MultHyFuel

Deliverable 2.4

Fire and explosion hazard assessment summary report

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Content

Executive Summary

This work is part of the MULTHYFUEL E.U. research program [1] aiming at enabling the implementation of hydrogen dispensers in multifuel refuelling stations. One important challenge is the estimation of severity of accidents due to a leakage of hydrogen from a dispenser in the forecourt.

This deliverable summarizes the work performed on the fire and explosion risks in multifuel refuelling stations incorporating high pressure H_2 dispensers. The practical consequences of ignited leakages of hydrogen onto other dispensers (and vice versa) are presented.

In the first part of this report the experimental choices are presented and justified. In the second part, results are given regarding the consequences on the forecourt. In the third part, the efficiency of potential safety barriers is discussed based on experimental evidence.

It is shown first that the chosen experimental conditions are representative of the technologies used and figure out correctly the critical hazardous scenarios identified by the consortium. The main conclusions are:

1. The leakage mass flowrates on leaking components might range from 1 to 30 g/s;
2. In a rather closed dispenser, such a flowrate will produce a homogeneous flammable atmosphere within a second time scale;
3. For leaking components, spontaneous ignition is unlikely. External sources are required. If ignition sources present inside the dispenser might be rather easily kept under control (ATEX rules for instance), it might be harder for those in the forecourt. The latter have to be considered because the flammable cloud extends outside;
4. An efficient way to mitigate the flammable cloud formed inside the dispenser is to provide a top venting;
5. The leakage flowrate on a broken hose can be in the order of 100 g/s;
6. Outside flammable clouds amounting to tens of m^3 can be formed in seconds laps of time depending on the presence of obstacles;
7. Spontaneous ignition of the clouds is probable but anyway due to the potential large size of the flammable cloud, the cloud will reach many ignition sources present on the forecourt. In such situations, ignition can be held as certain;
8. Because of this, immediate ignition is postulated producing jet flames as long as 5 m or more. Outside the flame, the heat flux remains acceptable.

1 Introduction

This deliverable summarizes the work performed about the fire and explosion risks in multifuel refuelling stations incorporating high pressure H_2 dispensers. The practical consequences of ignited leakages of hydrogen onto other dispensers (and vice versa) are presented.

In the first part of this report the experimental choices are presented and justified. In the second part, results are given regarding the consequences on the forecourt. In the third part, the efficiency of potential safety barriers is discussed based on experimental evidence.

This report is a summary of the work largely performed in WP2 but results from other projects are also used.

2 Experimental choices

2.1 Selection of the scenarios

A significant effort was devoted to a risk analysis in the MultHyFuel project (WP3). A qualitative HazID step was used to extract the most critical scenarios (D3.4 and D3.5) which had to be further investigated in WP2. Both the frequencies of the leakages, the flowrates (D2.1) and extent of the plumes, the probability of ignition and fire and explosion consequences (D2.3) were investigated using theoretical, numerical, and experimental methods.

The core of the project is what could happen in the forecourt if a high-pressure hydrogen leakage occurs on a dispenser. Details about the dispenser are given in the next section. The critical scenarios extracted from D3.5 to be investigated experimentally are presented in Table 2.1-1.

Table 2.1--1. Critical scenarios to be investigated experimentally in WP2 (issued from D3.5)

Ref	Pressure	Scenario	Leak
A	350 bar	Outside H_2 leak on hose (nozzle, nipple, …)	10% full bore diameter
B	350 bar	Outside H_2 hose rupturing (driving off, ...)	full bore (2.54 mm) max 300 g/s
C	700 bar	Outside H_2 leak on hose (nozzle, nipple, …)	10% full bore bore diameter
D	700 bar	Outside H_2 hose rupturing (driving off, ...)	full bore (2.54 mm) max 120 g/s
E	350 bar	Inside H_2 leak on component	0.1 to 0.2 mm
F	700 bar	Inside H_2 leak on component	0.1 to 0.2 mm
G	Liquid	Outside gasoline pool fire	120 l gasoline
H	250 bar	Outside CNG leak on hose (nozzle, nipple, …)	DN15
I	Liquid	Outside LNG leak on hose (nozzle, nipple, …)	DN25

A specific point about ignition is targeted in scenario D where the free whipping of the hose is to be investigated.

2.2 Estimated leakage flowrates and plume dimensions

The size and turbulence of the cloud depends very significantly on the flowrate and on the surrounding geometry, including obstacles and obstructions.

The flowrate is likely to depend strongly on the nature of the leaking object (dimensions, structure, …) and head losses on the piping between the hydrogen storage and leakage point. The typical hardware of a dispenser is shown in Figure 2.2-1, with some characteristics of the components given in Table 2.2-1.

Figure 2.2--1. Typical arrangment of a high pressure H2 dispenser

A typical dispenser is fed using an underground 9/16” (ID = 7.8 mm) high pressure pipe running from the storage reservoir located in the backyard some 20 m away.

It seems that for very high pressures (700 to 900 bar) Cone and Thread (C&T) technologies would be preferred. But for lower pressures (up to 400/500 bar), Double Ring and Compression (DRC) techniques could also be employed. Not only the dimensions are different (thicker walls for very high pressure) but also the tightening methods favouring plastic deformations for DRC and elastic for C&T. The leaking areas could be different in both situations. Some work was done previously for DRC technologies (Houssin *et al*., 2012) but since little has been done on C&T, most of the effort in the present project (D2.1) centered around C&T.

Table 2.2-1. Components likely to be present in high pressure H2 dispensers

Designation	Inlet diameter	Outlet diameter	Working pressure	Specificities	Assumptions
Gas Detector	-	-	-	Catalytic	Not considered
Check Valve	1/4" DRC	1/4" DRC	250 bar	-	Smaller risk : ignored
Heat Exchanger	3/8" C&T	3/8" C&T	975 bar	Insulated	Assimilated to a 10 mm 3/8'' pipe + 2 fittings (appendix 1-Fig. A1-1)
Hose	3/8" C&T	3/8" C&T	875 bar	Length 4 m	4 m flexible pipe + 2 fittings (appendix 1-Fig. A1-2)
Flow Valve	1/4" C&T	1/4" C&T	975 bar	-	Standard ¼'' C&T valve + 2 fittings (appendix 1-Fig. A1-3)
Flow Valve	9/16" C&T	9/16" C&T	975 bar	-	Standard 9/16'' C&T valve + 2 fittings (appendix 1-Fig. A1-3)
Double Block and Bleed	9/16" C&T	9/16" C&T	975 bar	Vent connection 1/4" C&T	Assembly of 2 x 9/16'' valve + ¼'' valve + 2 fittings (appendix 1-Fig. A1-4)
Pressure Control Valve	9/16" C&T	9/16" C&T	975 bar	Vent connection 1/4" NPT	Valve + 2 fittings (appendix 1-Fig. A1-5)
Pressure indicator and transmitter	1/4" C&T	1/4" C&T	975 bar	Ex	10 cm pipe+ 2 fittings
Pressure Safety Valve	-	-	975 bar	6 mm - Vent connection 1" NPT	Valve + 2 fittings (appendix 1-Fig. A1-6)
Restricted Orifice	1/4" C&T	1/4" DRC	975 bar	0.7 mm	2 fittings
Solenoid Valve	6-8 mm	4-6 mm	10 bar	-	Smaller risk : ignored
Temperature Transmitter	1/4" C&T	-	-	Ex	10 cm pipe+ 2 fittings
Shock Detector	-	-	-	-	Not considered
Break-Away	3/8" C&T	3/8" C&T	875 bar	-	Complex assembly (appendix 1-Fig. A1-7)
Nozzle	3/8" C&T	3/8" C&T	875 bar	-	Complex assembly (appendix 1-Fig. A1-8)

DRC = Double ring compression fitting
C&T = Cone and thread fitting
NPT = National pipe thread fitting

2.2.1 Leakage flowrates

For ½'' DRC fitting type, the largest flowrate is obtained for an untightened fitting (bad mounting or untightening due to pressure cycling) corresponding to 0.2 mm orifice size[1]. Outside such extreme conditions, it seems that the representative leak orifice size is smaller than 0.1 mm. For C&T equipment (fittings, valves), measurements (D2.1) reveal that the equivalent orifice size for similar leakage scenarios is between 0.5 and 1 mm (under 700 bar). A catastrophic rupture is to be expected on the hose arrangement with a maximum equivalent orifice size corresponding to 2.54 mm.

The corresponding maximum flowrates under 700 bar and without upstream head losses are given in table 2.2-2 based on measurements (D2.1). To account for the heat losses not only the length (L) and inner diameter (D) of the piping is to be considered but also the singularities. On that aspect, there are many unknows. The "trick" of the hydraulic engineers may then be used which consists in multiplying the length of the pipe by 2 to account for the singularities. Since the fluid is highly compressible the calculation of the head losses is more complicated than the simple application of the Bernoulli law (Laurent, 2003). Assuming for instance, the flow through the pipe (cross section area S_{pipe}) is isothermal (at temperature T_{pipe}), then the following expression provides the mass flowrate (m) as function of the pressures at the entrance ($P_{entrance}$) and at the exit of the pipe (P_{exit}) (MM is the molar mass of the gas and Cf the friction coefficient of the flow typically Cf=0.02), in SI units:

$$\dot{m} = S_{pipe} \cdot \sqrt{\frac{\frac{MM \cdot \left(P_{exit}^2 - P_{entrance}^2\right)}{2 \cdot R \cdot T_{pipe}}}{ln\left(\frac{P_{exit}}{P_{entrance}}\right) - Cf \cdot \frac{L}{D}}} \qquad [1]$$

[1] Under 20 bar overpressure, might be higher under elevated pressure (Agbossom et al., 2012).

Since the pressure at the exit can be much above the ambient pressure (choked flow), then the total exit pressure should be estimated as (in SI units) :

$$P_{tot-exit} = P_{exit} + \frac{1}{2 \cdot \rho_{exit}} \cdot \left(\frac{\dot{m}}{S_{pipe}}\right)^2 \qquad [2]$$

Where the specific mass of the flow ρ_{exit} at the exit end is calculated at P_{exit} and T_{pipe}. If an orifice of section $S_{orifice}$ is placed at the exit end then the mass flowrate is expressed as (for a choked flow which is the case in the present situation, γ is the ratio of heat capacities):

$$\dot{m} = Cd \cdot S_{orifice} \cdot \sqrt{\rho_{exit} \cdot P_{tot-exit} \cdot \gamma \cdot \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}} \qquad [3]$$

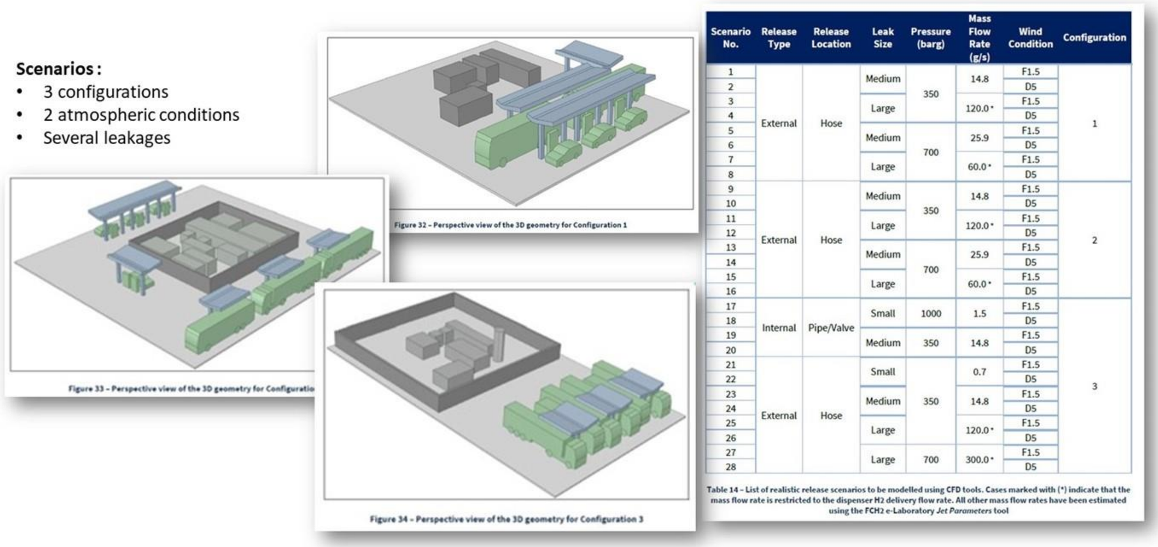
Where Cd is the discharge coefficient usually chosen equal to 0.62 but 0.8 was chosen as a good fit with the available data (Cd increases with the pressure which makes this assumption reasonable). $P_{entrance}$ is close to the pressure in the reservoir. To obtain the mass flowrate, P_{exit} should be chosen by trial and error until the values of the mass flowrate flowing through the pipe and through the orifice are equal. This method was applied to estimate the expected leakage mass flowrate considering the length of the piping (last column of Table 2.2-2).

Table 2.2-2. Leakage mass flowrates

Leakage eq. orifice (mm)	Preservoir (bar)	Maximum mass flowrate (g/s)	With piping (g/s)
0.1	350	0.1	0.1
0.1	700	0.2	0.2
0.2	350	0.5	0.5
0.2	700	1	1
0.5	350	3	3
0.5	700	6	6
1	350	15	15
1	700	30	30
2.54	350	90	75
2.54	700	180	150

2.2.2 Plume size

About the resulting plumes, reasonable methods are now available for under expanded jets but little is available when the jet impinges on an obstacle. The influence of the atmospheric conditions is also to be assessed. Because of the availability of CFD codes usable for such purposes, it was decided to investigate such technical questions numerically (D2.3). OPENFOAM, FLACS, CFX were employed, and the simulations were performed by experienced modellers. Scenarios A to F from Table 2.2-1 were considered under the forecourt configurations and atmospheric conditions shown on Figure 2.2-2. Note the chosen flowrates cover worst case scenarios of Table 2.2-2.



Scenario No.	Release Type	Release Location	Leak Size	Pressure (barg)	Mass Flow Rate (g/s)	Wind Condition	Configuration
1	External	Hose	Medium	350	14.8	F1.5	1
2						D5	
3			Large		120.0*	F1.5	
4						D5	
5			Medium	700	25.9	F1.5	
6						D5	
7			Large		60.0*	F1.5	
8						D5	
9	External	Hose	Medium	350	14.8	F1.5	2
10						D5	
11			Large		120.0*	F1.5	
12						D5	
13			Medium	700	25.9	F1.5	
14						D5	
15			Large		60.0*	F1.5	
16						D5	
17	Internal	Pipe/Valve	Small	1000	1.5	F1.5	3
18						D5	
19			Medium	350	14.8	F1.5	
20						D5	
21	External	Hose	Small	350	0.7	F1.5	
22						D5	
23			Medium		14.8	F1.5	
24						D5	
25			Large		120.0*	F1.5	
26						D5	
27			Large	700	300.0*	F1.5	
28						D5	

Table 14 – List of realistic release scenarios to be modelled using CFD tools. Cases marked with (*) indicate that the mass flow rate is restricted to the dispenser H2 delivery flow rate. All other mass flow rates have been estimated using the FCH2 e-Laboratory *Jet Parameters* tool

Figure 2.2-2. Conditions for the numerical simulation of the plume (D2.3)

It is usually acknowledged that CFD codes do not fully simulate the reality because of the physical and numerical approximations as for instance the necessity to use a pseudo source term to represent the leakage point. Because of this, the chosen codes were carefully validated on experimental data representative of the situations contained in Table 2.2-1 namely a very small (H_2) confined leakage inside a 1 m^3 box (Bernard-Michel and Houssin, 2017), a horizontal under expanded H2 free jet (Daubech *et al.*, 2015) and obstructed jets (with many cylindrical obstacles perpendicular to the axis of the jet). A typical outcome of this validation exercise is shown in Figure 2.2-3 (from D2.3) giving the typical spread of the predictions against experiments for a particular set of data.

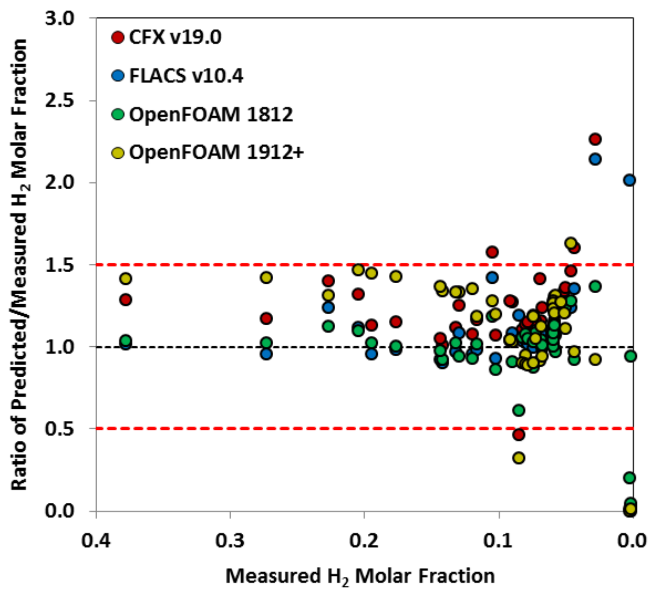
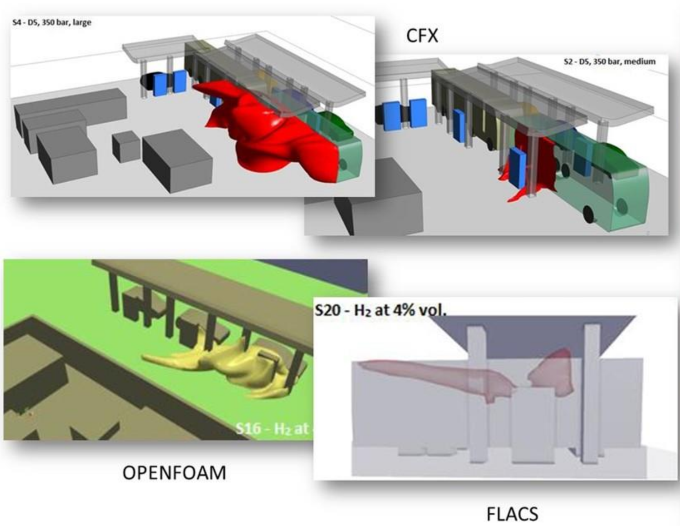


Figure 2.2-3. Ratio of predicted-to-measured concentration (from D2.3) as a function of H2 molar concentration for the unobstructed free jet scenario. Figure includes both centreline and radial data

This scattering is classical and judged satisfactory as compared to similar benchmarking of CFD codes. It seems the nature of the “pseudo source” model explains a significant part of the scattering.

Bearing this in mind, the results of the simulations can be interpreted. Typical results are shown on Figure 2.2-4 showing that the clouds may develop into the forecourt and engulf the vehicles. Even for confined releases, the flammable atmosphere may come out from the dispenser meters away.



Scenario No.	Release Type	Release Location	Leak Size	Pressure (barg)	Mass Flow Rate (g/s)	Wind Condition	Configuration
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4						D5	
5			Medium	700	25.9	F1.5	
6						D5	
7			Large		60.0*	F1.5	
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13			Medium	700	25.9	F1.5	
14						D5	
15			Large		60.0*	F1.5	
16						D5	
17	Internal	Pipe/Valve	Small	1000	1.5	F1.5	3
18						D5	
19			Medium	350	14.8	F1.5	
20						D5	
21	External	Hose	Small	350	0.7	F1.5	
22						D5	
23			Medium		14.8	F1.5	
24						D5	
25			Large		120.0*	F1.5	
26						D5	
27			Large	700	300.0*	F1.5	
28						D5	

Table 14 – List of realistic release scenarios to be modelled using CFD tools. Cases marked with (*) indicate that the mass flow rate is restricted to the dispenser H2 delivery flow rate. All other mass flow rates have been estimated using the FCH2 e-Laboratory *Jet Parameters* tool

Figure 2.2-4. Location of the Lower Flammable Limit isosurfaces for typical release scenarios (D2.3)

The dimensions of the flammable cloud depend on the leakage flowrate at the first order of magnitude. The geometry of the forecourt, included the presence of the canopy, seems of secondary importance so as the atmospheric conditions (Figure 2.2-5).

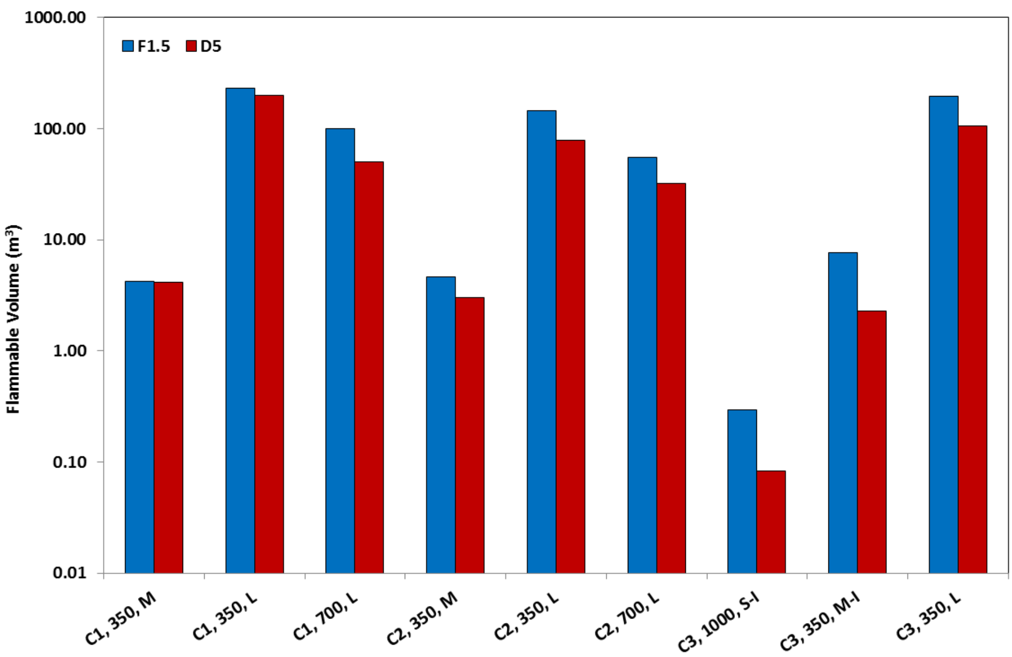

Figure 2.2-5. Volume of the flammable zone as function of the scenario and atmospheric conditions (D2.3)

Note that the flammable volumes of the free jets corresponding to the hose rupturing are 15 and 50 m^3 respectively, in line with this more precise (and relevant) CFD simulations.

2.3 Ignition likelihood

This aspect was investigated in task 2.1.4. The safety perspective is different whether it is considered that spontaneous ignition is possible or if only external source intervenes. In the former case, fire and explosion would occur simultaneously to the leakage so that explosion and fire protection is required. In the latter, controlling ignition sources remains a possibility as in classical ATEX approaches for instance.

Ignition physics was presented with some details in (Proust, 2022). A difference is made between the fundamental ignition mechanisms and the practical event likely to trigger one or several of the afore mentioned ignition mechanisms.

The fundamental ignition mechanisms are:

- Diffuse ignition which can occur in the contact zone between the pressurized hot air and the discharging hydrogen. Rather specific to hydrogen pressure discharges in air (requires a very thin reaction zone and small auto ignition temperature). A representative parameter is the auto-ignition temperature (AIT);
- Hot surface ignition which is a very traditional ignition mechanism. A representative parameter is the critical hot surface temperature (Tp).
- Spark ignition also a common ignition mechanism. Electrical/electrostatic sparks are known to belong to this category. Rather specific to hydrogen is the capability of corona discharges to ignite hydrogen leakages. Representative parameters are the minimum ignition energy (MIE) and the minimum ignition power (P_{min}).

In the same study the variations of these parameters which the pressure and the temperature were investigated (Table 2.3-1) showing that all characteristic ignition parameters drop when pressure rises, significantly increasing the ignition sensitivity as compared to ambient.

Table 2.3--1. Ignition parameters of hydrogen air mixtures ("~" means "proportional to", indice "o" is the process conditions and "st" to ambient)

Parameter	Dquench*	MIE	AIT	Tp	P_{min}
Standard	0.7 mm	0.017 mJ	833 K	863 K	0.15 W
Variations with T_0	$\sim(T_0/T_{st})^{-0.3}$	$\sim(T_0/T_{st})^{-0.6}$	N.A	$\sim(T_0/T_{st})^{-0.25}$	$\sim(T_0/T_{st})^{-1}$
Variations with P_0	$\sim(P_0/P_{st})^{-0.75}$	$\sim(P_0/P_{st})^{-1.5}$	$\sim(P_0/P_{st})^{-0.05}$	$\sim(P_0/P_{st})^{-0.25}$	$\sim(P_0/P_{st})^{-1}$

*Quenching distance

The various practical ignition sources possibly leading to a spontaneous ignition (from a leakage on the dispenser) were identified and the ignition thresholds investigated theoretically. The dust responsible for tribocharging is suspected to come from abrasion of the seat of valves (micron sized). Static electricity may be accumulated on a part of the dispenser or on some object placed in the plume due to the impingement of the particles. The ignition would occur by corona discharge in the plume outside. Not more than a fraction of a gram is necessary. Friction could occur at the seat of ball valves and friction velocities as low as 0.2 m/s may be enough as suggested by theory and experiments (van Wingerden, 2023). Energetic impacts of mm sized flying fragments expelled by the outflow can also ignite depending on their velocity hence on the driving pressure. This means only a few Joules of kinetic energy which does not seem incoherent with the very sparse experimental data available (van Wingerden, 2023). Diffuse ignition can occur in case of pipe rupturing enabling a shock wave to be formed for instance in the throttle of the breach. For a typical thickness of the wall of a few mm, the driving pressure require to produce a diffuse ignition is 10 to 20 MPa in line with available experimental data (Zhou *et al*., 2022). It appears that the higher the discharge pressure the more of these ignition situations can potentially ignite the release (Table 2.3-2) and so the more likely a spontaneous ignition.

Table 2.3--2. Potential ignition mechanisms as function of the pressure

P	Dust tribocharging	Friction	Fragment impact	Fragment tribocharging	Diffuse ignition*
Over 10 MPa	Yes	Yes	Yes	Yes	Yes
1 – 10 MPa	Yes	Yes	Yes	No	No
Below 1 MPa	Yes	Yes	No	No	No

*for a characteristic length on the order of mms corresponding to the thickness of the pipes/component

The conclusions which can be made are the following:

- Data from the field (INERIS, 2013), suggest between 1 and 2% probability of ignition in industrial conditions when hydrogen leakages are excluded from the database. For hydrogen leakages, the probability is ten times more which might reflect the fact that MIE and P_{min} are ten times lower than for standard fuels although a detailed analysis is to be done. This could be considered as the basic ignition probability (10-20%) in ATEX conditions e.g. excluding spontaneous ignition. This is in line which other estimating the hydrogen leakage ignition probability (Fossan, 2023).
- Spontaneous ignition could occur during catastrophic rupturing of high-pressure equipment (typically above 100 bar) because fragments can be ejected, powdered material resulting from wear expelled and produce corona discharges and the diffuse ignition mechanism could be also at work. So, in such situation 100% probability of ignition could be postulated.
- Leakage from restricted areas, like through untightened fitting may not induce the conditions for a spontaneous ignition because first the flow is strongly laminated so that shocks will not be created and second because the possibility to create static electricity would be reduced. So, ignition by an external source is more probable (Cf ATEX mechanism).

External ignition sources may be numerous and the possibility that a vehicle engulfed into the plume need to be considered very seriously. Globally, ignition is probable. Depending on where the ignition source is located both explosion and fires need to be envisioned justifying the experimental campaign.

2.4 Fire and explosion conditions

Going back to Table 2.1-1 and considering the discussion above, the rupture of the hose could produce a severe accident because of the massive flowrate. But in this situation, immediate ignition is expected either because of spontaneous ignition or because of the large number of external ignition sources at reach, specifically in the vehicles. Mostly a sustained jet flame can be expected, possibly setting fire to the vehicles. The maximum extend of the jet fire is normally observed in the open field. The safety parameters are the heat fluxes radiated outwards, the flame length and the flame temperature.

Explosion would rather result from “restricted” leakage, with little possibility for spontaneous ignition and lower plume extent limiting the likelihood for an immediate ignition. Larger consequences are expected in a confined area like inside the dispenser. The relevant scenarios are leakages on components. The characteristics of the cloud are expected to depend on the geometry of the dispenser and on the leakage flowrate. The characteristics of the explosion would depend on the internal obstruction and on the location of the ignition source. The safety parameters are mostly the explosion overpressure and pressure field around.

The test pad, instrumentation and testing plan were arranged according to these constrains.

The experimental device (D2.3) is a mock-up of a high pressure H_2 dispenser for light duty vehicles (Figure 2.4.1). The outer dimensions of the dispenser, the size and location of the openings (2 lateral top and bottom openings 120 mm x 100 mm and on top plate 800 mm x 300 mm) and internal obstruction (20%) were chosen in relationship with specialists. A vehicle was left aside to visualize the consequences of the accidents.

Figure 2.4-1. Mock-up dispenser and forecourt experimental arrangment (D2.3)

Hydrogen is supplied from two 50 L cylinders under 350 or 700 bar (located behind the concrete blocks visible at the right edge of the photograph above). They are connected to about 10 m long and rigid pipe (5.3 mm inner diameter) via a few meters 3/8” hose (flow restriction due to the nipple typically 2.54 mm).

The measurement devices are: pressure transducers in the feeding line ahead of the hose, inside and outside the dispenser (where people are standing), temperature sensors on the axis of the flame, heat flux gauges perpendicular to the flame jet. A standard camera, an infrared camera and a high-speed camera were systematically used. For some tests without ignition, katharometers were employed to measure the concentration of hydrogen in the cloud (in the dispenser). The mass flowrate is deduced from the pressure decrease in the reservoir using the Abel-Noble equation of state. This method was validated in the project (D2.1). For scenarios where external ignition would occur, the experimental ignition source is a powerful pyrotechnical torch located on the ground next to the dispenser and is used to trigger immediate ignition. For scenarios where internal delayed ignition is expected, a single spark pyrotechnical igniter is used (inside the dispenser).

The test matrix is presented in Table 2.4-1 showing how the risk situations are effectively covered.

Table 2.4--1. Tests performed to investigate fire and explosion effects (D2.3)

D2.3-test ref	Experimental conditions	Scenario from Table 2.1-1
TT1 and TT2	Outside horizontal leak via the 3/8" pipe under 700 bar. Ignition triggered close to the leakage point using the pyrotechnical torch.	D
TT3	Outside horizontal leak via the 3/8" pipe under 350 bar. Ignition triggered close to the leakage point using the pyrotechnical torch.	B
TT4 and TT5	Inside leak under 700 bar via a 0.2 mm orifice pointing upwards from the bottom third of the dispenser. Unignited. Two venting conditions	F
TT6 and TT7	Inside leak under 350 bar via a 0.2 mm orifice pointing upwards from the bottom third of the dispenser. Unignited. Two venting conditions	E
TT10 and TT11	Inside leak under 700 bar via a 0.5 mm orifice pointing upwards from the bottom third of the dispenser. Unignited. Two venting conditions	F (and C for the flowrate)
TT12 and TT13	Inside leak under 350 bar via a 0.5 mm orifice pointing upwards from the bottom third of the dispenser. Unignited. Two venting conditions	E (and A for the flowrate)
TT18	Inside leak under 700 bar via a 0.2 mm orifice pointing upwards from the bottom third of the dispenser. Ignited with a pyrotechnical spark inside the dispenser.	F
TT20	Inside leak under 700 bar via a 0.2 mm orifice pointing upwards from the bottom of the dispenser. Ignited with the pyrotechnical source outside the dispenser close to the openings.	F
TT22	2 m^2-120 l diesel pool fire located 2.7 m from the charged (700b) H_2 dispenser.	G to I

The link between TT22 and scenario G to I needs to be clarified. The amount of diesel fuel clearly conforms to scenario G. Note however it was explained in D2.3 that the size of the pool was chosen to represent a fire on a vehicle. It is then admitted that a leakage of fuel possibly resulting in a domino effect would result from a leakage on a nearby car and that such leakage will be ignited immediately and set the car to fire. The "thermal signature" of a car fire is well known (Tohir and Spearpoint, 2013) and depends primarily on the solid combustibles (tires, plastics). From Babrauskas (Babrauskas and Grayson, 1992), it can be found that the heat of combustion of diesel fuel is about 44 MJ/kg and that the evaporation rate from a burning pool is about 0.055 $kg/m^2/s$. The total power of the fire is between 4 and 5 MW which corresponds to the peak power of a burning car. The expected duration of the fire is between 15 and 20 mins which is also in line with this scenario. Under such perspective, scenarios G to I are correctly figured out by TT22.

3 Summary of the results

3.1 Explosions and fires resulting from a leakage on a H_2 dispenser

3.1.1 Unconfined external jet flames

TT1 to TT3 tests are considered.

As explained about the mass flowrate were deduced from the pressure decrease into the 2 x 50 l reservoir. The maximum flowrate at 700 bars is about 40 g/s and 20 g/s at 300 bars (a little less that 350 bar). They are smaller than those targeted to (resp. 150 and 75 g/s from Table 2.2-2). Equations [1] to [3] were used to simulate the flow from the 2 x 50 l reservoir to the release point via the hose and the rigid line, typically 15 m long, 5.3 mm ID with a flow restriction at 2.54 mm at the nipples of the hose. Using the same method to account for the singularities on the release line, a total flowrate of 75 g/s is found for a 700 bar release and 35 g/s for a 300 bars release. Those last values are closer to those measured, although conservative, suggesting the chosen model is too conservative by a factor of nearly 2. Thus, values from Table 2.2-2 might be overestimated by a factor of 2. By the end, the obtained experimental mass flowrate might be lower (by a factor of 2) as compared to the reality but remain in the correct order of magnitude to that the tests are representative.

A typical jet flame is shown on Figure 3.1-1. It was again realized that the flame is hardly visible. The IR flame was more than 5 m long at 700 bar release and about 4 m long at 300 bar. The maximum temperature measured into the flame jet was about 1200 °C.

Figure 3.1-1. Standard (left) and IR image of a jet flame (right) from test TT2

3.1.2 Internal explosions and fires

Tests TT4 to TT20 are considered.

The measured mass flowrates are given in Table 3.1-1. The range of flowrate covers very well what is expected as leakages on components inside the dispenser (Table 2.2-2).

Table 3.1--1. Mass flowrate through orifices inside the dispenser and characteristics of the flammable layer

TT	Orifice size (mm)	Pressure in the 2x 50 l cylinders (B)	Estimated mass flowrate (g/s)	Max. H_2 concentration (%v/v)	Location of the layer
04	0.2	700	9	25	From release point to top
06	0.2	350	4.5	20	From release point to top
10	0.5	700	16	50	From bottom to top
12	0.5	350	8	42	From bottom to top

The release point is oriented upwards, on the axis and at 0.69 m from the bottom. The cross section of the casing is 0.5 m^2 and its height 2 m. In standard conditions, with only the lateral vents opened, a homogeneous flammable layer is rapidly formed into the casing (Figure 3.1-2). The characteristics of the layers are given in Table 3-1.1. Given the momentum of the release (sonic flow at 1000 m/s), it is not surprising that the mixture forms a homogeneous layer. Rather simple models can be used to correctly estimate the maximum concentration in the layer.

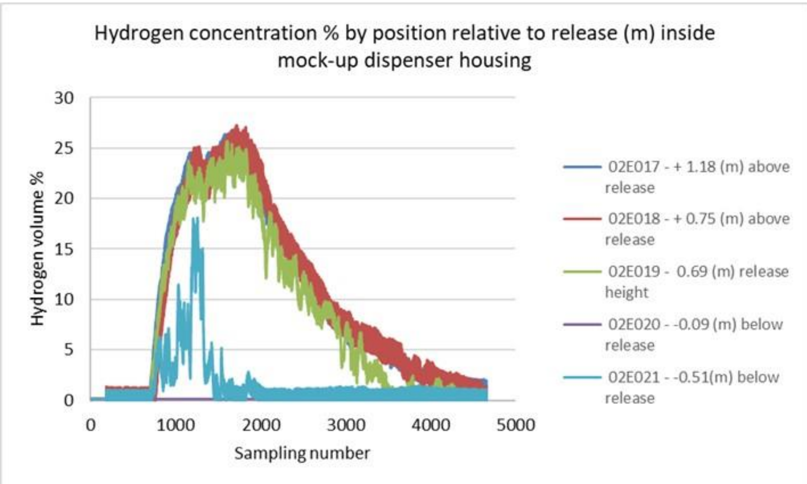

Figure 3.1-2. concentration of H2 in the dispenser on the vertical axis during test TT04 (10 sampling points for 1 s)

Ignition tests (TT18 and TT20) were done under the release condition of the second line of table 3.1-1. In case of an internal ignition, significant effects were expected because of the size and high sensitivity of the flammable cloud. More than 600 mbar was measured inside the dispenser (Table 3.1-2), with a gradual decrease of the pressure outside on the forecourt (measured at 1 m high). The dispenser was damaged (Figure 3.1-3). In case of an external ignition source, which is the most probable situation, the pressure effects (Table 3.1-2) are much less despite the same flammable cloud. This is due to the venting effects of the burnt gases while the flame is propagating which reduce the expansion of flame. The dispenser casing is hardly distorted, and the overpressure effect are tolerable.

Table 3.1-2. Explosion effects inside and outside the dispenser for an ignition point inside and outside the dispenser (0.2 mm upwards release @ 700 bar)

Measurement location	Overpressure (mbar) – inside ignition	Overpressure (mbar) – outside ignition
Inside dispenser	626	50
1.2 m away @ 1 m high	134	1
2.4 m away @ 1 m high	85	7
5 m away @ 1 m high	20	4

Figure 3.1-3. Explosion of the internal flammable cloud by an internal ignition source (left TT18) and by an external ignition source (right TT20)

Heat fluxes and temperatures were measured in the forecourt showing no significant adverse consequences. But inside the dispenser a fire is maintained all along the leakage duration with temperatures raising above 200°C (200 °C-500°C) causing damage to plastics in particular.

3.2 Consequence on a pressurized H2 dispenser of an external fire.

This corresponds to test TT22.

A photo of the flame is as shown on Figure 3.2-1. The duration of the fire was about 15 minutes in line with the expectations. As can be seen the flame touches transiently the dispenser. Nevertheless, the temperature inside the mock-up dispenser hardly changes. In addition, there was no sign of any internal pressure increase in the pipework.

Figure 3.2-1. 120 l-2 m^2 diesel fuel pool fire at 2.7 m from the dispenser (TT22)

4 Safety barriers

From D3.5 a preliminary list of safety measures was listed. For a safety measure to be considered as a "safety barrier" several criteria need to be verified such as it should work independently from the causes of the accident, be resistant to the accident, be maintainable and be efficient.

A selection of the safety measures that could be considered as safety barriers and could be checked experimentally with the available setups was discussed in milestone M2.3 (Table 4.1-1). Since many different technical items can be chosen to build the safety barriers, it would not have been possible to test each possible configuration. Rather, it was chosen to extract from experimental data criteria to assess the efficiency of the barrier.

Table 4.1-1. potential safety measures

Typical scenarios	Associated potential safety measure
Hose detached from dispenser due to drive off	Breakaway
Hose bursting due to ageing or damage	Pressure drop detection + Emergency shut-down valve
Component leak in dispenser	Gaz detection in dispenser + Emergency shut-down valve
Component leak in dispenser	Venting

4.1 Stopping a full-bore leakage from the hose

This situation corresponds to scenarios B and D and can be mitigated using a breakaway or some pressure drop detection associated to an emergency shut down valve.

Some information of the rapidity of the development of the plume could be extracted for the videos of the tests (such as from Figure 3.1-1 right). Since it is a rather slow camera, only an estimate is obtained but it appears, at least for test TT01, that the full length of the jet flame is reached in much less that one second. Another estimate can be extracted from earlier work (Proust *et al*., 2011). In Figure 4.1-1, an excerpt of a jet flame issued from a 2 mm hole releasing pressurized hydrogen under 900 bar at a higher flowrate (80 g/s). The test was done in an underground gallery enabling a direct observation of the reddish flame normally hardly visible in the day light. The opening time of the high-pressure valve is about 200 ms. As can be seen from Figure 4.1-1, the jet flame is fully established in about half a second.

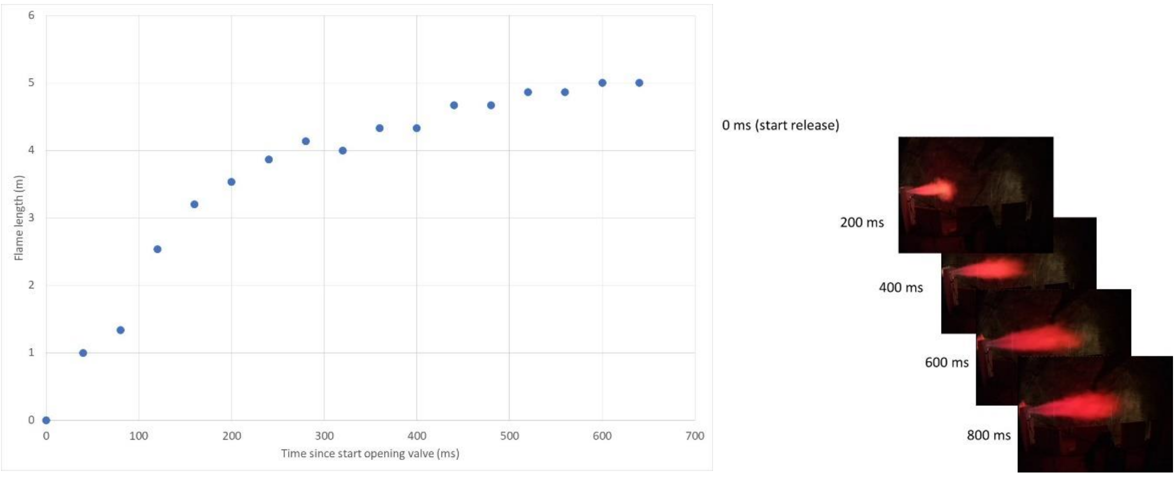

Figure 4.1-1. evolution of the flame length in a horizontal flame jet issued from a 2 mm orifice under 900 bar (80 g/s)

It could be useful to establish a simple law to estimate this characteristic time. It is proposed to use the concept of residence time (t_{res_ext}), well known in chemical engineering. In a "well-stirred" continuous flow reactor it is the ratio between the volume of the reactor to the volume flow rate of the input. In the present case, the cloud is surely well stirred. The volume of the "reactor" could be the volume of the flammable zone of the cloud. The flowrate is that of the jet and that of the outside air entrained. The latter is not straightforward to determine, and it is suggested to replace by a flowrate of energy which is the mass flowrate of the leakage multiplied by the heat of combustion of hydrogen in air (ΔH_{comb} = 120 MJ/kg). To estimate the amount of energy contained in the flammable zone of the cloud, the volume of this flammable zone (V_{flam}) should be multiplied by an average specific energy ($E_{spe\text{-}exp}$) of combustion[2]. At the lower flammability limit (LFL), this specific energy is about 0.5 MJ/m^3, at the upper flammability limit (UFL), 0.5 MJ/m^3, and at the stoichiometry, about 1.7 MJ/m^3. An averaged value is 1 MJ/m^3 can be chosen. Then (SI units):

[2] If T_{ad} is the maximum flame temperature of the burnt gases, the specific energy released by the combustion (explosion) is $E_{spe-exp} = \rho_{reactants} \cdot Cp \cdot (T_{ad} - T_{init})$ where $\rho_{reactants}$ is the specific mass of the reactants, Cp the average specific heat between T_{ad} and T_{init} and T_{init} the initial temperature of the reactants. Cp is about 1100 J/kg/K, T_{ad} is about 400°C at LFL ($\rho_{reactants}$=1.15 kg/m^3), 1200°C at UFL ($\rho_{reactants}$=0.35 kg/m^3) and 2000°C at stoichiometry (at 40% v/v, $\rho_{reactants}$=0.75 kg/m^3).

$$t_{res\_ext} = \frac{V_{flam} \cdot E_{spe-exp}}{\dot{m} \cdot \Delta H_{comb}} \qquad [4]$$

For the experiment corresponding to Figure 4.1-1, V_{flam} is a little less than 8 m^3 (small orifice). Since the mass flowrate is 80 g/s, a residence time of 0.7 s is estimate, in reasonable order of magnitude with the measurements. Going back to the data from section 2.2, the residence times for outside leakages are typically ranging from 1 to 5 seconds.

It can be anticipated that the closing time of any emergency shut down device should be much smaller than these values and perhaps even short enough to avoid that the flammable cloud reaches external ignition source or to limit the consequences to people. Note that the kind of valve which was used to produce data from Figure 4.1-1 is what is foreseen for H_2 dispensers (Figure 4.1-2). For this model, the opening time from closed to fully open is about 200 ms, but the total operating time might be larger need to pressurize the operator of the valve).

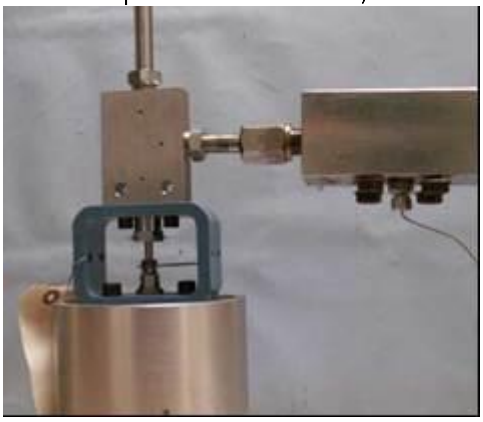

Figure 4.1-2. Air operated high pressure valve used to perform the test of figure 4.1-1

4.2 Mitigating a component leakage inside the dispenser

4.2.1 Detection for emergency shutdown

It was shown that any component leakage inside the dispenser can produce a hazardous cloud. It is desirable to attempt the detection of a flammable atmosphere to stop the flow of hydrogen and proceed to repairs.

Looking at the early H_2 detection times in Figure 3.2-1, these suggest that LFL (4 % v/v) is reached inside the dispenser within a few seconds and the maximum concentration in 20/30 seconds. Unfortunately, the real timescales might be shorter because of the length of the sampling lines. Similar situations were investigated (Audrey *et al.*, 2017) in a somewhat larger volume (4 m^3). The sampling lines were much shorter so that the response time of the lines were of only a few seconds. The results shown in Figure 4.2-1 were obtained with an upwards flowrate of 3.81 g/s of hydrogen. The typical rise time of the concentration curves is 10 seconds. It could be anticipated that, in a smaller volume like the dispenser, this rise time could be much smaller.

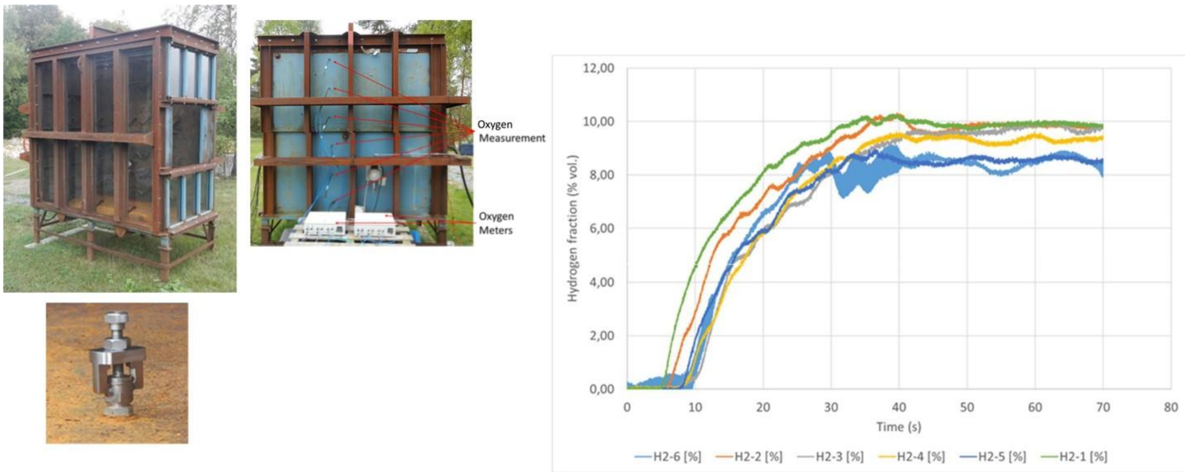

Figure 4.2-1. experimental configuration from Duclos *et al.*, 2017. 4 m³, upwards H2 release of 3.81 g/s

Again, it could be useful to establish a simple law to estimate this characteristic time. It is (again) proposed to use the concept of residence time (t_{res_int}). Going back to the discussion above (section 3.1.2), the volume inside the dispenser ($V_{dispenser}$) can be considered as a well-mixed reactor. The maximum volumetric fraction of H_2 (X_{H2_max}) can be calculated using the models presented in D3.5. Knowing that the specific mass of hydrogen in ambient conditions, $\rho_{H2\text{-}standard}$, is about 0.08 kg/m³, it becomes:

$$t_{res\_int} = \rho_{H2\_standard} \frac{X_{H2\_max} \cdot V_{dispenser}}{\dot{m}} \qquad [5]$$

For the experiment corresponding to Figure 4.2-1, $V_{dispenser}$ is 4 m³, the leakage flowrate 3.81 g/s and the maximum concentration of hydrogen 10% v/v. Using equation [5] gives a residence time in the order of 8 seconds, in reasonable agreement with the experiment.

When dispenser of volumes of 1 m³ as in the present work and leakage flowrates of 10 g/s, 30 % v/v of hydrogen, <u>the residence time is 2 seconds. But again, the LFL can be reached much more rapidly</u>.

This might be considered too short to mitigate this scenario.

4.2.2 Venting out the flammable cloud

Another option is to increase the ventilation surface. As hydrogen-air mixtures are lighter than air, they accumulate in upper areas. Venting should then be done at the top of the enclosure. This was attempted during the experiments (D2.3), by adding an extra natural ventilation area (0.3 m x 0.8 m) on the top of the mock-up dispenser (tests TT05, TT07, TT11 and TT13). The results from Table 3.1-1 can now be compared to those below.

Table 4.2-1. Mass flowrate through orifices inside the dispenser and characteristics of the flammable layer

TT	Orifice size (mm)	Pressure in the 2x 50 l cylinders (B)	Estimated mass flowrate (g/s)	Max. H_2 concentration (%v/v)	Location of the layer
05	0.2	700	9	3-4	From release point to top
07	0.2	350	4	2-3	From release point to top
10	0.5	700	16	6-8	From release point to top
12	0.5	350	8	7-9	From release point to top

This is a very efficient method since when the concentration of hydrogen in a cloud is less than 10%, explosions may still occur, but with very small consequences.

This was checked experimentally in test TT16 (0.2 mm-700 bar). In this experiment, the top ventilation area was covered by a thin foil. It is known that the flammable cloud will be richer than in Table 4.2-1 (25 % H2). This is thus a conservative situation. Nothing is visible but only with infrared video showing a hot pocket of burnt gases raising away (Figure 4.2-2). The pressure inside the dispenser is about 80 mbar but its integrity is preserved. In the forecourt the overpressure is well below 50 mbar which is safe. In the real situation with an open vent on top, the consequences will be less.

Figure 4.2-2. Standard (left) and IR image (right) from test TT16

5 Conclusions

The present deliverable is a summary of the ignition, fire and explosion work performed in WP2 of MultHyFuel project.

It is shown first that the chosen experimental conditions are representative of the technologies used and figure out correctly the critical hazardous scenarios identified by the consortium. The main conclusions are:

1. The leakage mass flowrates on leaking components might range from 1 to 30 g/s;
2. In a rather closed dispenser, such a flowrate will produce a homogeneous flammable atmosphere within a second time scale;
3. For leaking components, spontaneous ignition is unlikely. External sources are required. If ignition sources present inside the dispenser might be rather easily kept under control (ATEX rules for instance), it might be harder for those in the forecourt. The latter have to be considered because the flammable cloud extends outside;
4. An efficient way to mitigate the flammable cloud formed inside the dispenser is to provide a top venting;
5. The leakage flowrate on a broken hose can be in the order of 100 g/s;
6. Outside flammable clouds amounting to tens of m^3 can be formed in seconds laps of time depending on the presence of obstacles;
7. Spontaneous ignition of the clouds is probable but anyway due to the potential large size of the flammable cloud, the cloud will reach many ignition sources present on the forecourt. In such situations, ignition can be held as certain;
8. Because of this, immediate ignition is postulated producing jet flames as long as 5 m or more. Outside the flame, the heat flux remains acceptable.

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7 What is MultHyFuel?

The goal of MultHyFuel is to contribute to the effective deployment of hydrogen as an alternative fuel by developing a common strategy for implementing Hydrogen Refueling Stations (HRS) in multi-fuel contexts, contributing to the harmonisation of existing laws and standards based on practical, theoretical and experimental data as well as on the active and continuous engagement of key stakeholders.

MultHyFuel is a project funded by the Clean Hydrogen Partnership.

Further information can be found under https://www.multhyfuel.eu.

For feedback on the MultHyFuel project or the published deliverables, please contact info@multhyfuel.eu.

The MultHyFuel Consortium:

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