Pre-normative research on safe indoor use of fuel cells and hydrogen systems

*Small or medium-scale focused research project*
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# *Work Package 6*
# *Hyindoor Final Report*

## *D6.2*

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## Abstract

Hydrogen energy applications often require that systems be used indoors (e.g., forklifts in warehouse, refuelling stations, fuel cells for offgrid or backup applications. It may also be necessary or desirable to locate some hydrogen system components/equipment in indoor or outdoor enclosures for security or safety reasons to isolate them from the end-user and the public, or from weather conditions. Use of hydrogen in confined environment requires detailed assessment of hazards and associated risks, including potential risk prevention and mitigation features. The release of hydrogen can potentially lead to the accumulation of hydrogen and the formation of a flammable hydrogen-air mixture. The aim of the Hyindoor project is to develop safety design guidelines & engineering tools as well as RCS recommendations intended to prevent and mitigate hazardous consequences of hydrogen release in confined environments. Closing knowledge gaps is critical to this effort in 3 main areas: hydrogen release conditions and accumulation, vented deflagration and under-ventilated flame regimes.

Each of these phenomena has been subject to analytical, experimental and numerical analysis within a dedicated work package (WP2-Dispersion and accumulation, WP3-Vented deflagrations, WP4-Indoor fire). They each have shared state of the art information in order to prioritize the research objectives. Existing analytical and numerical models were initially used as well as RCS lists (which were updated from time to time) were prepared and RCS gaps were identified. These results were used to facilitate the formulation of the test program, while the experimental results were subsequently used to validate and improve the models and formulate guidelines (WP5-Safety strategies and guidelines) and identify RCS recommendations (WP6-RCS).

Key words : Hydrogen, Indoor use, Fuel cell, Electrolysers, Forklifts, Safety, Risks, Engineering models, codes an standards.

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# *Introduction*

Hydrogen indoor use is an emerging early market which is more and more developed in developed countries. The applications are numerous : hydrogen fuelled forklifts for logistic warehouses, backup power for strategic applications (banks, datacenter, ambassades, ...), off-grid electricity production (wifi and mobile telephony antenna, isolated locations), refueling stations (electrolysers or small reformers, compressor zone, …).
The Hyindoor project addresses the issue of safe indoor use of hydrogen and fuel cells systems (priority 4.6 of the call FCH-JU-2010-1) for early markets. The consortium includes key players in the field comprising industry (Air Liquide, HFCS), research organisations (CEA, KIT-G, HSL, JRC, NCSRD), academia (UU), and an actor in RCS development (CCS Global Group).
The project provides scientific and engineering knowledge for the specification of cost-effective means to control hazards specific to the use of hydrogen indoors or in confined space and developing state-of-the-art guidelines for European stakeholders.
Specific knowledge gaps have been closed in the areas k=like indoor hydrogen accumulations, vented deflagrations, and under-ventilated jet fires in order to be able to optimally implement the most effective safety strategies.
The generated knowledge has been translated into state-of-the-art safety guidelines including specific engineering tools supporting their implementation.
Recommendations have been formulated with regards to evolutions needed in the Regulations Codes and Standards framework at European and International levels to support the safe introduction of fuel cells and hydrogen in early markets.
The outputs of the project is being and will be disseminated to the hydrogen safety community through different channels including international and national associations (IA-HySafe, EHA, EIGA, etc.), standard development organisation (ISO, CEN, etc.), national regulators (e.g. HSE/HSL in the UK) and educational/training programs (e.g. MSc course in Hydrogen Safety Engineering and International short course and advanced research workshop series “Progress in Hydrogen Safety“ at Ulster).

# 1 General safety approach and definition of safety

## *1.1 Safety objectives*

There are three generic safety objectives for any safety system including for use of hydrogen systems indoors:

- Life Safety
- Property protection
- Environment protection

Primary consideration should be given to life safety, including site workers, customers and general public. The **life safety** objectives may include, but not limited to (Saffers and Molkov, 2014):

a) The occupants are able to leave building/facility in reasonable time, or consequences to occupants are acceptably low;

b) First responders are able to operate in reasonable safety;
c) Collapse or debris does not endanger bystanders, first responders and other people likely to be near facility.

## 1.2 General safety strategies

A number of general safety rules, strategies and recommendations for hydrogen infrastructure design and utilization had been identified within HyIndoor project. These include (as related in D5.1, Guideline on fuel cell indoor installation and use):

- Consider whether it is really necessary to house the hydrogen system within a room / enclosure, or whether it could be relocated outdoor where accidental leak would less likely lead to accumulation of hydrogen in flammable concentrations due to better ventilation;
- Reduction of hydrogen supply pipeline diameter and operational pressure to the minimum required to satisfy technological requirements for mass flow rate If decrease of pipe diameter is impossible or undesirable, utilization of flow restrictors;
- Minimization of hydrogen operational pressure whenever possible;
- Sighting of hydrogen infrastructure in a way ensuring jet decay before impingement on neighbouring obstacles in order to prevent formation of the layers with flammable hydrogen concentration;
- Identification, and, where possible, reduction of number and separation of potential ignition sources;
- Utilization of storage tanks with high fire resistance rating to ensure at least sufficient time for evacuation of people;
- Minimization of hydrogen inventory to prevent formation of flammable mixture in confined enclosure even after complete release and dispersion of hydrogen or limit it below amount which will produce structural damage in low strength equipment and buildings in case of deflagration
- Evaluation of deterministic separation distances before quantitative risk assessment (QRA). Deterministic separation distances can be calculated for unignited releases and for well-ventilated jet fires using published and validated nomograms (Molkov, 2012)
- Consider preferential use of side vents over roof vents in order to improve passive ventilation and vertical versus horizontal vents of the same area
- Consider preferential use of several vents over a single vent of the same area with difference in height of vents location as large as possible and vents located on all sides of the building to enhance wind-assisted venting irrespective of its direction;
- Consider exclusion of venting pipes and ducts as much as possible;

## 1.3 Section references

Molkov V.V. (2012), Fundamentals of hydrogen safety engineering, www.bookboon.com.
Saffers J.-B. and Molkov V.V. (2014), Hydrogen safety engineering framework and elementary design safety tools, *Intl. J. of Hydrogen Energy*, 39 (2014), pp. 6268-6285.

# 2 Dispersion of hydrogen in a room or enclosure

The goal of this work package is to provide validation and improvement of analytical and numerical models through numerical benchmarks and comparisons with experimental results. Those models are then used to perform safety calculation of fuel cells and surroundings with a better knowledge of their reliability.

## 2.1 Analytical Models

Analytical models have been developed or referenced for different fundamental situations:

- Concentration distribution of hydrogen in a free jet, which is useful in the case of a pipe rupture and also to improve the simplified models of jets developed for closed or vented enclosures.
- Concentration distribution of hydrogen in enclosures with no vent, 1 vent or 2 vents. Those are typical fuel cells or/and room idealized configurations. For the cases of closed and 2 vents enclosures, reference models are proposed. For the case of one vent enclosure, an improved model has been developed and validated.
- Conditions to reach 100% of $H_2$ in a box.
- Pressure peaking phenomenon in a 1 vent box, which is an important phenomenon to validate the structural resistance of the enclosure in the case of hydrogen release, even before any potential ignition.

Those models allow safety pre-calculations on simplified geometries of fuel cells giving access to the maximum concentration and the maximum pressure in enclosures, in connection with design parameters (vent size and or position, flow rate ...).

### 2.1.1 Hydrogen concentration decay

UU developed a nomogram for graphical calculation of hydrogen concentration decay in round momentum-dominated unignited jets. It is based on the similarity law from (Molkov 2012), see page 11 of D2.2 first intermediate report.

### 2.1.2 Hydrogen release in a one vent enclosure

UU performed an analysis of a hydrogen release into a one vent enclosure(Molkov et al., 2014) in the assumption of steady state release and uniform mixture in the enclosure. Existing Linden model (1994) has been improved to take into account the varying position of the neutral plan in the vent. Linden model results may differ from the results obtained with the new model up to a factor of 2. Validations of the new ventilation model have been performed by comparison with CEA experiments (Cariteau et al, 2011). It is demonstrated that the new model predictions (conservative maximum values) at $C_D$ = 0.60 are close to experiments. A nomogram for calculation of vent dimensions for a specific maximum allowable uniform gas concentration is also given, Figure 3 page 11 of the D2.2 report.
An engineering nomogram, illustrated in Figure 1, had been developed on the basis of this model (D2.3).

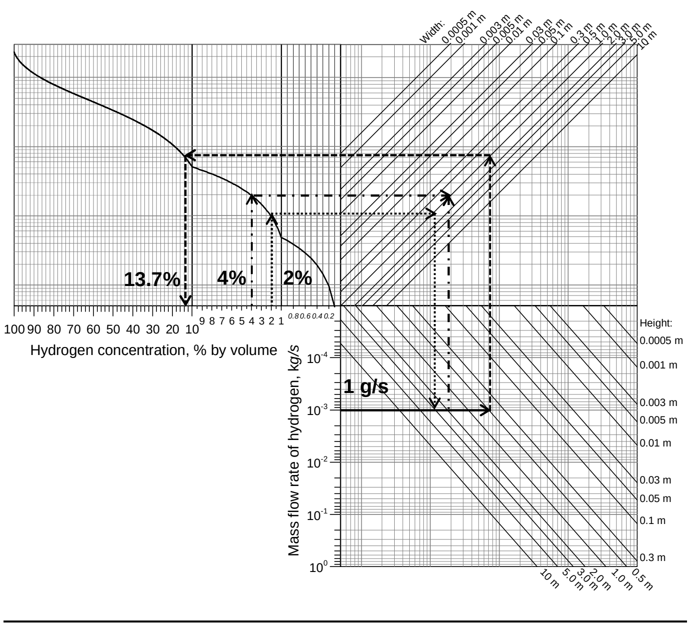


**Figure 1. Nomogram for calculation of maximum value of steady state concentration in the enclosure with one vent (D2.3, 2014).**

### 2.1.3 Nomogram for 100% gas concentration

UU developed a nomogram to calculate the mass flow rate limit leading to 100% gas concentration in the enclosure as a function of the vent width and height. Models and nomogram are published in the D2.4 report, page 12-16.

### 2.1.4 Nomogram for pressure peaking phenomena

UU revealed theoretically so-called Pressure Peaking Phenomena (PPP) –a transient peak in the pressure dynamics during hydrogen release in enclosures with vent(s) (Brennan, Molkov 2013). The phenomenon was validated in HyIndoor against KIT experiments (D2.4) This phenomenon is characteristic only for lighter than air gases and the most pronounced for hydrogen. Given sufficiently high flow rate, PPP can result in a structural damage up to complete collapse of the enclosure. Thus this phenomenon should always be taken into account during safety design process. Engineering nomograms and methodology for PPP calculations are provided in deliverables D2.3, D2.4 and D5.1 (Guidelines).

PPP even more pronounced for ignited releases (fires) in enclosures (D5.1). The "rule of thumb" (D5.1) allows estimation of the pressure peak produced by hydrogen jet fire in vented enclosure.

### 2.1.5 Referenced models for closed and 2 vents enclosures

Worster and Huppert (1983) approach is presented in D2.1 to model closed enclosures and Linden model (1999) is presented in D2.1 and D2.4 to model 2 vents enclosures. Worster and huppert model is used with an entrainment coefficient of 0.1 for most of the encountered situations, nevertheless a coefficient of 0.8 is advised to maximise safely the hydrogen concentration. For the Linden model, an entrainment coefficient of 0.055 is used to maximise the predicted maximum concentration, combined with an Cd coefficient of 0.25.

## *2.2 Pre-test CFD Calculations and CFD validation*

In this subtask, CFD and/or analytical calculations are performed with different goals:

- To assess the validity of turbulent models, through a benchmark comparison of CFD calculations and experimental results in various configurations.
- To extend the applicability of the analytical models and evaluate the influence of parameters which are not yet taken into account in simplified models such as the jet source orientation or height.
- To pre calculate experimental facilities of task 4.

### 2.2.1 CFD Benchmark

JRC, UU, NCSRD, AL and CEA simulate a series of experiments achieved on GAMELAN set-up (Cariteau 2010). The purpose of the benchmark is to validate the efficiency of CFD models to simulate turbulent plumes/jets in closed and opened enclosures. Two flow rates have been selected, through a 20mm diameter: 4Nl/min for a plume release; 60 Nl/min for a jet released. The enclosure is either closed (with a small hole at the bottom to prevent overpressure), or opened with one opening at the top of a side wall. Results show that RANS turbulent models are not accurate for small leak simulations 4Nl/min (Bernard-Michel *etal.* 2013). They underestimate the maximum of gas concentrations by overestimating the turbulent diffusion. Nevertheless, the error of prediction compared to experimental results remains reasonable (within 20% on average). Our main concern is that concentration distributions along the vertical axis and also versus time behave quite differently from experimental results. The use of different codes (Fluent, CFX, Cast3m....) and of different models doesn't change much those conclusions: SST (JRC), RNG-Kepsilon (NCSRD), LES 2D (CEA), standard k-epsilon (almost all the participants). Detailed results are provided in D2.2, D2.3 and D2.4 reports. Laminar models (CEA, JRC), on the other hand tend to overestimate the maximum concentration, by underestimating the turbulent diffusion. 3D LES calculations, UU in report D2.3 page 16-22, provide results in good agreement with experiments: good accuracy but also correct physical variations of the observed quantities. Nevertheless, it is still computationally expensive. The same calculation on a larger volume, for example a garage instead of a 1 $m^3$ enclosure, would be more difficult to realize (calculation time in months). LES should therefore be privileged whenever such approach is feasible. For the large leaks (60 Nl/min), RANS models reproduce quite well the physical evolution of the concentration and inaccuracy is quite low. A modelling strategy based on k-epsilon approach is therefore very satisfactory. The task of determining a threshold, between the low injection and high injection, above which RANS approach is accurate remains. The presence of a vent doesn't modify those conclusions for maximum concentration prediction. Numerical modelling strategies, as long as grid independency is proven, do not modify significantly those conclusions. JRC gives more details in report D2.4 on discretisation strategies. The choice of a turbulent model is the main key issue of simulations.

### 2.2.2 Impact of the vent geometry

Following the development of a one vent model, presented in previous section, UU performed a numerical simulation to evaluate the efficiency of a release through a vertical slot, D2.4 page 18-19. It is shown that for a same surface, a vertical vent shows a higher efficiency producing lower level of hydrogen in the enclosure for the same release rate. JRC performed numerical simulations to investigate the influence of the vent thickness, of a rain protection device, and of an external duct outside of the box. The presence of the external duct might double the maximum concentration of hydrogen in the enclosure, D2.4 pages 76-78.

### 2.2.3 Impact of the source position

JRC investigated the influence of the jet release vertical position in the closed box configuration, for the 4 NL/min and the 60 NL/min release rates, D2.4 page 48-50. It is shown that the maximum concentration of the injected light gas is strongly dependant on the vertical position, for a same release rate. The concentration is strongly increasing when the injection source is getting closer to the ceiling.

### 2.2.4 Impact of the source orientation

JRC varied the source orientation, modelling a horizontal source and a vertical source at the same position, all other parameters remaining unchanged, D2.4 pages 51-53. It is shown that for inertial jets (60 Nl/min in the simulated configurations) the orientation does not affect sensibly the hydrogen distribution. On the other hand, for slow relases (plumes), the orientation affects the distribution, especially at the mid-height of the box but does not lead to significant modifications of the maximum concentration.

### 2.2.5 Pre-test for HSL experiments

UU, AL and HSL performed calculations to design the test matrix, calculating flow rates to limit the maximum hydrogen concentration but also to ensure that maximum concentrations are high enough for the oxygen sensors to provide accurate enough measurements. Those calculations are detailed in D2.2 and D2.3 reports.

## *2.3 Experiments*

### 2.3.1 HSL experimental set-up

In D2.2 first intermediate report, HSL presents its experimental set-up and defines the test matrix for the experimental program. The initial proposition consists in 27 experiments: varying the number and the position of vents on a 31 $m^3$ enclosure, the flow rate for the injection, the height of the injection release point and perform the experiments with different wind direction and intensity. 27 electrochemical cell oxygen sensors were mounted on suspending wires within the enclosure, in “layers” at three different heights from the floor (1 m, 1.75 m and 2.25 m). Additional oxygen sensors were placed within the open vents as required. The hydrogen concentration was then calculated from the oxygen depletion that was detected by each sensor.  Additional sensors are used for other work packages. Overall, the results suggest that multi-vent configurations provide much more efficient ventilation than single-vent configurations. For multi-vent configurations ventilation tended to be wind dominated and often led to ventilation rates that were an order of magnitude higher than ventilation rates for single-vent configurations. For single vent configurations, it was observed that a wall vent can provide more efficient ventilation than a chimney vent of equal area. Concerning analytical models, for multi-vent configurations the wind-driven model generally gives good predictions of the average hydrogen concentration. The Linden model is applicable to a wider range of vent configurations. Both models tend to provide conservative predictions of the hydrogen concentration. However, there were two notable exceptions where volume averaged hydrogen concentration measurements were higher than both the Linden model predictions and the wind-driven ventilation rate calculations: one potential explanation is opposing wind and buoyancy leading to unreliable conservative predictions of hydrogen accumulation in naturally ventilated enclosures.

#### 2.3.2 CEA experimental set-up

The experimental set-up is based on the redesigned GAMELAN experiment: a one cubic meter enclosure which can be equipped with vents of different shapes. The new aspect of CEA work is that PIV measurements are carried out, giving access to global velocities, but also to velocity fluctuations on local areas. The final goal is to be able to produce a map of the average flow in the GAMELAN enclosure (about the size of a fuel cell) and also to be able to describe the mixing properties of the jet, giving access to the entrainment coefficient. CEA obtained velocity maps in a closed enclosure configuration and in a one vent configuration (Bernard-Michel 2015). The entrainment coefficient, on the other hand, couldn't be obtained from the sole velocity measurements. Extra information on concentration distribution is needed, otherwise statistical moments involved are too high and statistic is too poor to provide accurate results on the entrainment. This work will be continued in the frame of H2FC project.

### 2.4 Perspectives

Advances have been made providing better confidence in the use of available models and CFD tools. Nevertheless progress still has to be made in the field of modelling and of CFD use:

- forced ventilation models need to be improved
- Improvement on 1 vent model should be extended to closed enclosures and 2 vents enclosures.
- Modelling of plumes on large enclosures remains a computational challenge (if LES approach is used).

### 2.5 References


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# 3 Deflagration in a ventilated / vented room or enclosure

## 3.1 Experimental work at KIT

The middle scale experiments carried out at KIT within this project should contribute to the definition of improved criteria for hydrogen-air mixture parameters and enclosure parameters to avoid unacceptable overpressure limits. Additionally vent sizing technology for hydrogen deflagrations in confined spaces should be developed, taking into account the peculiarities of lean hydrogen-air mixture deflagrations (obstacles, concentration gradients of the hydrogen-air mixture, size and shape of flammable cloud and vents, vent inertia, etc.).

A series of medium-scale experiments on vented hydrogen deflagration was carried out at the KIT test side in a chamber of 1 x 1 x 1 $m^3$ size with different vent areas placed inside the large safety room with dimensions 5.5 x 8.5 x 3.4 m (V = 160 $m^3$). The test facility itself and its location in a safety room are shown in **Erreur ! Source du renvoi introuvable.**.


**Figure 2. The sketch (left) and front view (right) of the test facility inside the room.**

The experimental program was divided in three series: (1) uniform hydrogen-air mixtures; (2) stratified hydrogen-air mixtures within the enclosure; (3) a layer deflagration of uniform mixture. Different uniform hydrogen-air mixtures from 7 to 18% hydrogen were tested with variable vent areas 0.01 - 1.0 $m^2$. One test was done for rich mixture with 50% $H_2$. All the experiments with a stratified hydrogen-air mixtures have about 4%H2 at the bottom and 10 to 25%$H_2$ at the top of enclosure in order to vary the gradient of concentration. The measurement system consisted of a set of pressure sensors and thermocouples inside and outside the enclosure, and four photo cameras combined with a Schlieren system (BOS) for visual observation of combustion process through transparent sidewalls. Four experiments were selected as benchmark experiments in order to compare them with CFD numerical simulations and to scale down other similar experiments of 4 times larger scale (Bauwens, 2011).

Test mixtures were ignited by a spark plug at different locations inside the chamber and then maximum over-pressure and temperature as integral characteristics of vented deflagration process were measured. The flame dynamics and the venting of combustion products were monitored by optical BOS method combined with high speed cameras. About 110 experiments were performed by KIT with full set of variables. Typical shadow images of vented deflagration are shown in **Erreur ! Source du renvoi introuvable.**.

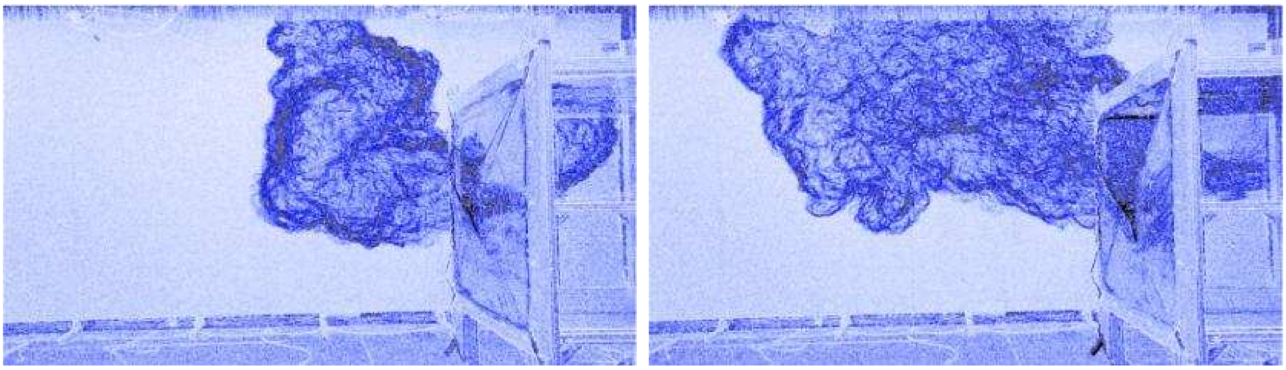

**Figure 3. A series of two processed BOS-images taken during experiment with a homogeneous H2-concentration of 10 % and a vent ratio of 100% with front ignition.**

The main observations during the KIT experiments are the following:

- A strong influence of mixture reactivity and vent area was intensively investigated within the project in order to provide an extended experimental data base for vent sizing technology.
- A multiple pressure peak structure occurs due to external explosion of unburned hydrogen released through the vent. It leads to significant (roughly two times) internal and external pressure increase
- Back and central ignition leads to the highest maximum combustion pressure and complex multi-peak structure of pressure signal due to secondary external explosion. The front ignition never produce the external secondary explosion
- A series of four benchmark experiments with 18% $H_2$-air mixtures was performed in order to scale it down and compare with FM Global experiments. A scaling factor $V^{2/3}/A$ was found to be suitable to compare experimental results on maximum overpressure in different scales for the same mixture reactivity. The data of benchmark experiments were used for numerical code validations by members of the project.
- Vented deflagration of a stratified hydrogen-air mixture and in a layer of hydrogen-air mixture leads to several times higher maximum overpressure compared to the uniform hydrogen-air composition with the same hydrogen inventory. The secondary external explosion was never occurred for central vent location
- Heavier vent cover leads to combustion pressure increase during the vented deflagration. Enormous negative pressure phase was occurred. It was never the secondary external explosion occurred.
- Higher blockage ratio results in higher maximum overpressure due to the turbulence and flame acceleration.

Several practical applications based on KIT experiments could finally be recommended:

- Updated Molkov's correlation (Molkov&Bragin, 2013) could be used for vent sizing technology to predict unacceptable level of combustion over-pressures
- A single vent or multiple vents of larger area will suppress flame acceleration and higher deflagration overpressures
- A lower vent position may eliminate the probability of secondary external explosion with high combustion over-pressure in case of stratified mixture or layered geometry of the mixture
- Position potential ignition sources close to explosion relief if possible
- Minimize congestion (not higher than 4-5% of volumetric blockage ratio)
- A lighter cover (with less inertia) should be used as a vent inertia

## 3.2 HSL Experimental

The large scale tests carried out at HSL were to investigate a number of aspects related to the explosion relief of deflagrations of hydrogen/air mixtures. The enclosure has a volume of approximately 30 $m^3$ and has geometry similar to many ISO container-based hydrogen facilities. The aim of the tests is to provide data from vented deflagrations within a large scale enclosure. There are three areas of interest:

- The relationship between explosion relief area and explosion pressures for deflagrating, well-mixed, lean hydrogen / air mixtures (typically 10 – 15% v/v). The hydrogen concentration, ignition position and relief area will be varied. There are several models available to predict explosion pressures and various sources of the input variables to those models (such as burning velocity). The data should aid in the identification of the best model for geometries like the experimental enclosure.
- The degree of inherent explosion relief provided by passive vents (that is, those installed to mitigate hydrogen accumulation in the event of a leak). It is envisaged that this work would involve the study of well-mixed hydrogen / air mixtures as well as inhomogeneous (layered) mixtures.

Some experiments were carried out in which the deflagrations were vented through explosion relief areas in the enclosure roof and others were carried out in which the explosion was vented through the areas provided by the passive vents within the enclosure walls. Internal and external pressures were measured, as were internal temperatures, hydrogen concentration and external weather conditions.

The following instrumentation was used:

- H2 concentration before ignition – at up to 7 positions using $O_2$ sensors (hydrogen concentration inferred from oxygen depletion)
- Temperature measurement – 20 Type K thermocouples, 12 thermocouples internally, 5 thermocouples in the centre of five sides of the vessel (excluding the floor) and 3 thermocouples at three different passive vent locations. These will not be of sufficient response time to determine internal flame speed.
- Meteorological monitoring using ultrasonic weather station local to test pad and further ultrasonic wind speed monitors in close proximity to the enclosure, near to the passive vents as appropriate. General atmospheric conditions (temperature, humidity, wind speed and direction) measured 10m from the enclosure.

- Pressure measurement – 4 piezoelectric pressure transducers, one transducer located within the vessel, one transducer positioned outside of each explosion relief vent location as appropriate.
- Video footage of vented explosions (external to the enclosure) using IR camera located at a distance from the enclosure whereby all of the passive vents and relief panels can be filmed simultaneously

For the well-mixed hydrogen / air mixtures, the hydrogen was introduced to the enclosure through venturi mixers (air amplifiers). For non-uniform test mixtures the hydrogen was introduced using the vertical release arrangement used in WP2. These are shown in Figure 4. A small hole in the floor was used to avoid over-pressurising the enclosure during the addition of the hydrogen.

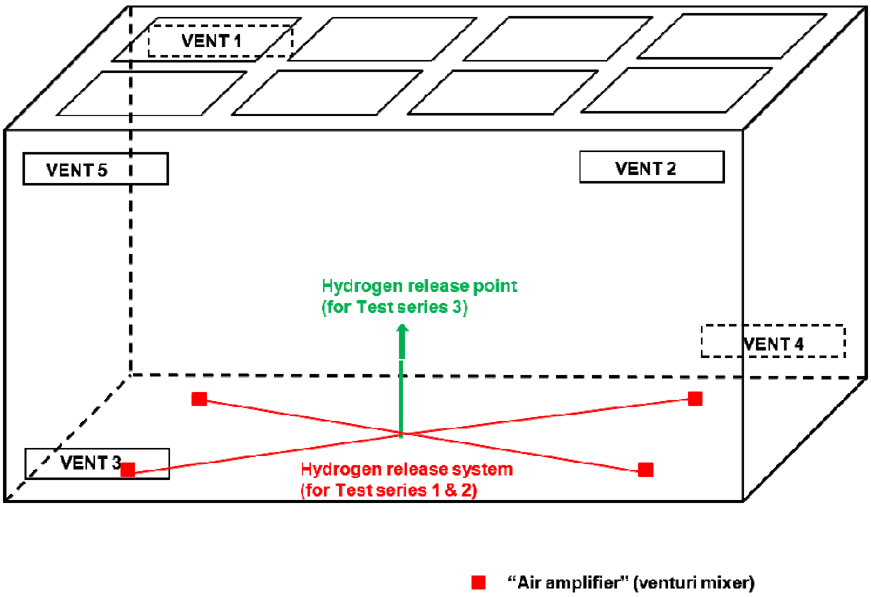


**Figure 4. Hydrogen introduction.**

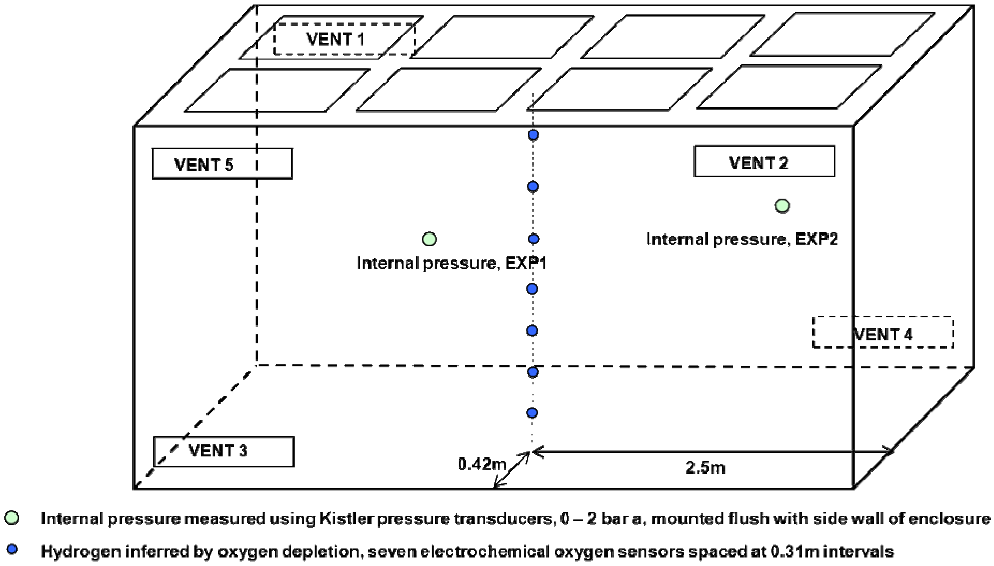


**Figure 5. Internal pressure and gas composition measurement.**

Explosion relief was provided by covering the selected vent area with 20 micron polypropylene sheeting, pre-perforated around its perimeter to facilitate a "clean" opening of the cover during a deflagration (Figure 6). This method has been used previously by others (Bauwens *et al,* 2012). This arrangement typically gave an opening pressure of approximately 10 mbar for the relief panels used at HSL.

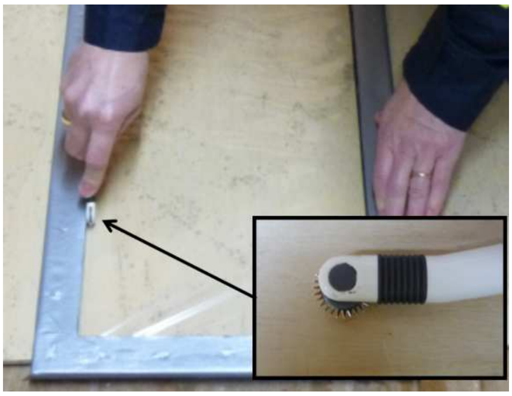

**Figure 6. Perforating the polypropylene film for the explosion relief.**

For most of experiments, the ignition source was positioned as far as possible from the explosion relief to maximise explosion pressure, although some tests were carried out with ignition close to the vents for comparison.

The main findings from the HSL experimental work are given below:

Comparison between the measured over-pressures and the values calculated using a method by Molkov and Bragin (2013) shows the calculated values to be reasonable and slightly conservative.

The distance of flame (to 70ºC) emitted fro the passoive side vents is less than that calculated using method given in EN14994 (for the conditions tested - up to 10% v/v and internal pressure ~100 mbar).

Ignition far away from the explosion relief vent(s) leads to a higher over-pressure than ignition close to the vent.

Explosion relief via side wall vents appears to be as effective as via roof vents (at least for mixtures of up to 10% v/v).
The vented deflagration of a stratified hydrogen-air mixture leads to higher maximum overpressure compared to uniform hydrogen-air composition with the same hydrogen inventory.

The ignition of the plume of released hydrogen can generate significant pressures even if the average concentration in the enclosure is low (e.g. ~1% v/v)

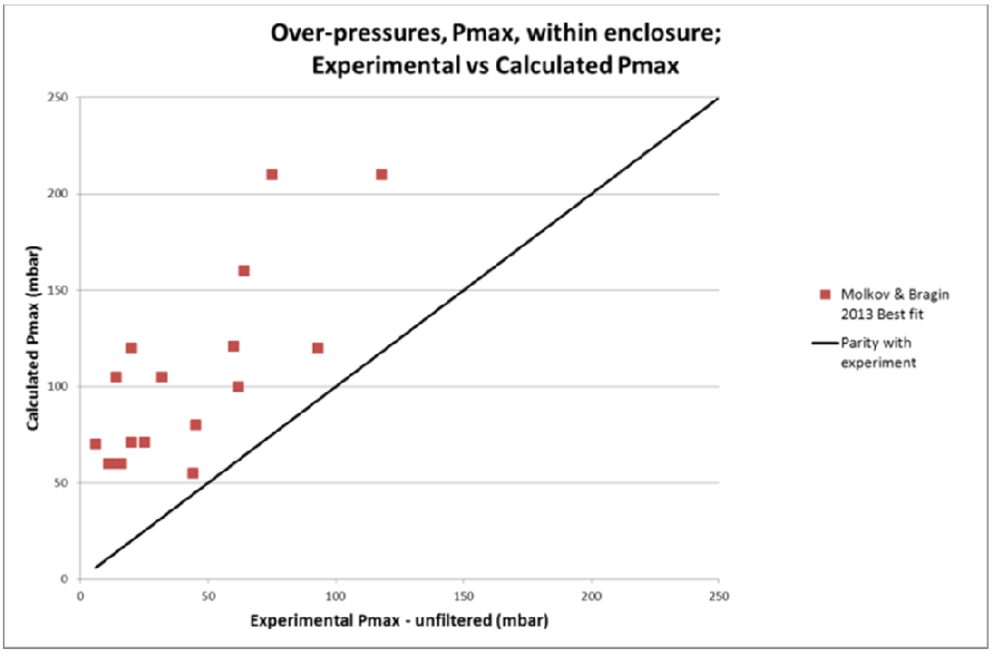


**Figure 7. Comparison of measured and predicted over-pressures.**

## 3.3 Analytical studies

An analytical model was developed by the University of Ulster (UU) to specify an upper limit on hydrogen inventory as a safety strategy to exclude the need in deflagration mitigation. A thermodynamic model is built on assumption of perfect and adiabatic combustion of lean localised hydrogen-air mixture in a completely sealed compartment. The model was validated against experimental data (D3.2). Maximum 10 kPa overpressure in an enclosure (the typical threshold value causing minor structural damage) was applied as a safety criterion. The solution was obtained in a form of hydrogen inventory (mass) as a function of enclosure volume $m_{H2} < 2.61 \cdot 10^{-4} V$, where $m_{H2}$ is the mass of hydrogen (kg), $V$ is the enclosure volume (m$^3$). Where inventory is higher than the specified limit, the use of deflagration venting as a major mitigation technique should be considered.

University of Ulster has developed a correlation which allows calculation of the area of the vent required to keep deflagration pressure below specified value. It had been previously demonstrated that dimensionless reduced deflagration pressure depends only on the turbulent Bradley number $Br_t$, which in turn is uniquely dependent on the deflagration-outflow interaction (DOI) number, $\chi / \mu$ (Molkov, 1996). Accordingly, a general form of correlation had been proposed (Molkov et al., 1999) in the form $\pi_{red} = \lambda \cdot Br_t^{-\sigma}$, where $\lambda$ and $\sigma$ are empirical coefficients (theoretical value of $\sigma$ is 2 (Molkov, 1996), $\pi_{red} = P_{red} / P_i$ is the dimensionless reduced deflagration pressure, $P_{red}$ and $P_i$ are reduced (gauge) deflagration pressure and initial absolute pressure respectively, and $Br_t$ is the turbulent Bradley number

$$Br_t = \frac{\sqrt{E_i / \gamma_u}}{\sqrt[3]{36\pi_0}} \cdot \frac{Br}{\chi / \mu}, \qquad (1)$$

where $Br$ is the Bradley number $Br = \frac{F}{V^{2/3}} \cdot \frac{c_{ui}}{S_{ui}(E_i - 1)}$,

in which $E_i$ is the combustion products expansion coefficient, $\gamma_u$ is the specific heat ratio of unburned mixture, $\chi / \mu$ is the DOI number, $F$ is the vent area, $V$ is the enclosure volume, $S_{ui}$ is the initial laminar burning velocity, and $c_{ui}$ is the speed of sound in the initial unburned mixture. UU approach presents DOI number as a product of different flame wrinkling factors (Molkov and Bragin, 2013)

$$\frac{\chi}{\mu} = \Xi_K \cdot \Xi_{LP} \cdot \Xi_{FR} \cdot \Xi_{u'} \cdot \Xi_{AR} \cdot \Xi_o, \qquad (2)$$

where $\Xi_{AR}$ is the aspect ratio wrinkling factor, $\Xi_{FR}$ is the wrinkling factor due to fractal increase of the flame front area, $\Xi_K$ is the Karlowitz wrinkling factor due to turbulence generated by flame front itself, $\Xi_{LP}$ is the leading point wrinkling factor, $\Xi_O$ is the wrinkling factor due to the presence of obstacles and $\Xi_{u'}$ is the wrinkling factor due to initial turbulence.

The correlation had been derived and validated for deflagrations in low strength equipment and buildings (overpressure not exceeding 1 bar). The detailed methodology for calculation of each of these factors is provided in HyIndoor D3.4. Molkov and Bragin (2013) used a large number of experiments to obtain coefficients $\lambda$ and $\sigma$. Coefficients were further fine-tuned using new experimental data obtained by KIT and HSL within HyIndoor project.

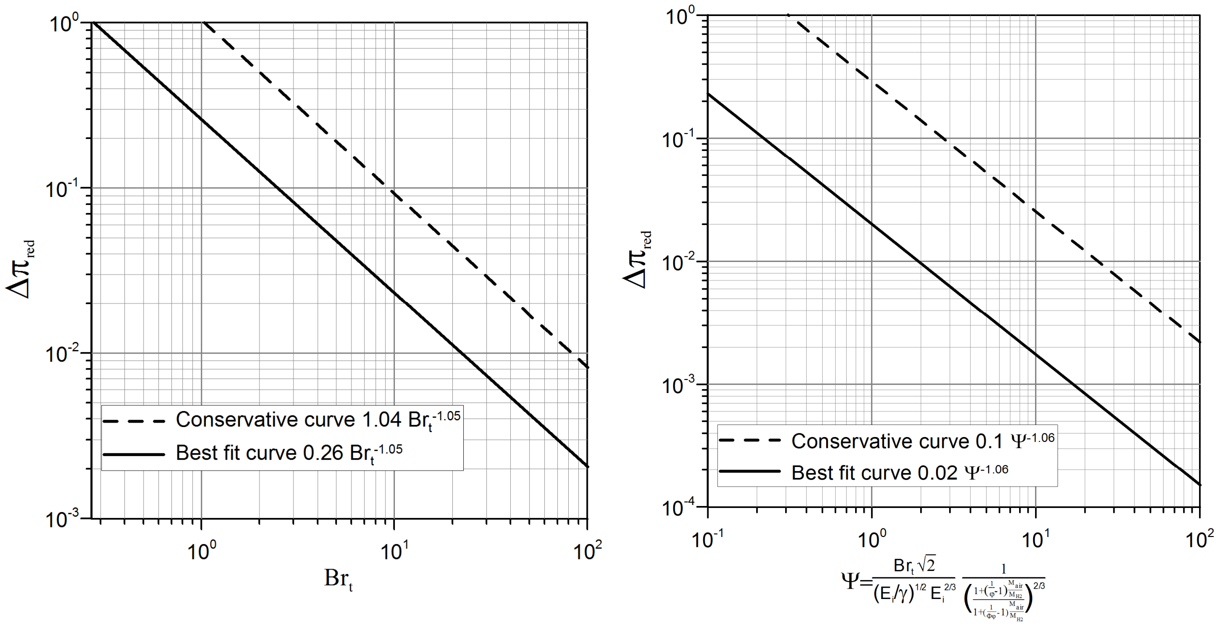


**Figure 8. Vent sizing correlation for uniform mixture deflagration occupying the entire enclosure (left) and localized mixture (right) (HyIndoor D3.4, 2014).**

The ultimate data were found to be (see Figure 8, left) $\pi_{red} = 0.26 \cdot Br_t^{-1.05}$, for the best fit for all experimental data and $\pi_{red} = 1.04 \cdot Br_t^{-1.05}$ for the conservative correlation (drawn above all experimental data).

For the first time UU developed a model for venting deflagration of a localised, e.g. layered, hydrogen-air mixtures. The correlation shown below was validated against 25 experiments (uniform and gradient mixture deflagrations) performed by KIT and HSL within HyIndoor project:

$$\Delta\pi_r = 0.1\,Br_t^{-1.06}\left\{\frac{\sqrt{E_i/\gamma}\,E_i^{2/3}}{\sqrt{2}}\left(\frac{1+\left(\frac{1}{\varphi}-1\right)\frac{M_{air}}{M_{H2}}}{1+\left(\frac{1}{\Phi\varphi}-1\right)\frac{M_{air}}{M_{H2}}}\right)^{2/3}\right\}^{1.06}, \qquad (3)$$

where $\Delta\pi_r$ is the reduced maximum overpressure ratio, $E_i$ is the combustion products expansion coefficient, $\gamma$ = 1.4 is adiabatic index, $\Phi$ is volume fraction of combustible mixture in enclosure, $\varphi$ is volume fraction of hydrogen in combustible mixture, $M_{air}$ is molecular mass of air, $M_{H2}$ is molecular mass of hydrogen, and $Br_t$ is the turbulent Bradley number. Graphical representation of the correlation for layered mixtures is shown in Figure 8 (right). The methodology for use of deflagration venting correlations is described in detail in deliverable D3.4 and Guidelines (D5.1).

## 3.4 CFD simulation studies

*Benchmarking exercise*

Two rounds of CFD benchmarking exercise were carried out (D3.3):

- Large-scale experiment (Bauwens et al., 2011): FM Global facility, 64 $m^3$, 18% v/v hydrogen-air mixture, 5.4 $m^2$ vent, back wall ignition (participating partners AL, CEA, NCSRD, UU);
- Medium scale experiment (HyIndoor deliverable D3.3): KIT facility, 1$m^3$, 18% vol. hydrogen-air mixture, 0.25 $m^2$ vent, back wall ignition (participating partners AL, CEA, NCSRD, UU).

Particular attention was paid to reproduction of two-peak structure of pressure dynamics and nature of external explosion responsible for the maximum overpressure.

*Post-experimental analysis and model development*
The activity included:

- Modelling Rayleigh-Taylor instability (RT) effect on deflagration dynamics; performed by KIT and UU; results reported in HyIndoor deliverable D2.2, (Keenan et al., 2014), (Keenan et al., 2013a), (Keenan et al. 2013b);
- Study of CFD models capacity to predict lean hydrogen-air mixture deflagration – simulation of vented deflagration in AECL facility (Kumar, 2006), 120 $m^3$, 10% v/v hydrogen-air mixture, 0.55 $m^2$ vent, rear, central and front wall ignition locations; performed by UU (Makarov, Molkov 2013a) and (Makarov, Molkov, 2013b);
- Initial study of model capability to predict localised mixture + jet deflagration scenario (HSL test WP3/25, HyIndoor deliverable D2.3); performed by UU, reported at HyIndoor plenary meeting (Arnhem, 10-11 June 2013).

Main conclusions following CFD study programme include but not limited to:

- CFD models are capable to reproduce major experimentally observed deflagration dynamics features for moderately lean mixtures, e.g. 18% v/v/ in FM Global and KIT experiments, and may be used as an engineering tool to predict vented deflagration pressure dynamics, particularly where analytical engineering models are not applicable; however, care should be taken to ensure that CFD models are validated within a wider domain of parameters, including hydrogen concentration, enclosure scale, internal congestion, vent size, etc.
- For deflagration dynamics close to upward flame propagation limit (e.g. 10% v/v in AECL experiments) combustion instabilities have greater effect on deflagration dynamics and predictive capabilities of CFD models are lower. The mechanisms triggering combustion acceleration of lean hydrogen-air mixtures seems to depend on deflagration scenario. Deflagration with the near-vent ignition had the most complex dynamics of combustion acceleration. The simulated rear-wall ignited deflagration required the smallest tuning of flame acceleration and its venting didn't cause significant contribution to combustion instabilities and augmentation.
- Effect of external explosion on coherent deflagration dynamics and maximum overpressure in the vessel was confirmed. Modelling combustion augmentation in external explosion required special treatment. Partners CEA, NCSRD, UU used different treatment for external explosion. Further study is needed to conclude on the origin and nature of the external explosion to develop predictive models.
- The introduction of the RT modification into the UU LES model had a significant influence on the model performance allowing to reproduce in simulations two peak structure of pressure dynamics observed in FM Global experiment.

- Pressure peaks resulting from flame-acoustic interaction currently cannot be predicted at the moment. It is recommended that existing mitigation techniques are applied to reduce or eliminate the peak associated with flame-acoustic interaction.

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# 4 Hydrogen jet fire in an enclosure

## *4.1 HSL Experimental Work*

This section summarises experiments and modelling carried out for WP4 (hydrogen jet fires in ventilated enclosures) by the United Kingdom's Health and Safety Laboratory (HSL) for the European Union (EU) project Hyindoor. The work was to investigate the following areas of interest: visible flame length; temperature distribution, radiated heat, oxygen depletion, hydrogen accumulation and the conditions required for jet fires to become under-ventilated.

The experiments were carried out using a steel enclosure with a volume of approximately 31 $m^3$, with a cross sectional area of 2.5 m by 2.5 m and a length of 5 m, designed to withstand and internal explosion pressure of 0.2 bar g. The enclosure has five similar vents (0.83 m wide and 0.27 m in height) located on the sides of the enclosure which could be closed or opened as required. The enclosure is shown in **Erreur ! Source du renvoi introuvable.**.

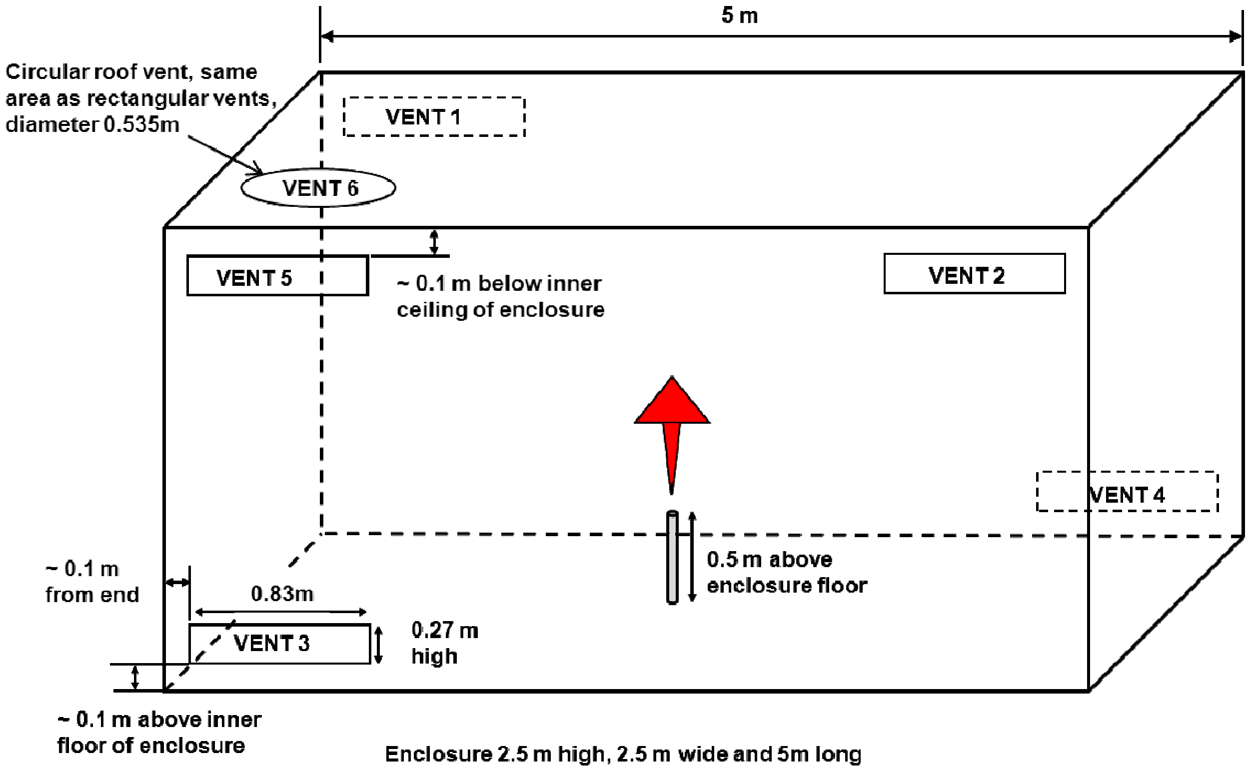


**Figure 9. Schematic of the 31 m3 enclosure used at HSL.**

Hydrogen was released through a pipe that was located in the centre of the enclosure and directed vertically upwards and was ignited using a pilot flame.

The oxygen and hydrogen concentrations were measured by extracting gas samples from five positions within the enclosure. Three humidity sensors were fitted into the enclosure walls. Temperature measurements were made within the enclosure and a thermocouple was also placed in each open vent. Video footage of flames was captured using three visible range cameras located within the enclosure and a further visible range camera was used to monitor the upper open vent for external flame. Radiometer measurements were also made using three radiometers placed within enclosure. Meteorological monitoring was also carried out.

Twelve experiments were carried out at flow rates up to 800 L/min, orifice sizes up to 10mm and several opening configurations. In total there were eight well-ventilated experiments and four under-ventilated experiments.

The key observations from the experiments are descibed below:

- Some choked releases did not continue to burn once pilot flame removed.
- Well-ventilated fires resulted in a small reduction in oxygen concentration (to 18.0 – 19.6% v/v oxygen) and no hydrogen accumulation
- Under-ventilated fires occurred when the available vent area was reduced and resulted in a large reduction in oxygen concentration and significant hydrogen accumulation (up to 16% v/v before the test was terminated).
- The visible flame lengths of the well-ventilated jet-fires were broadly in agreement with the estimates made using the correlation due to Molkov et al. The flame lengths for the choked releases were shorter than those of equivalent sub-sonic releases.
- The “steady-state” temperature range of the atmosphere in the upper part of the enclosure was narrower for the choked releases than for subsonic.
- Flames were not observed at vent opening in any of the tests, though the possibility not ruled out if the flame source was closer to vent.
- For under-ventilated fires nature of the flame changes as oxygen level falls.
- Hydrogen accumulation does not start until significant oxygen depletion has occurred (no accumulation when > 18% v/v oxygen).
- Total flame extinguishment was not observed before the hydrogen supply was deliberately shut off (high hydrogen levels in enclosure) but appeared to be close to occurring.
- The presence of a passive wall vent designed to avoid flammable hydrogen concentrations in unignited releases would also avoid under-ventilating a jet-fire of the same flow rate.
- Predicting air change rate due to buoyancy of the hot gases may give an indication of whether jet-fire will be under-ventilated.


50 s after ignition:
No accumulated $H_2$
18.2 – 21% $O_2$

9 min 20 s after ignition:
1.1 – 5.1% $H_2$
1.4 – 8.6% $O_2$

10 min 5 s after ignition:
3.6 – 10.5% $H_2$
1.5 – 8.6% $O_2$

**Figure 10. Change in flame behaviour, %O2 and %H2 versus time for WP4.**

## 4.2 Experimental studies at KIT

The main focus in the jet fire experiments was on conditions that lead to quenching (self-extinction) of an ignited jet in an enclosure due to reduction of oxygen concentration during combustion. In experimental work hydrogen jets with defined flow conditions were ignited inside the enclosure with different vent sizes. Under-ventilated fires were observed in enclosure with one small vent, and well-ventilated in enclosure with two vent openings. The test program also included experiments without ignition for validation of the pressure peaking phenomena, but the main emphasis lies on ignited jets. A pressure increase of up to 100 kPa inside the box due to the injected hydrogen, the flame and the hot combustion products should be reached before a pressure relief device stops a further pressure increase. A series of experiments on indoor hydrogen jet fire performed at the KIT HYKA facility in order to reproduce different combustion regimes in a typical fuel cell-like enclosure 1x1x1 $m^3$.

The main objectives of the experimental program were aimed at confirmation of the pressure peaking phenomena for burned and unburned hydrogen releases indoors; determination of influence of vent area and hydrogen flow rate on the characteristics of the jet fire; investigation of the ratio of vent area and hydrogen mass flow rate on the probability of self-extinction phenomena. Pressure, temperature and high speed BOS imaging were used in the tests. The following pressure signal were registered: primary pressure rise due to the pressure peaking phenomena, then steady state equilibrium atmospheric pressure and then, finally, oscillating pressure up to 20-30 mbar during the re-ignition or external–internal flame behaviour (Figure 11). A strong influence of steam condensation during jet fire experiments was observed in the tests. Very low under-pressure up to -100 mbar led to collapse of the test enclosure.

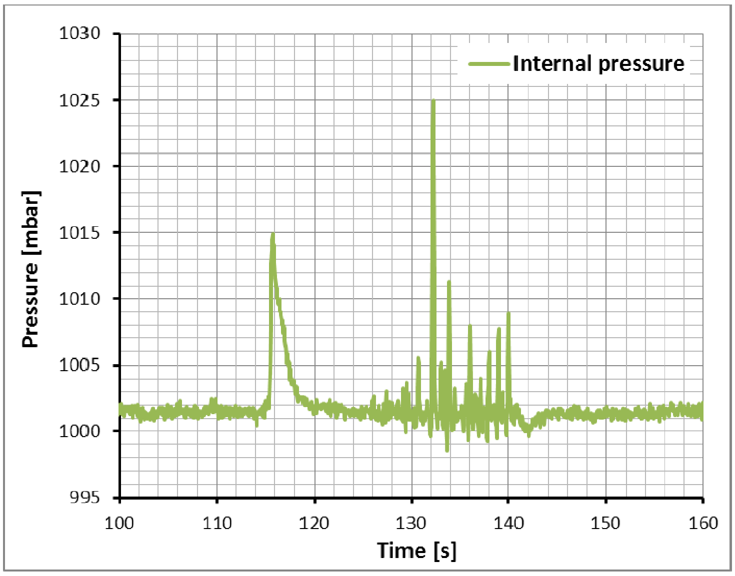


**Figure 11. Typical pressure signal inside the enclosure for under-ventilated regime with external-internal flame pulsations (test HIWP4-061, v=600 m/s, m=1.086 g/s H2).**

A series of experiments without ignition related to the pressure peaking phenomena was also performed at KIT. A maximum overpressure up to 60 mbar inside the box due to the injected hydrogen may also occur. The experiments carried out at KIT within this project were compared against the analytical model developed at Ulster and very good agreement was demonstrated.

### 4.3 Numerical studies at UU

This section outlines the conclusions of numerical work undertaken at Ulster. This includes a parametric study of a hydrogen jet fire in an enclosure with one upper, one lower vent, and finally with two vents (one upper and one lower vents). The aim of the study was to identify jet fire regimes indoors, estimate typical pressure loads generated by these jet fires, and conclude on the fire behaviour during the termination of hydrogen supply. The numerical experiments were carried out for different vent area (multiple or single vents, different area, vertical and horizontal vents) and different hydrogen mass flow rates. Both well-ventilated and under-ventilated fires were simulated. The following regimes were observed for under-ventilated fires: external flame, self-extinction, and micro-combustion. It is not recommended to locate high pressure pipelines in the vicinity of a vent.

The Reynolds averaged Navier Stokes (RANS) computational fluid dynamics (CFD) model based on the renormalization group (RNG) *k-ε* turbulence model, the eddy dissipation concept (EDC) model for simulation of combustion coupled with the 18-step reduced chemical mechanism (8 species), and the in-situ adaptive tabulation (ISAT) algorithm that accelerates the reacting flow calculations by two to three orders of magnitude was applied. The analysis of temperature and species (hydroxyl, hydrogen, oxygen, water) concentrations in time, as well as the velocity through the vent, shed a light on regimes and dynamics of indoor hydrogen fires. A well-ventilated fire is simulated in the enclosure at a lower release flow rate and is characterised by complete combustion of hydrogen within the enclosure. Fire becomes under-ventilated at higher release flow rates with two different modes observed for one vent enclosure, i.e. the external flame and self-extinction.

**Remarks on fires in enclosure with single upper vent:**
The general rule for indoor fire with one upper vent is formulated: an increase of hydrogen release flow rate changes fire regime from well-ventilated fire (small leak rates), to under-ventilated fire with external flame (moderate flow rates), to self-extinction of combustion (higher flow rates), and again to external flame regime (very high flow rates).

**Remarks on fires in enclosure with single lower vent:**
The general rule for indoor fire with one lower vent is: an increase of hydrogen release flow rate changes fire regime from well-ventilated fire (small leak rates), to under-ventilated fire with self-extinction, and then to external flame. The following should be noted: flame self-extinguishes at a lower leak rate comparable to the upper vent case. No external flame mode observed between well-ventilated mode and self-extinction mode. "Ghosting flames" are clearly seen at the bottom of the enclosure before self-extinction. Transition from self-extinction to external flame regime occurs at lower leak rate than for the upper vent case. "No-harm" distance based on temperature of 70 C is greater for the same leak in the upper vent scenario. This phenomenon was not observed in carried out simulations with upper vent or two vents.

**Remarks on fires in enclosure with two vents (one lower and one upper):**
The general rule for indoor fire with one upper and one lower vent is formulated: an increase of hydrogen release flow rate changes fire regime from well-ventilated fire (small leak rates), to transitional (higher release rates when combustion inside still exists but small increasing amount of hydrogen is flowing out of the enclosure through the upper vent), further increase of hydrogen flow rate leads to under-ventilated fire with micro-combustion (there is a tiny flame attached to the burner) and then to under-ventilated fire with external flame.

**"Re-ignition"**
Two simulations were performed to identify potential hazards during the termination of hydrogen release at the moment when there is small combustion spot just beneath the vent (one vent case) or external flame (two vents case). There was no overpressure observed during "weak" combustion in the enclosure with one vent. In the case with two vents the external flame did not propagate into the enclosure. Due to the presence of quite high concentration of water vapour at the moment of termination of hydrogen supply the potential deflagration hazard and associated risks from "re-ignition" are small, except a longer presence of flame and thus potential damage to pressurised piping. The potential for deflagration should be studied further, especially for mirco-combustion regime.

## 4.4 Analitycal studies at UU

The methodology has been developed to calculate the radiative heat fluxes from the hot layer and the ceiling indoors and compared the predicted results with those observed experimentally by HSL. The results comparison showed good agreement which further expanded to contribution to evacuation time estimation strategy based on the thermal doze.

An equation has been proposed for prediction of time when all oxygen will be consumed by the indoor fire. After this period of time two possible modes of under-ventilated regimes can occur: self-extinction or external flame. The applicability of the equation has been verified against numerical experiments with good agreement. In all cases the formula showed conservative time as reported in D4.4.

Flame length correlation were applied for assessment of flow restrictor effect on the flame length. It was concluded that the feed line pressure, diameter of a pipe and restrictor orifice should, by design, limit the mass flow rate of hydrogen to a technological level that is required for the hydrogen system to function.

The methodology (engineering tool) for calculation of overpressure generated by the jet fire indoors was developed and described in D4.4. It is based on the application of previously developed model of pressure peaking phenomenon for unignited release (Brennan & Molkov, 2013) to a jet fire from the same source of release using the rule of thumb developed within HyIndoor project.

## 4.5 Section references

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# 5 Guidelines and mitigation strategies

## 5.1 Guidelines

### 5.1.1 General safety strategies for inherently safer hydrogen use indoors

Research results and methodologies developed within HyIndoor project have been used to compile the Guideline for fuel cell indoor installation and use (deliverable D5.1). This document begins with the introduction of the objectives of hydrogen safety and provides reference definitions of the terms and concepts used in the field of hydrogen safety. It goes on to list the general rules and best practices of hydrogen safety, compiled on the basis of industry experience and insights obtained within HyIndoor project research. Guideline document also includes an overview of harm criteria relevant to the hydrogen safety

Analysis of the phenomena relevant to the hydrogen safety and their interrelations lead to development and inclusion in Guidelines the phenomena and consequences diagram (Figure 12). The diagram graphically represents potential chains of events associated with indoor incidents/accidents involving hydrogen systems and infrastructure and its consequences. More detailed description of individual elements of the diagram is provided in Deliverable D5.1.

Guidelines also outline the principles of Hydrogen Safety Engineering (H2SE) and approaches it uses.

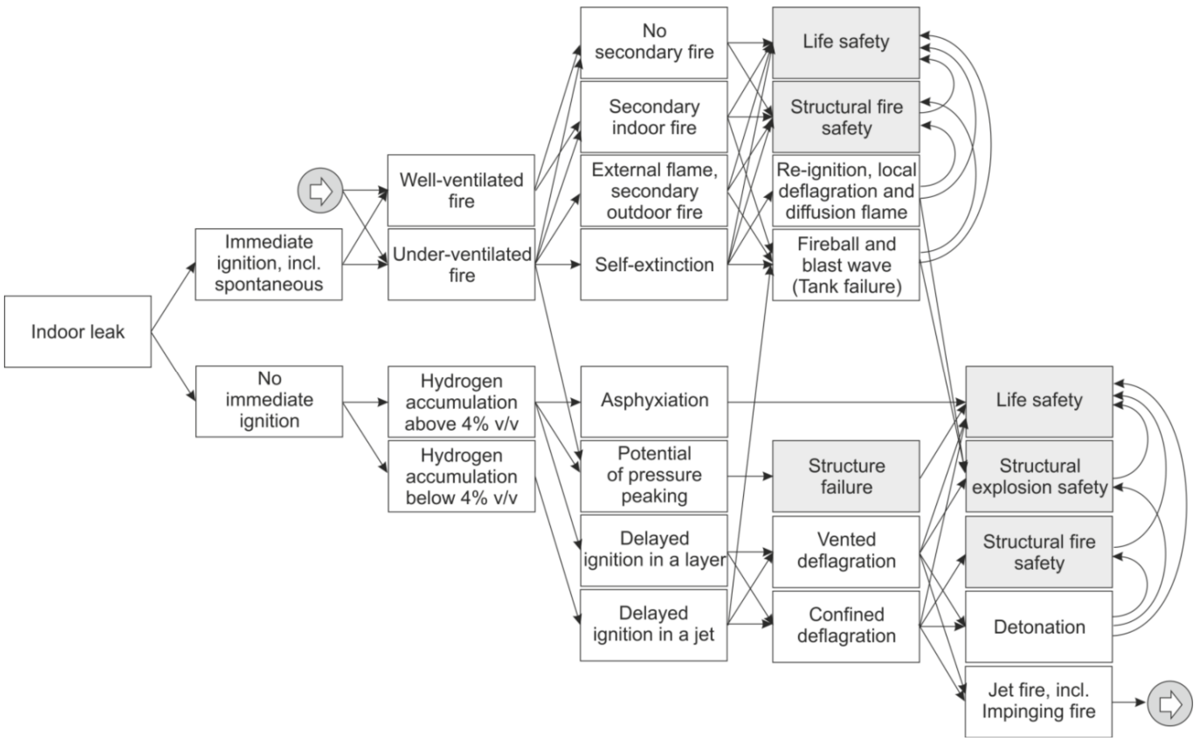


**Figure 12. Phenomena and consequences diagram. White boxes - various phenomena, starting with the development of hydrogen leak. Grey boxes - potential consequences. Note that even if no immediate ignition has occurred (lower branch), subsequent chain of events can lead to delayed ignition leading to transition to the upper branch, as indicated by arrow in a circle pictograms.**

The main body of the guidelines includes description of three main types of phenomena studied within HyIndoor project – hydrogen release and dispersion, deflagration and jet fires, lists hazards associated with each type and recommendations for mitigation of consequences and provides the practical outcome of research conducted within the project.

The main body of the guidelines is followed by appendices which include more technical descriptions of methods and techniques developed within HyIndoor project. They include equations and engineering nomograms obtained during the project research and their derivations, instruction for their application and examples of their utilization for representative engineering problems. Methodologies and nomograms listed in appendicies include:

- Nomogram for concentration decay in momentum-dominated jet;
- Nomogram to determine a leak rate leading to 100% of hydrogen in the enclosure;
- Nomograms for determination of overpressure due to pressure peaking phenomena;
- Nomograms for determination of ‘safe’ tubing diameter and blowdown duration with account for pressure peaking phenomenon;
- Equations and nomogram for steady state concentration in enclosure with one vent;
- Derivation of Thermodynamic model used for formulation of inventory limitation rule;
- Vent sizing correlation for low strength equipment and enclosures (entirely filled in with flammable mixture);
- Vent sizing correlation for the localized mixture deflagration;
- Dimensionless flame correlation;
- The equation for the effect of restrictor on the jet flame length;
- Methodology for calculation of the thermal radiation from a hot layer and ceiling during well-ventilated fire.

### 5.1.2 Recommendations from Hyindoor research results

Analysis of the research results of Hyindoor project were enabled to define guidelines and best practices easily usable by engineers for indoor safety use of hydrogen energy applications.

Four main topics were addressed in Hyindoor project:

- Hydrogen release inside a confined or semi-confined enclosure,
- Indoor hydrogen-air deflagration,
- Jet fire and underventilated fire,
- Hydrogen detection for confined spaces (treated in sections 5.2 and 5.2.4).

These topics were studied through:

- A review of the state of the art on published information and critically analyzed,
- Targeted experiments specifically performed in Hyindoor project,
- Evaluation and validation of analytical and numerical approaches to assess considered phenomena.

Thus general rules, best practices and means to assess and mitigate consequences are proposed and presented in the following section; recommendations usable for a safe design and calculation means are given.

*About releases in confined space and consequences assessment*

Recommendations were defined and can be applied at the conception level of a hydrogen energy application, allowing the safety to be increased.

These recommendations mainly concern the optimization for the increase of the effectiveness of the natural/passive ventilation.

These recommendations are the following:

- In order to prevent accumulation of flammable concentrations of hydrogen an enclosure should be provided with adequate passive vent(s). If practical, ventilation system should be designed to prevent concentrations exceeding LFL for realistic expected hydrogen release rates.
- Utilization of two (or more) vents located at different height is preferable; this ventilation configuration is more effective than a single vent (or more) only located at the top of the enclosure, considering the same total ventilation area.
- A one-opening ventilation configuration can be used when a two-openings ventilation configuration is not possible;
- Vents on vertical side walls of the enclosure are preferable to horizontal roof vents.
- Obstructions – like grids or ducts in front of the ventilation vents should be avoided. When it is not possible (e.g., due to thermal or security reasons), account should be taken for the reduction of the ventilation performance. The effective ventilation area has to be re-calculated and a correction factor addressing efficiency reduction should be introduced in order to take into account the reduction of the discharge coefficient due to vent obstruction.
- Forced venting could be applied in cases when purely passive ventilation is impractical, e.g. since it requires too large vents unacceptable at cold climate. It should be recognised, however, that such systems are not necessarily fail-safe and the reliability of the forced ventilation system needs to be considered;
- PPP has to be taken into account in risk assessment.

Calculation means for the design, for consequences and mitigation assessment were studied in Hyindoor to propose some tools (e.g. nomograms, simple analytical models...).

Thus proposed calculation means for build-up assessment and ventilation system sizing are the following:

- Ventilation system parameters can be calculated using engineering tools described in Hyindoor Guidelines report (Deliverable 5.1):
    - For one-opening ventilation mode
        - The passive ventilation approach proposed by Molkov et al. (2014)
            - By using equations
            - By using proposed nomograms

- The natural ventilation approach proposed by Linden (1999); the simple expression developed by Cariteau and Tkatschenko (2013) is validated and usable (see Hyindoor Guidelines report (Deliverable 5.1))
  - For two-openings ventilation mode
    - The natural ventilation approach proposed by Linden (1999) (see Hyindoor Guidelines report (Deliverable 5.1))
- Waiting new developments, forced ventilation in an enclosure with one opening could be calculated using equations of Hyindoor Guidelines report (Deliverable 5.1).
- Computational Fluid Dynamics (CFD) can be a promising approach especially for complex geometries, multiple vents and release parameters different from those more classical considered to develop analytical engineering tools.
- PPP can be assessed using Brennan and Molkov (2013) theoretical model, or using the experimental correlation proposed in Hyindoor Guidelines report (Deliverable 5.1).

*Consequences assessment and mitigation of hydrogen-air deflagration*

Experimental, analytical and numerical works on hydrogen-air deflagration were carried out in Hyindoor project. The critical analysis of these results allowed recommendations to be defined. These recommendations to limit deflagration consequences are the following:

- Venting of deflagrations is the most widespread technique to mitigate explosions in an enclosure decreasing overpressure.
- Apertures initially dedicated to ventilation will participate in the venting of the explosion.
- The size of the vents should be chosen to ensure that overpressure produced by mixture deflagration will not exceed structural strength of the enclosure.
- Internal overpressure in case of ignition decreases with increase of vent surface(s).
- Position potential ignition sources close to explosion relief vent if possible.
- When possible prefer vents dedicated to natural/passive ventilation without obstruction (or minimizing obstruction: grids for instance) to limit overpressure in case of deflagration.
- Avoid or minimize internal congestion in the enclosure.
- The gases vented from a deflagration need to be discharged into a safe area.

Associated calculation means proposed are given below:

- State-of-the art correlation for vent sizing developed within the HyIndoor project is presented in Hyindoor Guidelines report (Deliverable 5.1).
- Vent size can be calculated using analytically derived and experimentally validated correlations between allowable overpressure, enclosure volume, flammable mixture parameters, and vent area. Hyindoor Guidelines report presents a correlation for the case of hydrogen fraction uniform across the entire enclosure (Chernyavsky et al., 2014). Guidelines report presents a technique to calculate vent size for the case

when hydrogen-air mixture occupies only part of the enclosure volume, i.e. a layer with uniform and non-uniform concentration.

- CFD may be used to predict vented deflagration pressure dynamics, particularly - where simplified engineering models are not applicable.
- However, care should be taken to ensure that CFD models are validated within range of parameters for which they are applied, including:
    - hydrogen concentration
    - enclosure scale
    - internal congestion
    - vent size
    - vent inertia

*Dealing with jet fire and underventilated fire*

Work performed on jet fire and underventilated fire in Hyindoor project gave the following recommendations to take into account for application design:

- Where practicable, avoid the conditions for under-ventilated jet-fires to occur by providing sufficient ventilation. This may be achieved by providing sufficient passive vents to maintain an average concentration of less than the LFL resulting from an unignited hydrogen leak.
- Use fire resistant materials where possible;
- Avoid the presence of combustible materials close to vents if there is a potential for an under-ventilated jet-fire to occur.
- Consider protection against under-pressure due to rapid steam condensation (e.g. by providing vents for emergency air inflow or inert gas injection).

In the project, calculation means were studied and can be proposed:

- Hyindoor Guidelines report (Deliverable 5.1) presents the dimensionless correlation for calculation of flame length (Molkov and Saffers, 2013). Results of the flame length calculation can be used to find out three deterministic separation distances for well-ventilated jet fires. An example of the tool for calculation of deterministic separation distance is provided in Appendix part of the Hyindoor Guidelines report;
- Use piping of smallest possible diameter or introduce flow restrictors to reduce flame length (flame length is generally proportional to leak diameter). An example of calculation of the effect of flow restrictor on flame length is provided in Appendix part of the Hyindoor Guidelines report;
- Radiation heat flux from the hot layer of combustion products and heated ceiling can affect the evacuation. The methodology to calculate thermal radiation and example based on HSL experiment are given in Appendix part of the Hyindoor Guidelines report;
- Computational fluid dynamics (CFD) can be used as a contemporary tool for hydrogen safety engineering in assessment of jet fires indoors as no other tool available.

## 5.2 Sensors

### 5.2.1 Introduction

The institute of Energy and Transport (JRC-IET) of the European Commission (EC) has developed a testing facility (SenTeF) dedicated to independent characterization of hydrogen sensor performances and reliability. The facility performs the function of a reference laboratory for the Fuel Cells and Hydrogen Joint Undertaking (FCH JU). JRC-IET in collaboration with the industrial partners of the project, has been active in studying the role of hydrogen sensors for various indoor applications. Within the HyIndoor project a number of scenarios were selected describing typical indoor applications using hydrogen. The use of hydrogen sensors has been recognized as a practical instrument for mitigating the potential consequences of a hydrogen release indoors. In order to achieve the safety objectives, it is necessary to know the expected working conditions and functional expectations of the hydrogen sensor. Based on the information provided by the industrial project participants, suitable sensing technologies/products which meet the performance requirements have been identified. The performance of the sensors subsequently chosen were validated by testing the sensor performance under simulated ambient conditions representative of the real-life operating conditions of the sensor.  The type, the number and the position of the sensors are key issues and strategies need to be implemented which are application-specific. Those strategies are strongly dependent on the sensor performances, and the deployment cost, in term of price, power consumption and maintenance.

The study went through several steps:

1) A market survey has been conducted in order to make an inventory of identified commercial off-the-shelf (COTS) sensors.

2) Recommendations for suitable sensors were provided, based on the sensor requirements set by the consortium for indoor applications.

3) Five representative hydrogen sensors have been purchased and their performances have been tested at the JRC-IET SenTeF, according to the industrial needs.

4) The experimental sensor performances have been compared to the requirements of Standard ISO 26142.

5) Recommendations and guidelines for sensor end-users have been made as for the type, number and position of sensor for the target application.

### 5.2.2 Market survey

The market survey was performed in order to identify price and performances of COTS sensors. The sensors were grouped according to the working principle in different platforms, i.e. the sensor working principle. The market survey shows that most common COTS platforms are Catalytic, Electrochemical, Thermal Conductivity and Metal-Oxide. There are a large number of hydrogen sensors available for purchase on the market and these sensors commonly employ one of the following detection technologies:

1. Catalytic (pellistor)
2. Electrochemical
3. Metal-oxide semiconductor
4. Thermal conductivity
5. MOSFET
6. Palladium thin film
7. Optical

In addition there are devices which employ more than one technology to detect the presence of and quantify the concentration of hydrogen.
The choice of sensing technology needs to be in line with the performance expectations in the specified environment. It should be noted that the electronics for signal management play an important role as they, often through the help of environmental sensors, allow for correcting for variation of external parameters.
The following sensor performances were surveyed: response time, measuring range, sensitivity, selectivity, stability (respect to change of environmental parameters), and resistance to poisons. The cost of hydrogen sensors of the survey varies in a broad range between 20 and 3000 euros and their declared performances are also very variable. Several elements contribute to the sensor pricing and performances:

- **The technology used**: non-conventional platforms (e.g. Pd-nanoparticles) are usually more expensive; performances are also highly dependent on the sensor platform, e.g. the best sensitivities are reported for EC and MOx sensors (down to 1 ppm); on the other side, thermal conductivity sensors offer the possibility to measure hydrogen up to 100 vol%.
- **The electronics and packaging:** the signal is usually transformed via electronic boards allowing for tuning the resolution and the measuring range; the integration with other sensor elements allows accounting for the influence of environmental parameters; those elements have a cost.
- **Filters, protective coating, and grids**: allow for improving selectivity, lifetime and preventing inflame respectively.
- **The certification,** e.g. ATEX protection, EMC resistance.
- **Micromachining**, which allows saving materials and decreasing sensor dimensions.

### 5.2.3 Recommendations for sensor choice

When considering hydrogen safety sensors as a risk mitigation device in applications involving hydrogen, one is immediately faced with the question exactly which sensor type to use, how many sensors to use and where to place them. Optimal deployment of hydrogen sensors depends on the specific application and on the corresponding requirements on the sensor performance. The use of hydrogen sensors has to be implemented into a strategy which is strongly dependent on specific application. Sensors with different performance requirements may be needed for each application. The typical indoor applications which were addressed are:

**The forklift vehicle and the refuelling system in the warehouse.**

Warehouses have commonly large surface areas (thousands of square meters) and roof heights of up to 10 m. The indoor air renewal in the warehouse can be either by natural ventilation through the doors or forced ventilation. An average of 50 $m^2$ (500 square feet) of warehouse space dedicated to hydrogen infrastructure were reported (NREL) in support of an average fleet size of 58 fuel cell materials handling vehicles. Depending on the area that needs to be monitored, a large number of sensors may need to be placed. In a warehouse setting, small variations in the environmental parameters such as temperature, RH and gas flow rate (in case of natural ventilation) can be expected. Fast, cheap (<100 euros) and sensitive (down to 10% LFL) hydrogen sensors are needed. Conventional sensors (TC, CAT, EC) were proposed as the most appropriate technologies.

**The hydrogen generator.**
The hydrogen generator is based on the process of hydrogen reforming from $CH_4$. The reaction generates $H_2O$, CO and $CO_2$ as secondary products. $H_2$, $CH_4$ and CO are the flammable species ad their release could determinate a dangerous situation. Combustible gas sensors are suggested for this application. Most common platforms for sensing combustible gases are MOx and CAT. MOx sensors are very sensitive, but lack in linearity and robustness. Due to their better linearity and improved stability, CAT sensors were identified as the most suitable platforms for this application. Small scale reformers have dimensions of a room, i.e. 10 $m^2$ surface area and 25 m height. Thus, they do not require a big number of sensors. The use of more robust hydrogen sensors with ATEX protection is recommended.

**The fuel cell for back-up power generation.**
The fuel cell can be placed in a container which can be regarded as a confined space and usually placed outdoors. It consists of three main volumes: the fuel cell part, the fuel cell cabinet hosting the fuel cell, and the storage part. The typical dimensions are those of a small room (33 $m^3$). Reliable, sensitive and robust (with respect to environmental parameters) hydrogen sensors are suggested for this application. The installation of a combustible gas detection system in the fuel cell power system enclosure is required. TC sensors allow for measuring hydrogen in a wide concentration range and show high resistance to poisoning (sulphur containing compounds) and can therefore be recommended for the fuel cell container.

**High pressure storage.**
The hydrogen cylinders are usually placed in an outdoor distribution room from which $H_2$ is transported through pipes. The ventilation of the distribution facilities should be such that the LFL will not be reached in case of heavy leak. Several sensors may be required depending on the size of the facility. Conventional sensors (TC, CAT, EC) were proposed as the most appropriate technologies.

### 5.2.4 Choice of representative hydrogen sensors for purchase and testing

Five representative hydrogen sensors have been chosen and purchased in order to assess their actual performances according to a set of tests agreed with the industrial partners:

- A micro-machined Thermal Conductivity sensor (TC-1) with a RH correction was chosen due to its optimum compromise between declared performances and price.
- A catalytic sensor (CAT-1) was chosen for the testing campaign due to its good declared performances combined to a low pricing.
- Two conventional catalytic sensors (CAT-2 and CAT-3) with ATEX protection were chosen for comparison in order to verify the influences of packaging on the senor performances of catalytic sensors.
- A highly sensitive electrochemical sensor (EC-1) was purchased as a back-up strategy for early detection of hydrogen due to small leaks.

### 5.2.5 Sensor performances

Table 1 reports the results of the testing campaign on the 5 sensors chosen. The results have been compared to the requirements of the Standard ISO26412 on safety sensors for stationary applications. The performances can be summarised as follow:

1. The TC sensor shows best performances in term of stability, robustness to poisons, response time. Its sensitivity allows detecting hydrogen down to 50 ppm.
2. The CAT sensors are sensitive to hydrogen and methane while their response show some influence from environmental parameters, e.g. flow rate.
3. The EC sensor is very sensitive (ppm range) but it is strongly influenced by environmental parameters (especially temperature and flow rate).

In general, sensors should be calibrated before use in order to get an accurate response. In some case the pre-calibration is required not to fail the requirements of the Standard ISO26142.
All sensors tested show a flow dependence, which have to be taken into account when installing the sensors. Low content of Si-based compounds (HMDS) did not poison the sensors.

| Performance parameter | CAT-1 | TC-1 | CAT-2 | CAT-3 | EC-1 |
|---|---|---|---|---|---|
| Manufacturer Calibration | X | √ | X | × | X |
| Accuracy and Precision | √ | √ | × | × | × |
| Short term stability | × | √ | √ | √ | x |
| Pressure ($p_0$ = 100kPa) | √ | √ | × | × | |
| RH ($RH_0$ = 50%) | √ | × | × | √ | × |
| Temperature ($T_0$ = 20C) | x | √ | √ | × | X |
| Lower Detection Limit (LDL) | 50 ppm | 50 ppm | 50 ppm | 500 ppm | <<50 ppm |
| CH4 (1%) | X | x | X | X | No |
| SO2 (0.05%) | X | No | No | small | X |
| CO (0.005%) | No | No | No | No | lower |
| HMDS (0.001%) | No | No | No | small | No |
| Response/Recovery time | 6 s | 4 s | ~10 s | ~10 s | ~50 s |
| Flow rate ($F_0$ = 200 ccm) | 16% | 3% | 8% | 13% | 39% |
| ATEX | IEC60079-15 | No | √ | √ | √ |

**Table 1. Tests results of the five sensors tested compared to ISO 26412: The dark green stands for outstanding performance; the light green stands for good performances; yellow stands for passing grade; red stands for unsatisfactory.**

### 5.2.6 Sensor deployment: recommendations and guidelines

The deployment of sensors for early detection of a hydrogen release indoors has to take into account several parameters related to the specific application, such as the expected position of the leak, the dimensions of the environment and the presence of ventilation.

The systems studied here can monitor the gas concentration only at the immediate location of the sensor. Therefore the placement of the sensor needs to be considered carefully. Several key parameters must be considered in order to develop an effective strategy, also including: the number of sensors; the sensor performances in term of response time, measuring range, sensitivity, selectivity, stability (respect to change of environmental parameters), and resistance to poisons; the possibility of using complementary sensors. Those parameters are to some extent interconnected, i.e. the number of sensors which need to be installed is related to their sensitivity while sensor price and maintenance costs may prohibit the deployment of a large number of sensors.

The two basic approaches to the location of gas detectors are:

1) **Point source monitoring**, where the sensor is sited close to an identified potential leakage point, such as such as valve stem seals, gaskets, compression fittings and expansion joints;

2) **Perimeter or area monitoring**, where a plant or process is ringed by monitors to give early warning of a leak but no specific source is identified.

General industry experience suggests that gas monitors are of most value if located in accordance with the point source philosophy within the operation facility where the probability of leakage or release is high. However, being lighter than air, $CH_4$ and $H_2$ will diffuse towards and along the ceiling and will tend to escape in presence of openings. Therefore as a general rule, the position of the sensor should be on the ceiling, especially in areas where gas build-up is likely to happen, such as corners or stopping points of gas-releasing moving devices. Workpackage2 has shown that the concentration of the gas is high along the vertical to the leak but decreases rapidly as along the radial direction because of slow diffusion on the horizontal plane. This means that in cases where a potential leak source can be identified, the sensor should be placed right above. As the performance of hydrogen sensors tested has a marked flow dependence, the ventilation pattern needs to be taken into account when installing the sensors. As the presence of openings will decrease the hydrogen concentration locally, the sensor must be sufficiently sensitive. Detectors should be placed above the level of ventilation openings. In case a point leak source cannot be identified, a grid of hydrogen sensors may be placed on the ceiling. If the ceiling is compartmentalized by an obstruction, sensors should be placed in each compartment. The sensor orientation should preferably face down towards the area where the leak is expected. This position would also avoid the accumulation of dust on the sensing head, which may impede the diffusion of gas into the sensor.

As shown in Table 1, all the sensors considered in this study present a good sensitivity to hydrogen. Both catalytic sensors and thermal conductivity sensors show good performances allowing for indoor applications such **as the warehouse, the high pressure storage and the fuel cell container**. In particular, warehouses where large spaces are involved and stationary (refuelling station) and mobile (forklifts) applications are present, it may be necessary to deploy a net of sensors. Here the inexpensive sensors, such as CAT-1 and TC-1 may be considered. Due to their high cross sensitivity to methane, catalytic sensors seem more appropriate for applications where combustible gases are present, i.e. the **hydrogen generator**.

# 6 RCS

## 6.1 Global RCS inputs

Hydrogen energy applications often require that systems be used indoors (e.g., industrial trucks for materials handling in a warehouse facility, fuel cells located in a room, or hydrogen stored and distributed from a gas cabinet). It may also be necessary or desirable to locate some hydrogen system components/equipment in indoor or outdoor enclosures for security or safety reasons to isolate them from the end-user and the public, or from weather conditions. Use of hydrogen in confined environment requires detailed assessment of hazards and associated risks, including potential risk prevention and mitigation features. The release of hydrogen can potentially lead to the accumulation of hydrogen and the formation of a flammable hydrogen-air mixture.
The aim of the Hyindoor project was to develop safety design guidelines & engineering tools as well as RCS recommendations intended to prevent and mitigate hazardous consequences of hydrogen release in confined environments. Closing knowledge gaps is critical to this effort in 3 main areas:

1. Hydrogen release conditions and accumulation,

2. Vented deflagration,

3. Jet fire and under-ventilated flame regimes (e.g., extinguishment or oscillating flames and steady burns).

For each phenomenon, the release position/conditions, the number, size and location of the openings in the room/enclosure of some given size, and the type of ventilation can significantly influence the prevention/mitigation strategy. Each of these phenomena has been subject to analytical, experimental and numerical analysis within a dedicated work package. They each have shared state of the art information in order to prioritize the research objectives. Existing analytical and numerical models were initially used as well as RCS lists (which were updated from time to time) were prepared and RCS gaps were identified. These results were used to facilitate the formulation of the test program, while the experimental results were subsequently used to validate and improve the models and identify RCS recommendations, where appropriate.

WP6 worked in conjunction with WP1 Safety objectives and strategies specified in existing RCS for selected configurations and summarized the findings of WP2-Dispersion and accumulation, WP3-Vented deflagrations, WP4-Hydrogen jet-fire and WP5-Safety strategies and guidelines (including deployment of hydrogen sensors) to identify RCS recommendations D6.1 and to prepare the final report D6.2, which is the subject of this present report..

The final D6.1 report on RCS recommendations has collected results from all Hyindoor Work Packages, built consensus within the group and presented them in a comprehensive report. The objective was to summarize the regulations, codes and standards (RCS) findings of the Hyindoor project and to categorize them to support RCS initiatives. The categories are:

a) Ventilation : Recommendations # 1-8

This section covers recommendations regarding the implementation of ventilation for preventing the formation of an explosive atmosphere, or for limiting the hydrogen concentration, in the event of a hydrogen leak release.

b) Limitations of over-pressure: Recommendations # 9-11

This section covers recommendations regarding the implementation of venting devices for limiting the overpressure developed in the event of a hydrogen release as a result either of the Pressure Peaking Phenomenon (PPP) or of the deflagration of a flammable hydrogen-air mixture.

c) Other: Recommendations # 12-14

This section covers jet-fire, sensors and flow restrictors.

Also, the D6.1 report includes a path forward with the aim to bring these recommendations to the international RCS bodies (e.g. ISO, IEC) and professional associations (AFGC, EIGA, CGA).

## *6.2 RCS strategy transfer*

First of all, the public releases of the guideline, RCS report and final report will be obviously the means for dissemination of the results of Hyindoor project.

Specifically, the Workshop of 11 December is the main mean for a wide stakeholder dissemination.

Additionally, Hyindoor partners who are engaged in RCS activities may continue to disseminate both with industries and RCS bodies.

Also the coordinator of the project will prepare an abstract for the ICHS 2015 conference.

The project Website will continue to stay online.

# 7 Perspectives

There are several perspectives of the Hyindoor project :

- Concerning RCS, since project partners (AL, UU, CCS, CEA) are also members to the ISO committees, they will push forward for that Hyindoor recommandations will be implemented in the new international norms.
- Concerning the scientific perspectives, the consortium has identified some remaining research gaps that still have to be filled. These gaps are the comprehensive design of forced ventilation systems, the structural response of structures (containers for example) to internal explosions, the prediction of the consequences for vented explosion in realistic conditions (vent panel deployment, non homogenous hydrogen distribution, initial turbulence...) and the reliable use of CFD in risk assessment. The consortium partners have already submitted and will submit some project proposals to European and national funding institutions to perform the pre-normative research on these still open research gaps.

# 8 USE AND DISSEMINATION OF FOREGROUND

**Section A (public)**

*This section shall include a list of planned dissemination activities (publications, conferences, workshops, web, press releases, flyers, etc) in free text format. Where articles have been published in the popular press, please provide a list as well.*

*In addition, please provide a list of all scientific (peer reviewed) publications relating to the foreground of the project, starting with the most important ones, in the table below.*

**TEMPLATE A: LIST OF SCIENTIFIC (PEER REVIEWED) PUBLICATIONS, STARTING WITH THE MOST IMPORTANT ONES**

- **ALPHABETICAL ORDER**

| NO. | Title | Main author | Title of the periodical or the series | Number, date or frequency | Publisher | Place of publication | Year of publication | Relevant pages | Permanent identifiers[1] (if available) | Is/Will open access[2] provided to this publication? |
|---|---|---|---|---|---|---|---|---|---|---|
| Journal publications | | | | | | | | | | |
| 1 | CFD benchmark of hydrogen release and dispersion in confined, naturally ventilated space with one vent | S. G. Giannissi, S. Shentsov, D. Melideo, D. Baraldi, A.G. Venetsanos, V. Molkov | International Journal of Hydrogen Energy | In preparation | *Elsevier* | | | | | No |
| 2 | Concentration measurements in a | N. Kotchourko, M. Kuznetsov, A. | International Journal of | v.39 (11) | *Elsevier* | | Apr 2014 | 6201-6209 | http://dx.doi.org/10.1016/j.ijhydene.2013.10.152 | No |

[1] A permanent identifier should be a persistent link to the published version full text if open access or abstract if article is pay per view) or to the final manuscript accepted for publication (link to article in repository).

[2] Open Access is defined as free of charge access for anyone via the internet. Please answer "yes" if the open access to the publication is already established and also if the embargo period for open access is not yet over but you intend to establish open access afterwards.

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|---|---|---|---|---|---|---|---|---|---|---|
| | round hydrogen jet using Background Oriented Schlieren (BOS) technique | Kotchourko, J. Grune, A. Lelyakin, T. Jordan | Hydrogen Energy | | | | | | | |
| 3 | Critical conditions of hydrogen–air detonation in partially confined geometry | W. Rudy, M. Kuznetsov, R. Porowski, A. Teodorczyk, J. Grune, K. Sempert | Proceedings of the Combustion Institute | v.34 (2) | *Elsevier* | | 2013 | 1965-1972 | http://dx.doi.org/10.1016/j.proci.2012.07.019 | No |
| 4 | Experimental and numerical investigation of premixed flame propagation with distorted tulip shape in a closed duct | H. Xiao, D. Makarov, J. Sun, and V. Molkov | Combustion and Flame | v.159 (4) | *Elsevier* | | 2012 | 1523-1538 | doi:10.1016/j.combustflame.2011.12.003 | No |
| 5 | Experimental Investigation of Hydrogen-Air Deflagrations and Detonations in Semi-Confined Flat Layers | J. Grune, K. Sempert, H. Haberstroh, M. Kuznetsov, T. Jordan | Journal of Loss Prevention in the Process Industries | v.26 (6) | *Elsevier* | | Nov 2013 | 317-323 | http://dx.doi.org/10.1016/j.jlp.2011.09.008 | No |
| 6 | Experimental study of ignited unsteady hydrogen jets into air | J. Grune, K. Sempert, M. Kuznetsov, and W. Breitung | Int. J. Hydrogen Energy | v.36 (3) | *Elsevier* | | Feb 2011 | 2497-2504 | http://dx.doi.org/10.1016/j.ijhydene.2010.04.152 | |
| 7 | Hydrogen jet flames | Molkov V, Saffers J-B. | International Journal of Hydrogen Energy | v.38 (19) | *Elsevier* | | June 2013 | 8141-8158 | doi:10.1016/j.ijhydene.2012.08.106. | No |
| 8 | Hydrogen–air deflagrations: Vent sizing correlation for low-strength equipment and buildings | Molkov V., Bragin M. | International Journal of Hydrogen Energy | v.40 (2) | *Elsevier* | | Jan 2015 | 1256-1266 | doi:10.1016/j.ijhydene.2014.11.067 | No |
| 9 | Hydrogen non-premixed | V. Molkov, V. Shentsov, S. | International Journal of | v.39 (20) | *Elsevier* | | July 2014 | 10788-10801 | doi:10.1016/j.ijhydene.2014.05.007 | No |

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| | combustion in enclosure with one vent and sustained release: numerical experiments | Brennan, and D. Makarov | Hydrogen Energy | | | | | | | |
| 10 | Numerical and physical requirements to simulation of gas release and dispersion in an enclosure with one vent | V. Molkov and V. Shentsov | International Journal of Hydrogen Energy | V.39 (35) | *Elsevier* | | Aug 2014 | 13328-13345 | doi:10.1016/j.ijhydene.2014.06.154 | No |
| 11 | Passive ventilation of a sustained gaseous release in an enclosure with one vent | V. Molkov, V. Shentsov, and J. Quintiere | International Journal of Hydrogen Energy | v.39 (20) | *Elsevier* | | May 2014 | 10788-10801 | doi:10.1016/j.ijhydene.2014.03.069 | No |
| 12 | Plane Hydrogen jets | Makarov D. and Molkov, V. | International Journal of Hydrogen Energy | v.38 (19) | *Elsevier* | | June 2013 | 8068-8083 | doi:10.1016/j.ijhydene.2013.03.017 | No |
| 13 | Rayleigh-Taylor instability: modelling and effect on coherent deflagrations | Keenan J.J., Makarov D.V., Molkov V.V. | International Journal of Hydrogen Energy | v. 39 (35) | *Elsevier* | | Aug 2014 | 20467-20473 | doi:10.1016/j.ijhydene.2014.03.230 | No |
| 14 | Safety assessment of unignited hydrogen discharge from onboard storage in garages with low levels of natural ventilation | Brennan S, Molkov V. | International Journal of Hydrogen Energy | v.38 (19) | *Elsevier* | | Jun 2013 | 8159-8166 | doi:10.1016/j.ijhydene.2012.08.036 | No |
| 15 | Vent sizing correlation for mitigation of hydrogen-air deflagrations in low strength equipment | B. Chernyavsky, P. Hooker, J. Hall, M. Kuznetsov and V. Molkov | Journal of Hazardous Materials | In preparation | *Elsevier* | | | | | No |

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| | and buildings | | | | | | | | | |
| Conference proceedings | | | | | | | | | | |
| 16 | Accumulation of hydrogen released into a vented enclosure – experimental results | Hooker P., Willoughby, D., Hall, J. and Hoyes, J. | Published in proceedings of ICHS5 | | | | 2013 | | | Yes |
| 17 | CFD benchmark based on experiments of helium dispersion in a 1 m3 enclosure – intercomparisons for plumes and buoyant jets | G. Bernard-Michel, B. Cariteau, J. Ni, S. Jallais, E. Vyazmina, D. Melideo, D. Baraldi, A. Venetsanos | Published in proceedings of ICHS5 | | | | 2013 | | | Yes |
| 18 | Dynamics of Hydrogen Flame Self-Extinction in a Vented Enclosure. | Molkov V, Shentsov V, Brennan S, Makarov D. | Proceedings of the 7th International Seminar on Fire and Explosion Hazards | | | | 2013 | 922-931 | | |
| 19 | Evaluation of the adrea-hf cfd code against a hydrogen deflagration in a tunnel | Tolias, I.C., Markatos, N., Venetsanos, A.G. | Published in proceedings of ICHS5 | | | | 2013 | | | Yes |
| 20 | Hydrogen-air deflagrations: vent sizing correlation for low-strength equipment and buildings | Molkov V., Bragin M. | Published in proceedings of ICHS5 | | | | 2013 | | | Yes |
| 21 | Hydrogen-Air Deflagrations and Detonations in a Semi-Confined Flat Layer | M. Kuznetsov, J. Grune, A. Friedrich, K. Sempert, W. Breitung and T. Jordan | Fire and Explosion Hazards, Proceedings of the Sixth International Seminar | | | | 2011 | 125-136 | http://dx.doi.org/10.3850/978-981-08-7724-8_02-05 | Yes |

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| 22 | Hydrogen Combustion in a Flat Semi-Confined Layer with Respect to the Fukushima Daiichi Accident | M. Kuznetsov, J. Yanez, J. Grune, A. Friedrich, T. Jordan | Proceedings of ICAPP '12 Paper 12419 | | | | June 2012 | 1-10 | | |
| 23 | Indoor use of hydrogen, knowledge gaps and priorities for the improvement of current standards on hydrogen, a presentation of Hyindoor European project | S. Ruban, G. Bernard-Michel, A. Kotchourko, S. Brennan, R. Day, P. Hooker, D. Baraldi, A. Venetsanos, J. Der Kinderen | Published in proceedings of ICHS5 | | | | 2013 | | | Yes |
| 24 | Influence of the location of a buoyant gas release in several configurations varying the height of the release and the geometry of the enclosure | Deborah Houssin-Agbomson, Gilles Bernard-Michel, Benjamin Cariteau, Simon Jallais | Published in proceedings of ICHS5 | | | | 2013 | | | Yes |
| 25 | Modelling and simulation of lean hydrogen-air deflagrations | Makarov D., Molkov V | Published in proceedings of ICHS5 | | | | 2013 | | | Yes |
| 26 | A Novel Correlation for Vented Hydrogen-Air Deflagrations | Molkov V, Bragin M. | Proceedings of the 7th International Seminar on Fire and Explosion Hazards | | | | 2013 | 689-698. | doi:10.3850/978-981-07-5936-0_11-02 | |
| 27 | Numerical simulation of the helium dispersion in a semi-confined air-filled cavity | Huong-Lan Tran, Anne Sergent, Gilles Bernard-Michel, Patrick Le Quere (CEA) | Published in proceedings of ICHS5 | | | | 2013 | | | Yes |

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| 28 | Numerical Simulation of 10% Hydrogen-Air Vented Deflagration in a 120 m3 Enclosure | Makarov D, Molkov V. | Proceedings of the 7th International Seminar on Fire and Explosion Hazards, | | | | 2013 | 975-984 | | |
| 29 | Numerical simulations of hydrogen non-premixed combustion and self-extinction in an enclosure | Molkov V, Shentsov V, Brennan S, Makarov D | Published in proceedings of ICHS5 | | | | 2013 | | | Yes |
| 30 | Passive ventilation of a sustained gaseous release in an enclosure with one vent | V. Molkov, V. Shentsov, and J. Quintiere | Published in proceedings of ICHS5 | | | | 2013 | | | Yes |
| 31 | Rayleigh-Taylor instability: modelling and effect on coherent deflagrations | Keenan J.J., Makarov D.V., Molkov V.V. | Published in proceedings of ICHS5 | | | | 2013 | | | Yes |
| 32 | Sustained Hydrogen Leak Concentration in Enclosure with One Vent | Molkov V, Shentsov V, Quintiere J. | Proceedings of the 7th International Seminar on Fire and Explosion Hazards, | | | | 2013 | 903-912 | | |
| 33 | Towards the Implementation of Rayleigh-Taylor Instability into the Multi-Phenomena Deflagration Model | Keenan J, Makarov D, Molkov V. | Proceedings of the 7th International Seminar on Fire and Explosion Hazards, | | | | 2013 | 932-941 | | |
| 34 | Towards Numerical Simulations of the Hydrogen-Air Deflagration in Fukushima-Daiichi | Ishikawa D, Matsuo A, Makarov D, Molkov V. | Proceedings of the IX International Symposium on Hazards, | | | | | | | |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Nuclear Power Plant Unit No.1. | | Prevention and Mitigation of Industrial Explosions. | | | | | | | |
| | | | | Books and book chapters | | | | | | |
| 35 | Rethinking hydrogen jet flames. | Molkov V, Saffers J-B. | In: Non-equilibrium processes, Eds. S Frolov, A Starik, | | *Torus* | Moscow | 2012 | 242-247 | | No |
| 36 | Fundamentals of Hydrogen Safety Engineering, Part I & II | Molkov V | | | *www.bookboon.com* | | 2012 | | ISBN 978-87-403-0226-4 ISBN 978-87-403-0279-0 | Yes |
| 37 | Fire and Explosion Hazards | D Bradley, G Makhviladze, V Molkov, F Tamanini, P Sunderland. | | | *Research Publishing* | Singapore | 2011 | | ISBN-13: 978-981-07-5936-0 | No |
| 38 | Hydrogen Safety Engineering: The State-of-the-Art and Future Progress | Molkov V | In: Comprehensive Renewable Energy, Vol 4 Sayigh A, (ed.), | | *Elsevier* | Oxford | 2012 | 77-109 | Electronic ISBN: 9780080878737. Print ISBN: 97800878720. | No |
| 39 | Fuel-cell (hydrogen) electric hybrid vehicles | BG Pollet, I Staffell, JL Shang, V Molkov | In: Alternative fuels and advanced vehicle technologies. | | *Woodhead Publishing* | | 2014 | 685-735 | ISBN 0857095226 | No |

*Please complete the table hereafter:*

| TEMPLATE B2: OVERVIEW TABLE WITH EXPLOITABLE FOREGROUND | | | | | |
|---|---|---|---|---|---|
| **Exploitable Foreground (description)** | **Exploitable product(s) or measure(s)** | **Sector(s) of application** | **Timetable, commercial use** | **Patents or other IPR exploitation (licences)** | **Owner & Other Beneficiary(s) involved** |
| | | | | | |
| | | | | | |
| | | | | | |

*In addition to the table, please provide a text to explain the exploitable foreground, in particular:*

- *Its purpose*
- *How the foreground might be exploited, when and by whom*
- *IPR exploitable measures taken or intended*
- *Further research necessary, if any*
- *Potential/expected impact (quantify where possible)*

# 9 REPORT ON SOCIETAL IMPLICATIONS

## A General Information *(completed automatically when **Grant Agreement number** is entered.*

| | |
|---|---|
| **FCH JU Grant Agreement Number:** | |
| **Title of Project:** | |
| **Name and Title of Coordinator:** | |

## B Ethics

| | | |
|---|---|---|
| **1. Did you have ethicists or others with specific experience of ethical issues involved in the project?** | O<br>O | ~~**Yes**~~<br>**No** |
| **2. Please indicate whether your project involved any of the following issues (tick box) :** | ***YES*** | |
| **INFORMED CONSENT** | | |
| • Did the project involve children? | No | |
| • Did the project involve patients or persons not able to give consent? | No | |
| • Did the project involve adult healthy volunteers? | No | |
| • Did the project involve Human Genetic Material? | No | |
| • Did the project involve Human biological samples? | No | |
| • Did the project involve Human data collection? | No | |
| **RESEARCH ON HUMAN EMBRYO/FOETUS** | | |
| • Did the project involve Human Embryos? | No | |
| • Did the project involve Human Foetal Tissue / Cells? | No | |
| • Did the project involve Human Embryonic Stem Cells? | No | |
| **PRIVACY** | | |
| • Did the project involve processing of genetic information or personal data (eg. health, sexual lifestyle, ethnicity, political opinion, religious or philosophical conviction) | no | |
| • Did the project involve tracking the location or observation of people? | No | |
| **RESEARCH ON ANIMALS** | | |
| • Did the project involve research on animals? | No | |
| • Were those animals transgenic small laboratory animals? | No | |
| • Were those animals transgenic farm animals? | No | |
| • Were those animals cloning farm animals? | No | |
| • Were those animals non-human primates? | No | |
| **RESEARCH INVOLVING DEVELOPING COUNTRIES** | | |
| • Use of local resources (genetic, animal, plant etc) | **No** | |
| • Benefit to local community (capacity building ie access to healthcare, education etc) | **No** | |
| **DUAL USE** | | |
| • Research having potential military / terrorist application | No | |

## C Workforce Statistics

**3 Workforce statistics for the project: Please indicate in the table below the number of people who worked on the project (on a headcount basis).**

| **Type of Position** | **Number of Women** | **Number of Men** |
|---|---|---|
| Scientific Coordinator | | |
| Work package leader | | |
| Experienced researcher (i.e. PhD holders) | | |

| | | |
|---|---|---|
| PhD Students | 1 NCSRD 2 KIT | 1 UU |
| Other | | |

| | |
|---|---|
| **4 How many additional researchers (in companies and universities) were recruited specifically for this project?** | |
| Of which, indicate the number of men: | 1 NCSRD<br>3 UU |
| Of which, indicate the number of women: | |

## D Gender Aspects

**5 Did you carry out specific Gender Equality Actions under the project ?**

○ ~~Yes~~
○ No

**6 Which of the following actions did you carry out and how effective were they?**

| | | Not at all effective | | | | Very effective |
|---|---|---|---|---|---|---|
| ❑ | Design and implement an equal opportunity policy | ○ | ○ | ○ | ○ | ○ |
| ❑ | Set targets to achieve a gender balance in the workforce | ○ | ○ | ○ | ○ | ○ |
| ❑ | Organise conferences and workshops on gender | ○ | ○ | ○ | ○ | ○ |
| ❑ | Actions to improve work-life balance | ○ | ○ | ○ | ○ | ○ |
| ○ | Other: | | | | | |

**7 Was there a gender dimension associated with the research content – i.e. wherever people were the focus of the research as, for example, consumers, users, patients or in trials, was the issue of gender considered and addressed?**

○ ~~Yes- please specify~~

○ No

## E Synergies with Science Education

**8 Did your project involve working with students and/or school pupils (e.g. open days, participation in science festivals and events, prizes/competitions or joint projects)?**

○ Yes- please specify
UU MSc in Hydrogene Safety Engineering and PhD students
○ ~~No~~

**9 Did the project generate any science education material (e.g. kits, websites, explanatory booklets, DVDs)?**

○ Yes- please specify
Lectures and presentations at European Technical School on Hydrogen and Fuel Cell
○ ~~No~~

## F Interdisciplinarity

**10 Which disciplines (see list below) are involved in your project?**

○ Main discipline[3]:
○ Associated discipline**Erreur ! Signet non défini.**: ○ Associated discipline**Erreur ! Signet non défini.**:

## G Engaging with Civil society and policy makers

**11a Did your project engage with societal actors beyond the research community?** *(if 'No', go to Question 14)*

○ ~~Yes~~
○ No

**11b If yes, did you engage with citizens (citizens' panels / juries) or organised civil society (NGOs, patients' groups etc.)?**

○ No

[3] Insert number from list below (Frascati Manual)

- ○ Yes- in determining what research should be performed
- ○ Yes - in implementing the research
- ○ Yes, in communicating /disseminating / using the results of the project

| | | |
|---|---|---|
| **11c In doing so, did your project involve actors whose role is mainly to organise the dialogue with citizens and organised civil society (e.g. professional mediator; communication company, science museums)?** | ○<br>○ | Yes<br>No |

**12 Did you engage with government / public bodies or policy makers (including international organisations)**

- ○ ~~No~~
- ○ ~~Yes- in framing the research agenda~~
- ○ ~~Yes - in implementing the research agenda~~
- ○ Yes, in communicating /disseminating / using the results of the project

**13a Will the project generate outputs (expertise or scientific advice) which could be used by policy makers?**

- ○ Yes – as a **primary** objective (please indicate areas below- multiple answers possible)
- ○ ~~Yes – as a **secondary** objective (please indicate areas below - multiple answer possible)~~
- ○ ~~No~~

**13b If Yes, in which fields?**

| | | | | | |
|---|---|---|---|---|---|
| Agriculture<br>Audiovisual and Media<br>Budget<br>Competition<br>Consumers<br>Culture<br>Customs<br>Development Economic and Monetary Affairs<br>Education, Training, Youth<br>Employment and Social Affairs | | Energy<br>Enlargement<br>Enterprise<br>Environment<br>External Relations<br>External Trade<br>Fisheries and Maritime Affairs<br>Food Safety<br>Foreign and Security Policy<br>Fraud<br>Humanitarian aid | | Human rights<br>Information Society<br>Institutional affairs<br>Internal Market<br>Justice, freedom and security<br>Public Health<br>Regional Policy<br>Research and Innovation<br>Space<br>Taxation<br>Transport<br>Public safety | |

**13c If Yes, at which level?**

- ○ ~~Local / regional levels~~
- ○ National level
- ○ European level
- ○ International level

## H Use and dissemination

| | |
|---|---|
| **14 How many Articles were published/accepted for publication in peer-reviewed journals?** | |
| **To how many of these is open access[4] provided?** | **2** |
| **How many of these are published in open access journals?** | **None** |
| **How many of these are published in open repositories?** | **None** |
| **To how many of these is open access not provided?** | **All-2** |
| **Please check all applicable reasons for not providing open access:** | |
| ❑ publisher's licensing agreement would not permit publishing in a repository<br>❑ no suitable repository available<br>❑ no suitable open access journal available<br>❑ no funds available to publish in an open access journal<br>❑ lack of time and resources<br>❑ lack of information on open access<br>❑ other: the process started when project finished…………… | |

| | | |
|---|---|---|
| **15 How many new patent applications ('priority filings') have been made?** *("Technologically unique": multiple applications for the same invention in different jurisdictions should be counted as just one application of grant).* | | **None** |
| **16 Indicate how many of the following Intellectual Property Rights were applied for (give number in each box).** | Trademark | **None** |
| | Registered design | **None** |
| | Other | **None** |
| **17 How many spin-off companies were created / are planned as a direct result of the project?** | | **None** |
| ***Indicate the approximate number of additional jobs in these companies:*** | | |

**18 Please indicate whether your project has a potential impact on employment, in comparison with the situation before your project:**

| | | | |
|---|---|---|---|
| ❑ | Increase in employment, or | ❑ | In small & medium-sized enterprises |
| ❑ | Safeguard employment, or | ❑ | In large companies |
| ❑ | Decrease in employment, | ❑ | None of the above / not relevant to the project |
| ❑ | Difficult to estimate / not possible to quantify | ❑ | Research organisations |

| | |
|---|---|
| **19 For your project partnership please estimate the employment effect resulting directly from your participation in Full Time Equivalent (*FTE = one person working fulltime for a year*) jobs:** | *Indicate figure:*<br><br>3years |

[4] Open Access is defined as free of charge access for anyone via the internet.

| Difficult to estimate / not possible to quantify | ❑ |
|---|---|

## I Media and Communication to the general public

**20 As part of the project, were any of the beneficiaries professionals in communication or media relations?**

○ ~~Yes~~ ○ No

**21 As part of the project, have any beneficiaries received professional media / communication training / advice to improve communication with the general public?**

○ Yes MSc and FDW ○ ~~No~~

**22 Which of the following have been used to communicate information about your project to the general public, or have resulted from your project?**

| | | | |
|---|---|---|---|
| ❑ | Press Release | ❑ | Coverage in specialist press |
| ❑ | Media briefing | ❑ | Coverage in general (non-specialist) press |
| ❑ | TV coverage / report | ❑ | Coverage in national press |
| ❑ | Radio coverage / report | ❑ | Coverage in international press |
| ❑ | Brochures /posters / flyers | ❑ | Website for the general public / internet |
| ❑ | DVD /Film /Multimedia | ❑ | Event targeting general public (festival, conference, exhibition, science café) |

**23 In which languages are the information products for the general public produced?**

| | | | |
|---|---|---|---|
| ❑ | Language of the coordinator | ❑ | English |
| ❑ | Other language(s) | | |

***Question F-10***: Classification of Scientific Disciplines according to the Frascati Manual 2002 (Proposed Standard Practice for Surveys on Research and Experimental Development, OECD 2002):

**FIELDS OF SCIENCE AND TECHNOLOGY**

1. NATURAL SCIENCES

1.1 Mathematics and computer sciences [mathematics and other allied fields: computer sciences and other allied subjects (software development only; hardware development should be classified in the engineering fields)]

1.2 Physical sciences (astronomy and space sciences, physics and other allied subjects)

1.3 Chemical sciences (chemistry, other allied subjects)

1.4 Earth and related environmental sciences (geology, geophysics, mineralogy, physical geography and other geosciences, meteorology and other atmospheric sciences including climatic research, oceanography, vulcanology, palaeoecology, other allied sciences)

1.5 Biological sciences (biology, botany, bacteriology, microbiology, zoology, entomology, genetics, biochemistry, biophysics, other allied sciences, excluding clinical and veterinary sciences)

2 ENGINEERING AND TECHNOLOGY

2.1 Civil engineering (architecture engineering, building science and engineering, construction engineering, municipal and structural engineering and other allied subjects)

2.2 Electrical engineering, electronics [electrical engineering, electronics, communication engineering and systems, computer engineering (hardware only) and other allied subjects]

2.3. Other engineering sciences (such as chemical, aeronautical and space, mechanical, metallurgical and materials engineering, and their specialised subdivisions; forest products; applied sciences such as geodesy, industrial chemistry, etc.; the science and technology of food production; specialised technologies of interdisciplinary fields, e.g. systems analysis, metallurgy, mining, textile technology and other applied subjects) Hydrogen Safety Engineering

3. MEDICAL SCIENCES

3.1 Basic medicine (anatomy, cytology, physiology, genetics, pharmacy, pharmacology, toxicology, immunology and immunohaematology, clinical chemistry, clinical microbiology, pathology)

3.2 Clinical medicine (anaesthesiology, paediatrics, obstetrics and gynaecology, internal medicine, surgery, dentistry, neurology, psychiatry, radiology, therapeutics, otorhinolaryngology, ophthalmology)

3.3 Health sciences (public health services, social medicine, hygiene, nursing, epidemiology)

4. AGRICULTURAL SCIENCES

4.1 Agriculture, forestry, fisheries and allied sciences (agronomy, animal husbandry, fisheries, forestry, horticulture, other allied subjects)

4.2 Veterinary medicine

5. SOCIAL SCIENCES

5.1 Psychology

5.2 Economics

5.3 Educational sciences (education and training and other allied subjects)

5.4 Other social sciences [anthropology (social and cultural) and ethnology, demography, geography (human, economic and social), town and country planning, management, law, linguistics, political sciences, sociology, organisation and methods, miscellaneous social sciences and interdisciplinary , methodological and historical S1T activities relating to subjects in this group. Physical anthropology, physical geography and psychophysiology should normally be classified with the natural sciences].

6. HUMANITIES

6.1 History (history, prehistory and history, together with auxiliary historical disciplines such as archaeology, numismatics, palaeography, genealogy, etc.)

6.2 Languages and literature (ancient and modern)

6.3 Other humanities [philosophy (including the history of science and technology) arts, history of art, art criticism, painting, sculpture, musicology, dramatic art excluding artistic "research" of any kind, religion, theology, other fields and subjects pertaining to the humanities, methodological, historical and other S1T activities relating to the subjects in this group] .

# 10 FINAL REPORT ON THE DISTRIBUTION OF THE COMMUNITY FINANCIAL CONTRIBUTION

This report shall be submitted to the FCH JU Programme Office within 30 days after receipt of the final payment of the FCH JU financial contribution.

## Report on the distribution of the FCH JU financial contribution between beneficiaries

| Name of beneficiary | Final amount of FCH JU contribution per beneficiary in Euros |
|---|---|
| 1. | |
| 2. | |
| | |
| n. | |
| | |
| Total | |