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)
Grant Agreement Number 826193

Deliverable D2.1
Detailed research programme on unignited leaks in tunnels and confined space

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Version: 191130
Delivery date for internal review: 1 November 2019
Due date: 30 November 2019
Dissemination level: Public

Deliverable administration						
Work Package	WP2. Effect of mitigation systems on hydrogen release and dispersion in confined spaces					
N. and title	D2.1 (D6) Detailed research programme on unignited leaks in tunnels and confined space					
Type	Report					
Status	Draft/Working/**Released**	Due	M9	Date	30-11-2019	
Comments						

Development and revision			
Version N.	Date	Authors	Description
190920	20-09-2019	D. Cirrone, V. Shentsov, M. Dadashzadeh, S. Kashkarov, D. Makarov, V. Molkov, UU	UU contribution
191001	01-10-2019	Z. Xu (KIT), J. Grune(PS)	KIT/PS contribution
191009	09-10-2019	W. Rattigan, K. Moodie	HSE contribution
191011	11-10-2019	A. V. Gaathaug, K. Vågsæther (USN)	USN contribution
191115	15-11-2019	M. Pursell (HSE)	Internal review
191121	21-11-2019	K. Vågsæther (USN)	Internal review
191122	22-11-2019	D. Cirrone (UU)	Internal review

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Acknowledgments

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (JU) under grant agreement No 826193. The JU receives support from the European Union's Horizon 2020 research and innovation programme and United Kingdom, Germany, Greece, Denmark, Spain, Italy, Netherlands, Belgium, France, Norway, Switzerland.

Summary

HyTunnel-CS project aims to conduct internationally leading pre-normative research (PNR) to close knowledge gaps and technological bottlenecks in the provision of safety and acceptable level of risk in the use of hydrogen and fuel cell cars as well as hydrogen delivery transport in underground transportation systems. Work Package 2 (WP2) of HyTunnel-CS focuses on the investigation of hydrogen releases and dispersion in underground transportation systems.

This document presents the detailed research programme of WP2, regarding unignited leaks in tunnels and underground parking.

Keywords

Hydrogen, tunnel, release, dispersion, engineering tool, numerical simulation, experiment, confined space, unignited leak, research programme

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Abbreviations

ACH	Air Change per Hour
CFD	Computational Fluid Dynamics
DoA	Description of Actions
GA	Grant Agreement
KG	Knowledge Gap
LFL	Lower Flammability Limit
M	Month
P&ID	Piping & Instrumentation Diagram
PM	Project Meeting
PNR	Pre-Normative Research
PPP	Pressure Peaking Phenomena
PRD	Pressure Relief Device
RCS	Regulations, Codes and Standards
TPRD	Thermally activated Pressure Relief Device
UDF	User Defined Function
WP	Work Package

Definitions

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

Hazard is any potential source or condition that has the potential for causing damage to people, property and the environment.

Hazard distance is a distance from the (source of) hazard to a determined (by physical or numerical modelling, or by a regulation) physical effect value (normally, thermal or pressure) that may lead to a harm condition (ranging from “no harm” to “max harm”) to people, equipment or environment.

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1. Introduction

HyTunnel-CS project aims to conduct internationally leading pre-normative research (PNR) to close knowledge gaps and technological bottlenecks in the provision of safety and acceptable level of risk in the use of hydrogen and fuel cell cars as well as hydrogen delivery transport in underground transportation systems. Work Package 2 (WP2) of HyTunnel-CS focuses on the investigation of hydrogen releases and dispersion in underground transportation systems.

This document presents the detailed research programme of WP2, regarding unignited leaks in tunnels and underground parking.

An overview of WP2 according to Grant Agreement is performed in chapter 2. Analytical studies and development of engineering tools is considered in chapter 3. Numerical simulations are considered in chapter 4. Experiments are considered in chapter 5.

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 2 “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 1) as indicated by HyTunnel-CS Grant Agreement.

2. Work Package 2 overview

Work Package 2 focuses on the investigation of hydrogen releases and dispersion in underground transportation systems, such as tunnels and underground parking. The following sections will present the objectives of WP2, the addressed knowledge gaps and an overview of the WP structure.

2.1 Objectives

Work Package 2 has the following objectives, as identified in HyTunnel-CS Grant Agreement (GA):

1. Understand hydrogen dispersion in underground transportation systems and the effect of ventilation including its interaction with other mitigation systems, e.g. water spray and mist.
2. Generate unique experimental data to support further development and validation of relevant physics models, simulations, hazard and risk assessment tools.
3. Perform CFD simulations to support the experimental campaign and provide input to WP4 on delayed ignition scenarios.
4. Develop novel engineering correlations for ventilation of hydrogen unscheduled release in underground transportation systems and similar confined spaces.
5. Identify and evaluate innovative safety strategies and engineering solutions to prevent and mitigate accumulation of hydrogen above the lower flammability limit (LFL) in tunnel systems.
6. Underpin key Regulation, Codes and Standards (RCS) outputs and recommendations for inherently safer use of hydrogen vehicles in underground transportation systems and similar confined spaces by this pre-normative research (PNR) on hydrogen releases and dispersion.

2.2 Knowledge gaps and scenarios addressed

HyTunnel-CS D1.2 (2019) performed a critical review of the state of the art regarding hydrogen hazards and risks in tunnels and similar confined spaces. The report defined the areas where safety knowledge gaps and technological bottlenecks for characterisation of hazards and associated risks in tunnels are present. These were classified in different scenarios. The experimental campaigns, analytical and numerical studies in WP2 were shaped according to the outcomes of D1.2 regarding hydrogen unignited releases and dispersion. The aim is to address the areas where the current knowledge is insufficient to calculate hazards and risks of hydrogen-powered vehicles and other transport in tunnels and other confined spaces. WP2 will include investigation of the effect of current mitigation systems, e.g. water spray and mist, and ventilation systems on hydrogen releases. The scope is to identify innovative safety strategies and engineering solutions to prevent and mitigate the hydrogen accumulation in flammable concentrations. WP2 outcomes will be fed in to recommendations for RCSs and provide input to WP4 on delayed ignition scenarios.

2.3 Structure and synergy with HyTunnel-CS work plan

Work Package 2 follows the same structures of other technical WPs 3 and 4. It is structured in 5 tasks as follows:

- Task 2.1. This task aims at designing the research programme of WP2, which encompasses analytical, numerical and experimental studies to expand the current state of the art and fulfil the knowledge gaps in this area.
- Task 2.2. This task aims at the development of analytical studies and engineering tools to be used in hydrogen safety engineering. Experiments available in literature or performed within HyTunnel-CS experimental campaign in task 2.4 will be used for validation, and they will be specified in the description of the tools.
- Task 2.3. This task aims at the development and validation of computational fluid dynamics (CFD) models against experiments conducted in task 2.4. A close collaboration between

modellers and experimentalists has been ensured with two purposes: conduction of pre-test simulations for designing the tests to be conducted and refinement of the experimental set-up and parameters to meet the modelling needs.

- Task 2.4. This task focuses on the conduction of the experimental programme. The aim of experiments is to establish a scientific basis for understanding hydrogen release and dispersion, and its interaction with mitigation systems in tunnels and underground parking. The task will generate unique experimental data to support hazard and risk assessment and to validate the engineering tools and CFD models developed in tasks 2.2 and 2.3, respectively. For this reason, a close collaboration between modellers and experimentalists is being ensured to optimise and refine the design of experiments.
- Task 2.5. This task aims at gathering the knowledge and outcomes achieved in tasks 2, 3 and 4 and prepare the intermediate and final reports, respectively D2.2 and 2.3, on analytical, numerical and experimental studies on fires, including innovative prevention and mitigation studies.

The research conducted within WP2 is closely connected with WP4, which includes investigations on the consequences from delayed ignition of hydrogen jets and the deflagration of hydrogen-air clouds formed following a release. The outcomes developed within tasks 2.2-2.4 will be translated into a suitable language and format to be integrated into the guidelines and recommendations for RCSs developed within WP6.

Table 1 gives an outlook of the structure of the WP, tasks and corresponding sub-tasks.

Table 1. Structure of WP2.

Title (leader)
Task 2.1. Programme of research (NCSRD)
Task 2.2. Analytical studies, development and validation of engineering tools (CEA)
- Engineering tool for the assessment of ventilation system parameters in tunnels (CEA)
- Choked flow and tank blowdown model with Helmholtz free-energy-based hydrogen equation of state (NCSRD)
- Non-adiabatic blowdown model for under-expanded jets from the onboard storage tank” (UU)
- Engineering tool for mechanical ventilation in an underground parking (CEA, UU)
Task 2.3. Numerical studies (NCSRD)
Subtask 2.3.1. Pre-test and validation simulations (NCSRD)
- Pre-test simulations for the experiments of USN in sub-task 2.4.1 and experiments of HSE in sub-task 2.4.3 (NCSRD)
- Validation simulations (NCSRD)
- Pre-test and validation simulations of hydrogen release and dispersion in underground parking with mechanical ventilation following experiments by USN (sub-task 2.4.1) (CEA)
- Validation simulations of hydrogen release and dispersion CFD models following large-scale HSE tunnel tests (UU)
- Pre-test and validation simulations of the KIT/PS tunnel experiments in sub-task 2.4.4 (KIT)
Subtask 2.3.2. Effect of tunnel slope (NCSRD)
Task 2.4. Experiments (HSE)
Subtask 2.4.1. Mechanical ventilation in underground parking (USN)
Subtask 2.4.2. Pressure Peaking Phenomenon for unignited releases (USN)
Subtask 2.4.3. Dynamics of H2 release and dispersion in a tunnel (HSE)
Subtask 2.4.4. Efficiency of mechanical ventilation on H2 dispersion (PS)
Task 2.5. Reports on hydrogen jet fire effects and safety strategies (NCSRD, All)

The detailed programme presented in the following sections follows the subdivision in tasks 2.2-2.4 as given in the Description of Actions (DoA) of the Grant Agreement (GA). For each of the actions it will be specified which knowledge gaps and scenarios are addressed. Furthermore, description of the tools will include the interconnections with other HyTunnel-CS activities, either sub-tasks of the same WP or other WPs, where relevant. The detailed programme includes the timeline for the development of the engineering tools and numerical models, as well as for the planning and execution of the experimental programme. The project meetings will be used to monitor the progress of each of the listed actions. Therefore, along with the due month there is indication of the project meeting (PM) at which the progress will be reported. The activities will be reported in the intermediate and final reports, respectively D2.2 (due date M18) and D2.3 (M36), on analytical, numerical and experimental studies on hydrogen dispersion in tunnels, including innovative prevention and mitigation strategies.

3. Analytical studies and development of engineering tools (Task 2.2 / CEA)

3.1 Engineering tool for the assessment of ventilation system parameters in tunnels (CEA)

This analytical study has the scope to investigate the effectiveness and regulation parameters of ventilation systems in case of an unintended release of hydrogen in a tunnel. The same analytical tool can be used to assess the maximum hydrogen release rate for a certain ventilation rate in a tunnel to mitigate the formation of a flammable cloud.

Previously developed models (Xu et al., 2018), (Li et al., 2018) for ventilation in tunnels and smoke dispersion were extensively validated against experiments (real tunnels, galleries (INERIS) etc.). It is intended to expand those models to account for the presence of hydrogen-air mixture as a buoyant replacement for heated air.

The approach consists of the following steps and their planning:

(1) Extract a unified model out of the different existing models in the literature (M12, D2.2).
(2) Identify the thermal buoyant effects in the model to account for buoyant gas mixture instead (M12, D2.2).
(3) Numerical/analytical tool to solve the extended model (M21, D2.3).
(4) Validation of the model by experimental data available in other projects (INERIS for example, but also results from WP4 experiments carried out by CEA in a real tunnel with a dispersion of helium cloud and then a hydrogen cloud with forced ventilation) (M21, D2.3). At last HSE H2 dispersion experiment (task 2.4.3) could also be used for validation of the model.
(5) Final description of a tool for stakeholders use. (M30, D2.3).

3.2 Choked flow and tank blowdown model with Helmholtz free-energy-based hydrogen equation of state (NCSRD)

Previously developed choked flow release model (Venetsanos and Giannissi, 2017) (Venetsanos, 2018, 2019), which is applicable both for non-cryogenic and cryogenic releases, will be extended by including wall heat transfer effects for the storage tank.

Model will be validated using experiments from literature similar to (Dadashzadeh et al., 2019). Model could be validated also using experiments from HyTunnel-CS. In this case, it is suggested that experimentalists measure the mass flow rate and exit temperature as function of time.

Work is planned to be finished by M30 and documented in D2.3.

3.3 Engineering tool for mechanical ventilation in an underground parking (CEA, UU)

CEA and UU will jointly develop an engineering tool for mechanical ventilation in an underground parking. CEA will provide available experimental data on ventilation of enclosures with more than one vent to validate the tool.

The approach for calculation of hydrogen concentration in semi-confined space with forced ventilation will include of two models proposed in D1.2 (HyTunnel-CS D2.1, 2019) and will be based on the perfect mixing equation and model of passive ventilation.

The perfect mixing equation can be used to calculate the forced ventilation air flow rate (for a given hydrogen release rate) required to keep the hydrogen concentration below a safe level at steady-state conditions. Since in a realistic release the hydrogen concentration in an enclosure will be non-uniform and the model of passive ventilation was validated against maximum concentration of helium in small scale enclosure, the uniformity criterion will be applied for better prediction. Both models have to be validated against experimental studies performed in Subtask 2.4.1 by USN on mechanical ventilation in underground parking.

The validation experimental programme will be based on current regulations for ventilation and TPRD used in vehicles. The TPRD diameter will be reduced to satisfy the requirements that the hydrogen concentration remains below a safe concentration limit. The model will be used to answer the following questions:

- What is the upper limit of hydrogen release rate that will not require change in ventilation system?
- What is the current effectiveness of ventilation systems in case of hydrogen release accident?
- What should be an engineering tool for the assessment of ventilation system parameters in order to prevent and mitigate flammable mixture formation in underground parking?

The models will be validated by HyTunnel-CS experiments. Experimental problem formulation is based on the description of tests performed by USN within Task 2.4.1. It is planned to perform more than 33 tests with following variables:

- Various mass flow rates. The aim is to define the upper limit of hydrogen leak flow rate, and thus maximum TPRD diameter that would comply with the safety requirements of current RCS.
- Ventilation requirements of enclosed parking garages in UK are equal to maximum of 10 air changes per hour (ACH). These requirements will be defined as per description in section 5.1.5.
- Jet direction (up/down). Upwards or downwards releases under a vehicle will affect the value of this upper limit and help to identify if there are areas in the compartment where hydrogen, due to its buoyancy, can accumulate and form a flammable mixture.

Model for passive ventilation together with uniformity criterion will be used to assess the ventilation rate and will be tested against experiments.

Upon validation, the tool for mechanical ventilation will be fully described and implemented in Excel.

Final description and conclusion on the tool choice as well as recommendations on the use of tool will be based on the results of the model validation. The timeline for the model development is given in Table 2.

Table 2. Timeline of the development of the engineering tool for mechanical ventilation in an underground parking.

Analytical studies and engineering tools details	Due date	Report at Project Meeting (PM)
(1) Problem formulation	M8	3rd PM - Feb '20 (M12)
(2) Validation of models by HyTunnel-CS experiments	M14	4th PM - Sep '20 (M19)
(3) Tool implementation	M16	4th PM - Sep '20 (M19)
(4) Conclusions on the tool choice as well as recommendations	M24	5th PM - Feb '21 (M24)

3.4 Non-adiabatic blowdown model for under-expanded jets from the onboard storage tank (UU)

The developed non-adiabatic blowdown model (Dadashzadeh et al., 2019) calculates pressure and temperature dynamics inside a tank for different conditions. The model will be expanded to the scenario of a tank in a fire in WP4 (Task 2.2). The under-expanded jet theory (Molkov et al., 2009) is used 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 a Nusselt number correlation is applied (Woodfield et al., 2008). The energy conservation equation and Abel-Noble equation of state were employed to predict the dynamic pressure and temperature inside the tank. The under expanded jet theory was used to evaluate the pressurized gas behaviour after venting of the tank. To consider the heat transfer through the tank wall a one dimensional unsteady heat transfer equation was introduced and formulated to consider the thermal properties of a composite tank wall. The finite difference method was employed to solve the system of equations. At each time step Nusselt number correlations for forced and natural convection were employed to compute the heat transfer coefficients for the external and internal surfaces of the tank wall.

The validation data is already available from experiments carried out in the HYKA-HyJet research facility at Karlsruhe Institute of Technology (KIT) (Friedrich, 2019). 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 in to 70 MPa by helium and then cooled down to a normal room temperature (293 K) before the start of blowdown test. 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.

The time plan of the non-adiabatic blowdown model development is given in Table 3.

Table 3. Timeline of the non-adiabatic blowdown model development.

Analytical studies development and details	Due date	Report at Project Meeting (PM)
(1) Problem formulation	M1	2nd PM - Sep '19 (M7)
(2) Tool implementation: model simulations	M3	2nd PM - Sep '19 (M7)
(3) Validation of the tool by experimental data available in other projects	M7	2nd PM - Sep '19 (M7)
(4) Final description of the tool for stakeholders use	M24	5th PM - Feb '21 (M24)

4. Numerical simulations (Task 2.3 / NCSRD)

4.1 Pre-test and validation simulations (subtask 2.3.1 / NCSRD)

The aim of the task is to investigate the dynamics of release and dispersion of hydrogen in a tunnel, including the effect of tunnel ventilation on the resulting flammable cloud.

4.1.1 Scope / Methodology

Scope:

- To provide support to experimentalists regarding a) flammable mass/volume time and space evolution and b) sensors locations
- To validate / further develop computational tools and models based on the new experimental results.
- To produce scientific publications in support of HyTunnel-CS

Computational tools to be used:

- NCSRD release tool for blow-down, using NIST EoS formulation
- ADREA-HF CFD code for dispersion

The dispersion simulations will include high momentum hydrogen jets impinging on tunnels or underground garage walls. Depending on the convective discretization scheme used jet impingement could lead to unphysical butterfly effects (Tolias and Venetsanos, 2015). The issue will be re-examined within the current work with aim to find the best applicable scheme.

4.1.2 Planning

Planning for NCSRD pre-test and validation simulations is shown in the following table. Selected experiments within each subtask will be used for model validation.

Table 4. Simulations plan of experiments within sub-tasks 2.4.1-4.

Experiments	Pre-test simulations	Validation simulations
subtask 2.4.1 (USN)	M6, D2.2	M18, D2.2
subtask 2.4.2 (USN)		M34, D2.3
subtask 2.4.3 (HSE)	M13, D2.2	M34, D2.3
subtask 2.4.4 (PS/KIT		M18, D2.2

4.1.3 Pre-test simulations for the experiments of USN in subtask 2.4.1

The main features and parameters of pre-test simulations are described as follows.

Layout:

- 40 feet iso-container with internal dimensions 12.022×2.352×2.395 m shown in Figure 1 as provided by USN.
- Ventilation inlet at one side, fully open at the opposite side
- Mockup car with dimensions 3.5×1.176×0.5 m, located 4.5 m from ventilation wall, 0.2 m from floor, 0 m from lateral wall of container, as agreed with USN.

Release:

- Release nozzle laterally centred below car pointing vertically downwards, 5 m from ventilation wall

- Blow-down of 1kg of H_2 from stagnation conditions of 100 bar and 15 °C
- Two nozzle diameters 1 and 2 mm

Ventilation:

- 300 mm diameter, top of inlet 10 cm below ceiling
- Two ventilation rates 11.25 and 22.5 ACH

Numerical options:

- Two discretization schemes to test effect of jet impingement
- Computational domain and grid shown in Figure 2
- Total number of CFD runs: 8

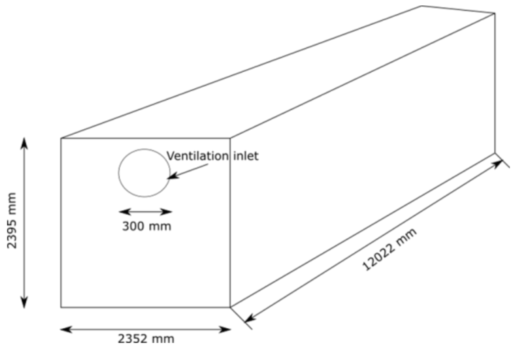


Figure 1. 40 feet iso-container with ventilation on one side and fully open on the other.

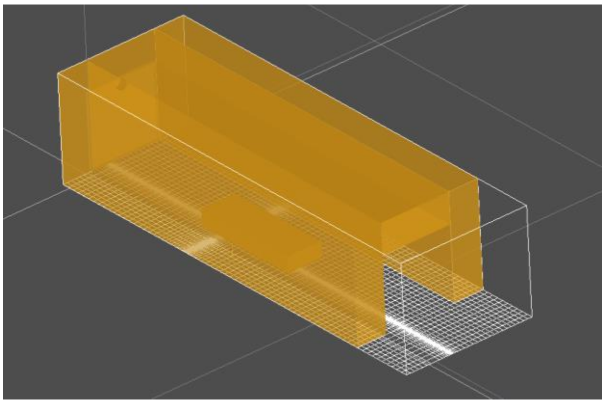


Figure 2. Computational domain and grid for pre-test simulations for the experiments of USN in subtask 2.4.1.

4.1.4 Pre-test / validation simulations for the experiments of HSE in subtask 2.4.3

Simulations will provide concentration field near source and downwind to establish flammable cloud non-uniformity and evolution.

The following are preliminary suggestions to the experimentalists:

- Measure the mass flow rate and exit temperature as function of time
- Measure upwind flow field conditions
- Measure concentration field near source and downwind to establish flammable cloud non-uniformity and evolution as the same vertical non-uniformity will have to be addressed by PS experiments within WP4

- Measure turbulence upwind and within flammable cloud, as this will be important for subsequent combustion modelling in WP4

4.2 Validation simulations of hydrogen release and dispersion CFD models following large-scale HSE tunnel tests (subtask 2.3.1 / UU)

UU will carry out validation simulations of their hydrogen release and dispersion CFD models implemented through User Defined Functions in ANSYS Fluent general-purpose software to create a predictive tool for the design of tunnel ventilation systems and corresponding ventilation protocols (following large-scale HSE tunnel tests in sub-task 2.4.3).

The numerical model will be based on recent publication (Giannissi et al., 2015) on CFD benchmark of hydrogen release and dispersion in a confined, naturally ventilated space with one vent (experiment in GAMELAN facility). For the turbulence modelling dynamic LES model will be used.

The series of tests with dispersion of hydrogen in a tunnel will be done by HSE in a 70 m length tunnel with internal diameter of 3.7 m presented in subtask 2.4.3. It is planned to show the current TPRD releases from 700 bar with 3 mm, and 350 bar with 5 mm. Concentration will be measured and TPRD will be reduced to expected safer size of 0.3 and 0.5 mm, which will prevent formation of flammable concentration.

Passive and controlled mechanical ventilation scenarios will be investigated up to and beyond the critical velocity required to control the flow of hydrogen in the buoyancy dominated far-field limit, using different configurations.

The total number of validation simulations is planned to be at least 8: 4 with current TPRD systems and 4 with safer TPRD solutions. The test matrix is proposed in Table 5.

Table 5. Simulations matrix on hydrogen release and dispersion in a tunnel.

Test	Release	Ventilation
1	3 mm, 700 bar (current system)	passive
2	5 mm, 350 bar (current system)	passive
3	3 mm, 700 bar (current system)	Mechanical at critical rate
4	5 mm, 350 bar (current system)	Mechanical at critical rate
5	0.3 mm 700 bar (safe system)	natural
6	0.5 mm 350 bar (safe system)	natural
7	0.3 mm 700 bar (safe system)	Mechanical at critical rate
8	0.5 mm 350 bar (safe system)	Mechanical at critical rate

The final outcome of simulations will be recommendations on the use of a tool based on the results of model validation where both current and safe solutions will be demonstrated and compared.

The plan of activities is presented in Table 6.

Table 6. Plan of activities.

Numerical studies details	Due date	Report at Project Meeting (PM)
(1) Problem formulation: Numerical model	M12	3rd PM - Feb '20 (M12)
(2) Validation of simulations against HSE tests	M24	5th PM - Feb '21 (M24)
(3) Recommendations on the use of tool based on the results of model validation.	M30	6th PM - Sep '21 (M31)

4.3 Simulations of hydrogen release and dispersion with CFD models following large-scale HSE tunnel tests 1 (subtask 2.3.1 / CEA)

CEA has put forward those simulations as a priority against calculation in an underground parking. Indeed CEA is developing an industrial model for cloud dispersion in a tunnel, performing experiments in such a tunnel and then igniting the resulting cloud (experiments and CFD in WP4 for CEA tunnel and HSE tunnel as second priority). CEA will therefore perform the following CFD simulations:

- Trust Trio CFD with mechanical ventilation (M18, D2.2). CFD turbulent (RANS model) 3D calculation of a cloud dispersion following HSE tunnel test. One test will be performed matching HSE experimental conditions. Comparisons with industrial model and experimental results are expected at M30, D2.3. The same simulations will be performed with NEPTUNE CEA CFC code. CEA takes engagement to produce the results with at least one code although expecting to use both.
- CEA will perform the same calculations on the selected CEA tunnel for cloud dispersion as an input for the H2 cloud ignition CFD calculation (WP4). Priority is the CEA tunnel calculation, therefore results delivery of HSE tunnel simulations would be moved from M18 to M30 if further time is required to perform those calculations.

Details on the discretisation, selected geometry or models will be given in the D2.2 report when first (or all) simulations will have been performed.

Concerning the pre-test and validation simulations of hydrogen release and dispersion in underground parking with mechanical ventilation following experiments by USN in sub-task 2.4, the topic has been discussed in Karlsruhe 2nd meeting. It is not a first priority for CEA. Therefore those calculations won't be performed for M18. CEA might do those simulations due to the "benchmark" interest they represent, but CEA takes no engagement on that topic and potential results would be produced at M30, but not sooner.

4.4 Pre-test and validation simulations of the KIT/PS tunnel experiments in sub-task 2.4.4 (subtask 2.3.1 / KIT)

The aim of the CFD simulations is to assess the efficiency of mechanical ventilation on hydrogen dispersion following an unintended unignited release. Commercial CFD code or KIT in-house CFD codes will be adopted. User-defined-function (UDF) models will be developed for high speed hydrogen jet flow with different ventilation conditions (co-flow, cross-flow and anti-flow).

Numerical geometry model and grids will be setup with local mesh refinement in the core region of the jet. Optimally designed locations of sensors will be proposed.

The planned simulation matrix will cover different hydrogen jets with different mass flow rates corresponding to different nozzle sizes, subject to different ventilation conditions with varying flow directions, i.e., co-, counter- and cross-flows, and different levels of ventilation power ranging from 0.1 m/s to 6 m/s.

The matrix of numerical simulations is shown in Table 7.

The computer hydrogen fraction distribution in air will be compared with measured data. The corresponding numerical models are verified by the comparisons.

The completion of the simulation work is planned in M18 (June 2020). The results will be documented in D2.3.

Table 7. Simulation cases of ventilated hydrogen jets flow without ignition.

	Weak ventilation			Strong ventilation		
	Co-flow	Counter-flow	Cross-flow	Co-flow	Counter-flow	Cross-flow
Small mass flow rate of H_2	1	2	3	7	8	9
Large mass flow rate of H_2	4	5	6	10	11	12

4.5 Effect of tunnel slope (subtask 2.3.2 / NCSRD)

4.5.1 Short Review

The vast majority of tunnels are actually inclined (Zhao et al., 2019). The reasons for inclination can be various. The obvious one is the physical restrictions, like for example in undersea tunnels. Other reasons include construction or drainage needs.

The slope is usually a few per cent. According to the current EU Directive, new tunnels are not allowed to have a slope higher than 5% (2.86°). Slopes under 2% (1.15°) are considered to be small. An inclined tunnel can have a longitudinal “V”, a “Lambda” (inverted V) or a straight-line shape. For one-directional circulation, the straight-line tunnel is mentioned as “ascending”, when the vehicles move towards the higher end of the tunnel and “descending” otherwise.

The most important physical consequence of the slope of a tunnel in the dispersion of hydrogen or smoke is the “stack effect”, or “chimney effect” due to buoyancy: for straight-line shaped tunnels, lower density gases have the tendency to be transferred upwards, towards the higher end of the tunnel.

Tunnel inclination (stack effect) for H_2 releases were not studied in the HyTunnel internal project of HYSAFE NoE.

In general, hydrogen dispersion studies in sloped tunnels are rare. Tunnel inclination has attracted the scientific interest especially concerning its effects on fire and smoke propagation. Due to the fact that both smoke and hydrogen are buoyant though, their dispersion is expected to present several similarities. Smoke propagation studies have revealed that the case of descending tunnels is one of the most unfavourable concerning safety and should be carefully examined (Ballesteros-Tajadura et al., 2006, Zhao et al., 2019). The work of Mukai et al. (2005) deserves special attention, since it examines hydrogen dispersion in inclined tunnels. Analysis was performed for three cases: 1) “Lambda” type (inverted V in the longitudinal direction) horseshoe-shaped tunnel with dimensions of 10x7x50 meters (WxHxL) and an inclination of 2%, 2) V-type rectangular tunnel with dimensions of 10x4.5x50 meters and an inclination of 5%, and 3) “Lambda” type horseshoe-shaped tunnel with dimensions of 10x7x200 meters and an inclination of 2%. In all cases the tunnels are uni-directional with 2 lanes, non-ventilated, having 5 cars simulated as boxes with dimensions of 4.7x1.8x1.7 meters. The leakage is horizontal, from the rear of the front-most car, which stops mid-way. The leak rate is set at 133 L/min (20°C), based on U.S. federal automobile safety standard FMVSS301, for a period of 30 minutes (in total 4 kg of H2 released) and the leak hole is square with sides of 0.05 m. The STAR-CD RANS CFD code is employed, with the k-ε turbulence model. The computation domain extends outside the tunnel with a constant-pressure boundary condition and the total number of cells is about 200000.

The results revealed that in all cases the potential risk due to a hydrogen-air mixture above the lower flammability limit is minimal, since only the core of the upward jet close to the car has volume concentrations above 4%. More specifically:

- In case 1, hydrogen is accumulated for about 600s at the ceiling, with a volume concentration there of about 0.006%. By this time it has reached the exits of the tunnel and concentrations practically do not change till the end of the simulation.
- In case 2, the hydrogen travels upwards towards the exits, the layer at the ceiling is extremely thin and concentrations there are lower than those of case 1.
- In case 3, the hydrogen is constantly accumulating, and a very thick layer is formed. Volume concentrations at the ceiling are close to 0.009%.

Seike et al. (2019), in their recent study, examine the thermal fume behaviour of a hydrogen fuel cell vehicle on fire in a non-ventilated tunnel. The CFD simulations do not include hydrogen dispersion, but are mentioned here since three different tunnel inclinations are studied (0%, 2% and 4%). As expected, as the slope increases, at the downwind side the fume propagates faster, while at the upwind side the fume propagation distance decreases. For example, at 240s after the ignition, the thermal fume has arrived at an upwind distance (from the fire point) of about 129m for 0%, of about 99m for 2% and of about 67m for 4% inclination.

4.5.2 Present contribution

Scope:

- To evaluate with CFD the effect of tunnel inclination on flammable cloud size and evolution.

Methodology:

- Review of phenomena/studies on tunnel inclination effects
- Perform simulations using ADREA-HF CFD as continuation of previous HYSAFE work.

Layout / scenarios:

- Tunnel geometry same as within HYSAFE NoE
- Blow-down from 700 bar CGH2 car tank containing 6 kg of H_2
- Release vertically down below car
- Simulate various inclinations starting from no inclination as basis up to 5%, which is the maximum according to the current EU Directive.

The work is planned to be delivered by M14 and documented in D2.2.

5. Experiments (Task 2.4 / HSE)

5.1 Mechanical ventilation in underground parking (subtask 2.4.1 / USN)

5.1.1 Introduction and motivation

The release of hydrogen inside buildings may pose a hazard to people and structures. It is given in (IEC 60079-10-1, 2015), (NFPA 2, 2011), and (ISO/DIS 19880-1, 2018) that the hydrogen concentration should not exceed 1% in air.

A real release of hydrogen inside a confined space, such as an underground parking garage, will give time and space dependent hydrogen concentration. This inhomogeneous nature of hydrogen distribution requires a set condition of the distance from the release to the position of desired 1% hydrogen. The ceiling directly above the release is one such position, while real systems may require a position offset by a distance.

The physical geometry is assumed to influence the concentration largely (both the actual concentration value and the dynamics of the concentration build-up).

It is important to find the release rates at which the mass flow of hydrogen does not create a cloud of concentration above 1% (or 4%, or other criteria). The influence of mechanical ventilation in such a setup is also an important factor in the investigation.

The direction of the release inside the enclosure is also important, as a downwards impinging jet will give a different concentration compared to a straight upwards jet.

The approach for calculation of hydrogen concentration in semi-confined space with forced ventilation will include two models proposed in (HyTunnel-CS D1.2, 2019) and will be based on the perfect mixing equation and model of passive ventilation. The perfect mixing equation is the simplest tool that can be used to calculate air flow by forced ventilation depending on hydrogen release rate to keep hydrogen concentration below required level at steady-state conditions (constant flow rates of hydrogen from a leak and air by forced ventilation):

$$\mathrm{C\%} = \frac{100 \cdot Qg}{Qa + Qg},$$

where C% is the steady state gas concentration (% by volume), Qa is the air flow rate (m^3/min), and Qg is the gas leakage rate (m^3/min).

The theory for mechanical ventilation is based on equation for passive ventilation by (Molkov et al., 2014) to calculate the hydrogen gas concentration, *X*, following a release ventilated enclosure:

$$X = f(X) \cdot \left[\frac{Q_0}{C_D A (g' H)^{1/2}} \right]^{2/3}$$

where Q_0 is the volumetric flow rate of release, C_D is a discharge coefficient, A is vent area, g is the gravity acceleration and H is the vent height. Function *f*(*X*) defines the difference between the approximate solution for volumetric fraction of hydrogen by the natural ventilation theory and the exact solution of the problem using the passive ventilation theory. Function *f*(*X*) is calculated as:

$$f(X) = \left(\frac{9}{8}\right)^{1/3} \cdot \left\{ \left[1 - X\left(1 - \frac{\rho_{H_2}}{\rho_{air}}\right)\right]^{1/3} + (1 - X)^{2/3} \right\}$$

A "forced ventilation" model has been built on the principles of the passive ventilation model (Molkov et al., 2014) that calculates ventilation flow rate to provide maximum hydrogen concentration in an enclosure below the required level.

The perfect mixing equation, which gives an average concentration of hydrogen in the volume under predicts the maximum concentration calculated by passive theory by 38%.

In most of realistic releases hydrogen concentration in enclosure will be rather non-uniform. Thus, averaged concentration calculated by perfect mixing equation could be below the maximum concentration under the enclosure ceiling and hence both theories have to be tested.

The forced ventilation tool, implementing the theory described above, is available at https://elab-prod.iket.kit.edu (login: **HyTunnel**, password: **Safety2019**).

5.1.2 Specific objectives and expected outcomes

The main expected outcome of this sub-task is a set of experimental data for validation of CFD methods. It could give a general recommendation on ventilations rates and hydrogen release rates, but the effect of geometry layout and scaling has to be identified. The effect of impinging hydrogen jets is expected to verify other similar investigations.

The experimental results might give enough data to verify which concentration model is valid for design of engineering car parking garages.

It is also expected to give recommendations on maximum TPRD diameter from the experiments.

5.1.3 Knowledge gaps and accident scenarios assessed

There are identified five knowledge gaps to be closed by this experimental campaign.

1. The upper limit of hydrogen release rate that will not require change in ventilation system
2. Effectiveness of regulated ventilation systems in case of hydrogen release accident
3. Engineering tool for the assessment of ventilation system parameters to prevent and mitigate flammable mixture formation in tunnels and especially its ventilation systems
4. The effect of using fans in confined spaces
5. Impinging hydrogen unignited jets

It is, however, not possible to close all of these gaps based on the experimental campaign, as it is not possible to address the effect of geometry in such problems. The geometrical effects should be addressed using numerical simulations and validate them against the experimental results. The knowledge gaps KG3 "Engineering tool for the assessment of ventilation system parameters to prevent and mitigate flammable mixture formation in tunnels and especially its ventilation systems" will only use the experimental results as input to modelling. It is not considered a part of this sub-task.

5.1.4 Links with other subtasks and work-packages

This work is connected to the modelling work in 2.2 and the numerical simulations in 2.3. The pre-test simulations in 2.3.1 will be used as design criteria for the experiments. It will also give the positions of the concentration sensors to be used it the experiments.

The numerical simulations in 2.3.1 will then use the experimental results as validation data.

5.1.5 Detailed specification

This section gives a detailed specification of the experiments as they are planned. It will provide sufficient data on the method of producing the experimental data.

5.1.5.1 Conceptual design

The key concept of this study is to use a 40 feet shipping container (or similar dimensions) as the confined space. There will be installed a mechanical ventilation system at the closed end, whereas the other end will be open. Figure 3 and Figure 4 gives a sketch of the experimental setup.

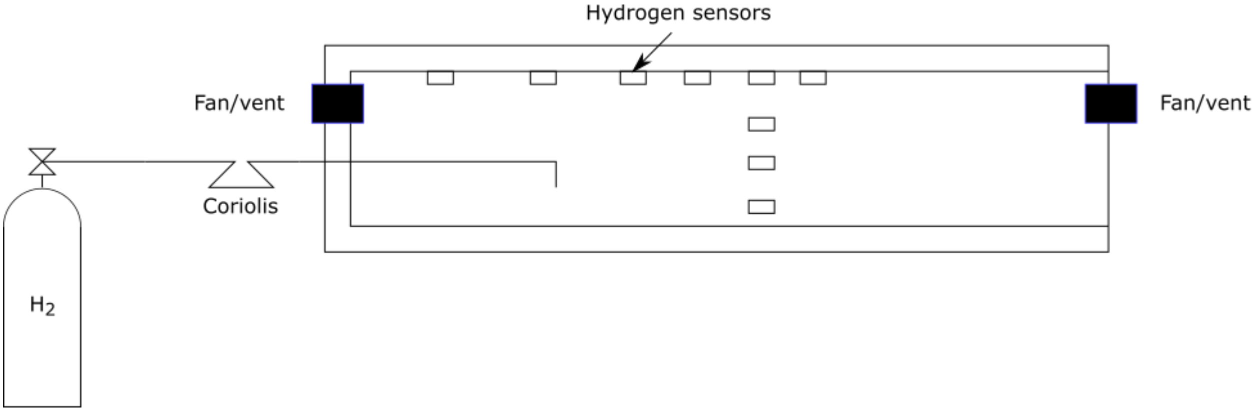


Figure 3. Sketch of the experimental setup.

The release of hydrogen inside the confined volume will be directed both upwards and downwards. The downwards release will be under a structure to simulate a scaled version of a car with a TPRD release under the car.

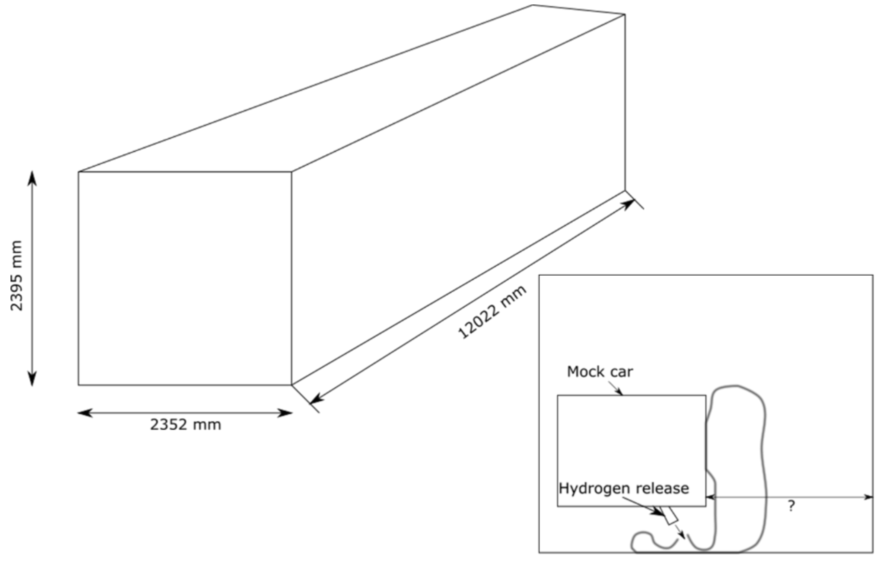


Figure 4. Sketch of release direction and geometry dimensions.

5.1.5.2 Instrumentation

The main instrumentation in this experimental test will be the concentration sensors by Xensor XEN-5320. The hydrogen mass flow will be measured by a coriolis type flow meter. A hot wire anemometer will be used to measure the ventilation velocity inside the container. Hydrogen concentration sensors will be positioned in the facility and their location will be set according to the outcomes of numerical simulations in sub-task 2.3.1.

5.1.5.3 Infrastructure

The 40” container and the Norward test site in Bamble Norway are the main infrastructures in this experimental investigation. There could be an option to use a concrete container with equal dimensions instead of the steel container.

5.1.5.4 Anticipated range/number of tests that can be undertaken

The agreed number of experiments is 25 in total (Grant Agreement). These 25 experiments will be selected from the proposed 33 experiments given in table below. The KG represents the knowledge gaps to be fully or partially answered within this experimental campaign.

Table 8. Anticipated number of the tests and main parameters.

exp num ber	release direction (u or d)	Hydrogen mass flow	Ventilation rates (m/s)					comments
1	u	m1	v1		KG2	KG4	KG5	low mass flow
2	u	m2	v1		KG2	KG4	KG5	high mass flow
3	u	m3	v1		KG2	KG4	KG5	medium mass flow
4	d	m1	v1		KG2	KG4	KG5	low mass flow
5	d	m2	v1		KG2	KG4	KG5	high mass flow
6	d	m3	v1		KG2	KG4	KG5	medium mass flow
7	u	m1	v2		KG2	KG4	KG5	low mass flow
8	u	m2	v2		KG2	KG4	KG5	high mass flow
9	u	m3	v2		KG2	KG4	KG5	medium mass flow
10	d	m1	v2		KG2	KG4	KG5	low mass flow
11	d	m2	v2		KG2	KG4	KG5	high mass flow
12	d	m3	v2		KG2	KG4	KG5	medium mass flow
13	u	m1	v3		KG2	KG4	KG5	low mass flow
14	u	m2	v3		KG2	KG4	KG5	high mass flow
15	u	m3	v3		KG2	KG4	KG5	medium mass flow
16	d	m1	v3		KG2	KG4	KG5	low mass flow
17	d	m2	v3		KG2	KG4	KG5	high mass flow
18	d	m3	v3		KG2	KG4	KG5	medium mass flow
19	d	m1.1	v1	KG1	KG2	KG4		1st iter. lim mass flow
20	d	m1.2	v1	KG1	KG2	KG4		2nd iter. lim mass flow
21	d	m1.3	v1	KG1	KG2	KG4		3rd iter. lim mass flow
22	d	m1.1	v2	KG1	KG2	KG4		1st iter. lim mass flow
23	d	m1.2	v2	KG1	KG2	KG4		2nd iter. lim mass flow
24	d	m1.3	v2	KG1	KG2	KG4		3rd iter. lim mass flow
25	d	m1.1	v3	KG1	KG2	KG4		1st iter. lim mass flow
26	d	m1.2	v3	KG1	KG2	KG4		2nd iter. lim mass flow
27	d	m1.3	v3	KG1	KG2	KG4		3rd iter. lim mass flow
28	d	d=2mm	v1	KG1	KG2	KG4		700bar Blow down
29	d	d=0.5mm	v1	KG1	KG2	KG4		700bar Blow down
30	d	d=0.2mm	v1	KG1	KG2	KG4		700bar Blow down
31	d	d=2mm	v3	KG1	KG2	KG4		700bar Blow down
32	d	d=0.5mm	v3	KG1	KG2	KG4		700bar Blow down
33	d	d=0.2mm	v3	KG1	KG2	KG4		700bar Blow down

5.1.5.5 Constraints (noise, pressure, site availability)

The total mass of hydrogen inside the container is a constraint, as there will be a limit on the total energy released per experiment. The site availability is also may also be a constraint, as experiments will be performed at a third party location.

5.1.6 Delivery timeline

The delivery timeline is given in Table 9.

Table 9. Delivery timeline for experimental campaign on mechanical ventilation in underground parking.

Experimental campaigns timeline	Month due	Report at project meeting (PM)
1. Detailed experimental series finalized before M12. The results will show the effect of typical ventilation rates on the hydrogen concentration from accidental releases of hydrogen in parking systems. Details will be on release rates and ventilation rates, obstructions and release direction. The experiments will be performed in 40’ iso-container with forced ventilation from jet-fan.	M12	3rd PM - Feb '20 (M12)
2. Experimental results obtained before summer 2020.	M16	4th PM - Sep '20 (M19)

5.2 Unignited Pressure Peaking Phenomenon (subtask 2.4.2 / USN)

5.2.1 Introduction and motivation

The rapid hydrogen discharge from the tank in confined spaces leads to high overpressure, that may cause property damages. The pressure peaking phenomenon (PPP) is characterized as a transient overpressure with a characteristic pressure peak in vented enclosures. PPP occurs while introducing gas with lower density than the gas already inside the enclosure. The phenomenon is distinct for hydrogen and occurs when released hydrogen mass flow rate is relatively high and the vent area is relatively small (Makarov et al., 2018). The overpressure will grow, then decrease to a steady state pressure. Previous numerical validation (Hussein et al., 2018) shows and confirmed that the two major parameters to determine the overpressure in an enclosure are the vent size and hydrogen mass flow rate into enclosure. It has the most significant role on creating the high overpressures. Brennan and Molkov (2018) have presented work where they have investigated ‘safety’ PRD (Pressure Relief Device) parameters with correlation of natural ventilation variables in enclosure for a blow down scenario. Their work provided a model description used during experiments described in this report. The study showed that with decreasing the PRD diameter, the overpressure will drop accordingly. Their study presented correlation between hydrogen concentration and the vent area.

5.2.2 Specific objectives and expected outcomes

This subtask will demonstrate the PPP in large scale experiments. This will result in a set of validation data for numerical simulations and engineering models, but also aim to provide experimental results that will directly give guideline recommendations.

5.2.3 Knowledge gaps and accident scenarios assessed

The knowledge gap that will be addressed in this subtask is the pressure peaking phenomenon validation for garage-like enclosures for unignited releases.

5.2.4 Links with other subtasks and work-packages

Subtask 2.4.2 is closely connected to subtask 2.2 on the engineering models for Pressure Peaking Phenomenon. It is also connected to the WP3 subtask 3.4.1 on ignited PPP in large scale. The experimental planning and execution is closely connected to the modelling work by UU in task 2.2 as it is used as input to the experimental work.

5.2.5 Detailed specification

This section gives a detailed specification of the experiments as they are planned. It will provide sufficient data on the method of producing the experimental data.

5.2.5.1 Conceptual design

The experimental work planned in this task will be conducted at a test site outside USN. The rationale behind this decision was based on the time and infrastructure available. At the external site, there was an available steel reinforced container of 14.9 m^3. This was considered to be optimal for these tests.

The steel container is shown in Figure 5. It has several M18 holes for instrumentation and a small door for access. A lot of work had to done to seal the joints between the side walls and the end walls. There are also five $80mm$ pipes through the walls or floor. Two flanges are used as ports for hydrogen and air (for flushing after experiment). The rest of the flanges are closed or open as vents.

Figure 5. Steel container for Pressure Peaking Phenomenon experiments.

A P&ID is shown in Figure 6. The whole experimental setup is controlled by a central timing unit (pulse generator), and all sensor data are stored by either two oscilloscopes (Sigma and Gen3i). The P&ID shows the pneumatically operated valves for H_2 and air (for flushing after experiment) and their control signal for the pulse generator.

The H_2 reservoir will use a 12 bottle stack at 200 bar for constant mass flow validation experiments and a 36 l pressure vessel with 700 bar H_2.

The vent opening area and the mass flow will be the variables in this experiment. The hydrogen nozzle will to a certain degree determine the mass flow of hydrogen into the enclosure.

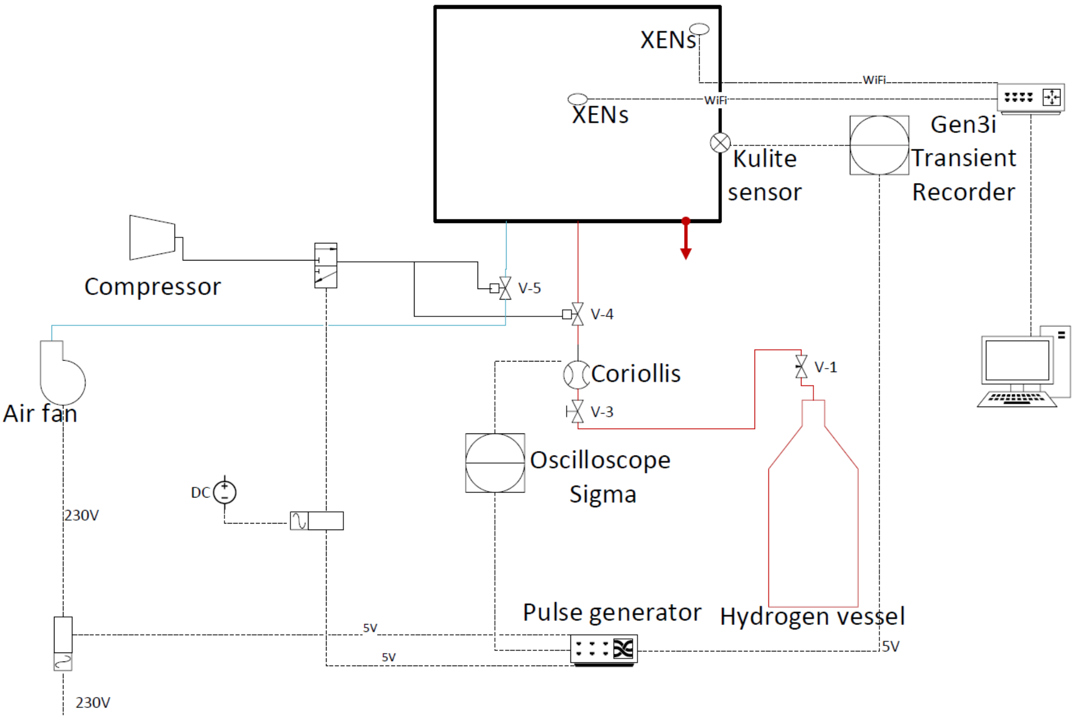


Figure 6. P&ID for the unignited PPP experiments.

5.2.5.2 Instrumentation

The main instrumentation in this experimental setup is the pressure measurement. A pressure transducer of type: Kulite pressure transducer XTM - 190-50A or similar will be used in the experiments. One or two sensors will be used. The pressure peaking phenomenon is a transient phenomenon with a characteristic time in the order of seconds. Based on this there is less interest to capture acoustic waves in the enclosure. The logging frequency will still be in the order of 1 to 10kHz.

Coriolis type mass flow meters will be used to measure the mass flow of hydrogen into the enclosure. XEN-5320 wireless sensors will be used to measure the hydrogen concentration and temperature inside the enclosure. The XEN-5320 has a complex accuracy depending on humidity and temperature, but has a sensor noise of 500ppm.

Table 10. Uncertainty of measurements.

Pressure sensor	±1% FSO BFSL (Full Scale Output - Best Fit Straight Line)	±3.5kPa
Mass flow sensor	±0.5% of flow rate	
Concentration sensor	1-3 %FS	1-3%

5.2.5.3 Infrastructure

The main infrastructure is the test site and the hydrogen tanks and pumps. The experimental progress is dependent on this infrastructure. The availability of the test site has to be coordinated with the owner of the test site. The delivery of the hydrogen tanks and pumps is still partially undecided, as the tank is ordered from Hexagon while USN is still waiting on a tender from Proserv company (national Haskel supplier).

5.2.5.4 Key resources

No key resources identified. Dedicated man-hours to this project are provided from USN.

5.2.5.5 Anticipated range/number of tests that can be undertaken

The experimental plan for this sub-task is given below. The first experimental campaign has been completed, and the 700 bar campaign will follow later.

Table 11. Experimental matrix for first PPP campaign.

Exp nr	Vent area (m^2)	Average mass flow (g/s)
1	0.0012	1.9
2	0.002	3.5
3	0.0014	9.05
4	0.0014	9.9
5	0.0006	10.1
6	0.0006	3.05
7	0.0006	3.05
8	0.0006	4.75
9	0.0006	4.2
10	0.0006	blowdown

The next PPP campaign will focus on 700 bar hydrogen in a 36 l tank, where the mass flow will be a blowdown of the tank with variable nozzle diameter and vent area.

Table 12. Experimental matrix for second PPP campaign.

Exp nr	Vent area (m^2)	Pressure (bar)	Nozzle d (mm)
11	A1	700 bar blowdown	2
12	A1	700 bar blowdown	0.5
13	A1	700 bar blowdown	0.3
14	A2	700 bar blowdown	2
15	A2	700 bar blowdown	0.5
16	A2	700 bar blowdown	0.3

The exact details of the vent area will be determined at a later stage on the basis of pre-calculations.

5.2.5.6 Constraints (noise, pressure, site availability)

The main constraint of this experimental sub-task is the availability of hydrogen and the 700 bar system of tank and pump. It is also a constraint on the mass flow measurements as the available 700 bar coriolis mass flow meter does not handle the maximum mass flow expected from a blow down of a 700 bar tank with a 2 mm nozzle. It is however, an unknown pressure drop in the whole system that will result in an effective lower mass flow. It is expected a substantial pressure drop through the mass flow meter.

5.2.6 Delivery timeline

Table 13. Delivery timeline for experiments on Pressure Peaking Phenomena.

Experimental campaigns timeline	Month due	Report at project meeting (PM)
1. Releases in 15 m3 volume with lower source pressure (can be reported in intermediate report)	M12	3rd PM - Feb '20 (M12)
2. Releases in 15 m3 volume with 700 bar pressure source	M30	6th PM - Sep '21 (M31)

5.3 Dynamics of H2 release and dispersion in a tunnel (subtask 2.4.3 / HSE)

This sub-task aims at investigating the dynamics of hydrogen release and dispersion in a tunnel, including the effect of ventilation. the experiments will aid the determination of hazard distances of unignited release, i.e. location of flammable hydrogen-air mixture for releases and dispersion in realistic scenarios at high storage pressures.

5.3.1 Objectives

The objectives of the proposed series of experiments are:

- Undertake a number of scaled hydrogen jet releases representing the blowdown of a vehicle fuel tank following operation of the TPRD.
- Measurement of the resultant hydrogen concentration profiles downstream of the release point for various ventilation flows.
- Measurement of the resultant near field hydrogen concentration profiles for three different jet orientations. This will include the effects of obstructions in the tunnel on near field dispersion.in the tunnel on near field dispersion.
- Provision of experimental data for relevant model developments and their validation.

5.3.2 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.

The tunnel will house a hydrogen storage vessel simulating hydrogen storage in a typical fuel cell powered vehicle, i.e. with the capacity to store an appropriate quantity of hydrogen gas at pressures up to 700 bar. The facility will be equipped with the following ancillary equipment for the purpose of delivering the desired experimental objectives:

- axial fan
- gas booster
- 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 vertically along the tunnel centreline to record concentration profiles. Figure 7 shows the axial positions of the sensor ports.

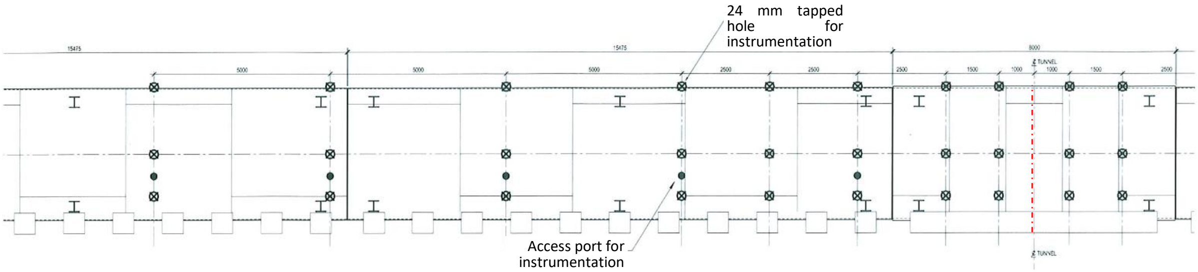


Figure 7. External elevation showing port location; port positions are mirrored around centreline (in red) and on both side elevations

Figure 8 shows the radial distribution of the instrument ports.

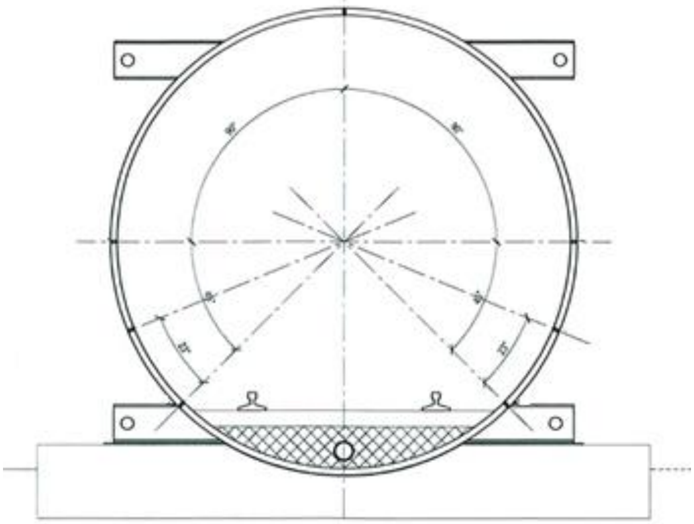


Figure 8. Tunnel cross section.

5.3.3 Experimental Arrangement

The gas storage vessel will have a volume equivalent to that of a storage vessel to be used in practice on future transport vehicles, and will store hydrogen at pressures up to 700 bar. The vessel will incorporate a double bursting disc assembly allowing for the (near) instantaneous release of hydrogen gas, as required for HSE's contribution to item D4.1 of the research programme. To allow dispersion experiments the vessel will incorporate a suitably sized off-take to which a nozzle representing a TPRD or an actual TRPD may be attached. The vessel is shown schematically in Figure 9.

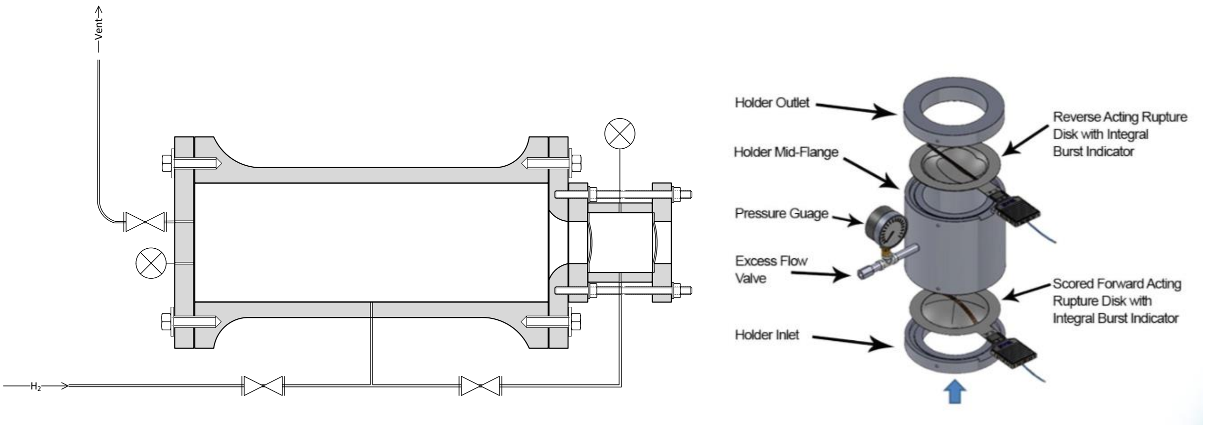


Figure 9. Schematic of proposed hydrogen storage vessel, incorporating double bursting disc assembly and TPRD off-take.

During the proposed experiments the double bursting disc unit will be sealed off, and 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 the test vessel at pressures up to 700 bar. The mass flow rate from the vessel will be measured with a Coriolis flow meter and/or a pressure transducer and thermocouple. The off-take pipework has a pneumatically operated stop valve to allow flow out of the vessel through the nozzle. Flow rates up to 100 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 alongside a type-K thermocouple for temperature measurement. The nozzle will be set in three different orientations to represent possible release scenarios namely; vertically upwards, vertically downwards, and horizontally co-current to the ventilation flow.

A small central section of the tunnel will be concreted to the approximate depth shown in Figure 8; this will provide a secure mounting area for the storage vessel in order to prevent movement during testing. A metal plate will also be secured directly under the vertically downwards pointing jet to act as a spreader plate for the jet during these tests, to simulate the effect of the tunnel floor.

A variable-speed axial fan(s) will be located at the northern entrance to the tunnel, capable of achieving volumetric flow rates up to 1.2×10^5 m^3/h. This equates to a maximum linear air flow velocity of 3 m/s. The fan will drive air through the tunnel from this end. The airflow along the tunnel will be measured and characterised particularly within the centre section. If necessary, baffle plates and/or flow straighteners will be added near the tunnel entrance to produce a well-developed swirl-free inlet flow.

5.3.4 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 from vehicles such as a car, bus or train in a typical full-sized tunnel. The actual representations are suggested in section 5.3.8 following a study of the various accident scenarios and will be scaled as described in the following sections following the method described by Hall and Walker (1997). Appendix 2 describes the approach implemented by HSE to the scaling criteria.

5.3.4.1 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 2) that: $U \propto H^{\frac{1}{2}}$ and $\dot{V} \propto H^{\frac{5}{2}}$, where H is the characteristic length scale, and U is the ventilation velocity and $\dot{V}$ is the volumetric source flow. In addition the mixing zones will be similar if the source momentum flux M scales as $M \propto H^3$.

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 $(7.6/3.7)^{1/2}$).

5.3.5 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 5.3.4.1, thus: $U \propto H^{\frac{1}{2}}$ and $\dot{V} \propto H^{\frac{5}{2}}$. However the mass released and the time of the release scale as follows. According to eq. (14) (see Appendix 2), 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 $t \propto H^{\frac{1}{2}}$.

In the example given in 5.3.4.1 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 blowdown 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 $m \propto H^{\frac{5}{2}}$.

5.3.6 Catastrophic releases

In this case the inventory is released in a time very short compared with the time scale of flow past the source. The structure of momentum driven flow will not be greatly affected by tunnel flow – the resulting cloud will simply be convected downstream. In this case the most appropriate scaling for the total inventory would be as the cube of length scale – see *Scaling rules for reduced-scale field releases of hydrogen fluoride* (Hall and Walker, 1997).

5.3.7 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 hydrogen concentrations will be measured downstream in the buoyancy dominated zone using fast thermal conductivity sensors and/or oxygen deficiency sensors. The exact numbers and locations of the sensors to be used will be confirmed once the behaviour of the jet release has been established. It is expected that up to seven vertical sensors arrays will be needed, positioned along the centerline of the tunnel. The greatest number of sensors will be located in the boundary layer near the crown of the tunnel.

The air flow characteristics for three ventilation flow rates will be measured by obtaining the velocity profiles across the tunnel immediately upstream of the jet release area. Several hot-wire anemometers will be used for this task. If required for modeling purposes the turbulence intensity near the crown and on the centerline of the tunnel will also be measured.

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 can also record at 100 kHz for several seconds should this prove necessary.

5.3.8 Proposed test programme

Based upon the accident scenario analysis carried out in HyTunnel-CS D1.3 (2019), 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 HyTunnel-CS D1.3 (2019), are as follows:

1. CAR: Five makes specified, all operating at 700 bar. Tank capacity varies between 115 to 156 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 Buxton 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 foregoing 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 14.

Table 14. Scaled hydrogen inventories for cars. buses and trains (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 using 1 or 3 vessels shown in Table 15.

Table 15. Correlation of proposed hydrogen to actual tank inventories.

	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

Calculation of orifice sizes for the total inventory contained on a car, bus and train as shown below. 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 16.

Table 16. Equivalent orifice sizes for full-sized releases.

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 17.

Table 17. Initial mass flow rates and discharge times for full size and for scaled inventories.

	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 dia's used (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.

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

If using standard 53 litre size cylinders then we can model the foregoing using different pressures but fixed volumes to give the same initial mass flow rates as follows:

Table 18. Scaled orifice size for experimental releases.

	Scaled total inventory (kg)	**Scaled initial mass flow rates (kg/s)**	**Discharge times (s)**	**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 we 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 10).

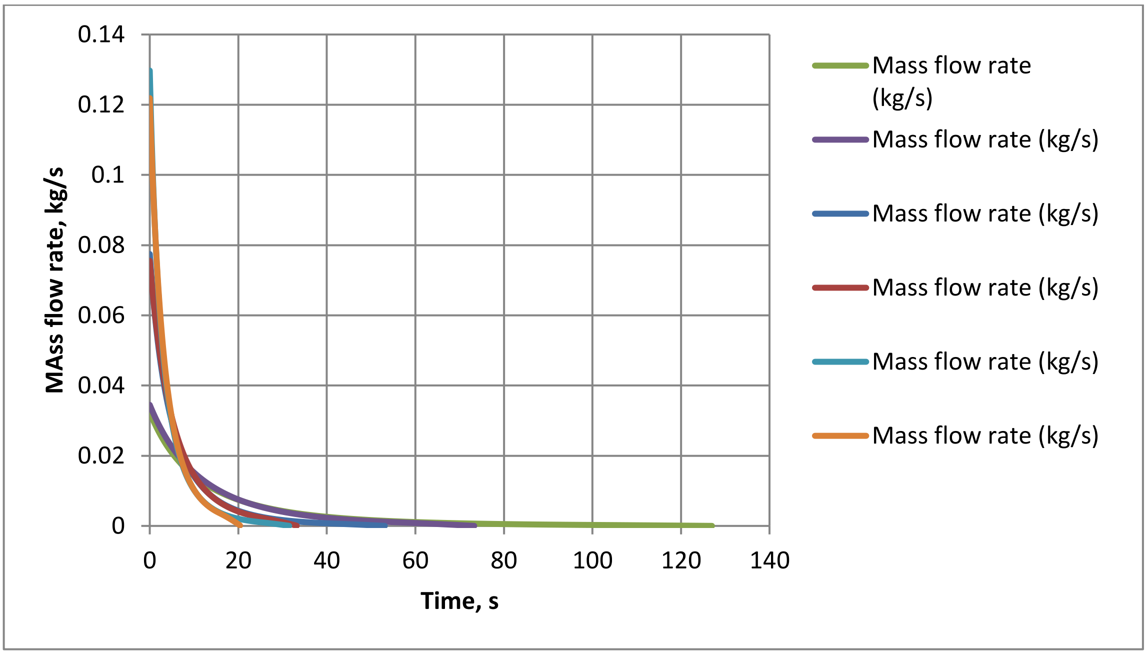


Figure 10. Mass flow rates of hydrogen releases from three scaled orifice sizes for a car compared with actual release rates.

5.3.9 Scaling of airflow in HSE tunnel

HyTunnel-CS D1.1 (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 needs. HyTunnel-CS D1.3 (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 19.

Table 19. 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

5.3.10 Test Matrix

Bases on the analysis in the previous sections 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 test matrix of 36 possible combinations, from which 27 tests will be chosen in consultation with the project partners.

Table 20. Proposed matrix of tests.

Hydrogen Quantity. (kg)	0.45												3.40												5.07											
Ventilation flow rate. (m/s)	2.5				3.7				4.7				2.4				3.5				4.5				2.7				4.0				5.2			
Velocities (m/s)	1.0		2.0		1.0		2.5		1.0		2.5		1.0		2.5		1.0		2.5		1.0		2.5		1.0		2.5		1.0		2.5		1.0		2.5	
Jet orientation	U	D	U	D	U	D	U	D	U	D	U	D	U	D	U	D	U	D	U	D	U	D	U	D	U	D	U	D	U	D	U	D	U	D	U	D

5.3.11 Expected Results

Hydrogen concentration profiles along the tunnel centreline will be obtained for the various test conditions proposed. These are the three scaled vessel blowdowns, nozzle orientations and the ventilation flow velocities. 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 21.

Table 21. Timeline of pre-test and experimental delivery activities.

Experimental campaigns timeline	Month due	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)

5.4 Efficiency of mechanical ventilation on H2 dispersion (subtask 2.4.4 PS/KIT)

5.4.1 Objectives

The objectives of this series of experiments include:

- investigation of hydrogen jet structure and its dispersion in presence of co-, cross- and counter-flow for ventilation;
- experimental determination of hazard distances as a function of the ratio of hydrogen mass flow rate and air flow velocity;
- to provide unique experimental data for related model development and validation; contribution to the recommendations for inherently safer use of hydrogen vehicles in underground transportation systems.

5.4.2 Facility

The experiments will be performed in the safety vessel V220 (A2), as shown in Figure 11. The safety vessel with an inner diameter d_i = 6 m and a height h = 8 m provides a volume of 220 m^3. It is designed for a static overpressure of 11 bar and temperatures up to 150 ^oC. The vessel is equipped with numbers of vents and ports and windows for optical access. The largest two flanges with an inner diameter di = 1890 mm are parallel and located near the ground.

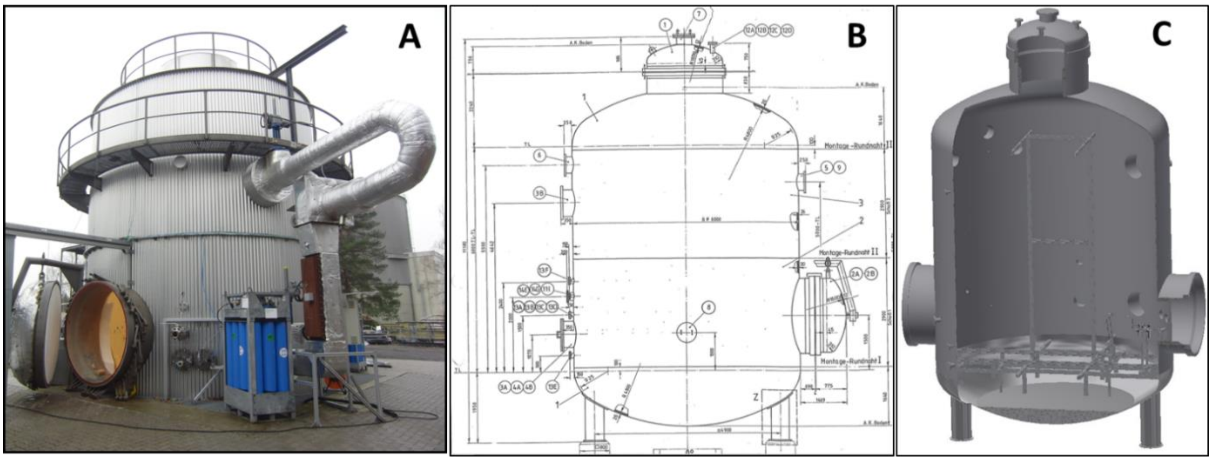
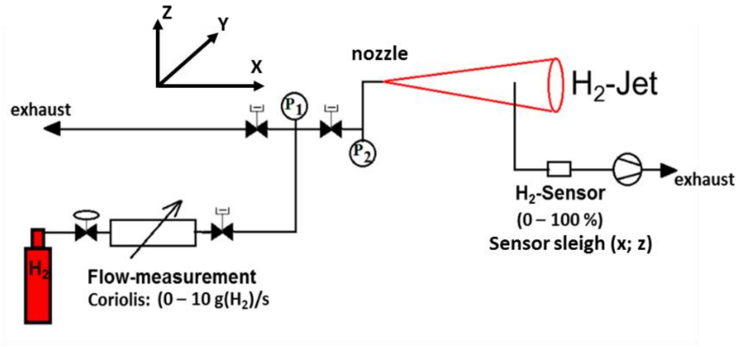


Figure 11. A) Safety vessel V220 (A2) of HYKA, B) Technical drawing, C) CAD-drawing.

The facility for unignited hydrogen jet dispersion tests, shown in Figure 12, is placed inside the safety vessel. The H_2 mass flow rate will be adjusted and controlled by ELITE (Emerson Process Management) Coriolis H_2 Flow Meters (0 – 10 g/s). The H_2 flow runs first through the bypass line. The bypass line is equipped with the same nozzle as the intended jet release nozzle. After a stable H_2 flow through the bypass line is established, the bypass valve will be closed and the jet release valve will be opened simultaneous. The H_2-Jet is characterised by the nozzle diameter and the measured values of the H_2 Flow rate and pressure P2 (Kistler 40058F250) which is measured close to the release nozzle. Additionally, the pressure P1 (WIKA S 20) between the bypass valve and the release valve will be monitored online and recorded with a sample rate of 2 Hz.



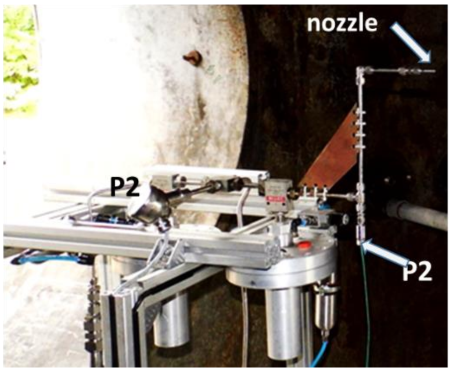


Figure 12. Left, schema of the jet-facility. Right, jet facility inside the safety vessel V220 (A2).

Figure 12 right shows the jet facility inside the safety vessel V220 (A2). The release nozzle is located above the release valve to avoid disturbance of the air flow from the ventilation, in the co-flow configuration. The centre axis of the jet is placed centred and perpendicular to the two large flanges of the vessel, in the co- and counter-flow configuration. In the cross flow configuration the jet will be adjusted parallel to the flange doors, see Figure 13. All experiments will be performed with open flange doors.

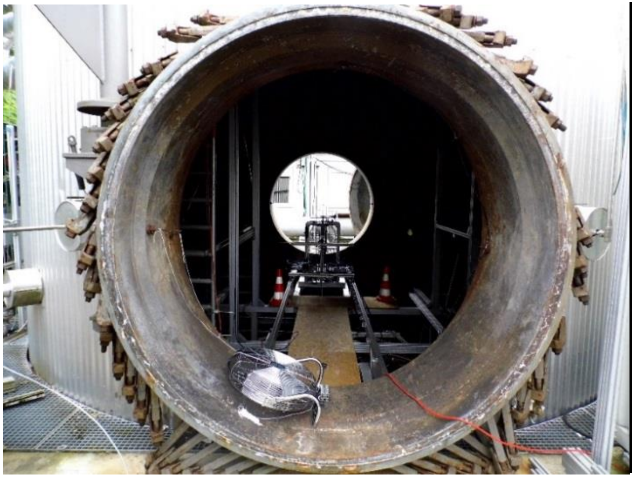
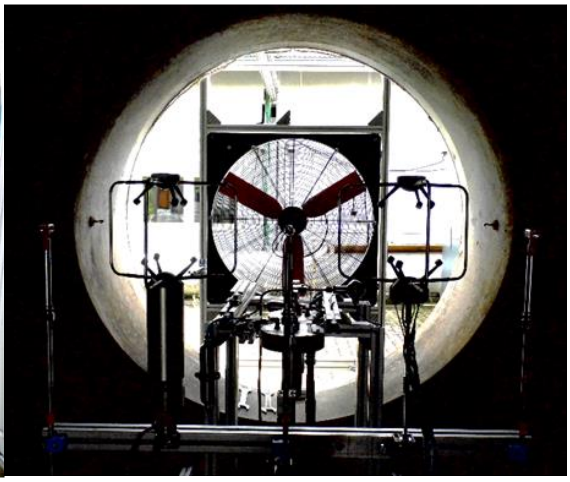



Figure 13. Left, jet facility inside the safety vessel V220 (A2). Right, jet facility inside the safety vessel V220 (A2) with wind machine and flow measurement devices in the co-flow configuration.

A wind machine (Trotec) TTW 20000 with a maximum air flow rate of 20000 m^3/h and a max air flow velocity of 8.8 m/s will be used to simulate a tunnel specific ventilation. Figure 13 left shows the wind machine in the co-flow configuration.

To observe the unignited H_2 jet structure a large scale shadowgraphy set-up for high speed applications will be installed in the safety vessel. The right part of Figure 14 sketches a side view of the optical set up installed in the safety vessel with 220 m^3 free volume. A point light source produces a conical light beam through the H_2 jet. The light beam is reflected on a special reflective foil on the floor of the test facility and returns as a cone to its origin on the top of the vessel. A mirror is used to capture the reflected light. A high speed camera (Fast Cam SA1) with a frame rate of up to 5000 f/s is used to observe the flame front propagation over an area of several m^2.

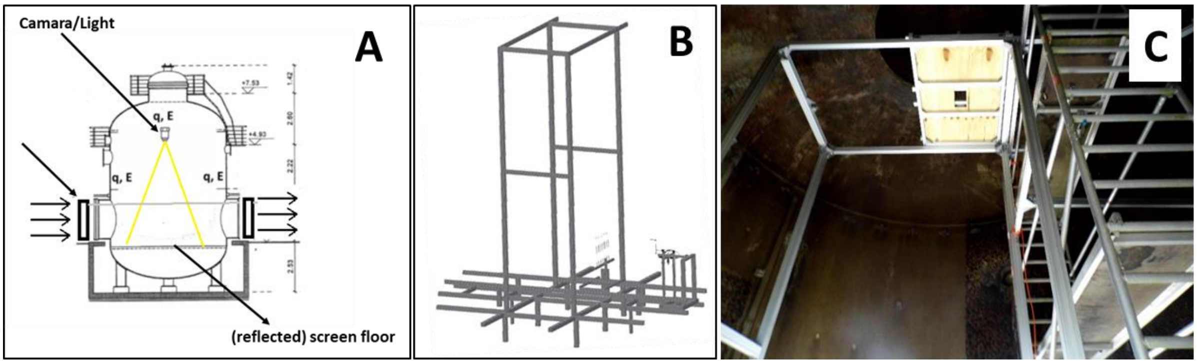


Figure 14. A) Scheme of the large scale shadowgraphy set-up in the safety vessel. B) CAD CAD-drawing of the installed equipment in the safety vessel. C) View to the hosting for camera and light source on the top of the safety vessel.

5.4.3 Measurements

The H_2-Jet is characterised by the nozzle diameter and the measured values of the H_2 flow rate and pressure P2 measured close to the release nozzle.

Hydrogen concentrations will be measured synchronously with 7 fast thermal conductive analyzers (FTC2OO.OEM Messkonzept). Therefore, a small sample gas flow will be sucked continuously, by a small pump, though a capillary tube (di = 2 mm) from the domain of the H_2-Jet. The thermal conductive H_2-Sensor is placed between the sample point (capillary tube) and the pump. The 7 gas sample points will be placed perpendicular to the jet axis to avoid a disturbance of the free jet. The arrangement of the sample points (capillary tube) is placed on a sleigh parallel to the jet axis, Figure 15. This set up allows the investigation of the H_2 concentration in the full 3D domain of the H_2-Jets by shifting the sample points arrangement and re-run the jet release. The 7 H_2-concentration signals will be monitored online and recorded with a sample rate of 2 Hz.

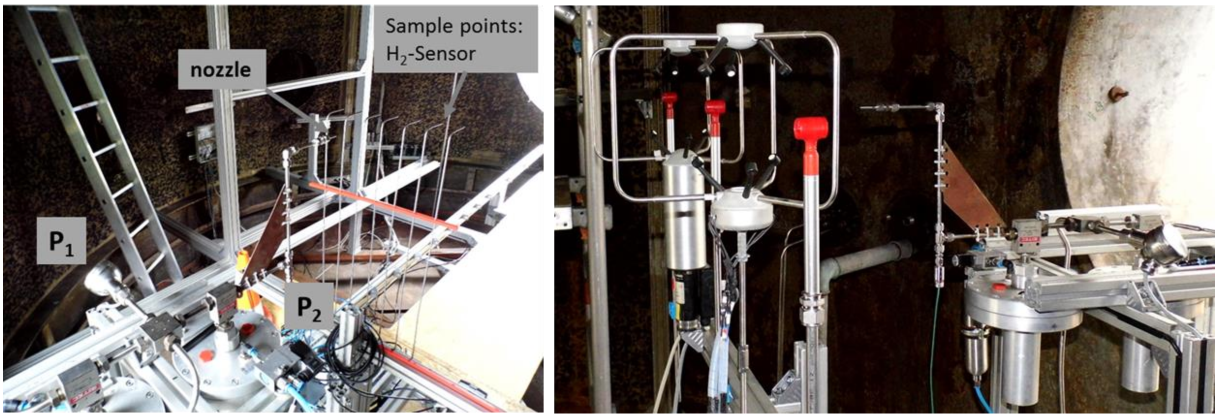


Figure 15. Left, 7 gas sample points in the domain of the H_2-Jet. Right. Air flow measurement devices in the domain of the H_2-Jet.

The flow field produced from the wind machine will be accurately specified in the expected domain of the H_2-Jet. Therefore, 5 air flow measurement devices are used, 3 mechanical MiniAir6 (Schildknecht Messtechnik AG) 1D air flow meters and 2 ultrasonic anemometers (YOUNG MODEL 81000) which are able to measure a 3D air flow. The sensors were placed perpendicularly to the main air flow, in a similar way as the H2 measurement sample points, Figure 15.

5.4.4 Test matrix

The tests of unignited hydrogen jet will be performed in the facility of V220 (A2). The big vents on the bottom side are used as ventilation in- and outlet. The designed test cases are summarized in Table

22. It was considered relevant to analyse hydrogen mass flow rates of 1 and 5 g/s and ventilation velocities of 0, 3.5 and 5 m/s.

Table 22. Test matrix of unignited H_2 jets.

H_2 jet nozzle	1 mm						4 mm					
H_2 mass flow rate, g/s	1			5			1			5		
Ventilation flow velocity, m/s	0	3.5	5	0	3.5	5	0	3.5	5	0	3.5	5
Co-flow	1	2	5	8	9	12	15	16	19	22	23	26
Counter-flow		3	6		10	13		17	20		24	27
Cross-flow		4	7		11	14		18	21		25	28

5.4.5 Results

Hydrogen concentration distributions are obtained as functions of distance, jet mass flow rate, jet nozzle diameter and ventilation flow velocity for the three, co-, counter- and cross-flow cases.

The main conclusion about the hazard distance of a hydrogen jet is obtained through flammability limits. The influence of the forced ventilation can change the axial concentration profile of the free jet, Figure 16 left. This effect can lead to a derivation of the free jet theory, expressed by the H_2-concentration on the jet axis, Figure 16 right.

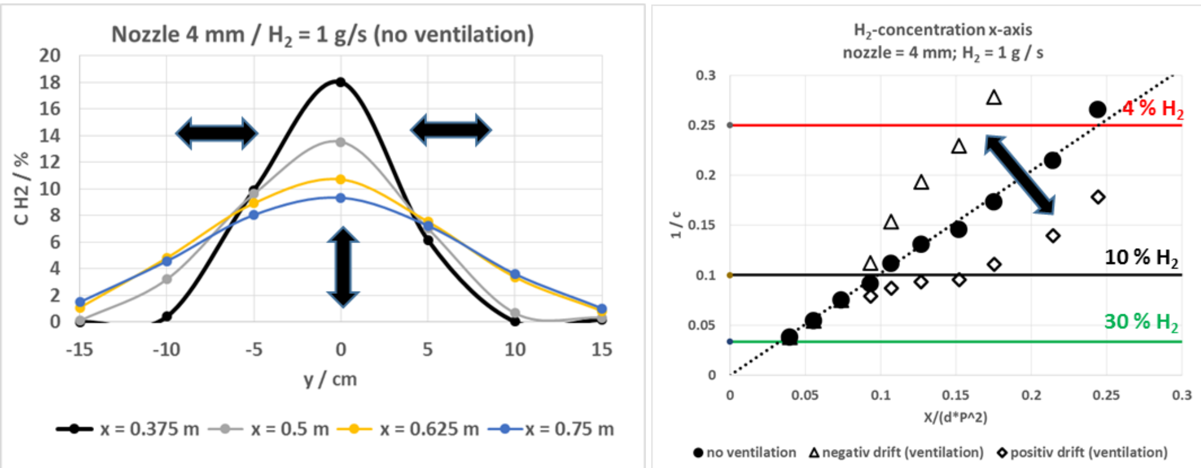


Figure 16. Examples of expected results: Left, change the axial concentration profile of the free jet. Right, derivation of the free jet theory.

6. Summary and interaction of work tasks

The detailed research programme of Work Package 2 on unignited leaks in tunnels and confined spaces has been presented in detail.

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 strong interaction is expected between the experimental program and the simulations program both at the level of pre-test and post-test simulations, which will lead to strong improvement of models, simulation capabilities and deepen our understanding of the relevant phenomena.

A strong interaction is also expected between WP2 and WP3, WP4 as dispersion simulations and experiments will provide the necessary input for any subsequent combustion phenomena.

Finally, the findings from the new experiments and new engineering models will feed into WP6 to provide a set of recommendations for inherently safer use of hydrogen vehicles in underground transportation systems.

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Appendix 1. Milestone 2.1: matrix of experiments, simulations, schedule of tools development (MS2)

Milestone 2.1 presents in matrix form the activities and planning of the a) engineering tools development to be performed within task 2.2 b) numerical simulations to be performed within task 2.3 and c) experiments to be performed within task 2.4. The milestone was prepared and delivered in M6 (August 2019). The document was uploaded on the members area of HyTunnel-CS website. Here, it is included in deliverable 2.1 following the directives given in the Grant Agreement.

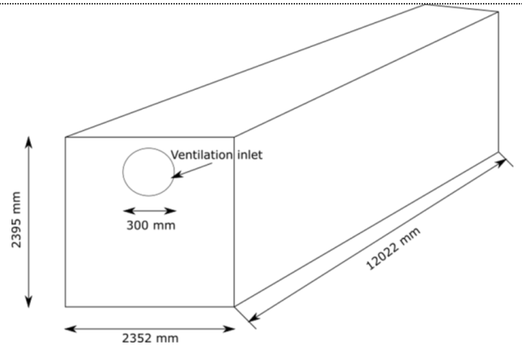
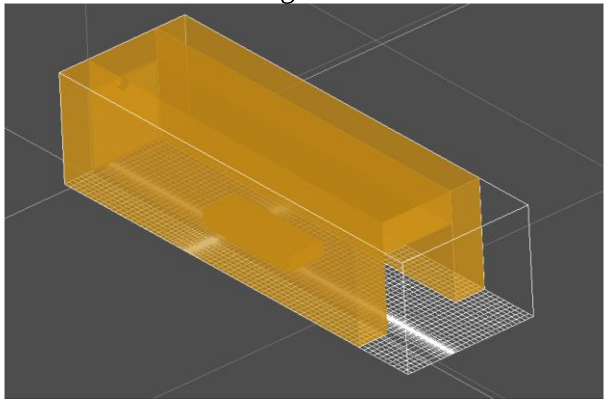
A1.1 Schedule of engineering tools development within Task 2.2 (CEA)

Analytical studies and engineering tools details	Planned date	Report at Project Meeting (PM):	Report in deliverable (M):
Engineering tool for the assessment of ventilation system parameters in tunnels (CEA) Previously developed at RISE (Sweden) or Beijing university models for ventilation in tunnels and smoke dispersion were extensively validated against experiments (real tunnels, galleries (INERIS) etc. We intend to expand those models to account for the presence of hydrogen-air mixture as a buoyant replacement for heated air. The approach is quite straightforward but requires the following steps : (1) Extract a unified model out of the different existing models in the literature ; (2) Identify the thermal buoyant effects in the model to account for buoyant gas mixture instead; (3) Numerical/analytical tool to solve the extended model ; (4) Validation of the model by experimental data available in other projects (INERIS for example, but also results from WP4 experiments carried out by CEA in a real tunnel with a dispersion of helium cloud and then a hydrogen cloud with forced ventilation) ; (5) Final description of a tool for stakeholders use.	M12 M12 M21 M21 M30	3rd PM - February '20 - M12 3rd PM - February '20 - M12 5th PM - February '21 - M24 6th PM - September '21 - M31	D2.2. Intermediate report (M18) D2.3. Final report (M36)
Choked flow and tank blowdown model with Helmholtz free-energy-based hydrogen equation of state (NCSRD) Intention is to include wall effects (friction + heat transfer)	M30	6th PM - September '21 - M31	D2.3. Final report (M36)
Non-adiabatic blowdown model for under-expanded jets from the onboard storage tank (UU) Previously developed at UU adiabatic blowdown model will be expanded to account heat exchange with environment and to provide more accurate and realistic simulation of pressure and temperature in the storage tank and in the underexpanded jet. (1) Problem formulation; (2) Tool implementation; (3) Validation of a tool by experimental data available in other projects; (4) Final description of a tool for stakeholders use.	M7 M7 M12 M31	2nd PM - September '19 - M7 2nd PM - September '19 - M7 4th PM - September '20 - M19 6th PM - September '21 - M31	D2.2. Intermediate report (M18) D2.3. Final report (M36)

Engineering tool for mechanical ventilation in an underground parking (CEA, UU) The model for hydrogen concentration in semi-confined space with forced ventilation will be based on the perfect mixing equation and model of passive ventilation as proposed in deliverable D1.2. The model of passive ventilation was validated against maximum concentration of helium in small scale enclosure. Since in the most of realistic releases the hydrogen concentration in enclosure will be rather non-uniform the perfect mixing equation will be used to calculate air flow by forced ventilation depending on hydrogen release rate to keep hydrogen concentration below required level at steady-state conditions. Both modelling approaches are to be validated against experimental studies performed in Subtask 2.4.1. (1) Problem formulation; (2) Tool implementation; (3) Validation of both tools by HyTunnel-CS experiments; (4) Final description and conclusion on the tool choice and for stakeholders use.	M12 (v.1) M24 (v.2)	3rd PM - February '20 - M12 5th PM - February '21 - M24	D2.2. Intermediate report (M18) D2.3. Final report (M36)

A1.2 Matrix of numerical simulations within Task 2.3 (NCSRD)

Numerical studies details	Planned date	Report at Project Meeting (PM):	Report in deliverable (M):
SUBTASK 2.3.1. Pre-test and validation simulations (NCSRD) This sub-task includes the investigations listed below:			
Pre-test simulations for the experiments of USN in sub-task 2.4.1 (NCSRD) Scope • Support of USN experiments • Provide predicted flammable mass and volume time series within container • Provide videos of flammable cloud evolution • Test jet impingement effects on simulation results Layout • 40 foot iso-container with internal dimensions 12.022×2.352×2.395 m shown in figure 1 • Ventilation inlet at one side, fully open at the opposite side • Mockup car with dimensions 3.5×1.176×0.5 m, located 4.5 m from ventilation wall, 0.2 m from floor, 0 m from lateral wall of container Release • Release nozzle laterally centred below car pointing vertically downwards, 5 m from ventilation wall • Blow-down of 1kg of h2 from stagnation conditions 100 bar, 15 C • Two nozzle diameters 1.0 and 2.0 mm Ventilation • 300 mm diameter, top of inlet 10 cm below ceiling • Two ventilation rates 11.25 and 22.5 ACH Computational tools • NCSRD release tool for blow-down, using NIST EoS formulation • ADREA-HF CFD code for dispersion • Two discretization schemes to test effect of jet impingement • Computational domain and grid shown in figure 2 • Total number of CFD runs: 8	M6	2nd PM - September '19 - M7	D2.2. Intermediate report (M18)

 Figure 1  Figure 2			
Pre-test CFD simulations for the experiments of HSE in sub-task 2.4.3 (NCSRD) Computational tools • NCSRD release tool for blow-down, using NIST EoS formulation • ADREA-HF CFD code for dispersion	M13	3rd PM - February '20 - M12	D2.2. Intermediate report (M18)
Validation simulations for the experiments of USN in sub-task 2.4.1 (NCSRD) Computational tools • NCSRD release tool for blow-down, using NIST EoS formulation • ADREA-HF CFD code for dispersion	M18	4th PM - September '20 - M19	D2.2. Intermediate report (M18)

Validation simulations for the experiments of USN in sub-task 2.4.2 (NCSRD) Computational tools • NCSRD release tool for blow-down, using NIST EoS formulation • ADREA-HF CFD code for dispersion	M34	5th PM - February '21 - M24 6th PM - September '21 - M31	D2.3. Final report (M36)
Validation simulations for the experiments of HSE in sub-task 2.4.3 (NCSRD) Computational tools • NCSRD release tool for blow-down, using NIST EoS formulation • ADREA-HF CFD code for dispersion	M34	5th PM - February '21 - M24 6th PM - September '21 - M31	D2.3. Final report (M36)
Validation simulations for the experiments of PS in sub-task 2.4.4 (NCSRD) Computational tools • NCSRD release tool for blow-down, using NIST EoS formulation • ADREA-HF CFD code for dispersion	M18	4th PM - September '20 - M19	D2.2. Intermediate report (M18)
Pre-test and validation simulations of hydrogen release and dispersion in underground parking with mechanical ventilation following experiments by USN in sub-task 2.4.1 (CEA) CEA will aim to perfom the following CFD simulation: • Thrust TrioCFD with mechanical ventilation • NEPTUNE CEA CFC code, same simulations with different discretisation Simulation results will be compared with experimental data (see M3.1)	M18 M30	2nd PM - September '19 - M7 6th PM - September '21 - M31	D2.2. Intermediate report (M18) D2.3. Final report (M36)
Validation simulations of hydrogen release and dispersion CFD models following large-scale HSE tunnel tests (UU) (1) Problem formulation: Numerical model will be based on recent publication on CFD benchmark on hydrogen release and dispersion in confined, naturally ventilated space with one vent by (Giannissi et al., 2015) validated by GAMELAN facility. For the turbulence modelling dynamic LES will be used. (2) Validation of simulations will be performed against experimental data to be obtained at HSE	M12 (v.1) M24 (v.2)	3rd PM - February '20 - M12 5th PM - February '21 - M24	D2.2. Intermediate report (M18) D2.3. Final report (M36)

Pre-test and validation simulations of the KIT/PS tunnel experiments in sub-task 2.4.4 (KIT) • Commercial CFD code or KIT in-house CFD codes will be adopted, user-defined-function (UDF) models will be developed for high speed hydrogen jet flow with different ventilation conditions (co-flow, cross-flow and anti-flow) • Numerical geometry model and grids will be setup with local mesh refinement in the core region of the jet, coordinates of “sensors” will be defined • Simulation results will be compared to against experimental data	M36	7th PM - February '22 - M36	D2.3. Final report (M36)
SUBTASK 2.3.2. Effect of tunnel slope (NCSRD) Background • Tunnel inclination (stack effect) for H2 releases were not studied with HyTunnel internal project of HYSAFE NoE Scope • To evaluate with CFD the effect of tunnel inclination on flammable cloud size and evolution. Methodology • Review of phenomena/studies on tunnel inclination effects • Perform simulations using ADREA-HF CFD as continuation of previous HYSAFE work Layout / scenarios • Tunnel geometry same as within HYSAFE NoE • Blow-down from 700 bar CGH2 car tank containing 6 kg of h2 • Release vertically down below car • Simulate various inclinations starting from no inclination as basis up to 5%, which is the maximum according to the current EU Directive.	M14	3rd PM - February '20 - M12	D2.2. Intermediate report (M18)

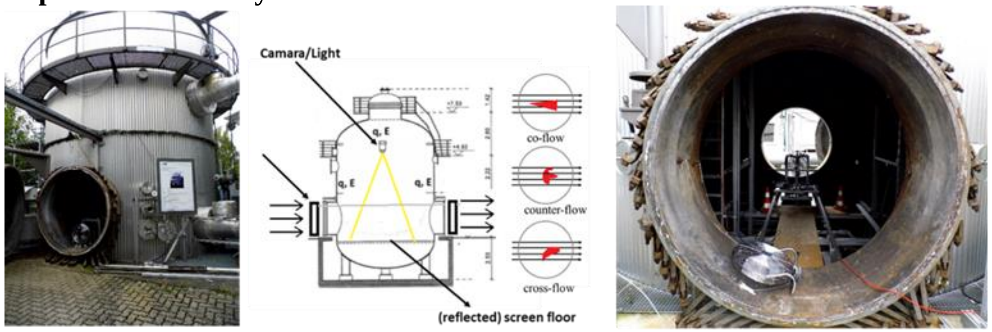
A1.3 Matrix of experiments within Task 2.4 (HSE)

Please provide details for every experimental series you plan for each task/sub-task as in example below.

Experiments details	Planned date	Report at Project Meeting (PM):	Report in deliverable (M):
SUBTASK 2.4.1. Mechanical ventilation in underground parking (USN) (1) Detailed experimental series finalized before M12. The results will show the effect of typical ventilation rates on the hydrogen concentration from accidental releases of hydrogen in parking systems. Details will be on release rates and ventilation rates, obstructions and release direction. The experiments will be performed in 40’ iso-container with forced ventilation from jet-fan. (2) Experimental results obtained before summer 2020.	M12 M16	3rd PM - February '20 - M12 4th PM - September '20 - M19	D2.2. Intermediate report (M18)
SUBTASK 2.4.2. Pressure Peaking Phenomenon for unignited releases (USN) The Experimental results will show pressure build-up in a closed compartment with small vent areas due to hydrogen releases. The experiments will be done in two campaigns. (1) Releases in 15 m3 volume with lower source pressure (can be reported in intermediate report). (2) Releases in 15 m3 volume with 700 bar pressure source	M12 M30	3rd PM - February '20 - M12 6th PM - September '21 - M31	D2.2. Intermediate report (M18) D2.3. Final report (M36)
SUBTASK 2.4.3. Dynamics of H2 release and dispersion in a tunnel (HSE) Experimental test programme to determine flammable concentration profile from continuous release from a 4mm TRPD, 70l, up to 70 MPa vessel in a 70m long, 3.7m diameters circular tunnel Delivery programme will be combined with WP4 ignition consequence experiments Variables assessed in test programme are: 1. Vessel Pressure 2. Bulkhead 3. Forced ventilation 4. Water spray	M15 M18 M24 M27	4th PM - September '20 - M19 6th PM - September '21 - M31	D2.2. Intermediate report (M18) D2.3. Final report (M36)

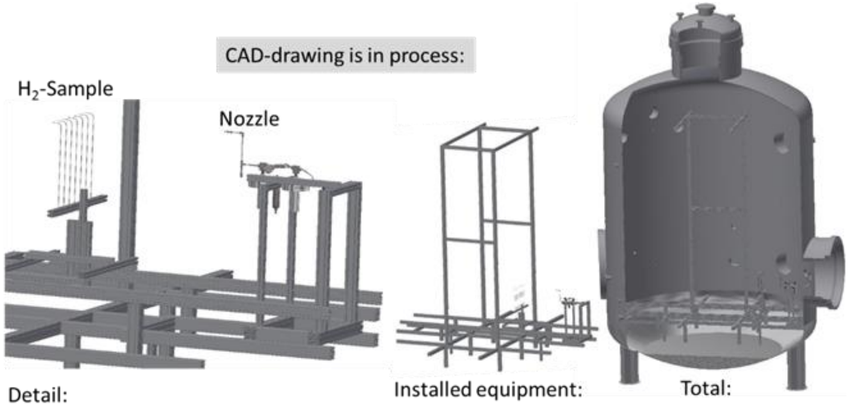
SUBTASK 2.4.4. Efficiency of mechanical ventilation on H2 dispersion (PS)
Investigation of hydrogen jet structure and its dispersion in presence of co-, cross- and counter-flow. Experimental determination of hazard distances as a function of the ratio of hydrogen mass flow rate and air flow velocity.

Experimental facility:



Fig, 1. Jet facility in 220 m3 safety vessel at KIT

The Jet facility was build up in 220 m3 safety vessel at KIT, see Fig.1, The CAD drawing of the facility is in process, and examples see Fig. 2. The CAD-files are available in “Inventor” format. Fig. 3 shows the schema of jet facility.



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Fig, 2. Examples of CAD-drawings: Jet facility in 220 m3 safety vessel at KIT

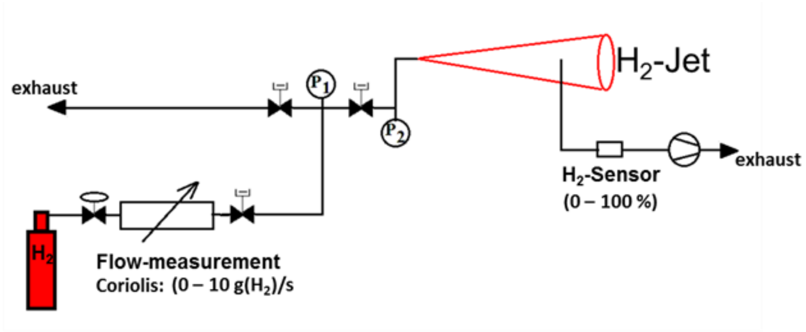

Fig. 3. Schema of jet facility

(1) Experimental series 1
H2--free-jet without forced air flow with Hydrogen concentration in the “steady state jet” in radial and axial directions. Example of H2-concentration measurement inside the H2-free-jet without forced air flow is shown in Fig. 4. The test matrix is listed in Fig, 5.

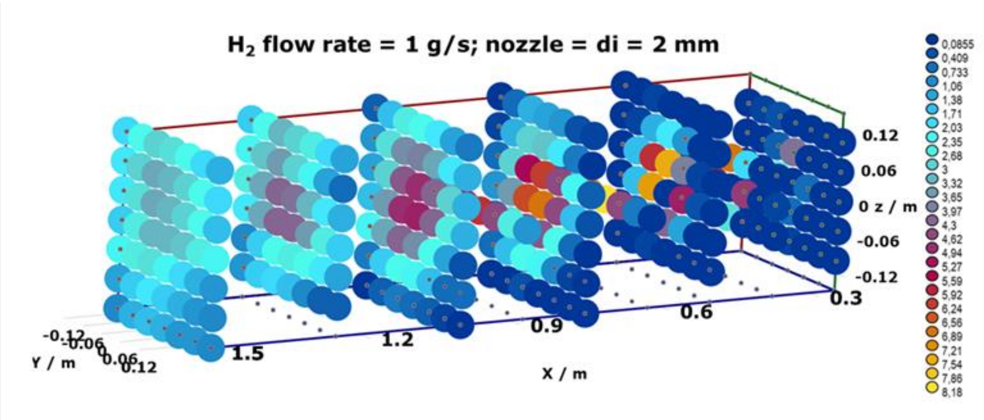

Fig. 4: Example of H2-concentration measurement inside the H2-free-jet without
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forced air flow.

<table>
<tr><td></td><td>Nozzle</td><td>Nozzle</td><td>Nozzle</td></tr>
<tr><td>HH_2-flow</td><td>1 mm</td><td>2 mm</td><td>4 mm</td></tr>
<tr><td>0.5 g/s</td><td></td><td>XXX</td><td></td></tr>
<tr><td>1 g/s</td><td></td><td>XXX</td><td>XX</td></tr>
<tr><td>2 g/s</td><td>XX</td><td>XX</td><td>X</td></tr>
<tr><td>3 g/s</td><td></td><td></td><td></td></tr>
<tr><td>4 g/s</td><td>XX</td><td></td><td>X</td></tr>
<tr><td>5 g/s</td><td>XX</td><td>XX</td><td>XX</td></tr>
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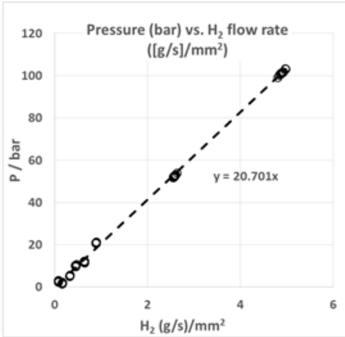

Fig. 5: Left, test matrix: H2-free-jet without forced air flow. Right, dependence between release pressure and H2-flow rate per nozzle area.

Visualization of the H2-Jet structure: A large scale shadow high speed observation system will be installed.
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(2) Experimental series 2
H2-free-jet with forced air flow in co- and counter-flow direction. The flow field will provided by a wind machine TTW 20000: Air flow: 0 - 20000 m³ / h (step less adjustable). Max air outlet speed: 8.8 m / s (31.69 km / h).

Flow field: Two or three different flow velocity’s were selected and investigated for (measurement of 3D flow field).

Test Matrix: see selection of the Matrix shown in Fig.4.

Visualization of the H2-Jet structure: see experimental series 1.
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(3) Experimental series 3
H2-free-jet with forced air flow in cross- flow direction.

Flow field: Two or three different flow velocity’s were selected and investigated for
</td><td>M10</td><td>3rd PM - February '20 - M12</td><td>D2.2. Intermediate report (M18)</td></tr>
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(measurement of 3D flow field). Test Matrix: Is a selection of the Matrix shown in Fig.4. Visualization of the H2-Jet structure: see experimental series 1.			

A1.4 WP2 activities timeline

Summer months
Planned date

			2019										2020												2021												2022	
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
WP	**Task**	**Activities (Leader)**	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2
2	1	MS2.1. Matrix of experiments, simulations, schedule of tools development (NCSRD)						MS																														
2	1	DS2.1. Detailed research programme on unignited leaks in tunnels and confined space (NCSRD)									D																											
2	2	- Engineering tool for the assessment of ventilation system parameters in tunnels (CEA)																																				
2	2	- Choked flow and tank blowdown model with Helmholtz free-energy-based hydrogen equation of state (NCSRD)																																				
2	2	- Non-adiabatic blowdown model for under-expanded jets from the onboard storage tank (UU)																																				
2	2	- Engineering tool for mechanical ventilation in an underground parking (CEA, UU)																																				
2	3	Subtask 2.3.1. Pre-test and validation simulations (NCSRD)																																				
2	3	- Pre-test simulations for the experiments of USN in sub-task 2.4.1 and experiments of HSE in sub-task 2.4.3 (NCSRD)																																				
2	3	- Validation simulations (NCSRD)																																				
2	3	- Pre-test and validation simulations of hydrogen release and dispersion in underground parking with mechanical ventilation following experiments by USN (sub-task 2.4.1) (CEA)																																				
2	3	- Validation simulations of hydrogen release and dispersion CFD models following large-scale HSE tunnel tests (UU)																																				
2	3	- Pre-test and validation simulations of the KIT/PS tunnel experiments in sub-task 2.4.4 (KIT)																																				
2	3	Subtask 2.3.2. Effect of tunnel slope (NCSRD)																																				
2	4	Subtask 2.4.1. Mechanical ventilation in underground parking (USN)																																				
2	4	Subtask 2.4.2. Pressure Peaking Phenomenon for unignited releases (USN)																																				
2	4	Subtask 2.4.3. Dynamics of H2 release and dispersion in a tunnel (HSE)																																				
2	4	Subtask 2.4.4. Efficiency of mechanical ventilation on H2 dispersion (PS)																																				
2	5	MS2.2. Initial results of experimental, analytical and numerical studies (NCSRD)																		MS																		
2	5	D2.2. Intermediate report on analytical, numerical and experimental studies (NCSRD)																		D																		
2	5	MS2.3. Results of experimental, analytical and numerical studies for final report (NCSRD)																																	MS			
2	5	D2.3. Final report on analytical, numerical and experimental studies on hydrogen dispersion in tunnels, including innovative prevention and mitigation strategies (NCSRD)																																				D

A1.5 References

Giannissi, S.G., Shentsov, V., D. Melideo, D., Cariteau, B., Baraldi, D., Venetsanos, A.G., Molkov, V. (2015) CFD benchmark on hydrogen release and dispersion in confined, naturally ventilated space with one vent, International Journal of Hydrogen Energy, Volume 40, Issue 5, Pages 2415-2429.

Critical wind velocity for arresting upwind gaz and smoke dispersion….. Road tunnel. Hu, Weng, Huo. 2007. ▪ Modelling of dense gas dispersion in tunnels. HSE. Robin C Hall WS Atkins Consultants Ltd ▪

Control of Smoke Flow in a Tunnel. Mouraad Boutera. 2013 ▪ Data from CEA H20/h2 interaction in MISTRA facility ▪ Data from CEA GARAGE/GAMELAN he dispersion.

Appendix 2. Scaling Criteria

The following section describes the scaling criteria implemented in HSE approach. 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 17.

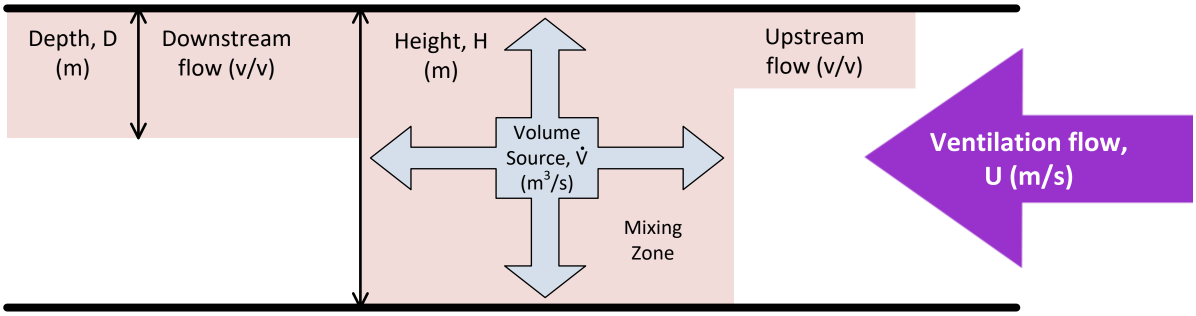

Figure 17. Schematic diagram showing modelling of jet and tunnel ventilation interactions.

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

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

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

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

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

A2.1 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 $U_{tunnel} \propto \sqrt{H}$ [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.