation systems

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Summary

The aim of the present deliverable is to improve the principal understanding of hydrogen explosion hazards in tunnels and similar confined spaces using complementary theoretical, numerical and experimental studies.

HSE will lead this work package following leadership of Task 1.3 "Selection and prioritisation of accident scenarios in tunnels and confined spaces" and as a partner delivering experimental work. HSE will coordinate the programme to build on the current state-of-the-art understanding of releases and dispersion of hydrogen in tunnels, subsequent deflagrations, DDT, blast waves and fireball hazards. As part of this work HSE will formulate requirements for analytical, numerical and experimental studies and identify the expected results from this research. The work will be through combined analytical, numerical modelling, and experimental techniques, with the partners linking across sub-tasks to deliver the data required to develop appropriate regulations, codes and standards along with recommendations for inherently safer use of hydrogen vehicles in underground transportation systems. Experimental data will be generated to support development and validation of relevant analytical models, numerical simulations, together with hazard and risk assessment tools.

More specifically, the work package (WP4) will investigate accident scenarios in tunnels and confined spaces including cars, buses, heavy goods vehicles and rail vehicles, addressing hydrogen inventory (scaled to facility), storage vessel location (high or low, under a car or on a bus roof) and orientation (horizontal or vertical, longitudinal or transverse). The work will also investigate and develop prevention and mitigation techniques for such events using passive and active measures, drawing upon in some cases intellectual property available within the consortium.

Three unique and complementary experimental facilities will be employed to thoroughly examine the proposed accident scenarios, aid the development of mitigation techniques, and to provide the data required for model development and validating numerical simulations.

The objectives of the research programme include but are not limited to: describe analytical, numerical and experimental studies in their complementarities to achieve synergies, including pre-trial simulations and post-trial evaluation and validation simulations; develop and validate analytical and numerical techniques to understand and quantify hazards from hydrogen tank rupture in a tunnel; experimentally assess tank failure hazards in different tunnel environments and to demonstrate robust nature of evaluation and analysis; measure and evaluate impact of tunnel and vehicle features on overpressure and fireball hazard in scaled instrumented explosion tunnel and real tunnel; demonstrate efficacy of mitigation measures on tank failure hazards in tunnels.

Keywords

Hydrogen safety; hazards; consequence assessment; unignited release; jet fire; deflagration; detonation; quantitative risk assessment; hydrogen in tunnel; explosion; mitigation; engineering correlation; numerical simulation; experiment; tunnel safety; ventilation; water mist; hydrogen vehicle; hydrogen dispersion; hydrogen combustion; concrete lining; concrete spalling.

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Abbreviations

BFRP	Basalt Fibre Reinforced Polymer
BOS	Background Oriented Schlieren
CEA	Commissariat à l'Énergie Atomique
CFD	Computational Fluid Dynamics
CFL	Courant-Friedrichs-Lewy (number)
CFRP	Carbon Fibre Reinforced Polymer
CGH2	Compressed Gas Hydrogen
CS	Confined Space
CV	Control Volume
DDT	Deflagration-to-Detonation Transition
DNS	Direct Numerical Simulation
DoW	Description of Work
DTU	Danmarks Tekniske Universitet
ECF	Energy Concentration Factor
EDC	Eddy Dissipation Concept
FCHV	Fuel Cell Hydrogen Vehicle
FLIC	Fluid dynamic incinerator code
FEM	Finite Element Modelling
FRP	Fibre Reinforced Polymer
FRR	Fire Resistance Rating
GTR	Global Technical Regulation
HDPE	High Density Polyethylene
HRR	Heat Release Rate
HSE	Health and Safety Executive
IBP	Initial Burst Pressure
KIT	Karlsruher Institut fuer Technologie
LES	Large Eddy Simulation
LFL	Lower Flammability Limit
LH2	Liquid Hydrogen
LNB	Leak No Burst
MIE	Minimum Ignition Energy
NCSRD	National Center for Scientific Research Demokritos
NoE	Network of Excellence
NTP	Normal Temperature and Pressure
NWP	Nominal Working Pressure
PA	Polyamide
PIARC	Permanent International Association of Road Congresses
PPP	Pressure Peaking Phenomena
PS	Pro-Science
QRA	Quantitative Risk Assessment
RANS	Reynolds Averaged Navier Stokes
RCS	Regulations, Codes & Standards
RNG	Re-Normalisation Group
TPL	Thermal Protection Layer
TPRD	Thermal Pressure Relief Device
TVD	Total variation diminishing
UFL	Upper Flammability Limit
USN	University of South-Eastern Norway
UU	Ulster University

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

Flammability range is the range of concentrations between the lower and the upper flammability limits. *The lower flammability limit* (LFL) is the lowest concentration of a combustible substance in a gaseous oxidizer that will propagate a flame. *The upper flammability limit* (UFL) is the highest concentration of a combustible substance in a gaseous oxidizer that will propagate a flame.

Deflagration is the phenomenon of combustion zone propagation at the velocity lower than the speed of sound (sub-sonic) into a fresh, unburned mixture.

Detonation is the process of combustion zone propagating at the velocity higher than the speed of sound (supersonic) in the unreacted mixture.

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1. Introduction and scope

Fuel Cell Hydrogen (FCH) vehicles represent a viable alternative to current internal combustion engine vehicles. The use of FCH vehicles or transport of compressed gaseous hydrogen (CGH2) and cryogenic liquid hydrogen (LH2) in tunnels and similar confined spaces, such as underground car parks or garages creates new challenges in providing an acceptable level of risk for people, property and the environment. Several studies have shown that confinement or congestion can increase the consequences of an accident compared to accidents in the open. Consequently, there is a pressing need to develop validated hazard and risk assessment tools for assessing the behaviour of hydrogen in tunnels, as was concluded in 2009 by the HyTunnel project by European Network of Excellence HySafe (NoE HySafe) (HyTunnel-D111, 2009).

This report presents the detail research programme for Work Package 4 (WP4) of the HyTunnel-CS project. WP4 will specifically address the identified knowledge gaps in relation to explosion prevention and mitigation.

The detailed programme may be updated during the project course according to new developments, findings and strategic advises from the Stakeholders Advisory Board (SAB).

A first step to the preparation of this report was given by Milestone 8 “Matrix of experiments, simulations, schedule of tools development”, which presented a first version of the research programme. Milestone is included in the present report (Appendix 2) as indicated by the Grant Agreement.

2. Work Package Objectives

The objectives of the WP4 research programme are:

1. Improve the principal understanding of hydrogen explosion hazards in tunnels and similar confined spaces using complementarities of theoretical, numerical and experimental studies.
2. Generate unique experimental data to support further development and validation of relevant physics models, simulations and hazard and risk assessment tools.
3. Perform numerical simulations, including coupled CFD/FEM simulations, to support the experimental campaign and get insights into explosion phenomena consequences.
4. Develop novel engineering correlations for explosion safety engineering in underground transportation systems and similar confined spaces.
5. Formulate requirements to prevent occurrence of a powerful deflagration and possibility deflagration-to-detonation transition (DDT) in a tunnel and its ventilation system.
6. Study blast wave and fireball dynamics after hydrogen tank rupture in a tunnel and its effect on people, vehicles and structural elements.
7. Identify and evaluate innovative safety strategies and engineering solutions to prevent and mitigate hydrogen explosions in underground transportation systems.

8. Underpin key RCS outputs and recommendations for inherently safer use of hydrogen vehicles in underground transportation systems by pre-normative research on explosion.

3. Knowledge gaps and accident scenarios assessed

A state-of-the-art review relating to the safety aspects relevant to FCH vehicle was given in D1.2. In that review a critical assessment of the existing knowledge base with respect to understanding and modelling accidents involving hydrogen fuel cell vehicles was presented. An output from the assessment was a detailed collection of knowledge gaps that needed to be investigated to allow industry and regulators to make informed decisions on the operation of FCH vehicles and associated infrastructure.

3.1 Overview

Work Package 4 consists of 5 tasks.

The first task, 4.1, describes the design of the research programme (this report), and demonstrates how the knowledge gaps identified in D1.2, HyTunnel-CS (2019) inform the key objectives of the work package. To achieve the objectives a programme of research has been devised that is divided into three sub tasks based on the approach to assessing the relevant scientific and engineering aspects, these tasks are: 4.2 – Analytical tool development, 4.3 – Numerical simulations and 4.4 – Experimental Studies. The final element of the work package is task 4.5, which will draw on the findings from each of the tasks 4.2 to 4.4 to produce mid-term and the final deliverables report (D4.2 and D4.3 respectively).

The interaction between tasks shown in Figure 1, highlights the interdependencies between the three core tasks, 4.2 to 4.4. The complex and time dependant nature of this interaction is detailed further in this report to ensure that all activities are scheduled appropriately.

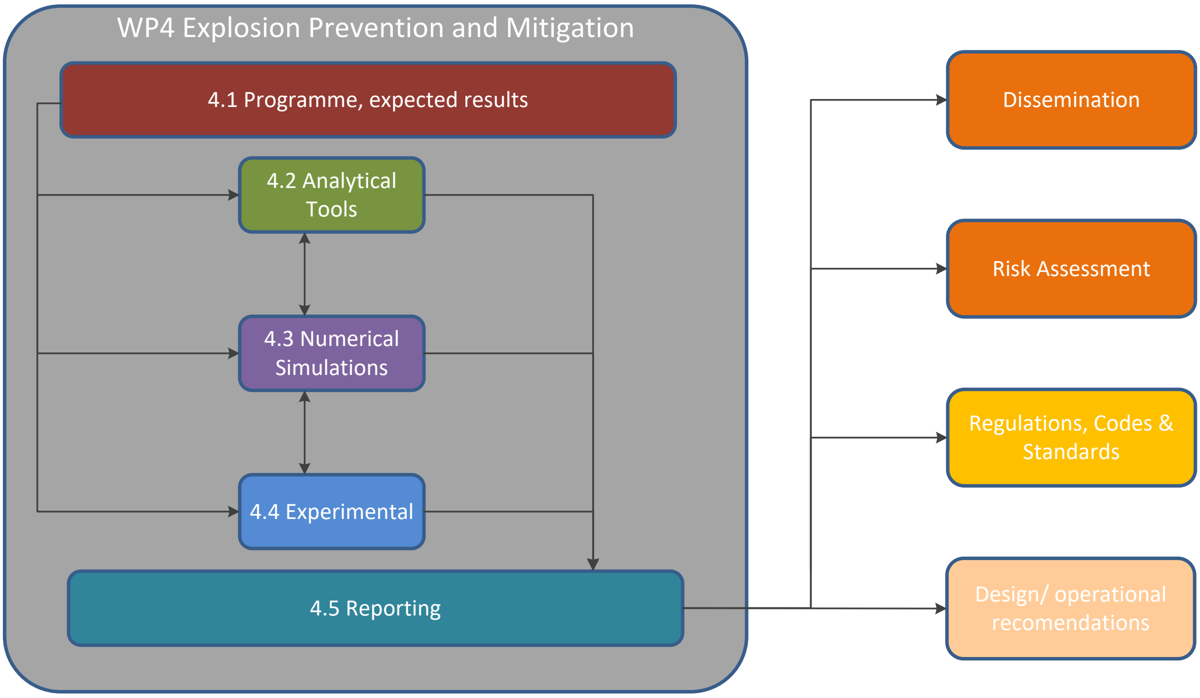

Figure 1. Interaction between the tasks of WP 4 and with other parts of the project and outcomes

4. Approach

This section provides an overview of how the different activities in WP4 will combine to meet the objective of WP4. There are three core tasks identified in the work package, namely 4.2, 4.3 and 4.4.

The first of these tasks numerically, (4.2), covers the development of analytical models and engineering-based correlations. Contributors have provided a summary of the underpinning science, the numerical scheme / code required to solve the proposed models, and detailed information on the data required to solve or validate the models.

Task 4.3 covers the use of CFD based numerical simulations. The information provided is an overview of the CFD code they propose to use (commercial / in-house), the assumptions / simplifications / customisations proposed, numerical simulations to be conducted and detailed information on the data requirements for validating the simulations.

Task 4.4 is the experimental work in support of the previous two tasks. Specifically, it covers conceptual design of the test facilities and the proposed instrumentation. The initial test proposals are also included, such as number of tests and the test parameters to be varied, including their range.

All contributors have provided a description of their proposed activities under each task, giving a total of 31 such activities across WP4. These are listed in Table 1. Following the table, a detailed description of each activity as provided by each contributor is presented. These form the main part of this report. At present no attempt has been made to bring together the various modelling / experimental requirements as expressed in the activities. This will be done over the course of the next two/three weeks.

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Table 1. Outline of activities within tasks 4.2, 4.3 and 4.4

Task	Activity	Who	Description
4.2 Analytical studies, development and validation of engineering correlations (UU)			
4.2	4.2-1	UU	Engineering models for assessment of blast wave and fireball of hydrogen tank rupture
4.2	4.2-2	UU	Engineering model for assessment of overpressure during spurious hydrogen release
4.2	4.2-3	UU	Engineering tool for prevention and mitigation of composite hydrogen storage tank explosion in a fire
4.2	4.2-4	KIT	Correlation for DDT in horizontal and vertical ventilation systems with non-uniform hydrogen-air mixtures in the presence of obstacles
4.2	4.2-5	KIT	Analytical model for water spray/mist system effect on hydrogen combustion and a shock wave attenuation
4.3 Numerical studies (NCSRD)			
4.3	4.3-1	CEA	Deflagration of non-uniform hydrogen-air cloud created by release in HSE tunnel experiments and PS experiments in Task
4.3	4.3-2	NCSRD	Deflagration of non-uniform hydrogen-air cloud created by release in HSE tunnel experiments Task 4.4
4.3	4.3-3	NCSRD	Deflagration of non-uniform hydrogen-air cloud created by release in PS tunnel experiments Task 4.4
4.3	4.3-4	KIT	Deflagration of non-uniform hydrogen-air cloud created by release in tunnel
4.3	4.3-5	NCSRD	Simulation of water injection effect on hydrogen combustion
4.3	4.3-6	KIT	Simulation of water injection effect on hydrogen combustion
4.3	4.3-7	KIT	Simulation of water injection effect on shock wave attenuation
4.3	4.3-8	KIT	Analysis of the interaction between absorbing materials and systems and shock wave
4.3	4.3-9	UU	Pre-test simulations and parametric study to find out the maximum allowed hydrogen inventory to mitigate the effect of blast wave and fireball
4.3	4.3-10	UU	Simulations to validate multi-phenomena turbulent burning velocity deflagration model (spurious release)
4.3	4.3-11	UU	Coupled CFD/FEM modelling and simulation of a tunnel structure reaction to the blast
4.3	4.3-12	USN	Simulations of flame acceleration and transition to detonation in tunnel structures
4.4 Experiments (HSE)			
4.4.1	4.4-1	CEA	Blast wave and fireball of tank rupture in tunnel: Demonstrations of car tank failure in fire experiments in two real tunnels
4.4.1	4.4-2	HSE	Blast wave and fireball of tank rupture in tunnel: Experiments utilising the experimental tubular steel "explosion" tunnel
4.4.2	4.4-3	HSE	Overpressure during spurious operation of TPRD
4.4.3	4.4-4	HSE	Deflagration of non-uniform cloud in a tunnel: Experiments on deflagrations in a 70 m and 3.7 m diameter tunnel with and without bulkheads
4.4.3	4.4-5	PS	Deflagration of non-uniform cloud in a tunnel: Experiments on deflagration of non-uniform hydrogen-air cloud created by release in mock-up tunnel sections
4.4.4	4.4-6	PS	Tests on flame propagation through a layer of fire extinguishing foam filled in by flammable hydrogen-air mixtures
4.4.4	4.4-7	PS	Tests on effect of water sprays and mist systems on combustion and DDT
4.4.4	4.4-8	USN	Effect of droplet size on mitigation of combustion and DDT
4.4.5	4.4-9	HSE	Shock wave attenuation: Tests on tank rupture in a tunnel with shock attenuation material/system
4.4.5	4.4-10	PS	Shock wave attenuation: Experiments on effect of water spray/mist system on shock wave attenuation
4.4.5	4.4-11	PS	Shock wave attenuation: Tests on shock wave attenuation by using shock absorbing materials, soft bulkheads and sacrificial pre-evacuated volumes
4.4.6	4.4-12	UU	Safety technology to prevent tank rupture: Development and manufacturing of four leak no burst composite type 4 tanks prototypes for testing in a tunnel fire at CEA and HSE tunnels
4.4.6	4.4-13	HSE	Safety technology to prevent tank rupture: Tests on prototypes of leak no burst composite type 4 tanks at HSE
4.4.6	4.4-14	CEA	Safety technology to prevent tank rupture: Tests on prototypes of leak no burst composite type 4 tanks at CEA

4.1 Engineering models for assessment of blast wave and fireball of hydrogen tank rupture (4.2, UU)

4.1.1 Engineering model development

High-pressure hydrogen tanks are currently fitted with thermally activated pressure relief devices (TPRDs) to release gas in case of a fire. Unfortunately, TPRDs have a non-zero probability of a failure (Dadashzadeh, Kashkarov et al. 2018). There is a chance for an explosion of a compressed hydrogen tank in fire followed by a destructive blast wave propagating from the tank and the fireball.

The experimental studies (Weyandt 2005, Weyandt 2006, Makarov, Kim et al. 2016) have mimicked such a scenario, i.e. TPRD malfunction, and demonstrated hydrogen tanks not equipped with TPRD rupturing in fire tests in open with fire resistance ratings (FRR), i.e. time from fire initiation until rupture, of 6.5 to 12 min. Tanks were fully filled with hydrogen at a pressure of 34.3 MPa for a type 4 tank and 31.8 MPa for a type 3 tank.

The fire tests conducted in the US (Weyandt 2005, Weyandt 2006) in open atmosphere with stand-alone and under-vehicle (onboard) tanks have shown that the blast waves from these explosions are significantly different. This is because the vehicle has absorbed the vast amount of mechanical energy which was directed to destroy the vehicle and translate its body by tens of meters. The analytical model for the blast wave in open atmosphere was used to demonstrate the decrease of mechanical energy by nearly 15 times due to the vehicle presence. Therefore, it is an important part of the study of blast waves in the tunnels – to understand more about the blast energy consumption for onboard tanks. There is a concern that should also be investigated, i.e. what would be the amount of the total energy of the explosion after rupture of the tank onboard an overturned vehicle? It is deemed the blast will be consumed partially by the vehicle and the reflection from the ground will not be as strong as if a tank was position close to the ground (it would be nearly doubled explosion energy in that case). One of the suggestions is to use the under-vehicle and above-vehicle (overturned vehicle) tanks for explosions experimental studies. The paper by (Molkov, Kashkarov 2015) demonstrated the decrease of the mechanical energy by vehicle from 180% (stand-alone tank) to 12%, i.e. 15 times! This is a unique indicator for blast strength and should be validated in this project.

Also, the above study demonstrated the contribution of combusted hydrogen to the blast wave strength. For instance, in the stand-alone tank case it took only 5.2% of the total amount of chemical energy of the burnt hydrogen contributing to the blast strength. Hence, it is suggested in this experimental programme that the effect of combustion is investigated by the use of hydrogen and an inert gas for the comparison.

4.1.2 Engineering model verification

The engineering model developed within this sub-task is being verified against 3D computational fluid dynamics (CFD) simulations of tank rupture in the tunnels performed within task 3.3 and reported in section 4.15. Delivery of the engineering model is planned in M15. The verification is being performed against ruptures of 10 to 120 L tanks of 350 and 700 bar internal pressures in tunnels. The tunnel geometries used in the simulations correspond to 1, 2 and 5 lane roadways. The CFD results will be used for extraction of the blast overpressure, mechanical energy of compression and kinetic energy of gases distribution along the tunnel, temperatures, blast velocities etc. The verification of the developed analytical model will be performed against overpressure-distance readings.

The matrix of numerical tests by Ulster (M7) (all or some selected to be used for model verification, M15)

- One-lane, two-lane and five-lane tunnels (each):
  - 10 L, 95 MPa tank rupture (stand-alone),
  - 30 L, 95 MPa tank rupture (stand-alone),
  - 60 L, 95 MPa tank rupture (stand-alone),
  - 120 L, 95 MPa tank rupture (stand-alone).
- Two-lane tunnel (also):
  - 120 L, 35 MPa tank rupture (stand-alone),
  - 120 L, 70 MPa tank rupture (stand-alone).

The matrix of numerical tests planned by Ulster (M16) (all or some selected to be used for model verification, M23)

- One-lane, two-lane and five-lane tunnels (each):
  - 10 L, 70 MPa tank rupture (under-vehicle),
  - 30 L, 70 MPa tank rupture (under-vehicle),
  - 60 L, 70 MPa tank rupture (under-vehicle),
  - 120 L, 70 MPa tank rupture (under-vehicle).

The analytical model of blast wave propagation is currently being tested in a 200 m single-lane tunnel with cross-sectional area of 25 m^2, simulating a tank rupture of 7 kg (94.5 MPa). Two different methodologies are being tested for blast wave predictions, as to verify the CFD simulations.

Firstly, based on previous work by Baker et al (Baker, Cox et al. 2012), a pressure vs distance relationship was derived from the results of numerical calculations of ruptures of tanks containing perfect gases. Latterly, the energy concentration factor (ECF) was used in the analytical model, which is also taken from previous studies, as the ratio between the volume of the confined region and the volume of the explosion hemisphere (Silvestrini, Genova et al. 2009). For instance, in a configuration whereby a charge is placed at the centre of a tunnel, the ECF can be written as follows:

$$\boldsymbol{ECF} = \frac{V_{hemisphere}}{V_{tunnel}} = \frac{2\pi r_{hem}^3}{2rA_{tun}} = \frac{\frac{1}{3}\pi r_{hem}^2}{A_{tun}}.$$

Here the volume of a hemisphere is the volume in which the blast would propagate assuming an open space and the tank being positioned on the ground. The ECF is then implemented using Sachs scaling, a dimensionless distance of a target from the energy release, allowing a similar pressure profile prediction as seen in Figure 2.

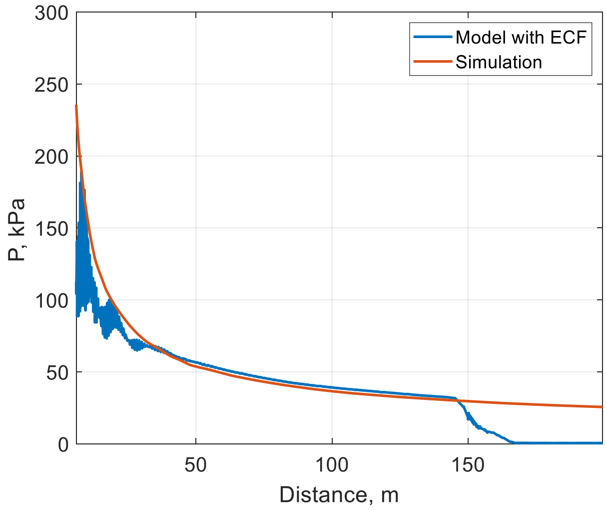


Figure 2. Trial model used for blast wave prediction in a single-lane tunnel using ECF method.

For certain tunnel geometry without any change of cross-sectional area and underestimating the effect of roughness of the wall and other obstacles, the initial energy of the tank can be presumed to be preserved throughout the tunnel. Therefore, the attenuation of the blast overpressure P_2 at a certain distance from the vessel V_2 can be calculated from the initial P_1 and V_1 of the tank:

$$P_1V_1 = P_2V_2,$$

where V_2 is the product of the area of the cross section and the distance from the tank position. However, to predict pressure decay at a certain distance we should be able to predict P_2 and V_1 in a characteristic pressure profile behind the shock front, using the analytical solution provided by Sedov (Sedov 1993) in Figure 3 below.

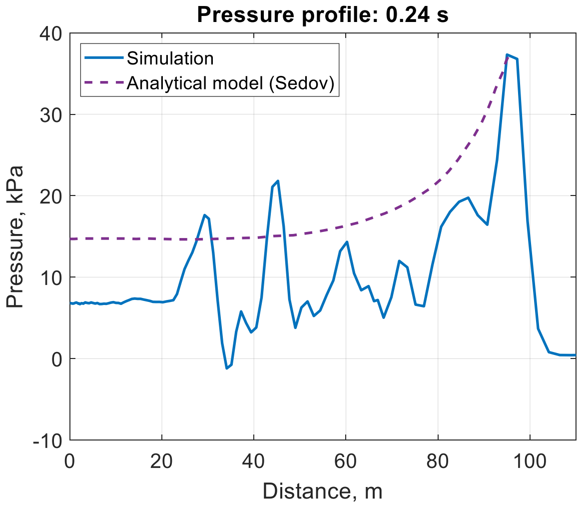


Figure 3. Pressure profile at a certain time after rupture: analytical model predictions vs CFD results

4.1.3 Suggested testing of tanks' rupture in a fire in CEA tunnel

- Effect of combustion on blast strength:
  - Test 1 (inside the tunnel). Stand-alone tank, P=700 bar. Gas – H_2. Burner sizes 1.65 m*tank width. Burner specific heat release rate (heat release rate divided by burner projection area) HRR/A ≥ 1 MW/m^2.
  - Test 2 (inside the tunnel). Stand-alone tank, P=700 bar. Gas – He or N_2. Same burner requirements.
  - Test 3 (inside the tunnel). Stand-alone tank, P=700 bar. Repetition of Test 1.
  - Mechanical energy of real gas (H_2 and He or N_2) should be equal. The starting shocks for different scenarios should be compared by calculations. If tanks will have the same volume the adjustment of mechanical energy should be done by varying initial pressure. The change of initial pressure during the fire up to rupture should be estimated to provide similar mechanical energy at rupture moment.
- Effect of vehicle presence on explosion energy absorption:
  - Test 4 (inside the tunnel). Under-vehicle tank, P=700 bar. Same burner requirements.
  - Test 5 (inside the tunnel). Above-vehicle tank (overturned vehicle), P=700 bar. Same burner requirements and/or burning car – fire origination beneath the car (or on the car under the tank).

4.1.4 Suggested testing of tanks in HSE tunnel using the reusable tanks

- Stand-alone, 350 and 700 bar pressures with the following volumes each:
  - Tests 1 (inside the tunnel). Stand-alone tanks, 10 L P=700 bar.
  - Tests 2 (inside the tunnel). Stand-alone tanks, 35 L P=700 bar.
  - Tests 3 (inside the tunnel). Stand-alone tanks, 70 L P=700 bar.
- Under-car, 350 and 700 bar pressures with the following volumes each:
  - Tests 1 (inside the tunnel). Stand-alone tanks, 10 L P=700 bar.
  - Tests 2 (inside the tunnel). Stand-alone tanks, 35 L P=700 bar.
  - Tests 3 (inside the tunnel). Stand-alone tanks, 70 L P=700 bar.

Model validation – the obtained experimental results will be used for the analysis of contribution of mechanical and chemical energies to the blast and their absorption by the vehicle presence, and model validation, due in M23.

4.1.5 Instrumentation requirements and testing outputs for validation

- Pressure and temperature monitoring inside the tanks, temperature under the tank (at 25 mm under tank bottom) in 3 locations, tank positioning distance above the burner/ground (as per GTR#13 fire test protocol).
- Burner dimensions (pipes dimensions, distances between pipes, number of holes in pipes and sizes, distances between holes), fuel flow rate, burner positioning distance above the ground, wind shield (if applicable) dimensions and positioning distances. Test requirements as per GTR#13 Engulfing fire test (section 6.2.5.2).
- Tank and burner positioning distances in relation to the facility/tunnel geometry, dimensions of facility/tunnel, ambient temperature, wind speed and direction

(sufficient wind shielding should be provided to ensure GTR#13 temperatures under the tank are reproduced).

- FRRs (time from fire initiation until rupture).
- Pressure transients after tank rupture at different locations along the whole tunnel to see pressure decay and pressure distribution along the tunnel length during blast propagation - measurement of blast wave in the entire tunnel, starting with at distance points, e.g.: 2 m, 5 m, 10 m, 20 m, etc.
- Temperature transients to define fireball dynamics - measurement of the fireball by thermocouples.
- Video for fireball dynamics. - Regular video cameras (2), infrared camera, high-speed camera.
- Radiometer for heat flux measurement to the tank.

4.2 Engineering model for assessment of overpressure during spurious hydrogen release (4.2, UU)

Experimental studies have shown that overpressure as high as 0.2 bar can be recorded at 4 m from a 400 bar hydrogen jet (10 mm diameter) when ignited with a 2 second delay (Takeno, Okabayashi et al. 2007). Ulster University (UU) will develop a reduced model to assess the overpressure from delayed ignition of turbulent high-pressure hydrogen jets produced by a spurious release, such as a TPRD opening.

In the reduced model, the hydrogen jets are assumed to be fully established. Knowing the storage conditions (temperature and pressure) and the orifice diameter, it is possible to calculate the conditions of the flow at the release orifice using Ulster's under-expanded jet theory (Molkov, Makarov et al. 2009). This methodology employs the Abel-Noble equation of state to take account of the non-ideal behaviour of the high-pressure gas. Temperature and pressure at the orifice are calculated assuming an isentropic expansion and conservation of energy between the storage and the orifice. The flow at the nozzle is considered sonic. The distribution of hydrogen concentration along the jet axis is calculated through the similarity law for momentum dominated jets (Chen and Rodi 1980), (Molkov, Bragin et al. 2010). The radial concentration decay is considered to have a Gaussian profile. Through combination of these models it is possible to determine the dimensions of a burning hydrogen cloud.

The reduced model also uses acoustic theory to calculate the pressure wave generated by the deflagration (Gorev, Miroshnikov et al. 1980). It is assumed that only the fast burning portion of the hydrogen cloud determines the maximum generated overpressure, herein indicated as the burning cloud. The overpressure at a certain location is function of distance, radius of the burning cloud and flame propagation velocity. The latter is calculated as $S_t = S_f X$, where S_f is the flame velocity and X a turbulence factor. The flame velocity is calculated as product of the laminar flame speed and expansion coefficient, both parameters depending on the hydrogen concentration. The turbulence factor includes the effects on the flame velocity of preferential diffusion, turbulence of the flow and turbulence generated by the flame itself. The turbulence factor can be characterised in terms of storage and release conditions, and ignition characteristics, as specified in the required input parameters.

4.2.1 Required input parameters

- storage or spouting pressure

- temperature
- release diameter
- ignition location
- ignition delay
- distance of sensor/target from ignition point

4.2.2 Resulting output parameters

- average flame propagation velocity
- maximum overpressure as function of distance from the jet

Once the problem has been formulated, the reduced model will be validated in two stages. Firstly, the reduced model will be validated against data from 8 experimental tests available in literature on experiments in open space. The range of validation includes jets released at pressure in the range 36 to 400 bar and a release diameter within the range 1 to 12 mm. Details of the tests are given in Table 2.

Table 2. Experimental tests available in literature used for first validation stage of the reduced model

No. Tests	Pressure, bar	Diameter, mm	Ignition axial location, m	Literature source
3	200	3.5, 6.4, 9.5	2	(Royle and Willoughby 2011)
2	36	12	1.8	(Daubech, Hebrard et al. 2015)
3	400	1, 2, 5	NA	(Takeno, Okabayashi et al. 2005)

The validation range of the reduced model for estimation of overpressure from delayed ignition will be expanded in a second stage against the experiments performed at HSE within sub-task 4.4.2 (M18).

4.2.3 Validation requirements

Table 3 shows the suggested matrix of the experimental tests to be used for comparison with reduced model performance, along with the measurements required for the reduced model validation. The indicated parameters are given for real-case scenarios. However, these would need to be scaled according to HSE tunnel dimensions during the experimental set-up definition. The suggested matrix may be updated and further refined at the stage of the experimental set-up preparation. The tests on delayed ignition of turbulent hydrogen jets should have the following characteristics:

- Release pressure = 700 bar.
- Tests will be performed in a tunnel.
- There are 10 suggested tests in total.
- These tests should be performed without ventilation in the tunnel.
- The jet should be released horizontally at approximately 1 to 1.5 m height from the ground.
- The ignition location is suggested as the location with stoichiometric composition (estimated through the similarity law).
- The ignition source used in experiments should be chosen in order to provoke the minimum disturbance to the flow.

The suggested ignition delay time is calculated as 4 times the time needed by the jet to reach the distance where hydrogen concentration is equal to 20%. The velocity of the jet at this distance is used to simplify calculations. This is considered to be a conservative assumption as it is known that velocity of the jet is much larger in proximity of the release point and it decays with distance. It is assumed that the jet is established in the zone up to 20% hydrogen concentration at these calculated times. Mass flow rate of hydrogen was calculated using e-laboratory tool developed within Net-Tools project (available at elab-prod.iket.kit.edu) for the initial moment of the release. Given that this scenario involves blowdown of the tank, this value decreases with the decrease of pressure. However, given the short ignition delay time it is not expected a significant variation in release parameters by the moment the jet is ignited.

Table 3 reports the suggested radial distances of the pressure sensors from the jet axis. They should be located at the same height as the jet and ideally at the same distance from the release point as the ignition location. If this is not possible, the pressure sensors should be located at an axial distance of 0.8 m for the releases with diameters in the range 0.5 to 1.5 mm and 2.5 m for diameters 2 to 5 mm.

Table 3. Suggested experimental tests within sub-task 4.4.2 for validation of the reduced model

N. Tests	Pressure, bar	Diameter, mm	Mass flow rate, kg/s	Ignition location, m	Ignition delay time, s	P sensors radial position, m
1	700	0.5	$6.7 \cdot 10^{-3}$	0.4	0.2	0.5, 1, 1.5, wall
2	700	1.0	0.027	0.8	0.2	0.5, 1, 1.5, wall
3	700	2.0	0.108	1.6	0.4	0.5, 1, 1.5, wall
4	700	2.0	0.108	1.6	0.8	1, 1.5, wall
5	700	2.0	0.108	2.8	0.8	1, 1.5, wall
6	350	5.0	0.378	4.0	0.9	1, 1.5, wall

The reduced model application will be expanded to the evaluation of overpressure from instantaneous ignition of the turbulent hydrogen jets. In this case releases will be immediately ignited in proximity of the orifice location. The model will be adapted by modification of the turbulent factor multiplying the turbulent flame speed. It is envisaged validation of the model against 6 tests to be performed in HSE. It is suggested that these tests have same release conditions given in Table 3 to assess the effect of immediate or delayed ignition on the produced overpressure.

The output from the work will be a complete description of the tool to be prepared in the form it can be used by stakeholders and in the form of recommendations.

4.3 Engineering tool for prevention and mitigation of composite hydrogen storage tank explosion in a fire (4.2, UU)

Ulster will perform a series of calculations of the tank-TPRD system performance in a fire, validated against available in literature data. The study will be performed with different TPRD orifice sizes, e.g. 0.2, 0.5, 2 mm, and different times to TPRD activation on the selected tanks (700 bar).

The developed non-adiabatic blowdown model calculates pressure and temperature dynamics inside a tank for different conditions. The under-expanded jet theory (Molkov, Makarov et al.

2009) is used in the model to calculate the gas parameters at the TPRD exit and at the notional nozzle exit. To calculate the heat transfer coefficient for the natural and forced convection, Nusselt number correlations are applied (Woodfield, Monde et al. 2008). The energy conservation equation and Abel-Noble equation of state will be employed to predict the dynamic pressure and temperature inside the tank. The under expanded jet theory will be used to evaluate the compressed gas behaviour after tank venting. To consider the heat transfer through the tank wall, one-dimensional unsteady heat transfer equation will be used and formulated to consider the thermal properties of a composite tank wall. The finite difference method will be used to solve the system of equations. At each time step, Nusselt number correlations for forced and natural convection will be employed to compute the heat transfer coefficients for the external and internal surfaces of the tank wall.

The validation experiment was carried out in the HYKA-HyJet research facility at Karlsruhe Institute of Technology (KIT). The impinging jet test platform was used with a high-pressure Type IV tank of volume 19 litres connected to a release nozzle with 1 mm diameter exit. The storage vessel was firstly filled to 70 MPa with helium and then cooled down to a normal room temperature (293 K) before the start of blowdown test. The temperature inside the tank was measured by a thermocouple installed in the middle of the tank. Pressure dynamics inside the tank was also measured during the blowdown test.

In this problem, the additional heat flux coming from a fire will be applied to simulate tank-TPRD system in a fire. The tank failure mechanism used in this model is based on the tank safety factor, the wall thickness fraction that bears the pressure and the material decomposition front that approaches the load-bearing thickness of the tank wall. As soon as the decomposition front reaches the load bearing thickness, the rupture happens, please see the scheme in Figure 4 below.

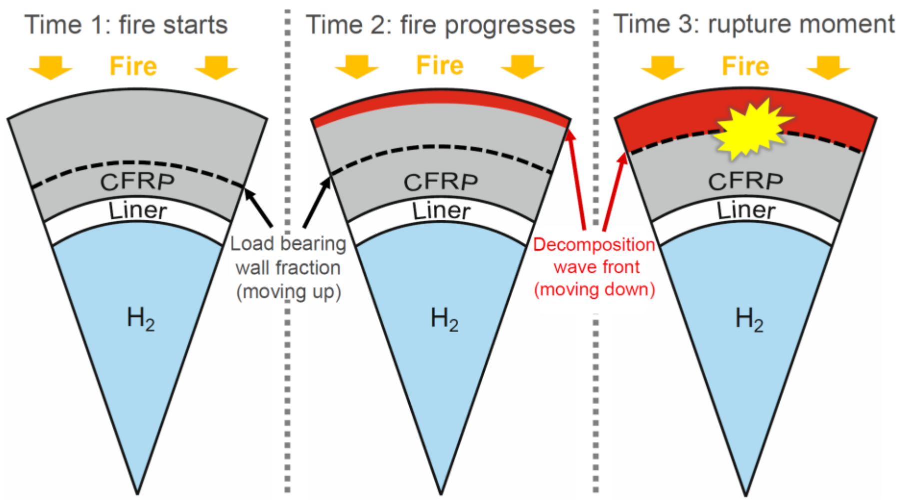


Figure 4. Scheme of the failure mechanism of composite tank in a fire

The example of the implemented model for the 36 L and 700 bar tank in a fire with the release through a hole of ∅=0.4 mm initiated about 30 s before the intended rupture is shown in Figure 5.

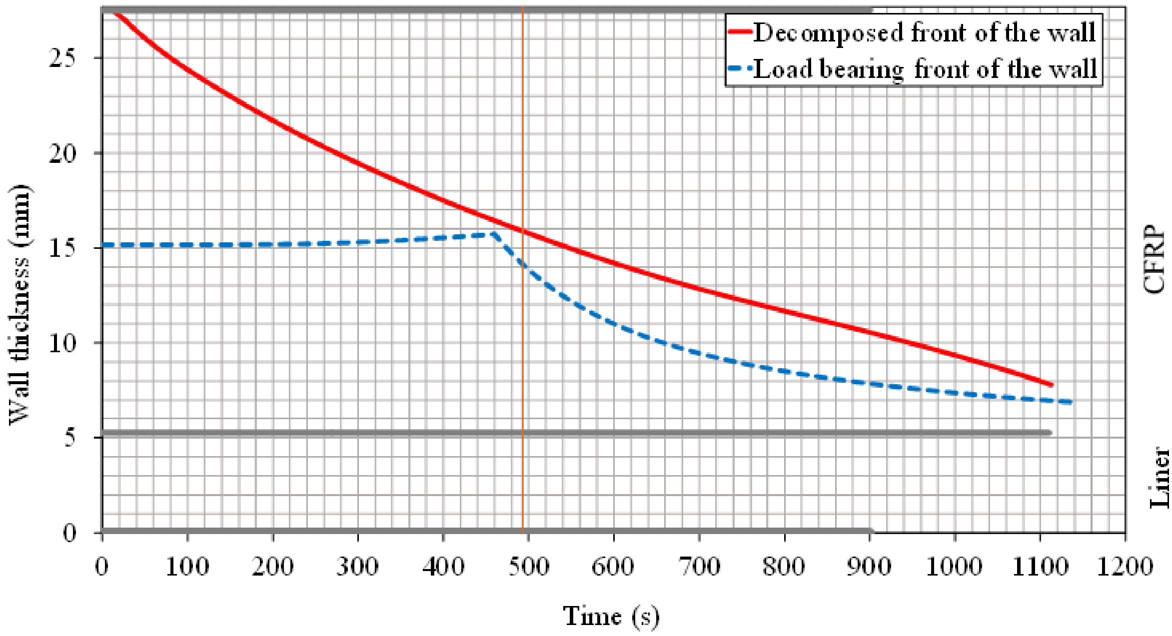


Figure 5. Example of trial simulation of the tank-TPRD system in a fire, TPRD ∅0.4 mm – potential rupture

4.3.1 Suggested testing of tanks in a tunnel

In case it will be possible to investigate tank-TPRD systems in a fire, either within or beyond HyTunnel-CS project, the following tests are suggested:

- One experiment of tank-TPRD system in a fire – stand-alone tank. In case of fire without a car, the burner sizes 1.65 m x tank width. HRR/A of the burner is burner A x total HRR = 1 MW/m^2.
- One experiment of tank-TPRD system in a fire – under-vehicle tank.

4.3.2 Suggested instrumentation requirements and testing outputs

- Pressure and temperature monitoring inside the tanks, temperature under the tank (at 25 mm under tank bottom) in 3 locations, tank positioning distance above the burner/ground, tank positioning under the car.
- Burner dimensions (pipes dimensions, distances between pipes, number of holes in pipes and sizes, distances between holes), fuel flow rate calculated to achieve required HRR/A for each Test, burner positioning distance above the ground, wind shield (if applicable) dimensions and positioning distances. Test requirements as per GTR#13 Engulfing fire test (section 6.2.5.2).
- Tank and burner positioning distances in relation to the facility/tunnel geometry, dimensions of facility/tunnel, ambient temperature, wind speed and direction (sufficient wind shielding should be provided to ensure GTR#13 temperatures under the tank are reproduced).
- Car dimensions and positioning in relation to the tunnel.
- Regular video cameras (2), infrared camera, high-speed camera.
- “Designed” in pre-calculations time of TPRD opening must be reproduced in test (for chosen TPRD diameter and tank volume).
- Heat flux to the tank.

4.4 Correlation for DDT in horizontal and vertical ventilation systems with non-uniform hydrogen-air mixtures in the presence of obstacles (4.2, KIT)

4.4.1 Existing DDT correlation (criteria) for homogeneous hydrogen-air mixtures

DDT can be influenced by many parameters such as thermal-dynamic conditions of the flammable mixture, gas compositions and the geometrical dimension of the confinement and obstacles, etc. Based on plentiful DDT experimental data, a DDT criterion has been developed at KIT previously, as a necessary but not sufficient condition for detonation onset for homogeneous hydrogen-air mixtures in a general case. However, in the assumed scenario in HyTunnel-CS, e.g., a hydrogen release in a tunnel, a non-homogeneous hydrogen mixture, mostly with a stratified distribution, is supposed to be encountered more often.

4.4.2 DDT criterion of layered hydrogen distribution in channels

DDT tests in stratified hydrogen-air mixtures were performed at KIT. This data will be used to develop new DDT criteria for non-homogeneous hydrogen mixtures in HyTunnel CS, by improvements or corrections to the existing DDT criterion.

4.5 Analytical model for water spray/mist system effect on hydrogen combustion and a shock wave attenuation (4.2, KIT)

4.5.1 Introduction

The hydrogen detonation shockwave represents an important hazard in traffic tunnels. Due to the tunnel geometry, the shock wave can only propagate in one dimension and its intensity decreases only slowly. A potential mitigation strategy could be to use the existing fire protection systems which can inject water spray in case of a hydrogen leakage. On the one hand, the injected water can contribute to preventing the possible ignition of the gas mixtures; on the other hand the detonation shock wave might be attenuated by the water droplets.

In order to assess the mitigation potential of water droplets a literature review will be undertaken to assess the state-of-the-art. To analyse the strength of shock attenuation of water droplets, numerical simulations will be performed using the KIT in-house computer code COM3D. The attenuation performance will be determined as a function of parameters such as droplet size, density of the droplets and Mach number of the shockwave. The results of the numerical calculation will be validated against experimental data.

4.5.2 Literature review

The use of water for the mitigation of shock waves offers several advantages. Due to its large heat capacity and latent heat of vaporization it is capable of absorbing a large amount of energy. Moreover, water is flexible, affordable and environmentally safe to use (Jourdan, Biamino et al. 2010).

Different researchers have investigated the method of using water droplets for attenuating shock waves. Practically, water spray is already in use for different safety applications. In most of the studies experiments were performed but also a few simulations were also conducted. Simplifications were introduced in some models in simulations, such as neglect of droplet breakup and vaporization. Some authors mentioned the need to improve these models in such aspects in order to generate reasonable results (Schwer and Kailasante 2002).

Investigations were performed with droplet diameters ranging from fine mist (1 – 10 µm, (Hanson, Davidson et al. 2007)) up to large droplets (1 - 2.5 mm, (Borisov, Gel'Fand et al. 1971)). The length of the droplet cloud varied from 15 cm (Chauvin, Jourdan et al. 2011) to 380 cm (Mataradze, Chikhradze et al. 2019). The liquid phase concentration ranged from very low concentrations (5 g/m^3, (Mataradze, Krauthammer et al. 2010) up to high concentrations of 14 kg/m^3 (Chauvin, Jourdan et al. 2011). In general, the liquid phase concentration appears to be the most important parameter for shockwave attenuation. (Chauvin, Jourdan et al. 2011) reached an overpressure attenuation of > 70 % using high liquid phase concentrations (> 10 kg/m^3) for droplet cloud length of only 15 cm.

4.5.3 Simulation of shock wave attenuation tests

The experiments conducted by (Chauvin, Jourdan et al. 2011) is selected to make COM3D simulations by using the particle models in the code.

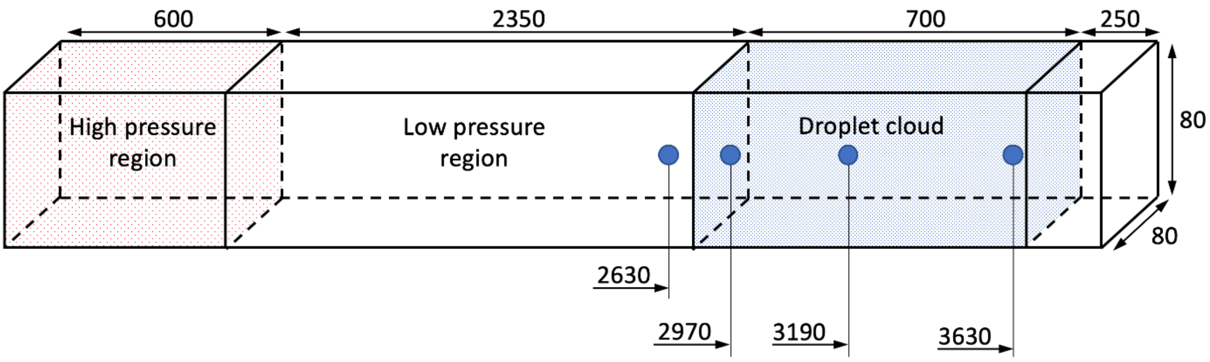


Figure 6. Scheme of test tube of planar shock wave propagation through a droplet cloud to study its attenuation effect on pressure shock

A series of shock tube experiments were performed by (Chauvin, Jourdan et al. 2011), to study the influence of a cloud of water droplets on the propagation of a planar shock wave. As shown in Figure 6, a cloud of droplets was released into the air at atmospheric pressure at the downstream section of the tube while the shock wave propagated from upstream. Incident shock waves with different Mach numbers of 1.3 and 1.5, and different lengths of droplet cloud sections, 150 mm, 400 mm, and 700 mm, were tested with an air-water volume fraction of 1.2% and a droplet diameter of 500 µm, respectively. High-speed visualization device and pressure sensors were applied to record the shock wave propagation process through the test tube.

By applying the current particle model in COM3D code, the Chauvin experiments were simulated. The preliminary simulation results about the pressure shock propagation are shown in Figure 7, as a comparison to measured data.

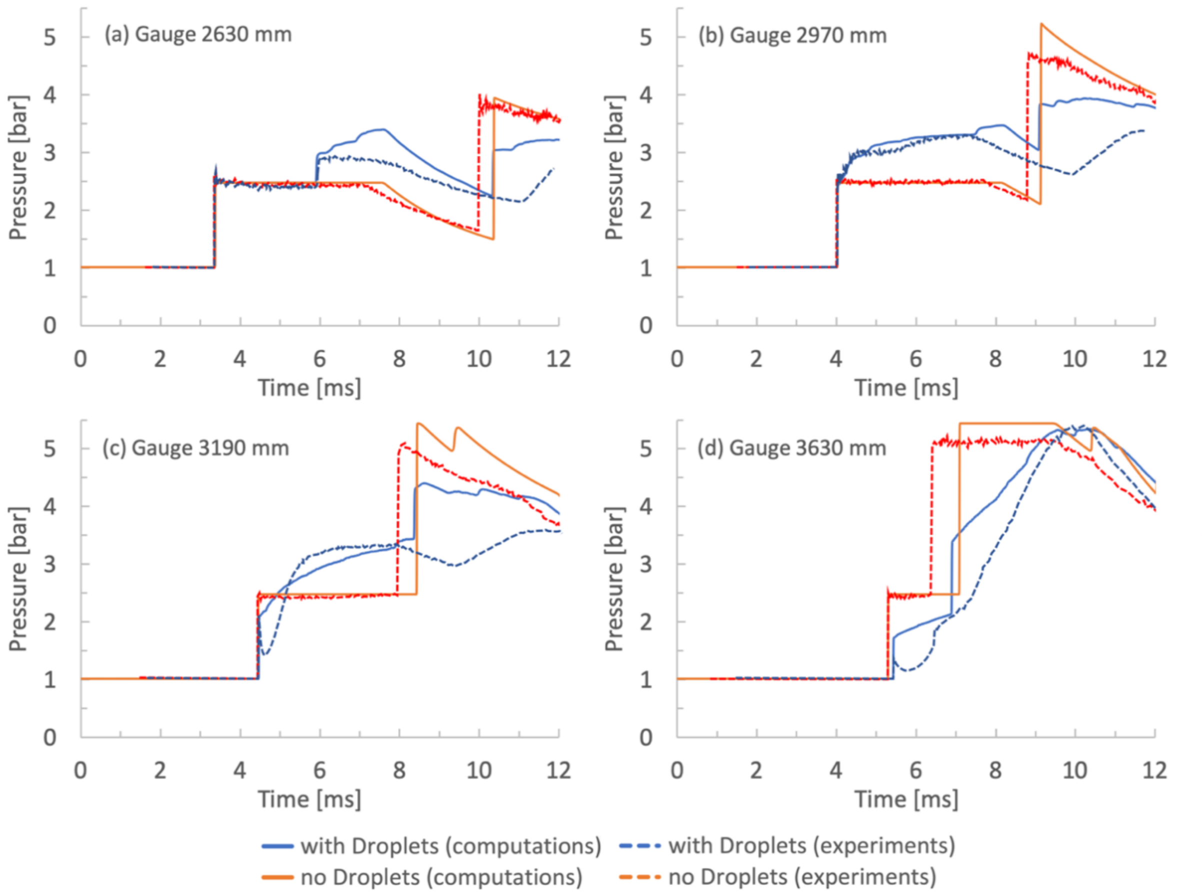


Figure 7. Preliminary results of simulations with current particle model in COM3D compared with test data (Chauvin et al., 2011)

In Figure 7, the gauge 2630 mm is not located in the cloud region referred to in Figure 6, the other three are positioned in the cloud. According to the time-history plots of pressures, especially those at the gauge 3190 mm and 3630 mm, which are at the later stage of shock wave propagation in the cloud, the peak pressure decrease is observed as an attenuation effect, which is clearly due to the droplet cloud.

However, minor inconsistency still exists between the simulating curve and the test data in Figure 7. A possible reason is that the droplet deformation and breakup phenomena are not considered yet in the current particle model.

The next step is to refine the particle model of COM3D, by introduce the mechanism of droplet deformation and breakup.

4.6 Deflagration of non-uniform hydrogen-air cloud created by release in HSE tunnel experiments and PS experiments in Task (4.3, CEA)

4.6.1 Objectives

The objective of this sub-task is to understand the deflagration effect of non-uniform hydrogen-air cloud created by release in the real tunnel experiments. After the numerical study, this sub-task consists of measuring physical parameters in the CEA real tunnel facility.

4.6.2 Numerical study

CEA will perform CFD calculation for the ignition and then combustion of a dispersed cloud of hydrogen in a tunnel. As a priority, CEA will perform the simulation using a previous calculation from WP2 - unignited dispersion of a hydrogen cloud in a tunnel - as the initial conditions for the present calculation. Therefore simulations will be performed on the geometry of CEA's selected tunnel for the experimental tests. Later, and only if there is still available time for the project, similar calculations will be performed on the combustion of a hydrogen cloud in the HSE tunnel. Initial conditions will be provided by HSE measurements performed during their experimental tests or by a CEA CFD calculation of HSE dispersion experiment in WP2. CEA will use Europlexus code in order to perform the CFD calculations for the combustion of the cloud. The geometrical dimension for the calculation won't extend to the full tunnel but will be determined partly based on the extension of the unignited cloud calculated with Neptune CFD code. The calculation process will consist in testing different models, different meshes in order to ensure convergence. High resolution approaches such as large eddy simulation (LES) or direct numerical simulation (DNS) will not be used due to the large size of the calculated domain; therefore careful attention will be focused on larger scale models validation. The calculation results will also be used to improve the preparation of the real scale experiment of cloud ignition in the CEA tunnel.

4.6.3 Test number 12 – Hydrogen dispersion with delayed ignition

4.6.3.1 Goals

The goal of this test is to characterise an unignited hydrogen jet in the real tunnel. The effects of delayed ignition of the hydrogen will be qualified. The reason why such an opening would occur could be either a failure of the TPRD (extremely unlikely) or due to thermal effect without fire such as hot air coming from a fire in the vicinity or radiations heating the device. This is unlikely to happen in a car where TPRD in located quite close to the ground but more likely in the case of a truck where the device might be at the top of the vehicle.

Due to the potential impact on facilities and device, this test will be carried out at the end of the tests matrix (see Table 7).

4.6.3.2 Operating conditions

During this test, the ventilation of the tunnel will be off and no obstacle will be present around the H_2 releasing device. This test will be conducted with hydrogen. The system of ignition will be chosen to guarantee the ignition of the hydrogen cloud.

The physical parameters in the representative area e.g. gas concentration, pressures and heat flux will be measured and background oriented Schlieren (BOS) will also be used.

4.7 Deflagration of non-uniform hydrogen-air cloud created by release in HSE tunnel experiments Task 4.4 (4.3, NCSRD)

The newly developed deflagration model (Tolias and Venetsanos 2018, Tolias and Venetsanos 2019) in ADREA-HF CFD code will be used in order to simulate PS and HSE tunnel experiments. The model has exhibited very good performance in uniform vented deflagration experiments but has not been tested for non-uniform clouds yet. ADREA-HF incorporates different sub-models for flame instabilities and turbulence that exist in front of the flame front along with sub-models for their interaction.

The outcome of the simulations and of the comparison with the experiments are expected to provide: 1) a better understanding of the physics of the phenomenon by evaluating the strength of the different factors that contribute to the overpressure development, and 2) the development of an improved CFD deflagration model for non-uniform clouds in tunnels.

The work on PS experiments is planned to finish by M24 and reported in D4.3 Final report. The work on HSE experiments is planned to finish by M31 and reported in D4.3 Final report.

4.8 Deflagration of non-uniform hydrogen-air cloud created by release in PS tunnel experiments Task 4.4 (4.3, NCSRD)

See Section 4.7

4.9 Deflagration of non-uniform hydrogen-air cloud created by release in tunnel (4.3, KIT)

4.9.1 Introduction

As the technology of hydrogen fuel cell vehicles (HFCV) develops, hydrogen application in road traffic becomes increasingly popular in the future. The impact of HFCV's on different traffic infrastructures must be identified. A key issue is hydrogen powered vehicle involved accident in tunnels (LaFleur, Bran-Anleu et al. 2017), because a potential hydrogen release is confined in tunnel structures, possibly leading to a severe hazard. According to the current design of HFCV, a possible scenario is the activation of the TPRD during a tunnel accident. The device is designed to open to protect the hydrogen storage tank when fire is detected. In this scenario, a hydrogen jet most likely occurs due to the activation of the TPRD, causing a combustible hydrogen cloud confined within the tunnel, which can bring significant thermal and pressure loads to the surrounding structures in case of ignition.

A number of research activities have been conducted regarding the safety of hydrogen vehicles in tunnels, both experimentally and numerically (Breitung, Bielert et al. 2000, Groethe, Merilo et al. 2007, Molkov, Verbecke et al. 2008, Venetsanos, Baraldi et al. 2008, Baraldi, Kotchourko et al. 2009). For example, an internal HyTunnel project was established in European NoE HySafe to extend knowledge and to develop safety procedures of hydrogen vehicle application in tunnels by both experimental and numerical methods (Kumar, Miles et al. 2009). Most current numerical simulations are concerned with hydrogen release, dispersion and combustion. Some of the most severe scenarios are focused in this sub-task, with relatively large amount of hydrogen released in a short time duration. A burnable and even detonable hydrogen cloud could form in a tunnel. The hydrogen combustion would bring serious mechanical and thermal loads to the infrastructure and endanger the involved human and property.

4.9.2 Tunnel model

An HFCV involved traffic accident in a tunnel is planned to be simulated using the KIT in-house computer code. The hydrogen dispersion and combustion will be simulated, respectively. The geometry model is shown in Figure 8.

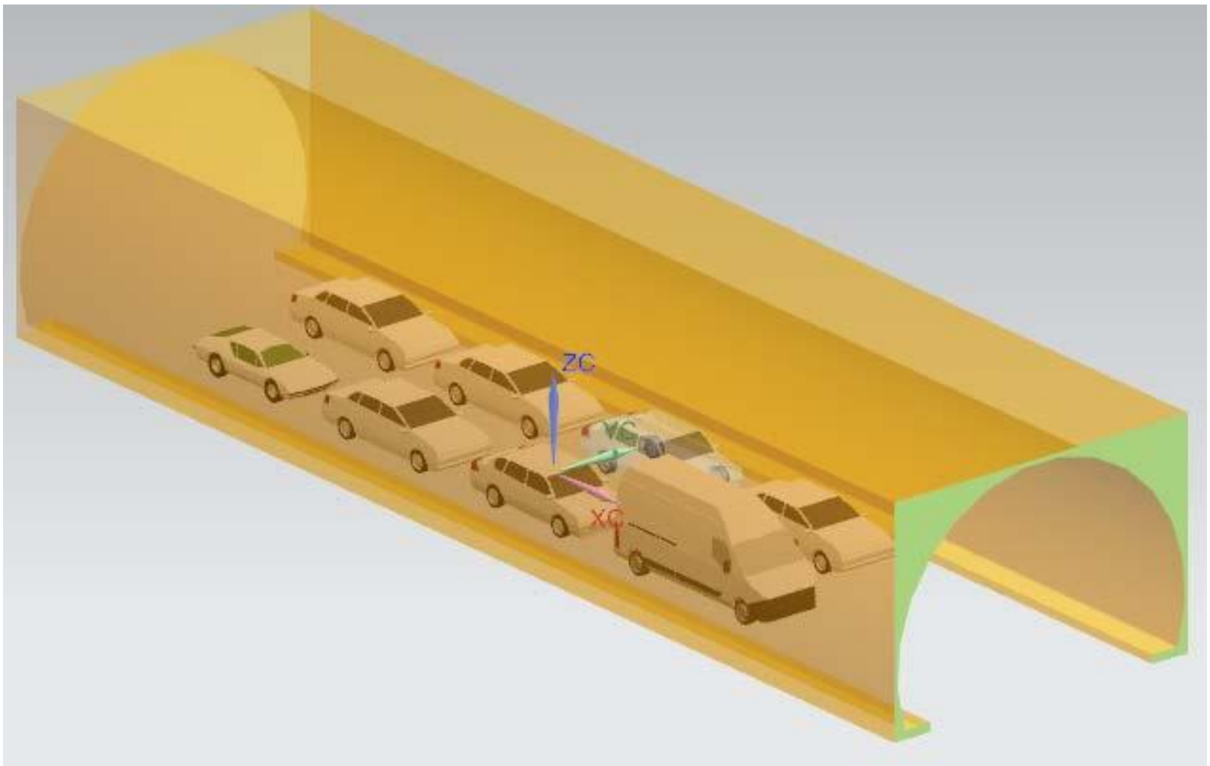


Figure 8. Geometry model of tunnels with cars

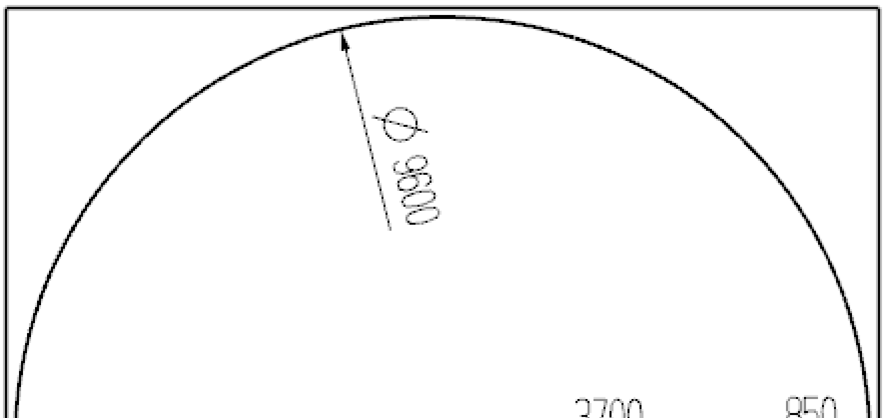


Figure 9. Geometrical information of tunnel

The geometry information for the cross section of the tunnel is shown in Figure 9 (Venetsanos, Baraldi et al. 2008). The model consists of eight cars placed in two lanes in the tunnel as shown in Figure 8. Each of the cars located at the center of each lane with a spacing distance of 1.3 m between cars to simulate a tight traffic condition. The hydrogen injection location is at the rear of the second car, venting towards the tunnel ceiling which is the most severe scenario based on the reference (LaFleur, Bran-Anleu et al. 2017). The mass flow rate injection given in

Figure 10 is equivalent to the flow rate when three TPRDs open within a hydrogen fuel cell car (70 MPa) (Middha and Hansen 2009, LaFleur, Bran-Anleu et al. 2017). The computational region is defined 12 m long, 9.6 m wide and 6.6 m high, as shown in Figure 11.

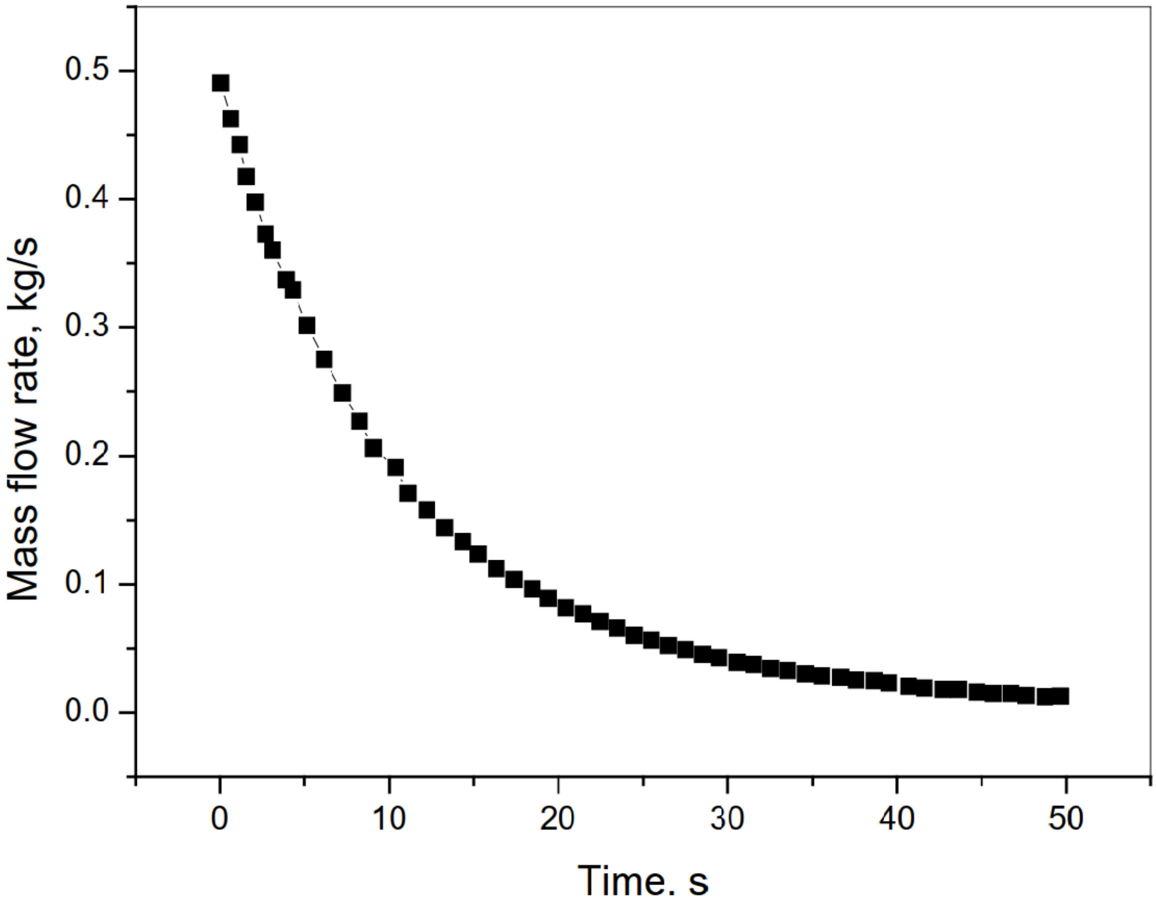


Figure 10. Hydrogen release rate as a source of dispersion in the domain

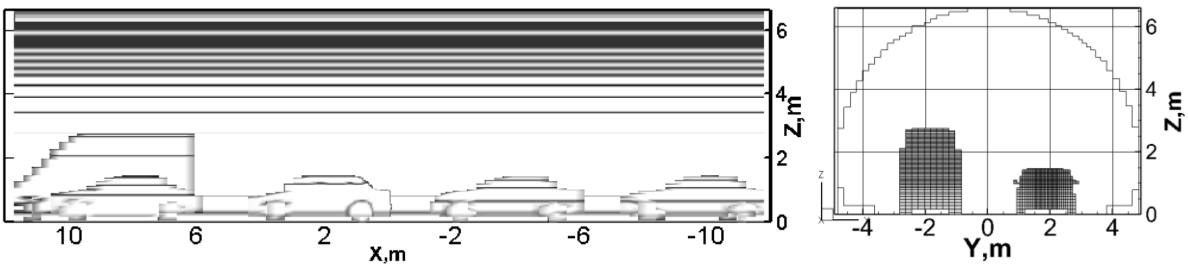
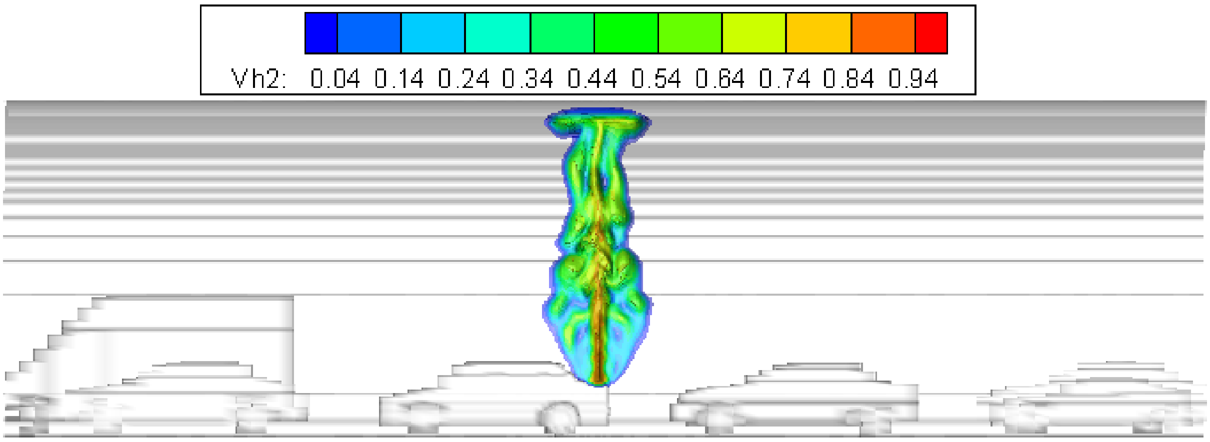


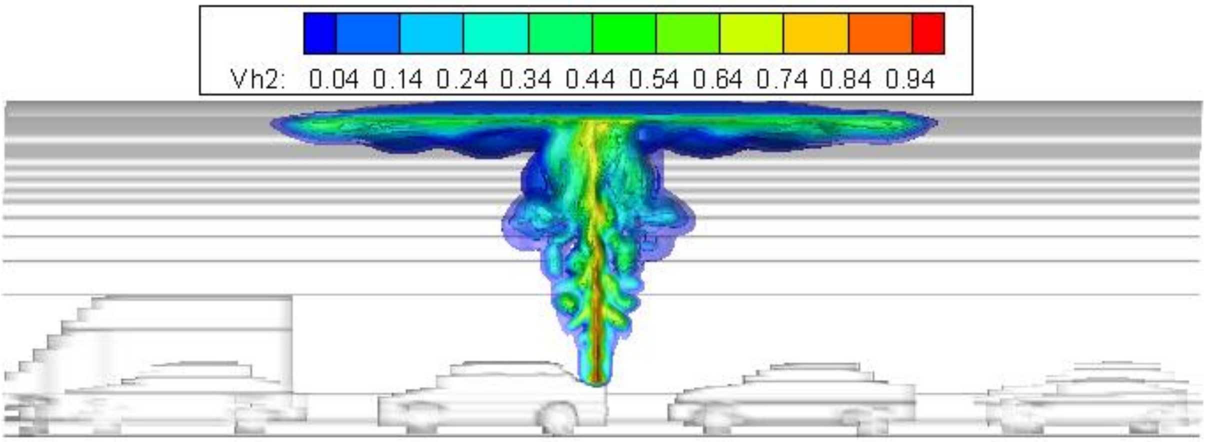
Figure 11. Vertical views of the computational domain, showing the dimenstions and the positions of the vehicle models

4.9.3 Preliminary results of hydrogen dispersion

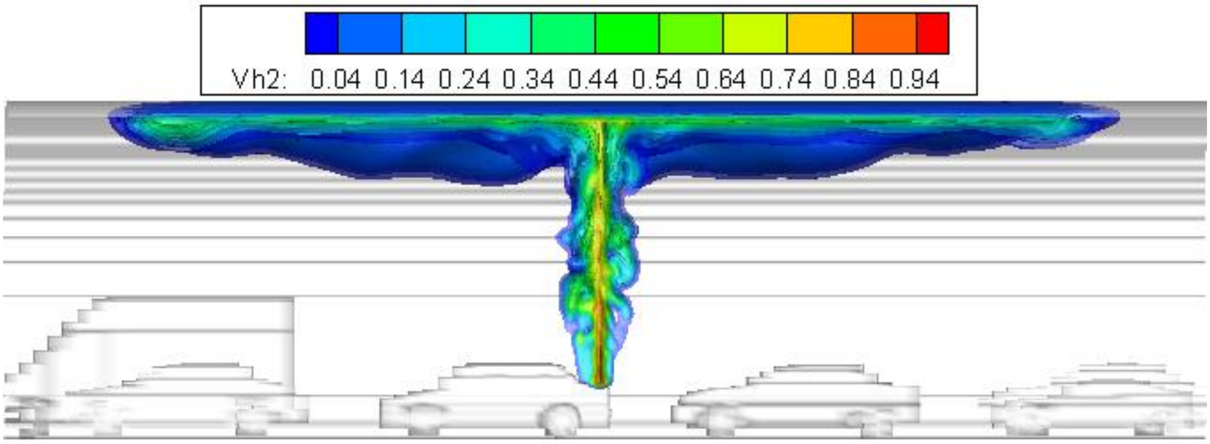
The hydrogen dispersion has been simulated in the previously described tunnel model. The flammable hydrogen clouds with hydrogen volume fraction larger than 4% are shown in Figure 12, at different time moments at 1 s, 4 s, 8 s, 16 s, respectively. (The time "0 s" stands for the starting moment of hydrogen injection).


Vh2: 0.04 0.14 0.24 0.34 0.44 0.54 0.64 0.74 0.84 0.94

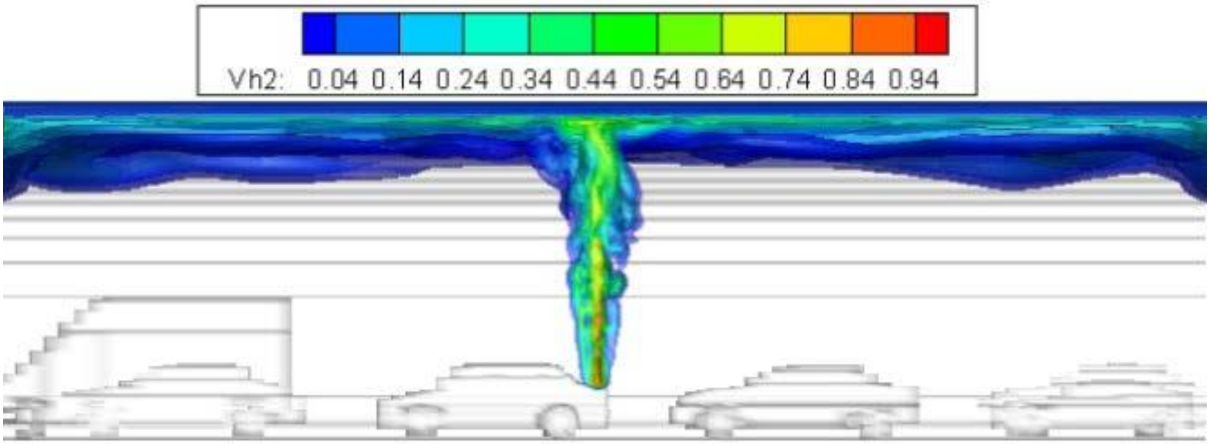
(a) 1 s


Vh2: 0.04 0.14 0.24 0.34 0.44 0.54 0.64 0.74 0.84 0.94

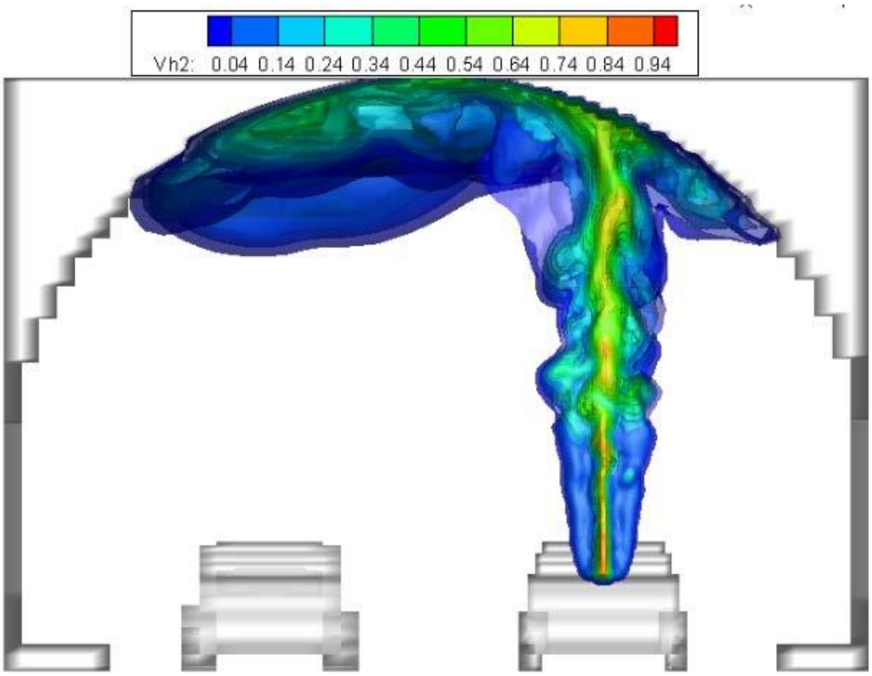
(b) 4s


Vh2: 0.04 0.14 0.24 0.34 0.44 0.54 0.64 0.74 0.84 0.94

(c) 8 s



(d) 16 s



(e) A hydrogen distribution in a transverse cross-section through the injection location

Figure 12. Simulated flammable hydrogen cloud distributions at different times and at different views

4.9.4 Simulation of hydrogen combustion

This will be done in the next step.

4.10 Simulation of water injection effect on hydrogen combustion (4.3, NCSRD)

The ADREA-HF code will be further developed in order to simulate the effect of water droplet injection on hydrogen combustion.

ADREA-HF is capable of simulating both combustion and dispersion of two phase flows. Premixed combustion is simulated using the newly developed deflagration model (Tolias and Venetsanos 2018, Tolias and Venetsanos 2019). Two-phase dispersion (e.g. with presence of water droplets in air) is modelled using the homogeneous mixture approach assuming thermal equilibrium, with and without hydrodynamic equilibrium (Venetsanos, Papanikolaou et al. 2010, Giannissi and Venetsanos 2018).

Initially, a literature review will be undertaken to examine the interaction of water injection with turbulence and with the flame front and to examine if additional models are needed to be incorporated in the code in order to take into account these interactions.

The CFD model will be evaluated against the experiments that will be conducted in sub-task 4.4.4. The outcome of the review and validation are expected to provide: 1) a better understanding of the physics of the interaction between water droplets, turbulence and combustion, and 2) the development of an improved CFD deflagration model with account of water injection effects.

The work is planned to finish by M35 and reported in D4.3 Final report.

4.11 Simulation of water injection effect on hydrogen combustion (4.3, KIT)

The basic configurations of the simulation case in this sub-task are similar to those of the sub-task 4.3.4. The only difference is that as simplified or reduced water droplet model will be developed and implemented into the computer code. The newly updated code will be used to simulate the hydrogen combustion with presence of droplet cloud. The thermal dynamic parameters of the hydrogen combustion will be output as simulation results, which will give a basis to identify the water injection effect on the hydrogen combustion.

4.12 Analysis of the interaction between absorbing materials and systems and shock wave (4.3, KIT)

4.12.1 Coupling of COM3D and ABAQUS

The KIT in-house COM3D code and the popular ABAQUS code will be coupled in a way of full 3D. The COM3D accomplishes the reactive fluid dynamics simulation, which supplies thermal-dynamic loads as inputs to the ABAQUS code, which accomplishes the mechanical calculation and the deformation or displacement calculation of elastic or absorbing boundaries. These displacements of boundaries will be feedback to the COM3D code as moving boundary conditions. These conditions influence further the gas dynamic in the confined volumes by the moving boundaries. The interaction between the gas dynamics and the absorbing elastic boundaries is simulated numerically by the fully coupled COM3D and ABAQUS codes.

4.12.2 Simulation and demonstration of the experimental cases in Sub-task 4.4.5

As planned, Pro-Science will perform shock wave attenuation tests by using absorbing materials in sub-task 4.4.5. The emitted shock wave from cubical-shaped 4 g H_2 combustion unit will be used to investigate the shock wave attenuation by absorbing materials, such as polystyrol, silicon or rubber in thickness of 10 cm or 20 cm. Probes of selected absorbing materials with an area of 1 m^2 will be fixed, at the same level of the combustion tube, on the wall of the safety vessel (HYKA - V220 or A2). Three fast pressure sensors will be placed as traverse in front of the test probes to measure precisely the incident shock wave history and the reflected answer from the absorbing materials.

By using the coupled COM3D and ABAQUS codes, the selected experimental cases will be simulated numerically, to manifest the attenuation effect of different absorbing materials on blast shock waves.

4.13 Pre-test simulations and parametric study to find out the maximum allowed hydrogen inventory to mitigate the effect of blast wave and fireball (4.3, UU)

UU are planning to perform pre-test simulations and parametric study to find out the maximum allowed hydrogen inventory to mitigate the effect of blast wave and fireball, after a hydrogen tank rupture in a fire in a tunnel, on people and structure. The established harm criteria for humans and damage criteria for structures will be applied to find out the parameters of inherently safer onboard storage tank. UU will develop and validate numerical techniques for understanding and quantifying hazards from hydrogen tank rupture in a tunnel.

ANSYS Fluent will be used as a CFD engine and the model will employ the LES approach coupled with Smagorinsky-Lilly as the sub-grid scale model for turbulence, and the eddy-dissipation-concept (EDC) for the simulation of combustion with direct integration. In order to conserve the mechanical energy of compressed hydrogen, the tank volume with "ideal gas" in simulations using the equations will get scaled using the following equation: $V_{ideal} = V_{real} - mb$, in order to reduce the volume compared to real tank and preserve the mechanical energy and the pressure as in experiment to get the same starting shock. The time step adapting technique will be used to maintain a constant Courant-Friedrichs-Lewy (CFL) number.

The numerical study will begin with validation of the CFD model using experimental data from rupture tests on a stand-alone vessel (Tamura, Takahashi et al. 2006) (35 L at 945 bar) and (Weyandt 2005) (72.4 L at 350 bar).

The second stage of CFD model development will include the problem formulation in order to define a maximum amount of hydrogen in an onboard vehicle storage tank that would not generate pressure loads capable of threatening life and destroying property along a tunnel. It is planned to perform realistic simulations of high-pressure tank rupture in a tunnel with the presence of a vehicle etc. A series of numerical simulations will be performed, with the following parameters, of the tanks and tunnels:

- Different tunnel cross-sections comprising of 1, 2 and 5 traffic lanes with cross-section areas of 24, 40 and 140 m^2 respectively.
- The fixed tunnel length for all simulations of 1000 m.
- There will be 4 tanks with various volumes of 10, 30, 60 and 120 litres at fixed storage pressure of 700 bar. The respective mass inventories are 0.40, 1.21, 2.43 and 4.86 kg.
- The simulations will be carried out to account for losses of mechanical energy required to damage and move the car and the effect of car geometry on the amount of released chemical energy.
- The model of a real car with a real tank onboard will be placed in those tunnels and simulations performed for the cases outlined above.
- There are a total of 12 simulations planned.

The established overpressure for the cases performed will be compared against harm criteria for humans and damage criteria for structures to find the maximum allowed inventory.

The third stage of development will be undertaken following the initial validation (stage 1) and identification of critical inventories (stage 2). The model will be tested against HyTunnel-CS experimental data, produced by CEA, from Task 4.4. In that work, experiments will be undertaken firstly with non-flammable nitrogen and helium, and then with flammable hydrogen in order to assess the impact of gas nature and the contribution of chemical energy of combustion on the strength of the blast wave. The numerical model and methodology will be applied for the tests performed in Task 4.4.1 and the following results expected from validation:

- Effect of different non-reacting gases on the blast for the same mechanical energy.
- Effect of combustion contribution to the strength of the blast wave.
- Dynamics of the maximum blast along the tunnel.
- Pressure profile throughout the whole length of the tunnel.
- Pressure drop due to losses and presence of obstacles and tunnel structures (e.g. car and/or ventilation system).
- Temperature profile from the fireball.

At the final step the results and conclusions i.e. safe distances along the tunnel, maximum inventory of hydrogen that would not generate life threatening pressure loads, and effect of gases will be presented and summarised for recommendations. The developed model will be recommended as a tool for hydrogen safety engineering and design.

4.14 Simulations to validate multi-phenomena turbulent burning velocity deflagration model (spurious release) (4.3, UU)

A CFD model will be developed and validated to assess the pressure and thermal hazards from delayed ignition of hydrogen jets. The CFD model employs the Ulster's multi-phenomena deflagration model, which is adapted to account for the non-uniformity of the hydrogen-air mixture and high-intensity turbulence in the jet. A reduced model is being developed within Task 4.2 to assess the overpressure effects. However, CFD simulations should be conducted additionally for the following reasons:

- CFD models allow more accurate predictions of overpressure dynamics;
- The CFD model can simulate the scenarios that cannot be reproduced by the engineering tool assumptions, such as the hypothesis of fully established hydrogen jets at the moment of ignition;
- Simulations can be a verification tool to expand the range of applicability of the reduced model;
- The study can be expanded to calculation of thermal and pressure loads on the structure.

4.14.1 Description of the CFD model

The under-expanded jet will be modelled in simulations by use of the notional nozzle approach, which allows the use of a coarser mesh at the release point and the use of an incompressible solver, at least for the first stage of the simulations. It is assumed that given the short ignition delay, variation of conditions in the tank due to the blowdown will be negligible. Therefore, constant release conditions can be assumed. The software used for building the calculation grid is ICEM-CFD, whereas ANSYS Fluent is used for the CFD simulation. A grid of around 1 million Control Volumes (CVs) is expected. This depends on the nozzle size and expected hydrogen cloud. Generally, a CFD simulation within this task will be subdivided in two stages characterised by different models:

- Unignited release simulation: the flow can be treated as an incompressible ideal gas. A pressure-based implicit solver is used. A constant time step of 10^{-3} s can be used in a first stage. Either a Reynolds-Averaged Navier-Stokes (RANS) or LES approach can be used to calculate the distribution of hydrogen concentration and the turbulence mapping of the flammable cloud until the time of ignition. It is expected that the calculation time may be around 2 to 3 days. However, this may increase substantially for time step and grid sensitivity analysis.
- Deflagration simulation: the distribution calculated for the unignited release will be used as initial condition for the second phase of the simulation. The CFD model is based on the density-based coupled solver with explicit time stepping. A Courant Friedrichs Lewy (CFL) number below 1 is maintained in all simulations. A LES approach is used for turbulence modelling, employing a re-normalisation group (RNG) sub-model. The multi-phenomena deflagration model is used for the premixed combustion (Verbecke et al., 2009). The premixed flame propagation is modelled through the progress variable c equation and the source term, S_c, which is calculated with the gradient method: $\overline{S_c} = \rho_u S_t |grad\tilde{c}|$, where ρ_u is the density of the unburnt mixture and S_t is the turbulent flame speed. The turbulent burning velocity includes the effect of flow turbulence (Ξ_{turb}), turbulence produced by the flame front (Ξ_{karl}), preferential diffusion (Ξ_{lp}) and the increase of flame radius with respect to the flame thickness (Ξ_{fract}):

$$S_t = S_u \cdot \Xi_{turb} \cdot \Xi_{karl} \cdot \Xi_{lp} \cdot \Xi_{fract}$$

  It is expected that the calculation time may be around 2 to 3 days. However, this may increase substantially for time step and grid sensitivity analysis.

4.14.2 Required input parameters

The following parameters will be required for simulations:

- storage or spouting pressure
- temperature
- release diameter
- ignition location and type
- ignition delay;
- distance of sensor/target from ignition point

4.14.3 Simulation outputs

The following data outputs will be provided following simulation:

- distribution of hydrogen and turbulence prior to ignition
- flame dynamics and thermal loads in the surrounding of the jet and on structures if release is in confined space
- overpressure dynamics in the surroundings of the jet.

4.14.4 Validation of the CFD model

The CFD model will be validated in two stages. Firstly, it will be validated against data from 2 experimental tests available in literature on tests in open space. The range of validation includes jets released at pressure in the range 36-200 bar and a release diameter within the range 6.4-12 mm. Details of the tests are given in Table 4.

Table 4. Experimental tests available in literature used for first validation stage of the reduced model

Test	Pressure [bar]	Diameter [mm]	Ignition location [m]	Ignition delay [s]	Literature source
1	200	6.4	2	0.8	(Royle and Willoughby 2011)
2	36	12	1.8	5	(Daubech, Hebrard et al. 2015)

The validation range of the reduced model will be expanded in a second stage against the experiments performed at HSE within sub-task 4.4.2 (M18) for releases at a higher pressure (700 bar). These tests will be performed in a tunnel; therefore a more complex overpressure dynamic is expected due to reflection of the pressure wave on the tunnel walls and ground. Table 5 shows the suggested matrix of the experimental tests to be simulated to validate the CFD model. All tests are part of the set of experiments suggested in Table 3. Validation tests are 4 in total. These tests should be performed without ventilation in the tunnel. The jet should be released horizontally at approximately 1 to 1.5 m height from the ground. The suggestions for the ignition location, delay time and pressure sensors location radial to jet follow the same considerations as for the reduced model in Task 4.2, thus are not repeated in this section. However, the following experimental measurements are suggested:

- The experimental set up should include 2 pressure sensors along the jet axis at least for release with diameter 2 mm (distance 8 and 12 m from the release point).
- Monitoring of pressure and temperature inside the tank and at the orifice, along with a mass flow meter in the release pipe for all releases.
- Hydrogen concentration probes located along the axis (1, 2 and 3 m from the release point) and radially to the location of ignition (0.1 and 0.4 m) or at an axial distance of 0.8 m for the releases with diameters in the range 0.5-1.5 mm and 2.5 m for diameter 2 mm.
- High-speed video camera showing flame dynamics.
- Two radiative heat flux sensors located at the wall of the tunnel at two distances from the release point (1 and 3 m from release point).

Table 5. Suggested experimental tests within sub-task 4.4.2 for validation of the CFD model

Test	Pressure, bar	Diameter, mm	Mass flow rate, kg/s	Ignition location, m	Ignition delay time, s	P sensors radial position, m
1	700	1.0	0.027	0.8	0.2	0.5, 1, 1.5, wall
2	700	2.0	0.108	1.6	0.4	1, 1.5, wall
3	700	2.0	0.108	1.6	0.8	1, 1.5, wall
4	700	2.0	0.108	2.8	0.8	1, 1.5, wall

4.15 Coupled CFD/FEM modelling and simulation of a tunnel structure reaction to the blast (4.3, UU)

UU and DTU will undertake coupled CFD/FEM modelling and simulation of a tunnel structure reaction to the blast produced by hydrogen storage tank rupture in a fire jointly with Task 3.3.

Validation of the model will be performed using experimental data from rupture tests provided by HSE in Task 4.4.1. The HSE tests will investigate the effect of turbulence generation from structural elements (e.g. ventilation ducts, bulkheads) on blast decay.

The problem formulation will start with the model parameters of the numerical programme mesh and elements as per experiments to be performed.

Initial and boundary conditioned to be defined as per HSE tests:

a. Tunnel dimensions: 70 m length, 3.7 m diameter.
b. Tank inventory: volume 36/60 L, pressure 700 bar.
c. Presence of structural elements in the tunnel: ventilation ducts and/or bulkheads.
d. Format of the CFD input data for the one-way coupling.

The model employed for this study is planned to be the same as per pre-test simulations and parametric study described in section 4.13.

Two simulations will be performed: the first will be with the presence of structural element(s), the second will be with an empty tunnel.

Upon completion of the experimental programme in M30 the CFD study will be performed and the results will be provided to DTU as CFD input for the FEM analysis of structural response of steel elements in tunnel to thermal and pressure loads following confined space accident.

Final results and conclusions for recommendations will be prepared based on the outcomes of numerical and experimental programmes.

4.16 Simulations of flame acceleration and transition to detonation in tunnel structures (4.3, USN)

4.16.1 Objectives

The objective of this task is to simulate flame acceleration and DDT in release scenarios of hydrogen from a train in a tunnel. The narrow gap between train and tunnel ceiling in addition to a moving train can cause a combustible hydrogen-air mixture and lead to severe explosion. The outcome of the simulation work will be a method for simulating flame acceleration and DDT in such scenarios, including the effect of a moving wall and concentration gradients.

The simulations performed will identify the effect of train velocity on flame acceleration in a homogenous and in-homogeneous hydrogen mixture.

Another outcome can be design parameters for TPRD on trains in tunnels.

4.16.2 CFD method

The CFD method that will be used in this work is a USN in-house code for flame acceleration, detonations, and shock waves. The code is based on the centred total variation diminishing (TVD) scheme, fluid dynamic incinerator code (FLIC) and includes combustion models for turbulent flames and chemical kinetics and viscous stresses. The code has been used in simulations of flame acceleration, DDT, detonation propagation, blast waves and shock-flow interactions.

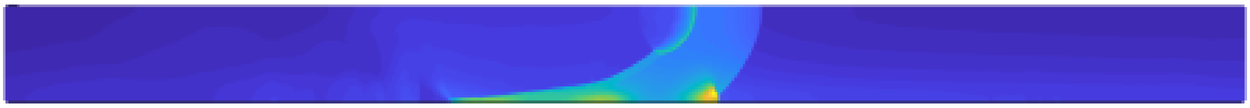


Figure 13. Simulation of DDT in inhomogeneous hydrogen-air cloud (pressure field) using the USN in-house code

4.16.3 Simulations to be performed

The simulations to be conducted in this work will show the effect of concentration gradients and a moving wall. A typical train velocity can be up to 55 m/s through a tunnel leading to a strained flow field in the gaps between train and tunnel walls. A typical height between train roof and tunnel ceiling is 0.5 m for standard tunnel and train sizes.

From the simulations, flow velocity, pressure, density and reaction variables are calculated for the whole domain. The results will show pressure build-up, and flame speed due to the propagating flame and possible DDT events. To ensure sufficient spatial resolution, 2D simulations of the domain above the train will be done. Simulating DDT requires mesh sizes below 1 mm, preferably much smaller. The simulated walls will be simplified to smooth boundaries to be able to identify the effect of train movement and concentration gradients.

There are no experiments planned in HyTunnel-CS for validating these simulations, however there are existing experiments for flame acceleration and DDT in concentration gradients that can be used. For moving walls, there are no existing experiments.

The simulations performed will identify the effect of train velocity on flame acceleration in a homogenous and in-homogeneous hydrogen mixture (Table 6).

Table 6. Matrix of planned simulations

Simulation No.	Description
1	Homogeneous 30% hydrogen mixture, stationary wall
2	Homogeneous 30% hydrogen mixture, moving wall 20 m/s
3	Homogeneous 30% hydrogen mixture, moving wall 50 m/s
4	Inhomogeneous 30% average hydrogen mixture, stationary wall
5	Inhomogeneous 30% average hydrogen mixture, moving wall 50 m/s

4.17 Blast wave and fireball of tank rupture in tunnel: Demonstrations of car tank failure in fire experiments in two real tunnels (4.4.1, CEA)

4.17.1 Introduction

This task is focused on the tunnel issue. The matrix in Table 7 presents a list of seven relevant tests (ID N°7, 8, 9A, 9B, 10, 11, 12).

A preliminary characterization and validation of the instruments, measurements and tunnel parameters is made in sub-task 3.4-5 (ex. dispersion under inert gas, ventilation, fire) to ensure a good results exploitation.

CEA will adopt a progressive approach to limit the impact on the tests facilities (tunnel, instrumentation). Calculation and pre-tests will be conducted before to consider the safety and the integrity of the facilities.

Table 7. Matrix tests of blast wave and fireball of tank rupture

Test N°	Description	Gas	Pressure [bar]	TPRD	Vehicle	Ventilation	Goal / Comments	Priority
7	Tank explosion / Gas sensitivity (1), Characterization with non-flammable gas	N_2, He	P_1	N	N	N	Check that the impact is independent of the gas nature (mechanical energy only)	1
8	Tank explosion / Gas sensitivity (2), Characterization with flammable gas	H_2	P_1	N	N	N	Tank explosion on fire without TPRD without obstacle (medium pressure) Evaluate the effect of H_2 combustion on the blast wave strength (tests 7 and 8)	1
9A	Tank explosion, similarity (Test 7 or 8 at high P)	N_2, He (H_2)	P_2 > P_1	N	N	N	(A) High pressure tank explosion Tests validation by similarity, check the scalability	1
9B	Tank non-explosion	N_2, He (H_2)	P_2 > P_1	N	N	N	(B) Test on leak no burst technology	1
10	Tank explosion – Vehicle effect	N_2, He	P_2 > P_1	N	Y	N	Tank explosion on fire without TPRD on encountering an obstacle Quantify the energy absorbed by the vehicle	1
11	Tank explosion – Vehicle effect	N_2, He	P_2 > P_1	N	Y	N	Quantify the energy absorbed by the vehicle in configuration Tank under vehicle, and returned vehicle	2
12	H_2 dispersion with delayed ignition (following test 2)	H_2		Y	N	Y	Unconfined vapour cloud explosion (UVCE) without fire (no ignition of the jet) in ventilated tunnel, following test 2. Representative an inadvertent opening of a TPRD	1

4.17.2 Test number 7– Tank explosion / gas sensibility (1/2)

4.17.2.1 Goals

Firstly, the tank explosion is characterized with non-flammable gas to validate the protocol. Then, the aim of this test is to verify that the impact of the explosion is non-dependant to gas nature if only mechanical energy is considered.

4.17.2.2 Operating conditions

During this test, the ventilation of the tunnel is off and no obstacle is present around the vessel. This test is conducted with non-flammable gas like nitrogen or helium.

The study of a reproducible technique for the tank rupture is still in progress. A solution with explosives seems more relevant.

The physical parameters will be measured in the representative area like gas concentration, pressures and heat fluxes.

4.17.3 Test number 8– Tank explosion / gas sensibility (2/2)

4.17.3.1 Goals

This test has two goals. Firstly, this test will check the contribution of the hydrogen compare to the uninflammable gas. If hydrogen does not bring more energy during the explosion, this test will conclude that the impact of the explosion is dependent on the mechanical energy of the tank and not of gas nature. If not, the effects of hydrogen will be considered according to measurements.

4.17.3.2 Operating conditions

During this test, operating condition are the same than TEST N°7. This test is conducted with HYDROGEN. The pressure will depend on facilities and safety consideration.

4.17.4 Test number 9A – Tank explosion / similarity

4.17.4.1 Goals

This test aims to check the laws of similarity. The objective is to demonstrate that the results at medium pressure can be transposed at high pressure.

4.17.4.2 Operating conditions

During this test, the operating conditions are the same as test 7 (or 8 if the Hydrogen impact is demonstrated). Furthermore, the ventilation of the tunnel is off and no obstacle is present around the vessel.

The physical parameters are measured in the representative area: gas concentration, pressures, heat fluxes are the main considering parameters.

4.17.5 Test number 9B – Tank non-explosion

4.17.5.1 Goals

This test aims to compare the conventional technologies with the new technology based on “leak – no burst” principle. The objective is to demonstrate the benefit of this technology.

4.17.5.2 Operating conditions

During this test, the operating conditions are the same as test 9A with Hydrogen. Furthermore, the ventilation of the tunnel is off and no obstacle is present around the vessel.

The physical parameters should be measured in the representative area: gas concentration, pressures and heat fluxes are the main considering parameters.

4.17.6 Test number 10 – Tank explosion / vehicle effect

4.17.6.1 Goals

This test aims to quantify the energy absorbed by the vehicle when the tank is placed under the vehicle. It is assumed that a tank position on the roof is considered in free field.

4.17.6.2 Operating conditions

During this test, the operating conditions are the same as test 9A with non-flammable gas (or hydrogen if necessary). The ventilation of the tunnel is off and as the main difference compare to the previous tests, an obstacle representative of a vehicle is placed above the tank.

The physical parameters should be measured in the representative area: gas concentration, pressures and heat fluxes are the main considering parameters.

4.17.7 Test number 11 – Tank explosion / vehicle effect

4.17.7.1 Goals

This test aims to quantify the energy absorbed by the vehicle when the tank is placed under the vehicle and the vehicle is overturned.

4.17.7.2 Operating conditions

During this test, the operating conditions are the same as test 10 with non-flammable gas (or hydrogen if necessary). The ventilation of the tunnel is off and as the main difference compare to the previous tests, an obstacle representative of a vehicle is placed between the ground and the vessel.

The physical parameters should be measured in the representative area: gas concentration, pressures and heat fluxes are the main considering parameters.

4.18 Blast wave and fireball of tank rupture in tunnel: Experiments utilising the experimental tubular steel “explosion” tunnel (4.4.1, HSE)

4.18.1 Objectives

HSE as part of its contribution to the HyTunnel-CS programme will undertake a series of hydrogen release and explosion tests using its steel tunnel test facility, which is located on its test site at Buxton, Derbyshire, UK. The ***objectives*** of the work are as follows:

- To complete a series of scaled ignited releases of hydrogen from containment simulating the rapid failure of the pressure containment vessel.
- To undertake a series of scaled releases at different orientations in combination with various levels of ventilation.
- To measure the pressure development, heat flux and associated flame speeds following ignition of the released hydrogen.
- To undertake a series of ignited scaled jet releases within the tunnel.
- To undertake a series of scaled jet releases within the tunnel such that a roof layer is formed and subsequently ignited.
- To undertake a bonfire test within the tunnel on a novel pressure vessel designed to leak but not burst.
- To generate from the foregoing test programme experimental data to support further development and validation of relevant physical models and risk assessment tools.

4.18.2 Facility

The experiments will be performed in the HSE test facility which consists of a circular steel tunnel; it is nominally 3.7 m in diameter and comprises 5 sections totalling 70 m in length. The central section is 8 m long and has a wall thickness of 55 mm. The outer sections have a wall thickness of 25 mm and together are approximately 31 metres in length each side of the central section. The central section is able to withstand static pressures up to 3 MPa. The outer sections are able to withstand static pressures up to 1.4 MPa. Both the central and outer sections can withstand higher dynamic pressures of at least 3 MPa resulting from a shock or blast wave travelling along the tunnel. The sections will be aligned with each other to within the manufacturing tolerances and the gaps between sections sealed to prevent any leakage of gas.

For these experiments a hydrogen supply and storage system will be situated immediately outside the central tunnel section and will feed into the tunnel through a suitable piped system. The capacity of the storage vessel will be sufficient to represent the scaled total inventory of the largest capacity inventory being modelled in a fuel cell powered vehicle, i.e. with the capacity to store an appropriate quantity of hydrogen gas at pressures up to 700 bar. In addition single storage vessels failing catastrophically will also be examined using a scaled vessel with a rapid release mechanism.

The facility will be equipped with the following ancillary equipment for the purpose of delivering the desired experimental objectives:

- axial fans
- gas boosters
- hydrogen storage tank
- gas release control system
- sensors
- data acquisition system

There are a total of 80 instrument ports located through the tunnel walls. The ports are located axially at 1.0 m, 2.5 m, 5.0 m, 7.5 m, 10.0 m, 15.0 m, 20.0 m and 25.0 m from the centre-point of the tunnel in both directions with 5 ports being distributed radially at each of the axial locations at 0° (top), +90°, –90°, +135° and –135°. There are a further 20 ports, 10 on each side of the tunnel, having a 25 mm diameter, for cable access allowing flexibility for sensor placement inside and along the tunnel. These will be used for placing sensors along the tunnel to record pressures, temperatures, flame speeds and heat flux levels. Figure 14 below shows the radial distribution of the sensor ports. The axial positions of the ports are shown in Figure 15.

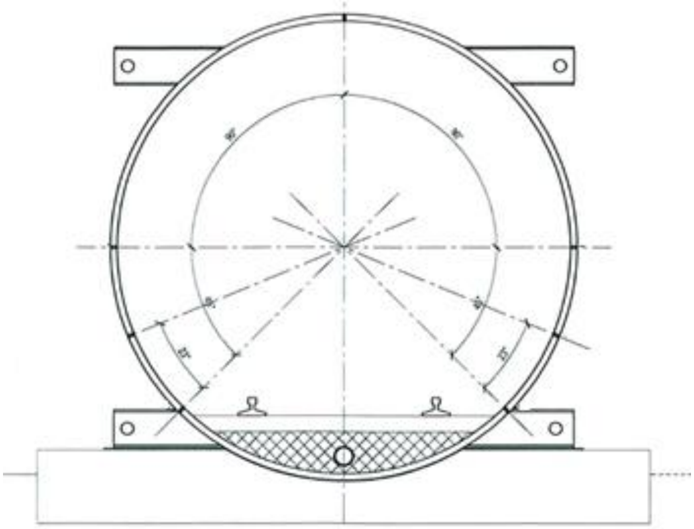


Figure 14. Cross-section of the tunnel showing radial port locations

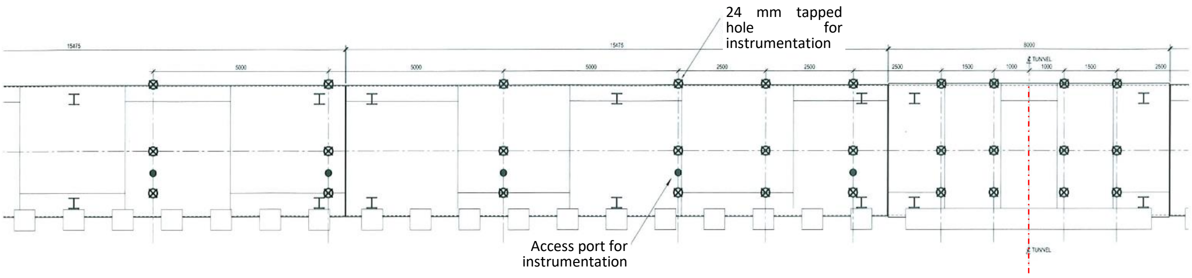


Figure 15. External elevation shows port locations. Port positions are mirrored around centre-line (in red) and on both side elevations

4.18.2.1 Experimental arrangement

One hydrogen gas storage vessel will have a scaled volume equivalent to that of the largest inventory being modelled that is representative of what will be used in practice on future transport vehicles. It will store hydrogen at pressures up to 700 bar. The vessel will incorporate a suitably sized off-take to which nozzles representing the TPRDs being modelled, or an actual TRPD, may be attached. The second smaller vessel will have scaled volumes representing the single storage tanks used on actual vehicles and be equipped with a double bursting disc mechanism to provide a rapid release. The vessels are shown schematically in Figure 16.

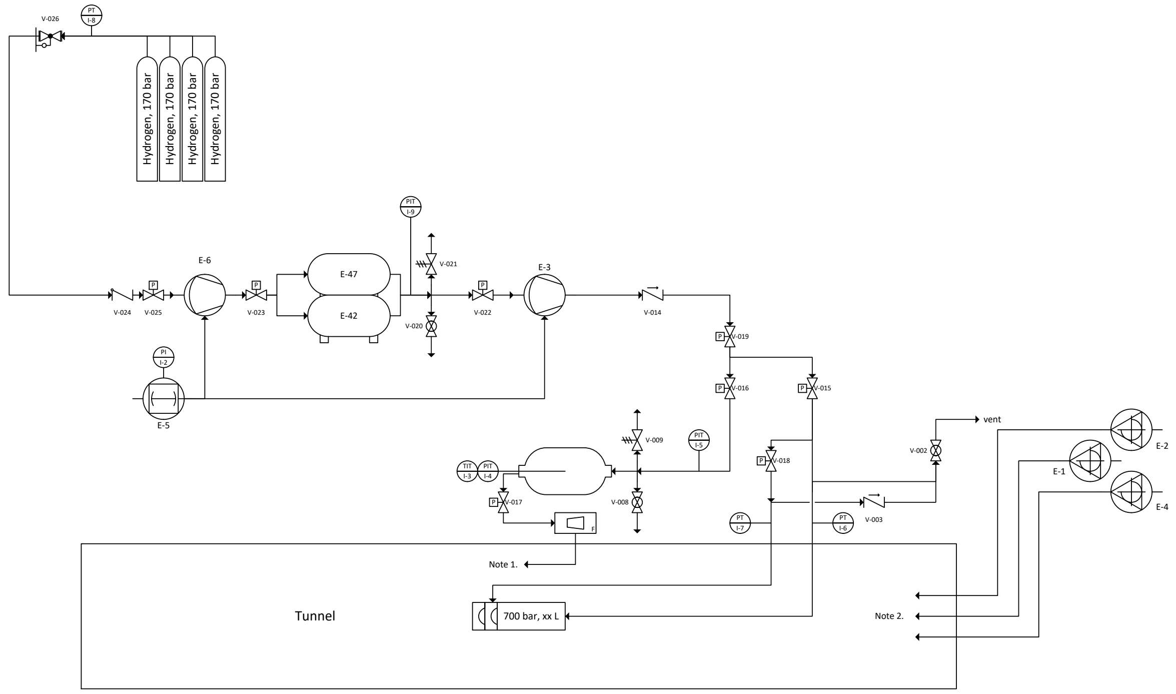


Figure 16. Schematic of proposed hydrogen storage vessel(s) and TPRD off-take

For the proposed experiments a pneumatically driven Haskel Gas Booster will be used to charge hydrogen from a multi-cylinder pack (MCP) at an initial pressure of 170 bar into a 440 litre holding tank at 200 bar from which it will be boosted by another Haskel gas booster up to 700 bar and into the test vessel representing the full inventory. The mass flow rate from this vessel will be measured with a Coriolis flow meter and/or a pressure transducer and thermocouple during the blowdown experiments. The off-take pipework will have a pneumatically operated stop valve to control the flow out of the vessel and through the nozzle. Flow rates up to about 500 g/s are expected to be used. A suitable Kulite pressure transducer will be used to measure the pressure in the test vessel during blowdown. The nozzle will be set in different orientations to represent possible release scenarios, such as vertically upwards or vertically downwards.

The second smaller vessel, with a capacity of no more than 15 litres will model the inventories in a single tank subject to a sudden failure. This vessel will be positioned within the tunnel on the centreline, with the release taking place in a suitable direction, i.e. upwards, downwards or horizontally. The possibility of doubling the vessel volume will also be considered during the experimental design phase.

The existing rail track will be removed from the tunnel and a section of the tunnel around the central area will be concreted to the approximate depth shown in Figure 14; this will provide a secure mounting area for test equipment and some instrumentation. A metal plate may also be secured directly under the vertically downwards pointing jet to act as a spreader plate for the jet during these tests, as well as simulating the tunnel floor.

Variable-speed axial fans will be located at the northern entrance to the tunnel that will be capable of achieving volumetric flow rates up to 1.4×10^5 m^3/h. This equates to a maximum linear air flow velocity of 3.5 m/s. The fans will drive air through a flow straightener and along the tunnel. The airflow along the tunnel will be measured and characterised particularly within the centre section.

4.18.2.2 Scaling Criteria

It is anticipated that three scaled releases will be undertaken, characterised by the quantity released and the time scale of the release. These will represent a blowdown and a catastrophic release from vehicles such as a car, bus or train in a typical full-sized tunnel. The actual representations are suggested in section 4.18.2.5 following a study of the various accident scenarios and will be scaled as described in the following sections, following the method given in the paper by Hall and Walker (Hall and Walker 1997).

4.18.2.2.1 Scaling for steady releases of hydrogen in tunnels

The objective of a scaled experiment is to match the concentration of hydrogen in the downstream flow and the proportion of the tunnel over which the flow is distributed.

Assuming that there is a mixing zone of limited size around the source where the flow is dominated by source momentum. Outside this zone the flow is controlled by the interaction between the buoyant gas and the tunnel flow. In which case it can be shown (Appendix A1) that:- $\mathrm{U} \propto \mathrm{H}^{\frac{1}{2}}$ and $\dot{\mathrm{V}} \propto \mathrm{H}^{\frac{5}{2}}$, where H is the characteristic length scale, and U is the ventilation velocity and $\dot{\mathrm{V}}$ is the volumetric source flow. In addition the mixing zones will be similar if the source momentum flux M scales as $M \propto \mathrm{H}^3$.

The release duration and the inventory are not considered for a steady release.

For example, if we are interested in a car releasing hydrogen at 100 g/s in a tunnel of diameter 7.6 m (e.g. Channel Tunnel) with an air flow of 3 m/s, then for a model tunnel of diameter 3.7 m the gas flow rate should be 16.54 g/s (reduced by a factor of $(7.6/3.7)^{5/2}$) and the air flow should be 2.09 m/s (reduced by a factor of $(7.6/3.7)^{1/2}$).

4.18.2.2.2 Scaling for blowdown releases of hydrogen in tunnels

In the case of a blowdown the ventilation velocity and the volumetric source flow scale as shown previously in 2.4.1, thus:- $\mathrm{U} \propto \mathrm{H}^{\frac{1}{2}}$ and $\dot{\mathrm{V}} \propto \mathrm{H}^{\frac{5}{2}}$. However the mass released and the time of the release scale as follows. According to (1) the mass m scales as $m \propto H^3$ and the time, t of the release scales such that the dimensionless times UT/L are the same thus $t \propto \mathrm{H}^{\frac{1}{2}}$.

In the example given in 2.4.1 this is a reduction to 11.54% of the real mass, and for an actual blowdown lasting say 100 seconds this reduces to 70 seconds.

If the timescale of the blow down process is reasonably long compared with the characteristic time scale for the tunnel flow past the source, then quasi-steady scaling will also give reasonable results. Thus the duration of the release should be similar to the real scale. This implies the inventory, m, should scale as $m \propto H^{\frac{5}{2}}$.

4.18.2.3 Catastrophic releases

In this case the inventory is released in a very short time period compared with the time scale of the flow past the source. The structure of the momentum driven flow will not be greatly affected by tunnel flow, as the resulting cloud will simply be convected downstream. In this case the most appropriate scaling for the total inventory would again be as the cube of the length scale, as shown in (Hall and Walker 1997).

4.18.2.4 Measurements

The hydrogen jet release will be in the form of a highly under-expanded jet characterised by the nozzle diameter and the measured values of the mass flow rate and pressure as measured in the storage vessel. The dispersion characteristics of this jet release are quantified by the similarity laws governing turbulent jet decay. This information will be used to establish approximately the downstream sensor concentration measuring positions.

The releases, both those following a blowdown and those following a sudden release will be ignited following release with both immediate and delayed ignitions being used. Blast pressures, flame speeds, temperatures and heat fluxes will all be measured at suitable locations.

The air flow characteristics for the chosen ventilation flow rates will be measured by obtaining the velocity profiles across the tunnel immediately upstream of the jet release zone, prior to any releases. It may be possible if required for modelling modeling purposes to measure the turbulence intensity near the crown and on the centerline of the tunnel prior to commencing the actual blowdown tests.

A data acquisition system comprising a National Instruments based data logging and processing system, capable of recording up to 64 channels at a rate of 100 Hz, will be used to collect and analyse the data. This system will record at 100 kHz for several seconds when measuring flame speeds and blast pressures.

4.18.2.5 Proposed test programme

Based upon the accident scenario analysis carried out in D1.3 we are proposing the following test programme and for which the rational is also shown:

1. In the case of normal TPRD operation in a fire, it is assumed that the total inventory is released through the TPRD’s. All TPRD’s opening at roughly the same time.
2. In the case of a spurious TPRD operation it is assumed that at least one tank is involved.
3. Only one tank fails catastrophically in a fire due to single TPRD malfunction.
4. A tunnel cross-sectional area is represented by a circle of the equivalent area.

The hydrogen inventories carried by the three different types of vehicle, based on D1.3, are as follows:

1. CAR: Five makes specified, all operating at 700 bar. Tank capacity varies between 115 to156 litres, usually made up from two tanks each of similar capacity. Average capacity 135 litres, containing a mass of 5.4 kg hydrogen. Vent lines specified as between 2 – 4 mm diameter, although 4.2 mm diameter seems to be used in some cases. Vent line is downwards from underneath the vehicle at 135 degrees backward.
2. BUS: Three makes specified, all operating at 350 bar. They use eight tanks, roof mounted, each with a capacity of 200 to 220 litres. Assume an average of 210 litres per tank containing 4.97 kg each of hydrogen, giving a total capacity of about 40 litres. Vent line is upwards from top of vehicle.

3. TRAIN: Only one make specified, manufactured by GE Alstom. They refer to a two carriage unit each with 96 kg of hydrogen operating at 350 bar. Each unit has 24 cylinders each with a capacity of 175 litres containing 4.14 kg of hydrogen. Assume that only one carriage is involved in the fire.
   A three carriage unit is also under consideration for the UK market. This will have a mass of hydrogen of 417 kg at 350 bar pressure, contained in 72 cylinders each with a capacity of 245 litres. Each cylinder contains 5.8 kg of hydrogen and there are 36 cylinders in both the lead and trailing cars. Assume that only one car is involved in the fire, consequently the total inventory per car will be 209 kg.

The cross-sectional areas (area through which vehicles are travelling) of the various types of ROAD tunnels under consideration are as follows:

1. Single lane tunnel: 24.1 m^2. Equivalent diameter D = 5.54 m.
2. Double lane tunnel: 39.5 m^2. Equivalent diameter D = 7.09 m.
3. Gotthard tunnel, double lane: 49.35 m^2. Equivalent diameter D = 7.93 m.
4. Rennsteig tunnel, double lane: 72.95 m^2. Equivalent diameter D = 9.64 m.
5. Tyne tunnel (Original), double lane: 48.1 m^2. Equivalent diameter D = 7.83 m.

The cross-sectional areas (area through which vehicles are travelling) of the various types of RAIL tunnels under consideration are as follows:

1. High speed traffic, two rail: 92 m^2. Equivalent diameter D = 10.82 m.
2. Express traffic tunnel, two rail: 79.2 m^2. Equivalent diameter D = 10.04 m.
3. Metro type traffic, single rail: 44.6 m^2. Equivalent diameter D = 7.54 m.
4. Rectangular section urban rail, two rail: 56.3 m^2. Equivalent diameter D = 8.47 m.
5. Severn tunnel, two rail: 60 m^2. Equivalent diameter 8.74 m.
6. Channel tunnel single bore, single rail: 53.5 m^2. Equivalent diameter D = 8.25 m.

HSE test tunnel

Radius = 1.85 m.

Depth of ballast = 0.45 m.

Area of segment containing ballast = 0.745 m^2.

Circular area of tunnel (no ballast) = 10.75 m^2.

Area through which vehicles travel = 10.0082 m^2.

Equivalent diameter D_{HSE} = 3.57 m.

Scaling factor (H) for tunnel diameter is: D/D_{HSE}

Scaling factor for mass of hydrogen stored is: H^3

Scaling factor for the mass flow rate is: $H^{5/2}$

Scaling factor for the discharge time is: $H^{1/2}$

Scaling factor for the airflow in the tunnel is: $H^{1/2}$.

Based on the previous average scaling factors for the various tunnel types (all tunnels, double bore only) can be obtained, then used to establish the scaled inventories for a car, bus and train in the relevant tunnels for both continuous and catastrophic releases as shown in Table 8.

Table 8. Averaged scaled inventory representing different vehicles in tunnels (Values shown in red are those to be used for the actual modelling exercise)

		Total Inventory	Single Tank Inventory	Average scaling Factor	Average % Mass Reduction	Scaled Total Inventory	Scaled Inventory Single Tank
CAR 700 bar	All Tunnels	5,4 kg	2.7 kg	2.13	10.35	0.56 kg	0.28 kg
CAR 700 bar	Double bore only	5.4 kg	2.7 kg	2.275	8.49	0.46 kg	0,23 kg
BUS 350 bar	All Tunnels	40.0 kg	4.97 kg	2.13	10.35	4,14 kg	0.51 kg
BUS 350 bar	Double bore only	40.0 kg	4.97 kg	2.275	8.49	3.40 kg	0.42 kg
TRAIN 350 bar	All Tunnels	96.0 kg 209.0 kg	4.14 kg 5.80 kg	2.513	6.30	6.05 kg 13.17 kg	0.26 kg 0.37 kg
TRAIN 350 bar	Double bore only	96.0 kg 209.0 kg	4.14kg 5.80kg	2.665	5.28	5.07 kg 11.04 kg	0.22 kg 0.31 kg

It is proposed that commercially available off-the-shelf cylinders are used to provide the necessary gas storage. Assuming that a 700 bar, 53 litre capacity vessel specifically for hydrogen is to be used then scaled vessel inventories, capacities, orifice diameters and mass flow rates can be calculated using the suite of programmes given in: https://elab-prod.iket.kit.edu/. We therefore obtain the scaled values shown in Table 9 using 1 or 3 vessels.

Table 9. Scaled inventory values

	Total Inventory (kg)	Pressure (bar)	Tank Volume (litres)	Single Tank Inventory (kg)	Pressure (bar)	Tank Volume (litres)
CAR	0.46	700	12	0.23	700	6
BUS	3.40	350	145	0.42	350	18
TRAIN	5.07	350	215	0.22	350	10
CAR	0.46	118	53	0.23	300	11
BUS	3.40	310	159	0.42	700	11
TRAIN	5.07	510	159	0.22	290	11

The orifice sizes were calculated for the total inventory contained on a car, bus and train as shown in Table 10. From the literature typical TPRD orifice sizes are 2.2, 3.3 & 4.4 mm diameter, in addition a car has two tanks, bus eight and train twenty-four tanks. In a fire it is assumed that the total inventories are discharged with all TPRD's open at the same time. The equivalent orifice sizes are shown in Table 10.

Table 10. TPRD equivalent diameters

Orifice Dia. (mm) Single TPRD	Car: Two TPRD's Equivalent diameter	Bus: 8 TPRD's Equivalent diameter	Train: 24 TPRD's Equivalent diameter
2.2 mm	3.1 mm	6.27 mm	10.78 mm
3.3 mm	4.67 mm	9.38 mm	16.17 mm
4.2 mm	5.94 mm	11.88 mm	20.57 mm

Using the above equivalent diameters the initial mass flow rates and discharge times (to choke point) are obtained for the actual full size inventories as shown in Table 11.

Table 11. Initial mass flow rates and discharge times

	Total Inventory (kg)	**Initial mass flow rates (kg/s)	Discharge times (secs)	^^Scaled total inventory (kg)	Scaled initial mass flow rates (kg/s)	^Scaled discharge times (secs)	*Scaled orifice diameters (mm)
CAR 700 bar	5.4	0.257 0.584 0.946	141 63 38	0.46 (12)	0.033 0.075 0.121	93 (84) 42 (39) 25 (23)	1.1 1.7 2.2
BUS 350 bar	40.0	0.591 1.32 2.12	370 165 103	3.40 (145)	0.076 0.169 0.272	245 (236) 109 (108) 68 (68)	2.3 3.4 4.3
TRAIN 350 bar	96.0	1.75 3.93 6.36	305 133 83	5.07 (215)	0.151 0.339 0.549	187 (183) 81 (81) 51 (50)	3.2 4.8 6.1

***The three values shown are for the three orifice sizes used.*

**These are the orifice diameters needed to give the correct scaled initial mass flow rates.*

^The values in brackets are those obtained from the model simulations corresponding to the scaled mass flow rates and orifice diameters.

^^Numbers in brackets are the volumes in litres required for the inventory.

Note: The approach is equally valid for orifice sizes other than those used here.

If using standard 53 litre size cylinders then we can model the foregoing values using different pressures but fixed volumes to give the same initial mass flow rates as shown in Table 12.

Table 12. Scaled initial mass flow rates for given parameters

	Scaled total inventory (kg)	Scaled initial mass flow rates (kg/s)	Discharge times (sec)	Scaled orifice diameters used (mm)
CAR 118 bar	0.46 (53)	0.033 0.075 0.121	56 (93) 25 (42) 15 (25)	2.5 3.7 4.7
BUS 310 bar	3.40 (159)	0.076 0.169 0.272	231 (245) 110 (109) 66 (68)	2.4 3.5 4.5
TRAIN 510 bar	5.07 (159)	0.151 0.339 0.549	205 (187) 93 (81) 55 (51)	2.7 4.0 5.2

As an example of this scaling approach if consider the results for the three orifice sizes used in the case of a car then plotting the three pairs of mass flow rates against scaled time shows that they are identical except for the final few seconds, but by this time the vast majority of the inventory has been released (see Figure 17).

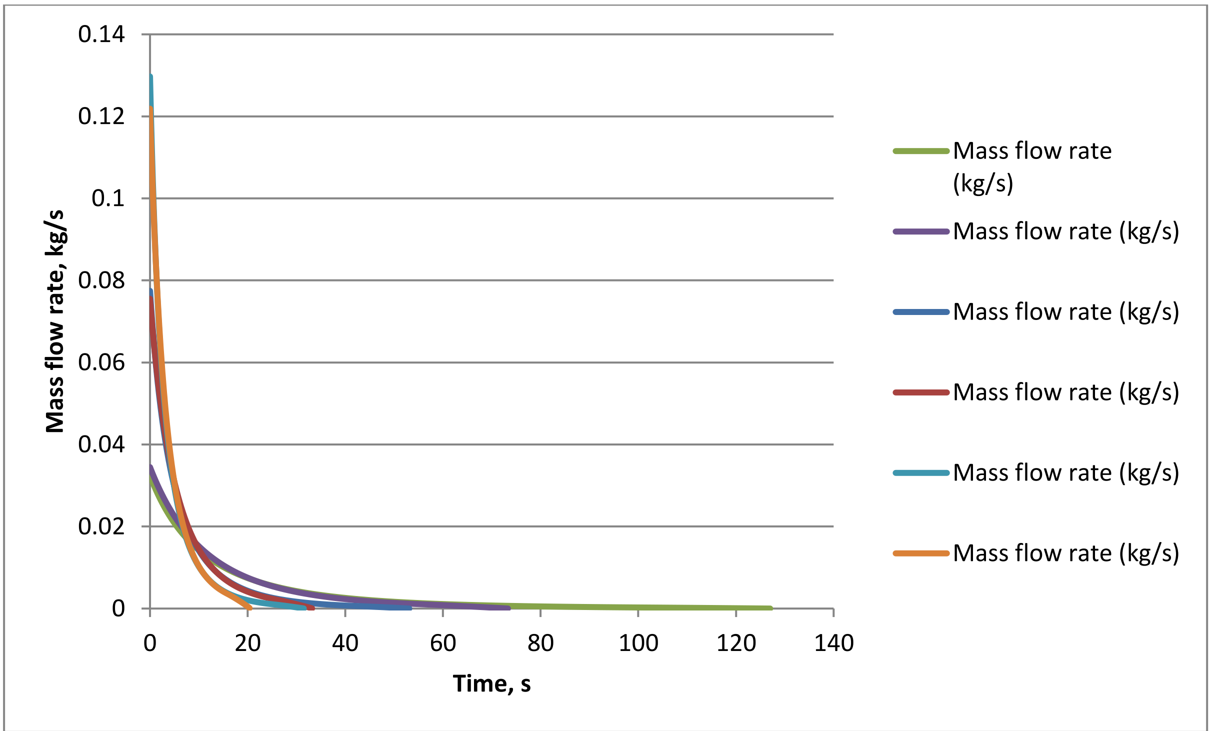


Figure 17. Mass flow rates from scaled TPRDs compared with full scale releases

4.18.2.6 Scaling of airflow in HSE tunnel

D1.2 HyTunnel-CS (2019) makes recommendations for maximum required ventilation velocity in actual tunnels. This is deemed to be 3.5 m/s based on physiological and fire-fighting requirements. D1.3 HyTunnel-CS (2019) has therefore recommended a range of actual tunnel ventilation velocities for study of 1, 2, 3.5 and 5 m/s. These values correspond to actual full-scale tunnel velocities and, according to the scaling rules which are being adopted, should be modified in line with the HSE tunnel being studied. Applying the velocity scaling factor given previously gives the reduced velocities shown in Table 13.

Table 13. Scaled ventilation velocities in HSE tunnel

Actual tunnel ventilation velocity (m/s)	**HSE ventilation velocity (m/s)**	
	Scale factor 2.275	Scale factor 2.665
1	0.66	0.61
2	1.33	1.22
3.5	2.32	2.14
5	3.31	3.06

4.18.3 Test Matrix

4.18.3.1 Blast wave and fireball of hydrogen tank rupture in a tunnel (4.4.1)

Two types of release are proposed namely, blowdown of full inventory and catastrophic releases from single tank.

Blowdown releases

Based on the foregoing analysis it is proposed to examine combinations taken from three orifice sizes, two ventilation rates and two jet orientations for the three scaled inventories shown. This gives the following test matrix of 36 possible combinations, from which 12 tests will be chosen in consultation with the other contributors. All of the releases will be ignited using an appropriate ignition mechanism. All of the releases will be approximately halfway along the tunnel, in the stronger central section. There will not be any obstructions present, however this will be reviewed during the experimental design phase and the inclusion of scaled vehicles considered.

Table 14. Proposed matrix of tests

Hydrogen Quantity (kg)	0.45											
Orifice diameters (mm)	2.5				3.7				4.7			
Velocities (m/s)	1.0		2.5		1.0		2.5		1.0		2.5	
Jet direction	U	D	U	D	U	D	U	D	U	D	U	D
Hydrogen Quantity (kg)	3.40											
Orifice diameters (mm)	2.4				3.5				4.5			
Velocities	1.0		2.5		1.0		2.5		1.0		2.5	

(m/s)												
Jet direction	U	D	U	D	U	D	U	D	U	D	U	D
Hydrogen Quantity (kg)	5.07											
Orifice diameters (mm)	2.7				4.0				5.2			
Velocities (m/s)	1.0		2.5		1.0		2.5		1.0		2.5	
Jet direction	U	D	U	D	U	D	U	D	U	D	U	D

Catastrophic releases

In these cases the inventories being released will be those shown in the second column of Table 15, namely: 0.23 kg (car), 0.42 kg (bus), 0.22 kg (train). It is proposed to undertake up to 12 releases using various combinations of orientation, pressure and tunnel air velocity. The possibility of some of these modelling a release from underneath a car will be considered. It is expected that all of these will ignite upon release or will be ignited by a suitable source. The scaled mechanical energy for these releases is shown in Table 15.

Table 15. Scaled mechanical energy

	Single Tank Inventory (kg)	Pressure (bar)	Tank Volume (litres)	Mechanical energy Brode (kJ)	TNT equivalence (kg)
CAR	0.23	700	6	1024	0.22
BUS	0.42	350	18	1536	0.33
TRAIN	0.22	350	10	853	0.19
CAR	0.23	300	11	804	0.17
BUS	0.42	700	11	1878	0.41
TRAIN	0.22	290	11	778	0.17

The final three rows represent the equivalent conditions if using a fixed volume of in this case 11 litres.

4.18.4 Overpressure during spurious release of TPRD (4.4.2)

This test series considers release from a single vessel through the TPRD followed by ignition. The tests will therefore be undertaken using either a single 53 litre vessel or the 15 litre vessel suitably modified. The final selection of the test parameters will be made during the experimental design phase in conjunction with HSE's partners prior to beginning the test programme. Up to six tests will be undertaken. All the releases will be ignited using an appropriate ignition source. The exact location of the ignition source will be agreed after further consultation with the HSE's work package partners. Initially the releases will be made in the presence of the ignition source (instantaneous ignition). The six tests will then be repeated with the ignition being delayed by a specified time period (delayed ignition) of several seconds. In all cases the blast wave pressure and flame speeds will be measured following ignition. Comparisons between the two data sets will form the basis of the output from this sub-task.

4.18.5 Deflagration of non-uniform cloud in a tunnel (4.4.3)

HSE will undertake six scaled jet releases in the crown of the tunnel starting with a storage pressure of 700 bar and letting the vessel blowdown. The six tests will be the same as those specified for sub-task 4.4.2, see above. In order to create a flammable roof layer the jet releases will be made into a tube running for some three-four metres along the tunnel crown. This tube will contain baffles and a series of holes along its length, its purpose being to rapidly reduce the momentum of the jet, thus limiting the rate of air entrainment to a level that will allow a flammable roof layer to form.

The concentration profile will be measured at three downstream positions along the tunnel axis before the mixture is ignited (delayed ignition). The resultant blast pressure and flame speed will be measured along the tunnel as previously specified.

Table 16. Proposed matrix of tests to be carried out at HSE Buxton

Hydrogen Quantity (kg)	*quantities to be decided following work in sub-task 4.4.2 (up to 6 variables in combination)*					
Ventilation Flow Rate (m/s)						
Without bulkhead	1	2	3	4	5	6
With bulkhead	7	8	9	10	11	12

The six tests will be repeated with a bulkhead(s) placed in a suitable downstream location. The purpose of which is to examine the effect of the bulkhead in creating additional turbulence which may increase the propensity for a DDT to occur.

4.18.6 Expected Results

Blast pressures, flame speeds, temperatures and heat fluxes along the tunnel will be obtained for the various test conditions proposed. These are the three scaled vessel blowdowns, nozzle orientations and sizes, and the ventilation flow velocities. In addition similar data will be obtained for the sudden releases. A detailed report presenting the results and their analysis will be provided following the conclusion of the experimental programme. The timeline for the programme is detailed in Table 17.

Table 17. Timeline of pre-test and experimental delivery activities

Delivery timeline	Due date	Report at Project Meeting (PM)
(1) Confirm test programme in discussion with partners.	M10	3rd PM - Feb '20 (M12)
(2) Complete design, build and commissioning of test facility.	M18	4th PM - Sep '20 (M19)
(3) Commence test programme.	M19	5th PM - Feb '21 (M24)

(4) Final results and conclusions for recommendations.	M24	6th PM - Sep '21 (M31)

4.19 Deflagration of non-uniform cloud in a tunnel: Experiments on deflagration of non-uniform hydrogen-air cloud created by release in mock-up tunnel sections (4.4.3, PS)

4.19.1 Objectives

The aim of the experiment is to investigate the deflagration of a stratified hydrogen-air mixture in tunnel-like structure with a rectangular cross section.

4.19.2 Facility

The tests will be performed in H110 (A1) vessel of HYKA, as shown in Figure 18. The safety vessel H110 has main dimensions of 3.5 m internal dimension and 12 m length with a volume of 100 m^3 and a design pressure of 100 bar. The vessel is used as a safety vessel. A rectangular sub-compartment of 9 x 3 x 0.6 m^3 will be used to study a combustion and detonation in a horizontal semi-confined layer of hydrogen air mixture, Figure 18 right. The safety vessel is equipped with measuring ports and windows for visual observations. A special gas-filling system allows for the creation of a layer of hydrogen-air mixtures with a linear vertical concentration gradient from 0.1 to 1.1 % H_2/cm. The measuring system for combustion detection consists of an array of thermocouples (flame arrival time); fast pressure gauges (combustion pressure and shock wave); photodiodes and ion probes (flame arrival time, flame speed). The data acquisition system is based on multi-channel (64) ADC with a sampling rate of 1 MHz.

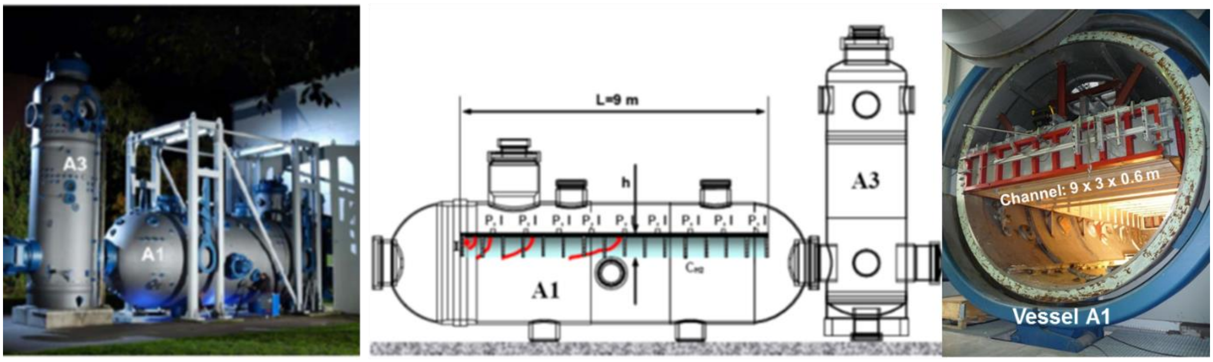


Figure 18. Test facility H110 (A1) of HYKA with large scale rectangular combustion channel 9 x 3 x 0.6 m^3, open from below

The mixture with concentration gradient will be created as a thin layer under the ceiling by a special gas injection system. The no uniform H_2-layer is quantified with a specific maximum H_2-concentration on the top and a concentration slope of 0.3 or 0.6% H_2/cm. In case of uniform H_2 layers the open from below side of combustion channel will be separated with a thin foil. The layer high is 60 cm. The separation foil will be cut short before ignition. The ignition will be performed in a special perforated tube which acts as line igniter.

4.19.3 Test matrix

The tests of deflagration of non-uniform hydrogen-air cloud in a tunnel will be performed in the facility of H110 (A1) of HYKA in large scale rectangular unobstructed combustion channel 9 x 3 x 0.6 m^3, open from below. The designed test cases are summarized in Table 18. The Test matrix includes tests which were performed in the past, the results will be provided for the project.

Table 18. Test matrix of non-uniform hydrogen-air cloud in a tunnel

	grad (H_2) 0.0%/cm uniform mixture layer high 60 cm	grad (H_2) 0.3%/cm mixture with concentration gradient	grad (H_2) 0.6%/cm mixture with concentration gradient
Maximum H_2 concentration on the ceiling	15	15	18
Maximum H_2 concentration on the ceiling	20	20	22,5
Maximum H_2 concentration on the ceiling	23	25	30
Maximum H_2 concentration on the ceiling		29	34

4.19.4 Measurement

To measure the flame propagation in 2D geometry the rectangular combustion channel will be equipped with 9 fast pressure gauges (PCB) for combustion pressure and an array of ion probes for detection of the flame arrival time.

4.19.5 Results

The investigation of the deflagration of stratified hydrogen-air mixture in tunnel-like structure with a rectangular cross section gives a data base for simulation and a comparison with deflagration of stratified hydrogen-air mixtures in tunnel-like structures with a semi-spherical cross section.

4.20 Tests on flame propagation through a layer of fire extinguishing foam filled in by flammable hydrogen-air mixtures (4.4.4, PS)

4.20.1 Objectives

The aim of the experiment is to demonstrate the interaction of fire extinguishing foam with H_2. Can the foam be enrich with H_2 and become burnable and what is the behaviour of flame propagation?

4.20.2 Facility

After the development of a method to enrich fire extinguishing foam with a well-defined H_2/air mixture, the behaviour of flame propagation will be investigated. Medium-scale tests on flame propagation through a layer of fire extinguishing foam of different properties will be performed. A rectangular reservoir H x W x L = 0.3 x 0.5 x 2 m open on the top will be used as combustion channel. The channel will be filled with burnable foam and ignited using hot a surface or a pilot flame. Test matrix

Foam density should be uniform and constant. The variables are the H_2 concentration and the height of the foam layer. The test matrix is shown in Table 19.

Table 19. Test matrix of water foam effect on hydrogen combustion and DDT

Foam layer thickness, m	0.1	0.2	0.3
15 % vol H_2	1	4	7
20 % vol H_2	2	5	8
25 % vol H_2	3	6	9

4.20.3 Measurement

An optical high-speed camera will be used to record the combustion process on the foam surface. Optionally an array of thermocouples will be used to observe the flame propagation inside the foam.

4.20.4 Results

The questions: can fire extinguishing foam can be enriched with H_2 and will it become burnable will be answered, as well as what combustion behaviour can be expected.

4.21 Tests on effect of water sprays and mist systems on combustion and DDT (4.4.4, PS)

4.21.1 Objectives

The aim of the experiment is to testify the suppression effect of water injection on the combustion of premixed hydrogen-air mixture.

4.21.2 Facility

The tests will be performed in H110 (A1) vessel of HYKA. The description refers to section 3.1.2. The half-length of the rectangular combustion channel 9 x 3 x 0.6 m^3 will be equipped with a water spray system. The water spray system will be characterized by the design of the release nozzle and the water supply pressure. The final selection of the nozzle design is in process. The test will be performed with uniform H_2 layers. The open from below side of combustion channel will be separated with a thin foil. The layer high is 60 cm. The separation foil will be cut short before ignition. The ignition will be performed in a special perforated tube which acts as line igniter. The flame propagates first the half channel in dry atmosphere and enters the water spray section after 4.5 m, Figure 19.

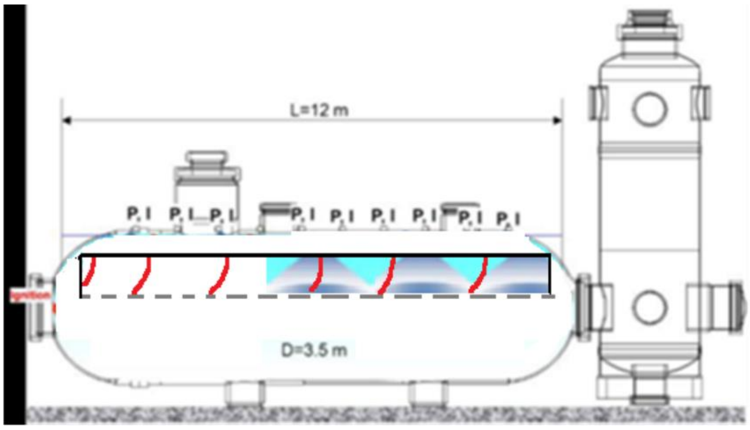


Figure 19. Test facility H110 (A1) of HYKA with large scale rectangular combustion channel 9 x 3 x 0.6 m³ and section with water spray

4.21.3 Test matrix

The premixed hydrogen-air mixture fills in a rectangular domain H x W x L = 0.6 x 3 x 9 m. The spray zone is 4.5 m long. The combustions with different hydrogen concentrations will be observed and measured with or without obstacles and with or without spray. The test matrix is shown in Table 20.

Table 20. Test matrix of water injection effect on hydrogen combustion and DDT

With obstacles	No (deflagration)		Yes (fast flame or DDT)	
With spray	no	yes	no	yes
15 % vol H_2	1	4	7	10
20 % vol H_2	2	5	8	11
23 % vol H_2	3	6	9	12

4.21.4 Measurement

To measure the flame propagation in 2D geometry an array of sensors is necessary. The rectangular combustion channel will be equipped with 9 fast pressure gauges (PCB) for combustion pressure and an array of ion probes for detection of the flame arrival time will be placed in the dry section. Optionally "one time use" cameras or light detectors will be used in the wet zone.

4.21.5 Results

Suppression efficiency of water injection on hydrogen deflagration and fast flame or detonation will be proven by the tests.

4.22 Effect of droplet size on mitigation of combustion and DDT (4.4.4, USN)

4.22.1 Introduction / background / motivation

In the literature, the availability of data on fire water spray is limited. Often the spray is described only by the orifice diameter of the fire water nozzles and spray angle. However, the flow properties of the spray (i.e., size and velocity distribution of the droplets) are known to influence the suppression efficiency. Small droplets will follow the gas flow, evaporate quickly, cool the fire gases and screen for heat radiation. In contrast, large droplets have high momentum and are more likely to reach the source of the fire and to cool objects such as process equipment and pipes. In explosion mitigation, the sizes of the droplets are important where small droplets can contribute to extinction and the large droplets have a high inertia and can reduce the local gas velocities (Bjerketvedt and Bjørkhaug 1991, Thomas 2000). Increased turbulence can also have an effect. Thus, to evaluate the efficiency of a water spray system it is necessary to know the size and velocity distribution of the droplets.

4.22.2 Specific objectives and expected outcomes

In a gas fire/explosion system, water spray will have an effect. The droplet size distribution and velocity of the water in the spray will determine the extinguishing/mitigation parameter. It is expected to get detailed information of the droplet sizes for different water sprays.

4.22.3 Knowledge gaps and accident scenarios assessed

- Foam and water spray/mist system effect on premixed combustion and DDT
- Shock wave attenuation by water and mist systems, absorbing materials, soft bulkheads, sacrificial pre-evacuated volumes
- Comparison of efficiency of cheaper water spray systems with more expensive water mist systems

4.22.4 Sinergy with WP4 and other HyTunnel-CS activities

This work package will produce the input parameters for the sub-tasks 4.4.4 activity 4.4-7, 4.4-10.

4.22.5 Detailed specification

4.22.5.1 Conceptual design

To find the droplet size distribution and velocity of the spray an established test rig will be used. The rig contains a water recirculation system with one water spray nozzle. It also contains a shadow-imaging system to determine the droplet size distribution and velocity.

4.22.5.2 Instrumentation

The shadow-imaging system contains a high-speed camera, laser, high-magnification lens and synchronization software.

High speed-camera: Photron SA-Z, Up to 20 000 fps at full resolution.

Laser: Photonics Industries DM60-523. Dual head diode pumped high repetition YAG laser with up to 30 kHz per cavity.

High-magnification lens: Questar QM-1. Narrow focus depth to produce sharp images of droplets in the focus plane.

Synchronization software: LaVision Davis or in-house image processing software.

4.22.5.3 Infrastructure

The equipment is stationary, but it can be moved.

4.22.5.4 Key resource

High-speed laser is crucial to preform experiments.

4.22.6 Anticipated range/number of tests that can be undertaken

20 days in the lab is required for the first nozzle for complete characterization of spray. Next nozzles can be performed faster.

4.22.6.1 Constraints (noise, pressure, site availability)

The rig is designed for single nozzle tests. In Figure 20 the pressure diagram for the pump and one general sprinkler nozzle is shown. Other pressurizing equipment can also be used if higher pressures are required.

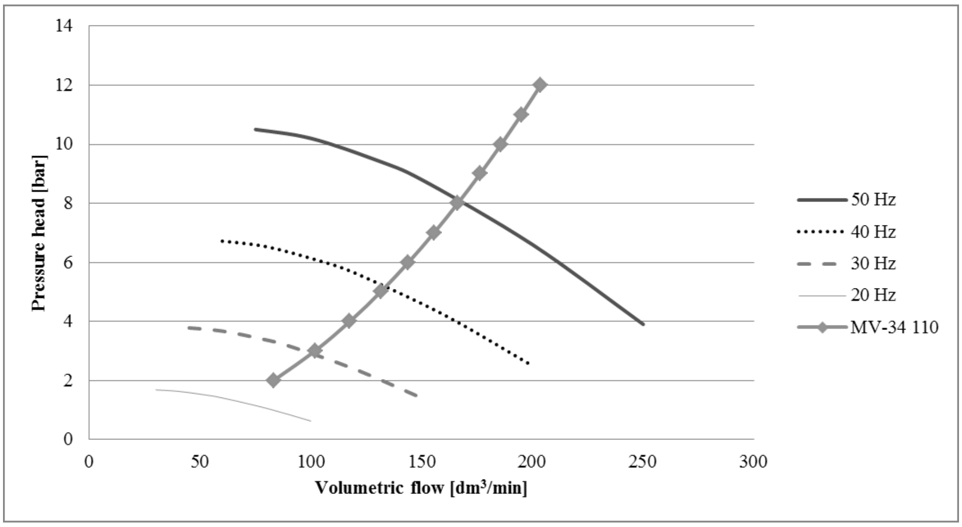


Figure 20. Pressure vs volumetric flow

The rig can be used for mists as well.

The site is available all the year.

4.23 Shock wave attenuation: Tests on tank rupture in a tunnel with shock attenuation material/system (4.4.5, HSE)

HSE will evaluate shock/blast wave attenuation by water spray or mist systems only. A literature survey will be carried out and the findings, alongside data obtained by WP partners KIT from work done in sub-task 4.4.4 and 4.4.5, will be used to establish the most effective water spray or mist system for blast wave mitigation in a confined space. An appropriate system will then be designed and installed in the tunnel. A maximum of six tests will be undertaken choosing the test parameters from the results obtained from sub-task 4.4.1.

4.24 Shock wave attenuation: Experiments on effect of water spray/mist system on shock wave attenuation (4.4.5, PS)

4.24.1 Objectives

The aim of the experiment is to investigate the attenuation effect of water injection on the shock wave of hydrogen detonation.

4.24.2 Facility

The experiments will be performed in the safety vessel V220 (A2), as shown in Figure 21. The safety vessel with an inner diameter of 6 m and a height of 8 m provides a volume of

220 m^3. It is designed for a static overpressure of 11 bar and temperatures up to 150 °C. The vessel is equipped with numbers of vents and ports and windows for optical access. The largest two flanges with an inner diameter of 1890 mm are parallel and located near the ground. Inside the safety vessel a defined H_2-detonation will be initiated. Figure 21 left side shows a sketch of the experimental set-up. A H_2 detonation will be performed in combustion unit with 4 g H_2 provided as stoichiometric H_2/air mixture, Figure 21 centre. The cubical-shaped 4 g H_2 combustion unit (0.5 x 0.5 x 0.5 m) is covert with thin plastic film and produces an unconfined H_2 detonation. Figure 21 right shows the dimensionless pressure in air blast wave versus distance in free field tests. The emitted shock wave will used to investigate the shock wave attenuation by water spray/ mist. The water sprinkler systems utilised is described in D3.1 (HyTunnel-CS, 2019), sub task 3.4.6.

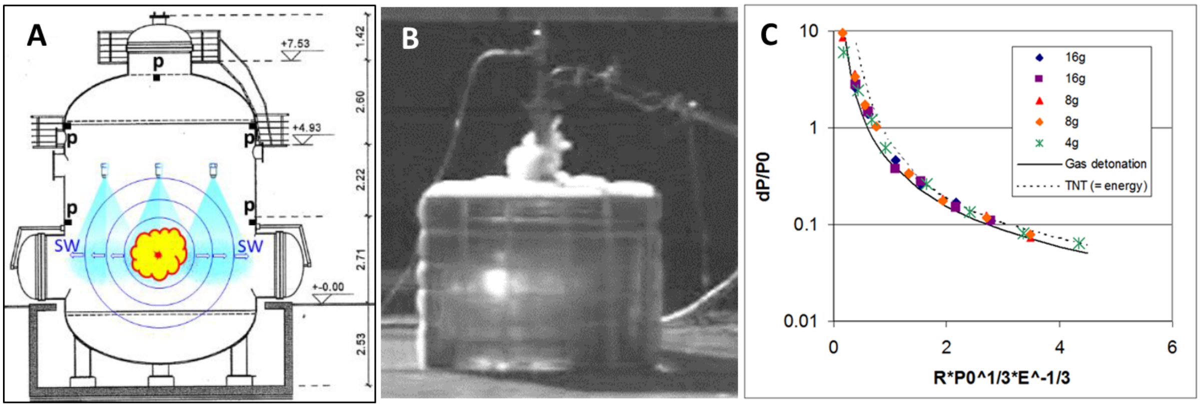


Figure 21. Test facility V220 (A2) of HYKA for attenuation of water spray on hydrogen detonation shock waves. A) Sketch of the set up for suppression tests of water spray on shock waves. B) Combustion unit with 4 g H_2 provided as stoichiometric H_2/air mixture. C) Results of free field tests of combustion units

4.24.3 Test matrix

A stoichiometric hydrogen-air mixture containing 4 g of hydrogen in a region of 0.5 x 0.5 x 0.5 m^3 is ignited. The propagation of shock waves is recorded and measured with or without different water injection configurations. The test matrix is shown in Table 21. The basic test without spray and mist will be repeated twice as a minimum.

Table 21. Test matrix of attenuation of water injection on shock wave of hydrogen detonation

Water mass flow rate, kg/min	0	low	high
Spray	1	2	4
Mist		3	5

4.24.4 Measurement

Fast pressure sensors will use to measure precisely the shock wave history. Additionally, a high-speed camera will be used to record the global interaction of the shock wave with the spray.

4.24.5 Results

The efficiency of water injection to attenuate shock waves gained from H_2 detonation will be concluded based on the experimental data.

4.25 Shock wave attenuation: Tests on shock wave attenuation by using shock absorbing materials, soft bulkheads and sacrificial pre-evacuated volumes (4.4.5, PS)

4.25.1 Objectives

The aim of the experiment is to investigate the attenuation effect of absorbing materials on the shock wave of hydrogen detonation.

4.25.2 Facility

The experiments will be performed in the safety vessel V220 (A2). The experimental set-up is the same as described in 4.24 for the tests without spray or mist. The emitted shock wave from a cubical-shaped 4 g H_2 combustion unit will used to investigate the shock wave attenuation by different absorbing materials. Samples of selected absorbing materials with an area of 1 m^2 will be fixed, at the same level as the combustion tube, on the wall of the safety vessel. Three fast pressure sensors will be placed axially in front of the test samples to measure precisely the history of the arriving and reflected shock waves.

4.25.3 Test matrix

Different absorbing materials with different thickness will be applied to test their attenuation effect of shock wave of hydrogen detonation. The test matrix is shown in Table 22. The final selection of the absorbing materials is in process.

Table 22. Test matrix of absorbing materials' attenuation effect on shock wave

Absorbing material	Polystyrol	Silicon	Rubber
Thickness, 10 cm	1	3	5
Thickness, 20 cm	2	4	6

4.25.4 Measurement

Fast pressure sensors will use to measure precisely the shock wave histories from the reflection on the absorbing materials. Optionally high-speed cameras will be used to record the shock wave reflection behaviour of the tested material.

4.25.5 Results

The efficiency of absorbing materials to attenuate detonation shock wave will be concluded based on the experimental data.

4.26 Safety technology to prevent tank rupture: Development and manufacturing of four leak no burst composite type 4 tanks prototypes for testing in a tunnel fire at CEA and HSE tunnels (4.4.6, UU)

The explosion-free tank developed following Ulster's leak-no-burst (LNB) safety technology aims at preventing the tank explosion hazards and resolving the safety concerns. The technology is described in Ulster's Patent Application (Molkov, Makarov et al. 2019) and it covers the following key points.

- A tank has a load bearing fibre-reinforced polymer (FRP) layer (or intermediate layer), inner liner reducing gas permeation to the regulated level and outer thermal protection layer (TPL) that can be load bearing too.
- The TPL thickness is a function of its thermal properties, the ratio of nominal working pressure (NWP) to initial burst pressure (IBP) in the vessel, and thermal properties of FRP and TPL calibration.
- The TPL thermal conductivity is below that of FRP to provide a failure of the liner, e.g. its melting, before a load-bearing fraction of the FRP wall is degraded to value: α·NWP/IBP, where α - coefficient of pressure increase above NWP.
- Liner melts to leak the gas through walls before rupture.

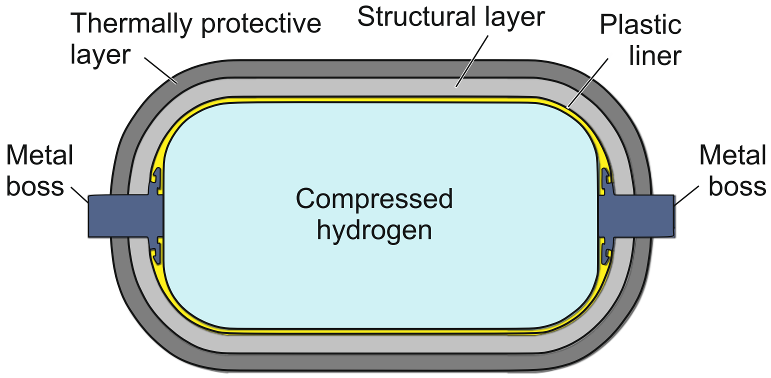


Figure 22. Schematic view of the explosion-free tanks (Molkov, Makarov et al. 2019)

UU is planning to develop the prototype designs based on Type IV tanks of either small volume, i.e. 7.5 L, or a larger volume, 30-60 L. The materials chosen for the prototypes will be high density polyethylene (HDPE) or polyamide (PA) for liner, carbon fibre reinforced polymer (CFRP) of higher thermal conductivity for the intermediate layer and CFRP or basalt fibre reinforced polymer (BFRP) of lower thermal conductivity for the TPL. The designs of the prototypes may have increased wall thickness compared to original, depending on the required temperature gradients across the tank wall when subject to heat.

The testing of LNB tanks will be performed in accordance with Global Technical Regulation No. 13 (GTR#13), Engulfing fire test. The tests should provide thermal insulation of the tanks' bosses. The example of insulation by a metal pipe is given below.

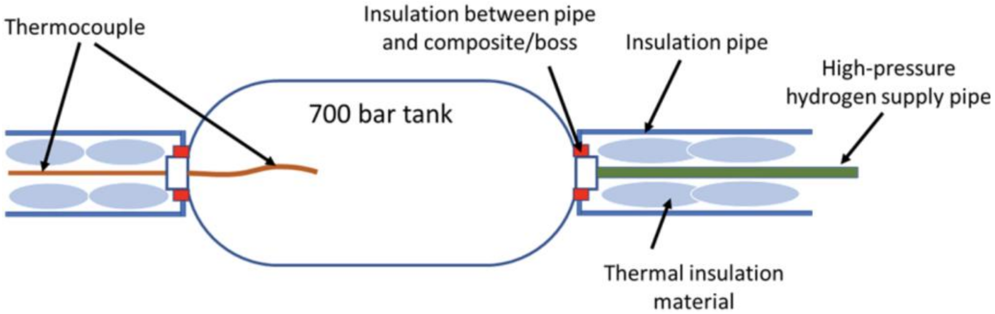


Figure 23. Schematic view of the proposed insulation of bosses

Ulster will advise on the burner design to CEA and HSE for fire tests. The expected heat release rate (HRR) of the fire per square meter of the burner area should be HRR/A=1 MW/m^2 to provide the fire test repeatability, conformity with GTR#13 and reproducible heat input to the tank.

As per description of work (DoW), the prototypes must be tested in CEA and HSE tunnels.

4.26.1 Testing of 2 leak no burst tanks inside CEA tunnel

- Test 1 (inside the tunnel). Leak no burst prototype#1 – stand-alone. Burner sizes 1.65 m * tank width. Burner HRR/A = 1 MW/m^2.
- Test 2 (inside the tunnel). Leak no burst prototype#2 – under car (if possible). Burner sizes 1.65 m * tank width. Burner HRR/A = 1 MW/m^2.

4.26.2 Testing of 2 leak no burst tanks inside HSE tunnel

- Test 3 (inside the tunnel). Leak no burst prototype#3 – stand-alone. Burner sizes 1.65 m x tank width. Burner HRR/A = 1 MW/m^2.
- Test 4 (inside the tunnel). Leak no burst prototype#4 – stand-alone. Burner sizes 1.65 m x tank width. Burner HRR/A = 1 MW/m^2.

4.26.3 Instrumentation requirements and testing outputs

- Pressure and temperature monitoring inside the tanks, temperature under the tank (at 25 mm under tank bottom) in 3 locations, tank positioning distance above the burner/ground.
- Burner dimensions (pipes dimensions, distances between pipes, number of holes in pipes and sizes, distances between holes), fuel flow rate calculated to achieve required HRR/A for each Test, burner positioning distance above the ground, wind shield (if applicable) dimensions and positioning distances. Test requirements as per GTR#13 Engulfing fire test (section 6.2.5.2).
- Tank and burner positioning distances in relation to the facility/tunnel geometry, dimensions of facility/tunnel, ambient temperature, wind speed and direction (sufficient wind shielding should be provided to ensure GTR#13 temperatures under the tank are reproduced).
- Time from fire initiation until leak.
- To account for the worst-case scenario (tank rupture) - measurement of blast wave in the entire tunnel, starting with at distance points, e.g.: 2 m, 5 m, 10 m, 20 m, etc. Measurement of the fireball by thermocouples. Regular video cameras (2), infrared camera, high-speed camera.

4.27 Safety technology to prevent tank rupture: Tests on prototypes of leak no burst composite type 4 tanks at HSE (4.4.6, HSE)

HSE will test two of the four prototypes of leak no burst (LNB) composite type 4 tanks being developed by UU. The tests will be the standard bonfire test specified in GTR13 (DoT 2007) carried out within the confines of the HSE tunnel central section. It is expected that the tank being subjected to a long duration fire will ultimately slowly leak hydrogen out and will not rupture. The pressure inside the tank will be monitored throughout to determine the performance of the LNB tanks. Thus, the efficacy of mitigation measures for controlling tank failure hazards in tunnels will be demonstrated.

4.28 Safety technology to prevent tank rupture: Tests on prototypes of leak no burst composite type 4 tanks at CEA (4.4.6, CEA)

This test is described as test 9A. Before testing, a risk analysis will be done between the manufacturer, by UU, in accordance with safety rules at CEA and owner of the tunnel.

4.28.1 Synopsis

Table 23 sums up and compares the defined tests carry by CEA in the real tunnel.

Table 23. Synopsis and comparison of CEA Tests in real tunnel.

Test No	0	1	2	3	4	5	6	7	8	9A	9B	10	11	12
0	-													
1	Device Control													
2	Jet Fire	Real Dependencies												
3	Jet Fire	Isolate fire properties	-											
4	Jet Fire	Ventilation impact	-	Impact of H2 on fire										
5	Jet Fire	TPRD orientation impact	-	TPRD orientation impact (up)	-									
6	Jet Fire	Second test repeatability	Gas nature	-	Ventilation impact	-								
7	Explosion	Hydrogen could be replaced by N_2 or He?												
8	Explosion	-	-	-	-	-	-	Role of H2						
9A	Explosion	-	-	-	-	-	-	Similarity and scalability	-					
9B	Non Explosion	-	-	-	-	-	-	-	-	Technology effect				
10	Explosion	-	-	-	-	-	-	-	-	-	-			
11	Explosion	-	-	-	-	-	-	-	-	-	Vehicle effect	Vehicle effect		
12	Explosion	Delayed explosion	-	-	-	Delayed explosion	-	-	-	-	-	-	-	

5. Combined delivery timeline for work package

This section aims at providing the overall and combined delivery timeline for all the activities within WP4. The time plan was built according to the partners input or milestone 4.1 contents. The project meetings will be used to monitor and report the progress of the research activities within each task. Therefore, the tables report the future project meetings during which the outcomes of the several activities will be discussed.

5.1.1 Task 4.2 Analytical studies and engineering tools details

Engineering models for assessment of blast wave and fireball of hydrogen tank rupture (UU)	***Due date***	***Report at project meeting (PM)***
(1) Getting numerical results (stand-alone tanks)	M7	
(2) Problem formulation and tool trial implementation	M11	3rd PM - Feb '20 (M12)
(3) Webex with CEA to discuss experimental programme	M8	3rd PM - Feb '20 (M12)
(4) Webex with HSE to discuss experimental programme	M8	3rd PM - Feb '20 (M12)
(5) Model verification against numerical tests	M15	4th PM - Sep '20 (M19)
(6) Getting numerical results (under-vehicle tanks)	M17	4th PM - Sep '20 (M19)
(7) Further verification of the reduced model of blast wave and fireball against simulations (stand-alone/under-car)	M23	5th PM - Feb '21 (M24)
(8) Validation of the reduced model by HyTunnel-CS experimental data	M23	5th PM - Feb '21 (M24)
(9) Final description of a tool for recommendations	M23	5th PM - Feb '21 (M24)
Engineering model for assessment of overpressure during spurious hydrogen release (UU)	***Due date***	***Report at project meeting (PM)***
(1) Problem formulation	M1	
(2) Communication with HSE to define experiments	M8	
(3) Validation of engineering tool against experiments in the open space available in literature (Pressure = 36-400 bar, release diameter = 1-12 mm)	M9	3rd PM - Feb '20 (M12)
(4) Input and discussion of HSE experimental results;	M18	4th PM - Sep '20 (M19)
(5) Validation of reduced model against delayed ignition experiments conducted by HSE in subtask 4.4.2 (Pressure=700 bar, release diameter 0.5-5.0 mm)	M20	5th PM - Feb '21 (M24)
(6) Validation of reduced model against immediate ignition experiments conducted by HSE in subtask 4.4.2 (Pressure=700 bar, release diameter 0.5-5.0 mm)	M20	5th PM - Feb '21 (M24)
(7) Final description of a tool for stakeholders use and compilation of recommendations	M21	5th PM - Feb '21 (M24)
Engineering tool for prevention and mitigation of composite hydrogen storage tank explosion in a fire (UU)	***Due date***	***Report at project meeting (PM)***
(1) Problem formulation (TPRD-tank system)	M1	
(2) Tool implementation	M3	
(3) Validation of a tool by experimental data available in literature	M6	
(4) Parametric study of effect of TPRD diameter and	M15	4th PM - Sep '20 (M19)

time of TPRD initiation on tank rupture		
(5) Final description of a tool for the recommendations	M28	6th PM - Sep '21 (M31)
Correlation for DDT in horizontal and vertical ventilation systems with non-uniform hydrogen-air mixtures in the presence of obstacles (KIT)	***Due date***	***Report at project meeting (PM)***
Completion of the task	M30	7th PM - Feb '22 (M36)
Analytical model for water spray/mist system effect on hydrogen combustion and a shock wave attenuation (KIT)	***Due date***	***Report at project meeting (PM)***
Completion of the task	M36	7th PM - Feb '22 (M36)

5.1.2 Task 4.3 Numerical simulations

Deflagration of non-uniform hydrogen-air cloud created by release in HSE tunnel experiments and PS experiments in Task (CEA)	***Due date***	***Report at project meeting (PM)***
(1) Problem formulation	M18	4th PM - Sep '20 (M19)
(2) Validation of a tool previous experimental data available in literature; and/or (3) Validation of a tool by HyTunnel-CS experimental data	M24	5th PM - Feb '21 (M24)
Deflagration of non-uniform hydrogen-air cloud created by release in HSE tunnel experiments Task 4.4 (NCSRD)	***Due date***	***Report at project meeting (PM)***
Simulations on HSE experiments	M31	6th PM - Sep '21 (M31)
Deflagration of non-uniform hydrogen-air cloud created by release in PS tunnel experiments Task 4.4 (NCSRD)	***Due date***	***Report at project meeting (PM)***
Simulations on PS experiments	M24	5th PM - Feb '21 (M24)
Deflagration of non-uniform hydrogen-air cloud created by release in tunnel (KIT)	***Due date***	***Report at project meeting (PM)***
Completion of the simulations	M33	7th PM - Feb '22 (M36)
Simulation of water injection effect on hydrogen combustion (NCSRD)	***Due date***	***Report at project meeting (PM)***
Completion of the task	M35	7th PM - Feb '22 (M36)
Simulation of water injection effect on hydrogen combustion (KIT)	***Due date***	***Report at project meeting (PM)***
Completion of the task	M34	7th PM - Feb '22 (M36)
Analysis of the interaction between absorbing materials and systems and shock wave (KIT)	***Due date***	***Report at project meeting (PM)***
Completion of the task	M35	7th PM - Feb '22 (M36)
Pre-test simulations and parametric study to find out the maximum allowed hydrogen inventory to mitigate the effect of blast wave and fireball (UU)	***Due date***	***Report at project meeting (PM)***
(1) CFD model validation by experimental data of stand-alone test against Japanese and USA tests. (35L @945 bar and 72.4L @350 bar)	M12	3rd PM - Feb '20 (M12)
(2) Problem formulation: to define a maximum amount of hydrogen in a storage tank, onboard of vehicle, that would not generate pressure loads able to	M16	4th PM - Sep '20 (M19)

threaten life and destroy property along a tunnel		
(3) Validation of a tool by HyTunnel-CS experimental data from Task 4.4.1	M26	6th PM - Sep '21 (M31)
(4) Final results and conclusions for recommendations	M30	6th PM - Sep '21 (M31)
Simulations to validate multi-phenomena turbulent burning velocity deflagration model (spurious release) (UU)	***Due date***	***Report at project meeting (PM)***
(1) Problem formulation	M10	3rd PM - Feb '20 (M12)
(2) Validation of CFD tool by experimental data available in literature on tests in the open space (release pressure 36-200 bar, release diameter 6.5-12 mm)	M16	4th PM - Sep '20 (M19)
(3) Validation of CFD tool against experiments conducted in Sub-task 4.4.2 at HSE	M24	5th PM - Feb '21 (M24)
Coupled CFD/FEM modelling and simulation of a tunnel structure reaction to the blast (UU)	***Due date***	***Report at project meeting (PM)***
(1) Communication with Luisa Giuliani (DTU) on the problem formulation	M7	3rd PM - Feb '20 (M12)
(2) Problem formulation: Provision of CFD input for the FEM analysis of structural response of steel elements in tunnel to thermal and pressure loads following confined space accident to DTU	M10	3rd PM - Feb '20 (M12)
(3) DTU will use UU input to perform FEM analysis on structural response of steel elements to the blast	M15	4th PM - Sep '20 (M19)
(4) Model validation by experimental data from experiments done in Task 4.4.1	M26	6th PM - Sep '21 (M31)
(5) Final results and conclusions for recommendations	M30	6th PM - Sep '21 (M31)
Simulations of flame acceleration and transition to detonation in tunnel structures (USN)	***Due date***	***Report at project meeting (PM)***
Completion of the task	M30	6th PM - Sep '21 (M31)

5.1.3 Task 4.4 Experiments

Blast wave and fireball of tank rupture in tunnel: Demonstrations of car tank failure in fire experiments in two real tunnels (CEA)	***Due date***	***Report at project meeting (PM)***
Pre experimental tests	M15	4th PM - Sep '20 (M19)
Experimental programme execution	M20	5th PM - Feb '21 (M24)
Blast wave and fireball of tank rupture in tunnel: Experiments utilising the experimental tubular steel "explosion" tunnel (HSE)	***Due date***	***Report at project meeting (PM)***
Confirm test programme in discussion with partners	M10	3rd PM - Feb '20 (M12)
Complete design, build and commissioning of test facility	M18	4th PM - Sep '20 (M19)
Commence test programme	M19	5th PM - Feb '21 (M24)
Final results and conclusions for recommendations	M24	6th PM - Sep '21 (M31)
Deflagration of non-uniform cloud in a tunnel: Experiments on deflagration of non-uniform hydrogen-air cloud created by release in mock-up tunnel sections (PS)	***Due date***	***Report at project meeting (PM)***
Execution of experimental tests	M22	5th PM - Feb '21 (M24)

Tests on flame propagation through a layer of fire extinguishing foam filled in by flammable hydrogen-air mixtures (PS)	***Due date***	***Report at project meeting (PM)***
Execution of experimental tests	M28	7th PM - Feb '22 (M36)
Tests on effect of water sprays and mist systems on combustion and DDT (PS)	***Due date***	***Report at project meeting (PM)***
Execution of experimental tests	M28	6th PM - Sep '21 (M31)
Effect of droplet size on mitigation of combustion and DDT (USN)	***Due date***	***Report at project meeting (PM)***
Execution of experimental tests	M35	7th PM - Feb '22 (M36)
Shock wave attenuation: Tests on tank rupture in a tunnel with shock attenuation material/system (HSE)	***Due date***	***Report at project meeting (PM)***
Execution of experimental tests	M27	6th PM - Sep '21 (M31)
Shock wave attenuation: Experiments on effect of water spray/mist system on shock wave attenuation (PS)	***Due date***	***Report at project meeting (PM)***
Execution of experimental tests	M18	4th PM - Sep '20 (M19)
Shock wave attenuation: Tests on shock wave attenuation by using shock absorbing materials, soft bulkheads and sacrificial pre-evacuated volumes (PS)	***Due date***	***Report at project meeting (PM)***
Execution of experimental tests	M18	4th PM - Sep '20 (M19)
Safety technology to prevent tank rupture: Development and manufacturing of four leak no burst composite type 4 tanks prototypes for testing in a tunnel fire at CEA and HSE tunnels (UU)	***Due date***	***Report at project meeting (PM)***
(1) Obtaining material properties	M8	3rd PM - Feb '20 (M12)
(2) Webex with HSE on experiments	M8	
(3) Webex with CEA on experiments	M8	
(4) Subcontracting tank manufacturer	M11	
(5) Simulations of burner design and passing design to HSE and/or CEA (further discussions needed)	M11	
(6) Design of leak-no-burst tanks	M11	
(7) Fabrication of leak-no-burst tanks	M15	4th PM - Sep '20 (M19)
(8) Shipment of LNB tanks from manufacturer to HSE and/or CEA	M15	
(9) HSE and/or CEA preparation for tests (burner, data acquisition system etc.).	M16	
(10) Suggested date for experiments with leak-no-burst tanks at HSE	M18	
(11) Suggested date for experiments with leak-no-burst tanks at CEA	M20	5th PM - Feb '21 (M24)

6. Conclusions

Deliverable D4.1 is presented. A detailed and comprehensive activity plan and schedule for the activities has been established in accordance to the project description attached to the Grant Agreement no. 826193 for HyTunnel-CS. The focus has been on the coordination of the various activities within WP 4 as well as coordination with relevant activities in the other work packages. The detailed programme combines the development and validation of engineering models and advanced CFD applications with state of the art experiments.

The outcome is expected to support and advance risk assessment and decision support related to the standardisation and regulation of hydrogen vehicles and bulk hydrogen transport through European tunnels and confined spaces.

Appendix A1. Scaling criteria

The objective of a steady state scaled experiment is to match the concentration of hydrogen in the downstream flow and the proportion of the tunnel over which the flow is distributed. The defined variables are described in Figure 24.

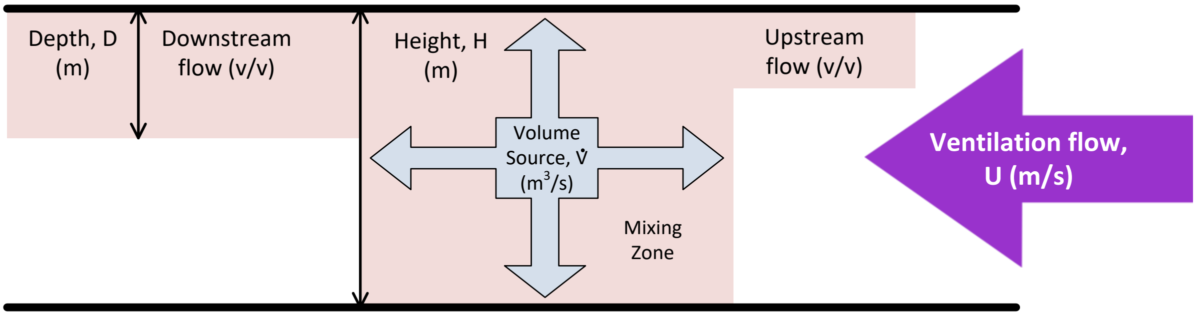


Figure 24. Schematic diagram showing modelling of jet and tunnel ventilation interactions

$$C_{model} = C_{fullscale} \qquad [1]$$

$$\frac{D_{model}}{H_{model}} = \frac{D_{fullscale}}{H_{fullscale}} \qquad [2]$$

Assume there is a mixing zone of limited size around the source where the flow is dominated by source momentum. Outside this zone the flow is controlled by the interaction between the buoyant gas and the tunnel flow.

If the downstream flow occupies the same proportion of the model as in the full scale tunnel area then mass conservation gives:

$$C \propto \frac{\dot{V}}{UH^2} \qquad [3]$$

Since hydrogen is very light the density difference associated with the downstream flow is:

$$\frac{\Delta\rho}{\rho_0} \sim C \qquad [4]$$

If $\Delta P_{buoyancy}$ is the buoyancy head associated with the flow:

$$\Delta P_{buoyancy} \propto Hg\rho_0 C \qquad [5]$$

The dynamic head associated with the tunnel flow is:

$$\Delta P_{tunnel\ flow} \propto \rho_0 U^2 \qquad [6]$$

If these are in the same proportion then the tendency for back flow and the stability of the downstream layer will be matched for the model and full-scale flow when:

$$\rho_0 U^2 \propto Hg\rho_0 C \qquad [7]$$

$$Or \qquad C \propto \frac{U^2}{H} \qquad [8]$$

This equation implies that the tunnel flow speed should be scaled as $\sqrt{H}$.

$$U \propto \sqrt{H} \qquad [9]$$

Combining this with [3] gives

$$\dot{V} \propto H^{5/2} \qquad [10]$$

Matching the mixing zone by choice of source momentum

The velocities associated with a jet source with a momentum flux, M, vary with scale as

$$M \propto H^2 U_{source}^2 \qquad [11]$$

The edge of the mixing zone corresponds to locations where $U_{source} \sim U_{tunnel}$

The mixing zones will have similar shapes at different scales if

$$U_{source} \propto \frac{\sqrt{M}}{H} \propto U_{tunnel} \qquad [12]$$

$$Since \quad U_{tunnel} \propto \sqrt{H} \quad [13]$$

This means that the mixing zones will be similar if

$$M \propto H^3 \qquad [14]$$

In summary, the appropriate scaling relationships between the tunnel flow, U, the hydrogen volume flow, $\dot{V}$, and the tunnel diameter, H, for a *steady* release experiment in a model tunnel is

$$U \propto H^{\frac{1}{2}} \qquad [15]$$

$$\dot{V} \propto H^{\frac{5}{2}} \qquad [16]$$

If U and $\dot{V}$ are chosen in this way then the concentration in the flow developing around the source will be the same and the relationship between the buoyancy head associated with the release and the dynamic head of the flow will be the same. This means there will be a similar tendency for the gas to be blown down stream or flow backwards at high level.

Appendix A2. Milestone 4.1: M4.1. Matrix of experiments, simulations, schedule of tools development

Milestone 8 (M4.1) presents the matrix of the activities and planning of the a) engineering tools development to be performed within task 4.2 b) numerical simulations to be performed within task 4.3 and c) experiments to be performed within task 4.4. The document was prepared and delivered in M6 (August 2019). The milestone was uploaded on the website members area as mean of verification. The milestone is reported as well as part of D4.1, following the directives of the Grant Agreement.

Keywords

Hydrogen, tunnel, explosion, mitigation, engineering correlation, numerical simulation, experiment

A2.1 Schedule of engineering tools development within Task 4.2 (UU)

Analytical studies and engineering tools details	Planned date	Report at Project Meeting (PM):	Report in deliverable (M):
Engineering models for assessment of blast wave and fireball of hydrogen tank rupture (UU) Development of the engineering model for blast wave after hydrogen tank rupture in a tunnel. Verification of engineering model to be performed against CFD simulations with 700 bar hydrogen tank rupture in tunnels (simulation results obtained at UU). Validation of engineering model of blast wave - UU would like to use the data obtained in experiments by partners CEA and HSE (experiments within the Sub-task 4.4.1. Blast wave and fireball of hydrogen tank rupture in a tunnel). (1) Problem formulation and tool trial implementation; (2) Tool verification against numerical tests; (3) Validation of the tool by HyTunnel-CS experimental data; (4) Final description of the tool for stakeholders use.	M12 M12 M36 M36	3rd PM - February '20 - M12 3rd PM - February '20 - M12 7th PM - February '22 - M36 7th PM - February '22 - M36	D4.2. Intermediate report (M18) D4.3. Final report (M36)
Engineering model for assessment of overpressure during spurious hydrogen release (UU) UU aims to develop a reduced model to assess overpressure from delayed ignition of turbulent hydrogen jets. The reduced model requires as input parameters the following: storage and spouting pressure and temperature; release diameter; ignition location; ignition delay; distance of sensor/target from ignition point. The reduced model is based on the use of Ulster's under-expanded jet theory and the similarity law for axial concentration decay to estimate the jet conditions at the release and the ignition point, respectively. Two stages of validation of the tool are envisaged: (v.1) Validation of the engineering tool by experimental data available	M8	3rd PM - February '20 - M12	D4.2. Intermediate report (M18)

in literature on experiments in the open space (Pressure = 36-400 bar, release diameter = 1-12 mm); (v.2) Validation of the engineering tool against experiments conducted by HSE in Sub-task 4.4.2 (P=700 bar and various release diameter for a mass flow rate up to 100 g/s);	(v.1) M30 (v.2)	6th PM - September '21 - M31	D4.3. Final report (M36)
Engineering tool for prevention and mitigation of composite hydrogen storage tank explosion in a fire (UU) The tool will implement developed at UU model for loss of load-bearing ability of the Type 4 storage tank. The tool implementation is planned as follows: (1) Problem formulation; (2) Tool implementation; (3) Validation of a tool by experimental data available in literature; (4) Final description of a tool for stakeholders use.	M12 M12 M12 M23	2nd PM - September '19 - M7 3rd PM - February '20 - M12 3rd PM - February '20 - M12 5th PM - February '21 - M24	D4.2. Intermediate report (M18) D4.3. Final report (M36)
Correlation for DDT in horizontal and vertical ventilation systems with non-uniform hydrogen-air mixtures in the presence of obstacles (KIT) • Collection of experimental data on DDT tests in stratified hydrogen-air mixture with different hydrogen concentration gradients, different confinement conditions and ventilations • Based on the developed DDT criteria for homogeneous hydrogen-air mixture, new correlation will be put forward for non-uniform explosive mixtures.	M30	6th PM - September '21 - M31	D4.3. Final report (M36)
Analytical model for water spray/mist system effect on hydrogen combustion and a shock wave attenuation • Analytical formula or correlation will be developed based on the existing experimental data at KIT, of thermal-dynamic properties and hydrogen flame measurements with water spray influence. • The experimental data about shock wave attenuation in Subtask 4.4.5, together with any available published data in literatures, if any, will be used to develop shock wave attenuation model.	M36	7th PM - February '22 - M36	D4.3. Final report (M36)

• The developed model can be compared to those, if any, published in literatures, and to the numerical simulation results about water injection on shock wave attenuation in Subtask 4.3.			

A2.2 Matrix of numerical simulations within Task 4.3 (NCSRD)

Numerical studies details	Planned date	Report at Project Meeting (PM):	Report in deliverable (M):
Deflagration of non-uniform hydrogen-air cloud created by release in HSE tunnel experiments and PS experiments in Task 4.4 (CEA) CEA is investigating between 2 types of simulations: either the simulation (with code Neptune) of fire jet release in a tunnel (with or without an existing fire) and the presence of a forced ventilation, or the simulation (with EUROPLEXUS) of a non-uniform hydrogen air-cloud with initial condition taken from task 2.3 CFD calculations (and experiments in Task 4.4). CEA will consider the confirmed experimental matrix before final choice. It mostly depends on the kind of authorizations the CEA will have to operate in the tunnel, the cloud explosion being the most energetic. Details on the numerical study: scope, short description of the CFD model, cases to be simulated, etc. Reporting stages may be structured similarly to analytical tools: (1) Problem formulation; (2) Validation of a tool previous experimental data available in literature; and/or (3) Validation of a tool by HyTunnel-CS experimental data;	M18 (model) M24 (results and comparisons	4th PM - September '20 - M19 5th PM - February '21 - M24	D4.3. Final report (M36)
Deflagration of non-uniform hydrogen-air cloud created by release in a HSE tunnel experiments of subtask 4.4.3 (NCSRD)	M24	5th PM - February '21 - M24	D4.3. Final report (M36)
Deflagration of non-uniform hydrogen-air cloud created by release	M31	6th PM - September '21 -	D4.3. Final report

in PS tunnel experiments of subtask 4.4.3 (NCSRD)		M31	(M36)
Deflagration of non-uniform hydrogen-air cloud created by release in a tunnel (KIT) • A tunnel-like geometrical model will be set up with numerical meshes, • Layered hydrogen distribution as the initial conditions, • Hydrogen combustion simulation, • Thermal-dynamic parameters about combustion are output as results.	M33	7th PM - February '22 - M36	D4.3. Final report (M36)
Simulation of water injection effect on hydrogen combustion (NCSRD) • ADREA-HF code further code development • Simulations against selected experiments	M35	7th PM - February '22 - M36	D4.3. Final report (M36)
Simulation of water injection effect on hydrogen combustion (KIT) • The basic configurations are similar to last subtask, • Simplified/ reduced water droplet model will be developed and implemented, • Hydrogen combustion with water presence will be simulated, • Thermal-dynamic parameters about combustion are output as results.	M34	7th PM - February '22 - M36	D4.3. Final report (M36)
Simulation of water injection effect on shock wave attenuation (KIT) • Further development of KIT in-house CFD codes COM3D and COM1D • Investigation on theoretical dynamics of shock wave attenuation parameters • Simulations against experimental data	M35	7th PM - February '22 - M36	D4.3. Final report (M36)
Analysis of the interaction between absorbing materials and			

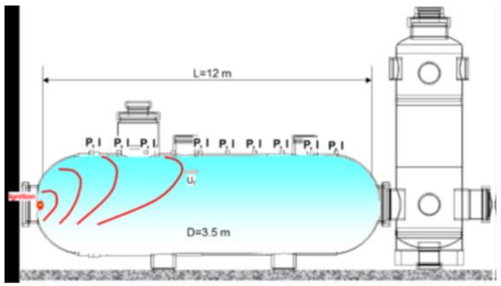
systems and shock wave (KIT) • Coupling of COM3D code to ABAQUS code • Demonstration and simulation of the interaction between fluid dynamic system and absorbing solid boundary	M36	7th PM - February '22 - M36	D4.3. Final report (M36)
Pre-test simulations and parametric study to find out the maximum allowed hydrogen inventory to mitigate the effect of blast wave and fireball (UU) (1) Problem formulation: to define a maximum amount of hydrogen in a storage tank, onboard of vehicle, that would not generate pressure loads able to threaten life and destroy property along a tunnel. (2) Model validation by experimental data available in literature. In particular against stan-alone tests by (Weyandt, 2006); (3) Validation of a tool by HyTunnel-CS experimental data from Subtask 4.4.1; (4) Final results and conclusions for stakeholders use.	M12	3rd PM - February '20 - M12	D4.2. Intermediate report (M18)
Simulations to validate multi-phenomena turbulent burning velocity deflagration model (spurious release) (UU) A CFD model will be developed and validated to assess the pressure and thermal hazards from delayed ignition of hydrogen jets. The reasons to conduct CFD simulations in addition to development of a reduced model (see Task 4.2) are the following: CFD models allow more accurate predictions of overpressure; scenarios that cannot be represented by the engineering tool assumptions can be modelled by CFD simulations; the range of applicability of the engineering model can be expanded by using simulations as verification tool; the study can be expanded to calculation of thermal and pressure loads on the structure. The CFD model will employ the Ulster's multi-phenomena deflagration model, which is adapted to take into account the non-uniformity of the hydrogen-air mixture and high-intensity turbulence in the jet. Two stages are envisaged for the CFD model development and validation:	M16 (v.1)	4th PM - September '20 - M19	D4.2. Intermediate report (M18)

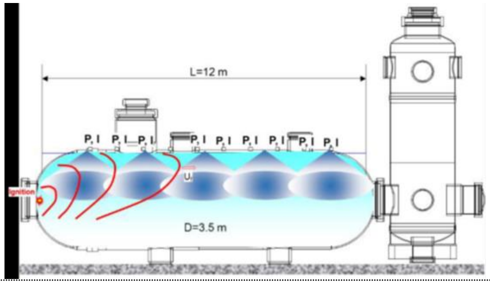
(v.1) Validation of engineering tool by experimental data available in literature on experiments in the open space (release pressure 36-200 bar, release diameter 6.5-12 mm); (v.2) Validation of engineering tool against experiments conducted in Sub-task 4.4.2 at HSE (pressure 700 bar and various release diameters for mass flow rates up to 100 g/s);	M35 (v.2)	7th PM - February '22 - M36	D4.3. Final report (M36)
Coupled CFD/FEM modelling and simulation of a tunnel structure reaction to the blast (UU, DTU) • UU will provide CFD input for the FEM analysis of structural response of steel elements in tunnel to thermal and pressure loads following confined space accident (to be performed by DTU). • DTU will use UU input to perform FEM analysis on structural response of steel elements to the blast. • UU will endeavour to perform two-way coupled CFD-FEM simulation of hydrogen storage tank rupture under a car. The blast wave attenuation by car deformation in comparison with the blast wave from a stand-alone tank rupture will be assessed.	M10 M15 M12	3rd PM - February '20 - M12 4th PM - September '20 - M19 3rd PM - February '20 - M12	D4.2. Intermediate report (M18) D4.2. Intermediate report (M18) D4.2. Intermediate report (M18)
Simulations of flame acceleration and transition to detonation in tunnel structures (USN) The simulations will be using existing data from experiments done on flame acceleration and DDT in inhomogeneous gas clouds in ducts for validation. The experiments has been done in previous projects by KIT/PS and at Technical University of Munchen. The study will identify model shortcomings and develop methods for simulating similar problems related to tunnel structures.	M30	6th PM - September '21 - M31	D4.3. Final report (M36)

A2.3 Matrix of experiments within Task 4.4 (HSE)

Experiments details	Planned date	Report at Project Meeting (PM):	Report in deliverable (M):
SUBTASK 4.4.1. Blast wave and fireball of tank rupture in tunnel (HSE, CEA) This sub-task includes the 2 investigations listed below:			
Demonstrations of car tank failure in fire experiments in a real tunnel (CEA) (1) 12 experiments are scheduled with a priority ordering. The first in the list will be done first, the last will be done if there is time left. Indeed the real tunnel will be at CEA disposal for 4 to 6 weeks (negotiation not completed yet): • The CEA will keep the engagement of testing: a TPRD release without ignition, with ignition, with surrounding fire. • The CEA will study a tank rupture with or without the presence of obstacle (car) • Depending on the schedule, the CEA will test different configurations of the previous aspects as well as dispersion and explosion of an initially unignited cloud. (2) 2 to 4 experiments will be performed to study the behaviour of UU tanks in a fire. Those tanks can't rupture due to leak in presence of a strong heat source. CEA has still to investigate whether or not those experiments will be carried out in a tunnel or outside (may be at a CEA facility). Indeed the influence of a tunnel is not the first matter of concern in those tests. See section 4.4.6. (3) Pre experimental tests: • All the instrumentation is going to be tested in-house at CEA. • Then realistic experiments which mimic phase 1 and 2 will be performed on field (but not in the real tunnel) near CEA Saclay in order to test all the experimental set-up in the most realistic environment. CEA has to be as	M20 M20 in case of the tunnel experiment (TBC otherwise) M11-M15	5th PM - February '21 - M24 3rd PM - February '20 - M12 4th PM - September '20 - M19	D4.3. Final report (M36) D4.2. Intermediate report (M18) D4.3. Final report (M36)

close as possible to the real tunnel site conditions to limit the uncertainties that might be encountered then. Advanced discussions have been taken place with possible facilities on this topic.			
Vessel rupture simulation in a tunnel (HSE) Experimental programme using reusable rupture vessel utilising large diameter bursting discs to create a rapid discharge (<1s) of 70MPa, 70l volume with in a 70m , 3.7m diameter tunnel. Obtain data that will support the development of engineering models and CFD model of tank rupture and fireball – measurements to include overpressure , heat flux an flame speed, together with imaging/visualisation where feasible • Vessel design and fabrication • Commissioning tests • Rupture tests (base line test including dispersion characterisation and ignition delay studies) • Rupture tests with turbulence generators (ventilation, bulkheads, structures)	M12 M15 M18 M24	4th PM - September '20 - M19 6th PM - September '21 - M31	D4.2. Intermediate report (M18) D4.3. Final report (M36)
SUBTASK 4.4.2. Overpressure during spurious operation of TPRD (HSE) Experimental programme discharge vessel utilising fitted with a TPRD to provide a continuous blowdown of 70MPa, 70l volume with in a 70m , 3.7m diameter tunnel. Obtain data that will support the development of engineering models and CFD model of vessel blowdown and subsequent ignition – measurements to include overpressure, heat flux and flame speed, together with imaging/visualisation where feasible. • Experimental tests aligned with subtask 2.4.3. Assessment of ignition delay and the formation of flammable volumes will be assessed with force ventilation	M18	4th PM - September '20 - M19	D4.2. Intermediate report (M18)

SUBTASK 4.4.3. Deflagration of non-uniform cloud in a tunnel (PS, HSE) This sub-task includes the 2 investigations listed below:			
Experiments on deflagrations in a 70 m and 3.7 m diameter tunnel with and without bulkheads (HSE) • Experimental programme discharge vessel utilising fitted with a TPRD to provide a continuous blowdown of 70MPa, 70l volume with in a 70m , 3.7m diameter tunnel. • Obtain data that will support the development of engineering models and CFD model of vessel blowdown and subsequent ignition – measurements to include overpressure, heat flux and flame speed, together with imaging/visualisation where feasible • Experimental tests aligned with subtask 2.4.3. Assessment of tunnel structures / bulkheads	M21	5th PM - February '21 - M24	D4.3. Final report (M36)
Experiments on deflagration of non-uniform hydrogen-air cloud created by release in mock-up tunnel sections (PS) Experiments will be performed in a rectangular geometry of HYKA A1 vessel (with a box 3x0.6x9 m) without bulkheads) on deflagration of non-uniform hydrogen-air cloud of the same gradient as in HSE experiments in order to compare with HSE experiments for round shape geometry (PS). 	M22	6th PM - September '21 - M31	D4.3. Final report (M36)
SUBTASK 4.4.4. Foam and water spray effect on combustion, DDT (PS, USN) This sub-task includes the 3 investigations listed below:			

Tests on flame propagation through a layer of fire extinguishing foam filled in by flammable hydrogen-air mixtures (PS) Small-scale tests on flame propagation through a layer of fire extinguishing foam of different properties filled in by flammable hydrogen-air mixtures (PS)	M28	7th PM - February '22 - M36	D4.3. Final report (M36)
Tests on effect of water sprays / mist systems on combustion and DDT (PS) Experiments will be performed in a rectangular geometry of HYKA A1 vessel (with a box 3x0.6x9 m). Tests on effect of water spray/mist systems on combustion and DDT of uniform layer of hydrogen –air mixture (PS).  	M28	7th PM - February '22 - M36	D4.3. Final report (M36)
Effect of droplet size on mitigation of combustion and DDT (USN) The droplet sizes will be measured using a high-speed microscopic imaging system with laser lighting for shadowgraphy. The nozzle will be tested at USN and results will be correlated with explosion tests by PS.	M35	7th PM - February '22 - M36	D4.3. Final report (M36)
SUBTASK 4.4.5. Shock wave attenuation (PS, HSE) This sub-task includes the 3 investigations listed below:			
Tests on tank rupture in a tunnel with shock attenuation material/system (HSE) • Experimental programme using reusable rupture vessel utilising large diameter bursting discs to create a rapid discharge (<1s) of 70MPa, 70l volume with in a 70m, 3.7m diameter tunnel. • Obtain data that will support the development of engineering models and CFD model of tank rupture and fireball – measurements to include			

overpressure , heat flux an flame speed, together with imaging/visualisation where feasible • Vessel rupture and ignition with mitigation systems (water sprays)	M27	6th PM - September '21 - M31	D4.3. Final report (M36)

Experiments on effect of water spray/mist system on shock wave attenuation (PS) The experiments will be performed inside the safety vessel HYKA A2. The sprinkler system used in Subtask 3.4.6 HYKA be applied. As shock wave source an extensively studied combustion unit will used. The combustion unit create shock waves emitted from H_2/air detonation. Several dynamic pressure sensors will be used to quantify the shock waves.	M18	5th PM - February '21 - M24	D4.3. Final report (M36)
Tests on shock wave attenuation by using shock absorbing materials, soft bulkheads and sacrificial pre-evacuated volumes (PS) The experiments will be performed inside the safety vessel HYKA A2. As shock wave source an extensively studied combustion unit will used. The combustion unit create shock waves emitted from H_2/air detonation. Several dynamic pressure sensors will be used to quantify the shock waves and its reflection behavior on absorbing materials.	M18	6th PM - September '21 - M31	D4.3. Final report (M36)
SUBTASK 4.4.6. Safety technology to prevent tank rupture (UU, HSE, CEA) This sub-task includes the 3 investigations listed below:			
Development and manufacturing of four leak-no-burst composite type 4 tanks prototypes for testing in a tunnel fire at CEA and HSE tunnels (UU) Ulster will develop the reduced model and perform simulations with different leak-no-burst prototype designs using the material properties from literature or obtained elsewhere. After identifying and sub-contracting a tank manufacturer, prototype designs will be passed to manufacturer for fabricating	M12	3rd PM - February '20 -	

up to 4 the explosion-free tanks. The tanks will be fire-tested using HSE and/or CEA facilities. (1) Model development for prototype design; (2) Subcontracting a tank supplier, prototypes manufacturing; (3) Prototypes testing.	M18 M36	M12 4th PM - September '20 - M19 7th PM - February '22 - M36	D4.2. Intermediate report (M18) D4.3. Final report (M36)
Tests on prototypes of leak-no-burst composite type 4 tanks at HSE (HSE) Bonfire testing of 2 prototype vessels	M36	7th PM - February '22 - M36	D4.3. Final report (M36)
Tests on prototypes of leak-no-burst composite type 4 tanks at CEA (CEA) Bonfire testing of 2 prototype vessels	M36	7th PM - February '22 - M36	D4.3. Final report (M36)

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