HyResponse

Grant agreement No: 325348

Deliverable D4.1

Elaboration of multi-level operational exercises

Status: Final

Dissemination level: PU - Public

Partner responsible for the deliverable: ENSOSP

Contributing partners: AL, AREVA, UU

New Energy World JU
fuel cells & hydrogen for sustainability

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Date of this document: September 28th 2015

File name:
D4.1_HYRESPONSE_Elaboration_of_multi-level_operational_training_exercises_v10_final.doc

Document history

Revision	Date	Modifications made	Author(s)
V1	04/02/2014	Elaboration of this document	François LAUMANN Franck Verbecke Laurent Verneuil Romaric Miler Lilian Demarle
V2	11/11/2014	UU contribution	Svetlana Tretsiakova-McNally, Donatella Cirrone
V3	21/11/2014	first draft	Svetlana Tretsiakova-McNally, Donatella Cirrone
V4	26/11/2014	Final draft of UU contribution	Svetlana Tretsiakova-McNally
V5	30/11/2014	Further revised version of the document based on group discussions	François LAUMANN Franck Verbecke Laurent Verneuil Romaric Miler Lilian Demarle
V6	10/12/2014	Further revised version of the document	François LAUMANN Verneuil Laurent
V7	31/03/2015	Final Draft of ENSOSP	François LAUMANN
V8	31/08/2015	Revised version	Sébastien.Bertau
V9	11/09/2015	Revised version	Sébastien.Bertau Franck Verbecke
V10	18/09/2015	Final	Svetlana Tretsiakova-McNally

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Introduction

Current document relates to the activities carried out by the HyResponse consortium with regards to the development of the operational training exercises, which will be implemented on the novel, operational hydrogen training facility within the European Hydrogen Safety Training Platform (EHSTP) as per WP 4 of the DoW. The purpose of the operational hydrogen training facility is to assist First Responders in visualizing a range of hydrogen and fuel cell applications. Also, First Responders will put into practice the knowledge gained during the educational classes (which will take place in the morning). The trainees will be able to simulate interventions, to test and implement operational emergency response strategies identified for the scenarios selected in WP2 (task 2.2 and task 2.3). The operational hydrogen training facility will also allow First Responders to discover, observe and compare the phenomena related to the behaviours of hydrogen and other fuels (LPG, CNG, etc) in a real incident and/or accident scene. The challenge is to create a dynamic accidental environment as real as possible while guarantying safety of First Responders.

The HyResponse face-to-face pilot training sessions will use two practical approaches to reach the educational goals. The first one is *operational*, which will be realized on the operational facility, currently under construction on the ENSOSP site, and the second one is *virtual* based on the novel virtual reality software and virtual tactical rooms at ENSOSP.

Task 4.1 of WP 4 aims to elaborate multi-level operational training exercises, which are to be implemented on the hydrogen training facility at ENSOSP. The elaboration of the operational training exercises is strongly linked to the work realized in WP2. Logically, it contributes significantly to the final specification of the operational hydrogen training facility.

1 *The operational training platform*

1.1 Location

The EHSTP is located at the ENSOSP, 1070 rue du lieutenant Parayre 13798 Aix en Provence,France . GPS Coordinates: N 43.507590, E 5.359310. The satellite and map views of the platform location are shown in Figures 1 and 2.

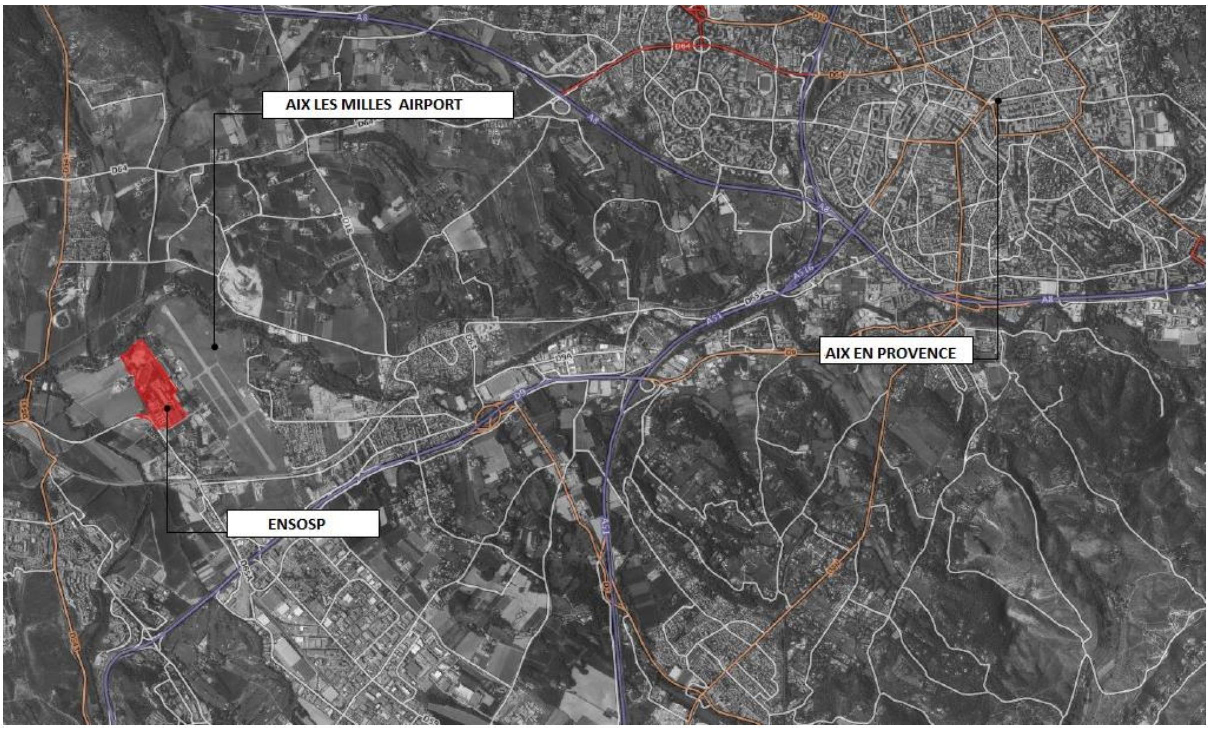


Figure 1. A location of the operational training facility: satellite view.

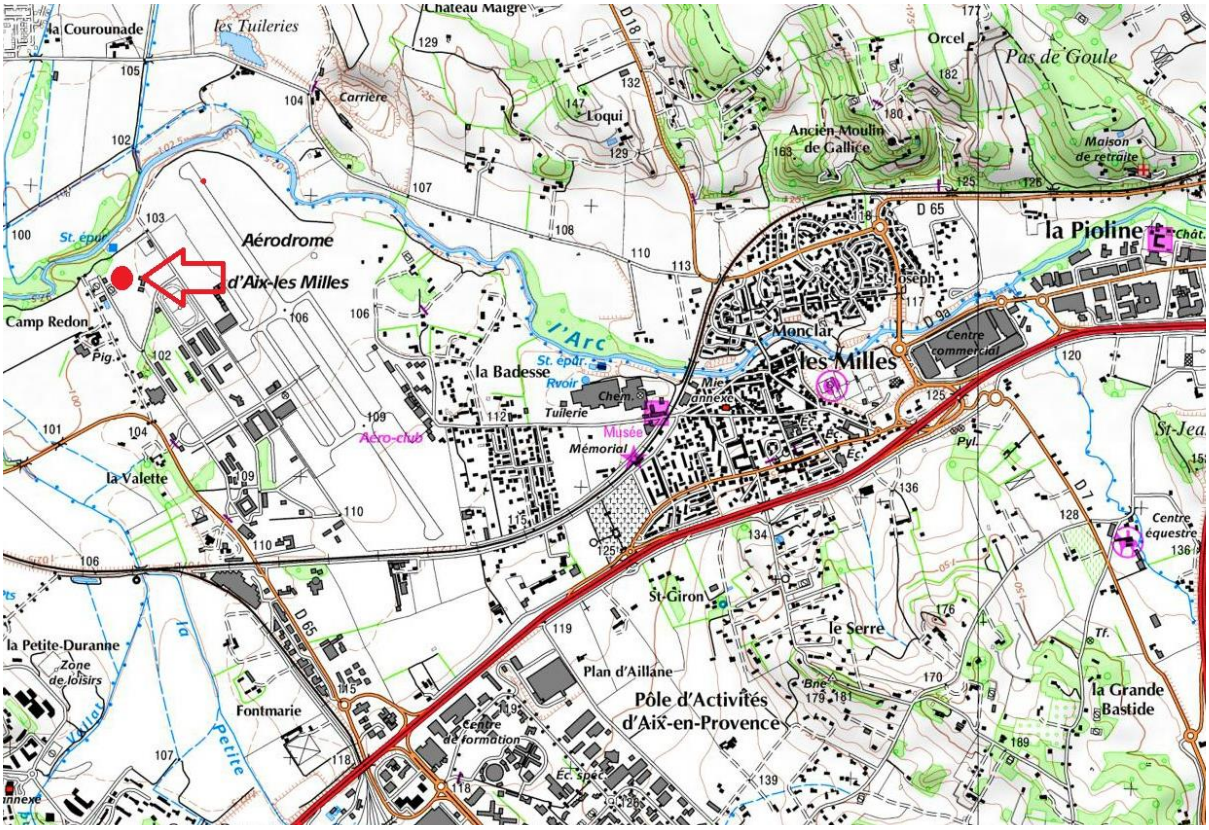


Figure 2. A location of the operational training facility: map view.

1.2 Description

The EHSTP has an area of 2500 m² and built on a 6000 m² of land..

The operational platform is divided into ten operational training exercise zones/features which would enable the carry out of several scenarios. The zones and features are listed below.

Leak zones:

1A : Gaseous hydrogen (H_2)

1B : Gaseous methane (CH_4)

1C : Liquefied petroleum gas (LPG)

Explosion zone:

2 : Variable concentration for explosion, a mock barrel (H_2, CH_4)

Dismantled hydrogen trailer:

3 : Dismantled long cigars, a mock trailer (H_2)

An FCH car:

4 : An FC car fire (on the roof and at the bottom, a release through a TPRD)

A multi-energy (hybrid) car:

5 : Variable release modes (H_2, CH_4, LPG)

A refuelling station:

6 : H_2 leak

An on-wheels trailer:

7 : Leak of H_2 and CH_4

A FC container:

8 : H_2 and CH_4 leak due to a technical failure

The positioning of the abovementioned zones and features of the operational platform are shown on Figure 3.

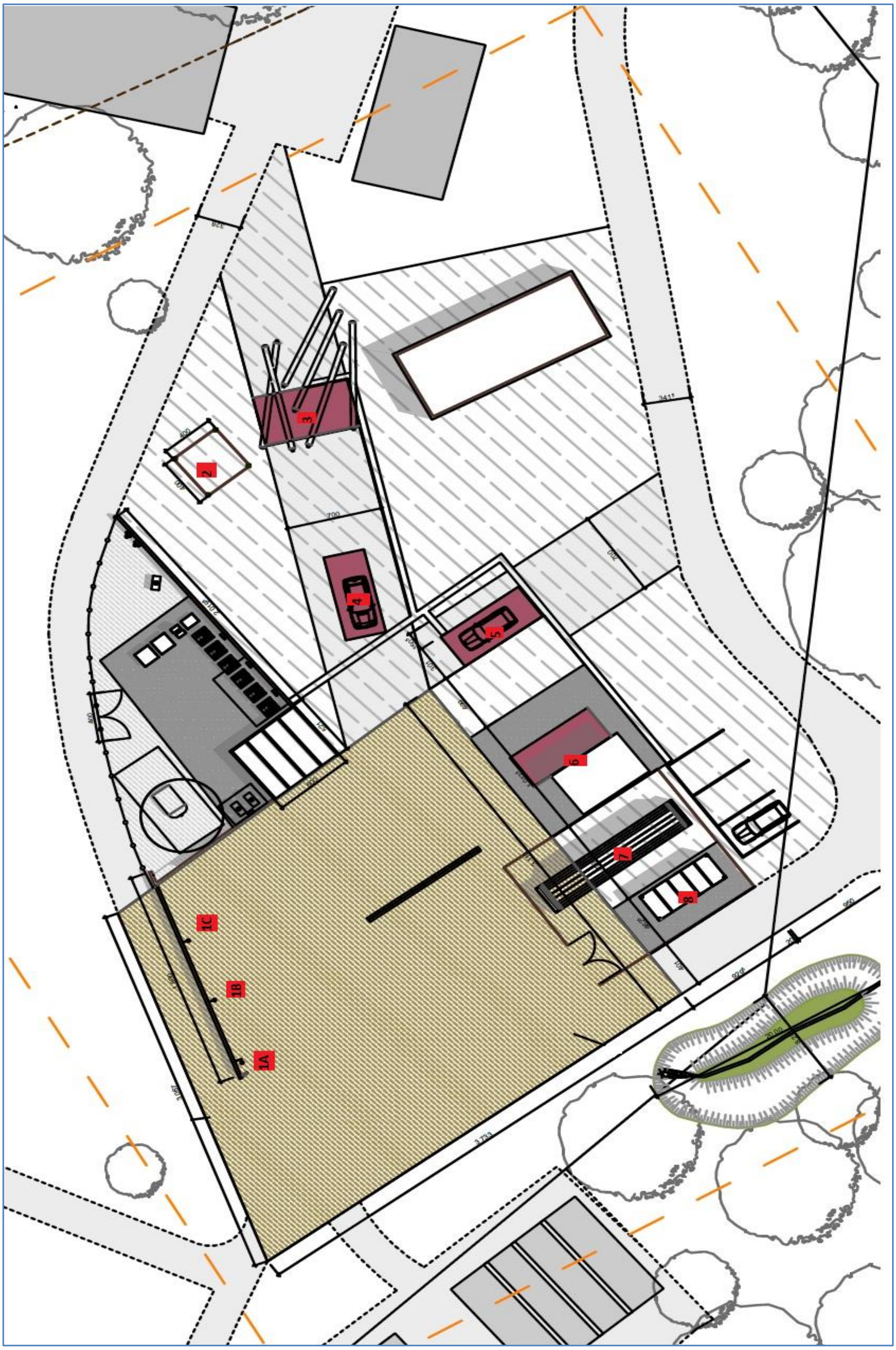


Figure 3. The zones and features of the operational training platform

2 Multi-level operational training exercises

2.1 The objectives of the operational training exercises

In the end of the operational training a trainee should be able, during an incident, to:

- Reach a high level of understanding of the situation, taking into account relevant information
- Choose the appropriate tactics to deal with the specific situation.
- Implement the required actions
- Maintain a safety as high as possible for First Responders and the general public

2.2 Scenarios

A scenario is mainly defined by the following factors:

- the FCH application involved (type, size, etc.)
- the area around the application (access, buildings, stakes, etc.)
- the weather conditions (wind)
- the incident occurring on the application (nature, duration, etc.)
- the presence of the casualties (location, number, etc.)

Thus, the number of possible scenarios is infinitely variable. 109 scenarios have been developed to cover a wide range of situations and FCH applications. The difficulty of the exercises can be varied as follows:

- Discovery level
- Advanced level
- Expert level

It should be mentioned that at the moment it is not possible to simulate all the scenarios developed in D2.2as it was not feasible/envisaged to create mock-ups of all FCH applications. As an example, there are no FC buses or forklift currently on the platform.

Currently, 59 scenarios could be simulated on the platform during the training sessions. For three pilot face-to-face sessions six of them have been selected (coloured in red in Table 1).

Table 1. The scenarios available on the operational platform and selected for face-to-face training

	FCH application	Potential danger	LEVEL	Description	Related tactics
2	**FC CAR**	**LEAK**	**DISCOVERY**	FC car default - **H2 leak** - simple environment (small road)	**2**
3	**FC CAR**	**LEAK**	**DISCOVERY**	Single FC car **accident** - **H2 leak** - no **extrication** - simple environment (small road)	**2**
4	**FC CAR**	**H2 FIRE**	**DISCOVERY**	FC car default - **FC car in a fire** - simple environment (small road)	**3**
5	**FC CAR**	**H2 FIRE**	**DISCOVERY**	Single FC car **accident** - **FC car in fire** - no **extrication** - simple environment (small road)	**3**
12	**H2 TRAILER (bundles cylinders or long cigars)**	**LEAK**	**DISCOVERY**	H2 trailer default - **H2 leak** - simple environment (small road)	**6**
13	**H2 TRAILER (bundles cylinders or long cigars)**	**LEAK**	**DISCOVERY**	Single H2 trailer **accident - storage on the trailer** - **H2 leak** - **extrication** - simple environment	**6**
14	**H2 TRAILER (bundles cylinders or long cigars)**	**LEAK**	**DISCOVERY**	Single H2 trailer **accident - dismantled storage (MIKADO)** - **H2 leak** - **extrication** - simple environment	**6**
17	**H2 TRAILER (bundles cylinders or long cigars)**	**H2 FIRE**	**DISCOVERY**	Single H2 trailer accident - dismantled storage (MIKADO) - H2 jet fire - extrication - simple environment	**7**
21	**H2 STORAGE**	**NO LEAK**	**DISCOVERY**	H2 storage false alarm - simple environment (remote environment)	**13**
22	**H2 STORAGE**	**LEAK**	**DISCOVERY**	H2 storage default - **H2 leak** - simple environment (remote environment)	**14**
23	**H2 STORAGE**	**H2 FIRE**	**DISCOVERY**	H2 storage default - H2 jet fire - simple environment (remote environment)	**15**
24	**H2 STORAGE**	**EXTERNAL THREAT**	**DISCOVERY**	**Fire in a simple environment (remote environment)** - Storage in the environment	**16**
25	**FC SYSTEM, ELECTROLYSER, CHP SYSTEM, BACK UP POWER SYSTEM, HYDROGEN-BASED ENERGY STORAGE SYSTEM**	**NO LEAK**	**DISCOVERY**	FC system false alarm - simple environment (remote environment)	**13**
26	**FC SYSTEM, ELECTROLYSER, CHP SYSTEM, BACK UP POWER SYSTEM, HYDROGEN-BASED ENERGY STORAGE SYSTEM**	**LEAK**	**DISCOVERY**	FC system default - **H2 leak** - simple environment (remote environment)	**14**
29	**H2 REFUELLING STATION (without storage)**	**NO LEAK**	**DISCOVERY**	Dispenser/FC car false alarm - Refuelling station in a remote environment	**9**
30	**H2 REFUELLING STATION (without storage)**	**LEAK**	**DISCOVERY**	Dispenser/FC car default - **H2 leak** - simple environment (remote environment)	**10**

	FCH application	Potential danger	LEVEL	Description	Related tactics
34	**FC CAR**	**LEAK**	**ADVANCED**	FC car default - H2 leak from the FC car - medium complex environment (car mechanics, domestic house, open space parking)	**2**
36	**FC CAR**	**LEAK**	**ADVANCED**	Multi vehicle **accident** - **H2 leak** from the FC car - **no extrication** - complex environment (motorway, urban environment, tunnel)	**2**
37	**FC CAR**	**H2 FIRE**	**ADVANCED**	FC car default - FC car in a **fire** - medium complex environment (car mechanics, domestic house, open space parking)	**3**
38	**FC CAR**	**H2 FIRE**	**ADVANCED**	Multi vehicle accident - FC car in fire - no extrication - complex environment (motorway, urban environment, tunnel)	**3**
39	**FC CAR**	**EXTERNAL THREAT**	**ADVANCED**	**Fire in a medium complex environment** (car mechanics, domestic house, open space parking) - FC car in the environment	**4**
48	**H2 TRAILER (bundles cylinders or long cigars)**	**LEAK**	**ADVANCED**	H2 trailer default - **H2 leak** from the H2 trailer - medium complex environment (trailer warehouse, parking, etc.)	**6**
50	**H2 TRAILER (bundles cylinders or long cigars)**	**LEAK**	**ADVANCED**	Multi vehicle **accident** - dismantled storage (MIKADO) - **H2 leak** from the H2 trailer - **extrication** - complex environment (motorway, urban environment, tunnel, industrial environment, etc.)	**6**
51	**H2 TRAILER (bundles cylinders or long cigars)**	**H2 FIRE**	**ADVANCED**	H2 trailer default - H2 trailer in a **fire** - medium complex environment (trailer warehouse, parking, ?)	**7**
53	**H2 TRAILER (bundles cylinders or long cigars)**	**H2 FIRE**	**ADVANCED**	Multi vehicle accident - dismantled storage (MIKADO) - H2 jet fire from the H2 trailer - extrication - complex environment (motorway, urban environment, tunnel, industrial environment)	**7**
54	**H2 TRAILER (bundles cylinders or long cigars)**	**EXTERNAL THREAT**	**ADVANCED**	Fire in a medium complex environment (trailer warehouse, parking, ?) - H2 trailer in the environment	**8**
58	**H2 STORAGE**	**NO LEAK**	**ADVANCED**	H2 storage false alarm - medium complex environment (outside urban or industrial environment)	**13**
59	**H2 STORAGE**	**LEAK**	**ADVANCED**	H2 storage default - H2 leak - medium complex environment (outside urban or industrial environment)	**14**
60	**H2 STORAGE**	**H2 FIRE**	**ADVANCED**	H2 storage default - H2 jet fire - medium complex environment (outside urban or industrial environment)	**15**
61	**H2 STORAGE**	**EXTERNAL THREAT**	**ADVANCED**	**Fire in a medium complex environment (outside urban or industrial environment)** - Storage in the environment	**16**
62	**FC SYSTEM, ELECTROLYSER, CHP SYSTEM, BACK UP POWER SYSTEM, HYDROGEN-BASED ENERGY STORAGE SYSTEM**	**NO LEAK**	**ADVANCED**	FC system false alarm - medium complex environment (outside urban or industrial environment)	**13**

	FCH application	Potential danger	LEVEL	Description	Related tactics
63	**FC SYSTEM, ELECTROLYSER, CHP SYSTEM, BACK UP POWER SYSTEM, HYDROGEN-BASED ENERGY STORAGE SYSTEM**	**LEAK**	**ADVANCED**	FC system default - H2 leak - medium complex environment (outside urban or industrial environment)	**14**
65	**FC SYSTEM, ELECTROLYSER, CHP SYSTEM, BACK UP POWER SYSTEM, HYDROGEN-BASED ENERGY STORAGE SYSTEM**	**EXTERNAL THREAT**	**EXPERT**	**Fire in a medium complex environment (outside urban or industrial environment)** - FC system in the environment	**16**
66	**H2 REFUELLING STATION (without storage)**	**NO LEAK**	**EXPERT**	Dispenser/FC car false alarm - Refuelling station in a medium complex environment (outside urban or industrial environment)	**9**
67	**H2 REFUELLING STATION (without storage)**	**LEAK**	**EXPERT**	Dispenser/FC car default - H2 leak - medium complex environment (outside urban or industrial environment)	**10**
69	**H2 REFUELLING STATION (without storage)**	**EXTERNAL THREAT**	**EXPERT**	**Fire in a refuelling station (outside urban or industrial environment)** - FC car in the environment	**12**
70	**FC CAR**	**LEAK**	**EXPERT**	FC car default - H2 leak from the FC car - complex environment (motorway, urban environment, tunnel, underground parking)	**2**
72	**FC CAR**	**H2 FIRE**	**EXPERT**	FC car default - FC car in a fire - complex environment (motorway, urban environment, tunnel, underground parking)	**3**
73	**FC CAR**	**EXTERNAL THREAT**	**EXPERT**	Multi vehicle accident - FC vehicle in fire - extrication (FC car and/or conventional car) - complex environment (motorway, urban environment, tunnel)	**4**
74	**FC CAR**	**EXTERNAL THREAT**	**EXPERT**	**Fire in a complex environment** (motorway, urban environment, tunnel, underground parking) - FC car in the environment	**4**
75	**FC CAR**	**EXTERNAL THREAT**	**EXPERT**	Multi vehicle accident - conventional car in fire - extrication from the FC vehicle - complex environment (motorway, urban environment, tunnel)	**4**
84	**H2 TRAILER (bundles cylinders or long cigars)**	**LEAK**	**EXPERT**	H2 trailer default - **H2 leak** from the H2 trailer - complex environment (motorway, urban environment, tunnel, industrial environment)	**6**
86	**H2 TRAILER (bundles cylinders or long cigars)**	**LEAK**	**EXPERT**	Multi vehicle **accident** - dismantled storage (MIKADO) - **H2 leak** from H2 trailer - **extrication** (H2 trailer and/or conventional car) - complex environment (motorway, urban environment, tunnel, industrial environment)	**6**
87	**H2 TRAILER (bundles cylinders or long cigars)**	**H2 FIRE**	**EXPERT**	H2 trailer default - H2 trailer in a **fire** - complex environment (motorway, urban environment, tunnel, industrial environment)	**7**

	FCH application	Potential danger	LEVEL	Description	Related tactics
90	**H2 TRAILER (bundles cylinders or long cigars)**	**H2 FIRE**	**EXPERT**	Multi vehicle accident - dismantled storage (MIKADO) - H2 jet fire from H2 trailer - extrication (H2 trailer and/or conventional car) - complexe environment (motorway, urban environment, tunnel?, industrial environment)	**7**
92	**H2 TRAILER (bundles cylinders or long cigars)**	**EXTERNAL THREAT**	**EXPERT**	Fire in a complex environment (motorway, urban environment, tunnel, industrial environment) - H2 trailer in the environment	**8**
93	**H2 TRAILER (bundles cylinders or long cigars)**	**EXTERNAL THREAT**	**EXPERT**	Multi vehicle accident - fire close to the trailer - complex environment (motorway, urban environment, tunnel)	**8**
98	**H2 STORAGE**	**NO LEAK**	**EXPERT**	H2 storage false alarm - complex environment (inside urban or industrial environments)	**13**
99	**H2 STORAGE**	**LEAK**	**EXPERT**	H2 storage default - H2 leak - complex environment (inside urban or industrial environments)	**14**
100	**H2 STORAGE**	**H2 FIRE**	**EXPERT**	H2 storage - H2 jet fire - complex environment (inside urban or industrial environments)	**15**
101	**H2 STORAGE**	**EXTERNAL THREAT**	**EXPERT**	Fire in a complex environment (inside urban or industrial environments) - Storage in the environment	**16**
102	**FC SYSTEM, ELECTROLYSER, CHP SYSTEM, BACK UP POWER SYSTEM, HYDROGEN-BASED ENERGY STORAGE SYSTEM**	**EXTERNAL THREAT**	**EXPERT**	FC system false alarm - complex environment (inside urban or industrial environments)	**16**
103	**FC SYSTEM, ELECTROLYSER, CHP SYSTEM, BACK UP POWER SYSTEM, HYDROGEN-BASED ENERGY STORAGE SYSTEM**	**LEAK**	**EXPERT**	FC system default - H2 leak - complex environment (inside urban or industrial environments)	**14**
104	**FC SYSTEM, ELECTROLYSER, CHP SYSTEM, BACK UP POWER SYSTEM, HYDROGEN-BASED ENERGY STORAGE SYSTEM**	**EXTERNAL THREAT**	**EXPERT**	FC system - H2 jet fire - complex environment (inside urban or industrial environments)	**16**
105	**FC SYSTEM, ELECTROLYSER, CHP SYSTEM, BACK UP POWER SYSTEM, HYDROGEN-BASED ENERGY STORAGE SYSTEM**	**EXTERNAL THREAT**	**EXPERT**	Fire in a complex environment (inside urban or industrial environments) - FC system in the environment	**16**
106	**H2 REFUELLING STATION (without storage)**	**NO LEAK**	**EXPERT**	Dispenser/FC car alarm - Refuelling station complex environment (inside urban or industrial environments)	**9**
107	**H2 REFUELLING STATION (without storage)**	**LEAK**	**EXPERT**	Dispenser/FC car default - H2 leak - complex environment (inside urban or industrial environments)	**10**

	FCH application	Potential danger	LEVEL	Description	Related tactics
108	**H2 REFUELLING STATION (without storage)**	**H2 FIRE**	**EXPERT**	Dispenser - H2 jet fire - complex environment (inside urban or industrial environments)	**11**
109	**H2 REFUELLING STATION (without storage)**	**EXTERNAL THREAT**	**EXPERT**	**Fire in a refuelling station** (inside urban or industrial environments) - FC car in the environment	**12**

2.3 The operational training exercises and related tactics

The strategies and tactics were previously developed in Deliverable 2.3 and will be taught during the educational part of the face-to-face training..

For each exercise, the trainee is supposed to apply the related and correct tactics. Table 2 shows the tactics expected for the 6 selected exercises, which are to be delivered during the pilot sessions.

Table 2. List of selected operational exercises and relevant tactics

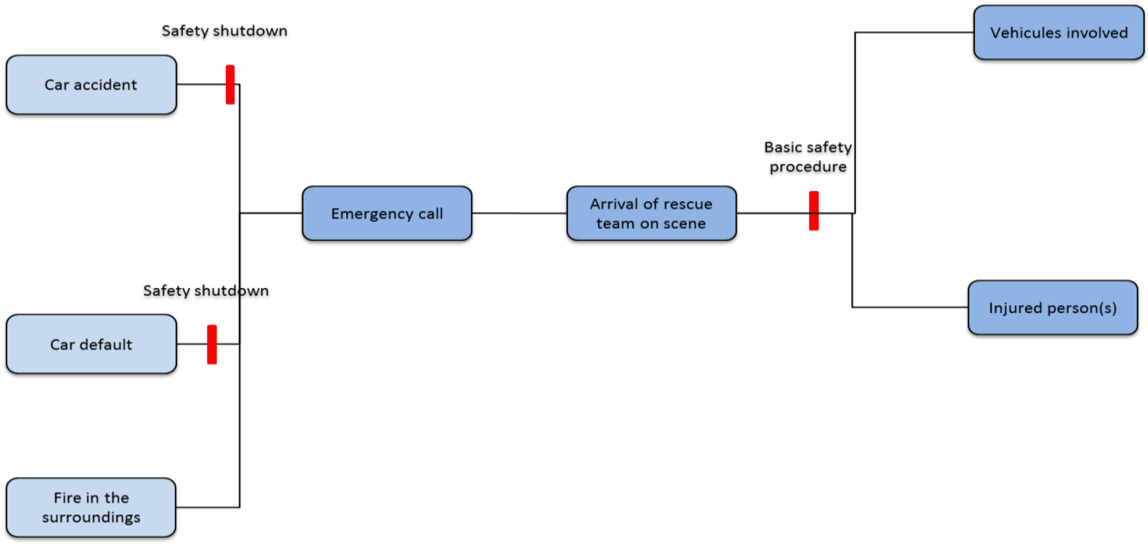
Exercise No	FCH application	Potential danger	LEVEL	Scenario identification	Description	Tactics No
5	**FC CAR**	**H2 FIRE**	**DISCOVERY**	FC_Car_D_F2	Single FC car **accident** - **FC car in fire** - no **extrication** - simple environment (small road)	3
38	**FC CAR**	**H2 FIRE**	**ADVANCED**	FC_Car_A_F2	Multi vehicle accident - FC car in fire - no extrication - complex environment (motorway, urban environment, tunnel)	3
63	**FC SYSTEM, ELECTROLYSER, CHP SYSTEM, BACK UP POWER SYSTEM, HYDROGEN-BASED ENERGY STORAGE SYSTEM**	**LEAK**	**ADVANCED**	FC_System_A_L1	FC system default - H2 leak - medium complex environment (outside urban or industrial environment)	14
67	**H2 REFUELLING STATION (without storage)**	**LEAK**	**EXPERT**	H2_Refuelling_A_L1	Dispenser/FC car default - H2 leak - medium complex environment (outside urban or industrial environment)	10
90	**H2 TRAILER (bundles cylinders or long cigars)**	**H2 FIRE**	**EXPERT**	H2_Trailer_E_F4	Multi vehicle accident - dismantled storage (MIKADO) - H2 jet fire from H2 trailer - extrication (H2 trailer and/or conventional car) - complex environment (motorway, urban environment or tunnel or industrial environment)	7
99	**H2 STORAGE**	**LEAK**	**EXPERT**	H2_Storage_E_L1	H2 storage default - H2 leak - complex environment (inside urban or industrial environments)	14

2.4 The flow-charts for the chosen scenarios

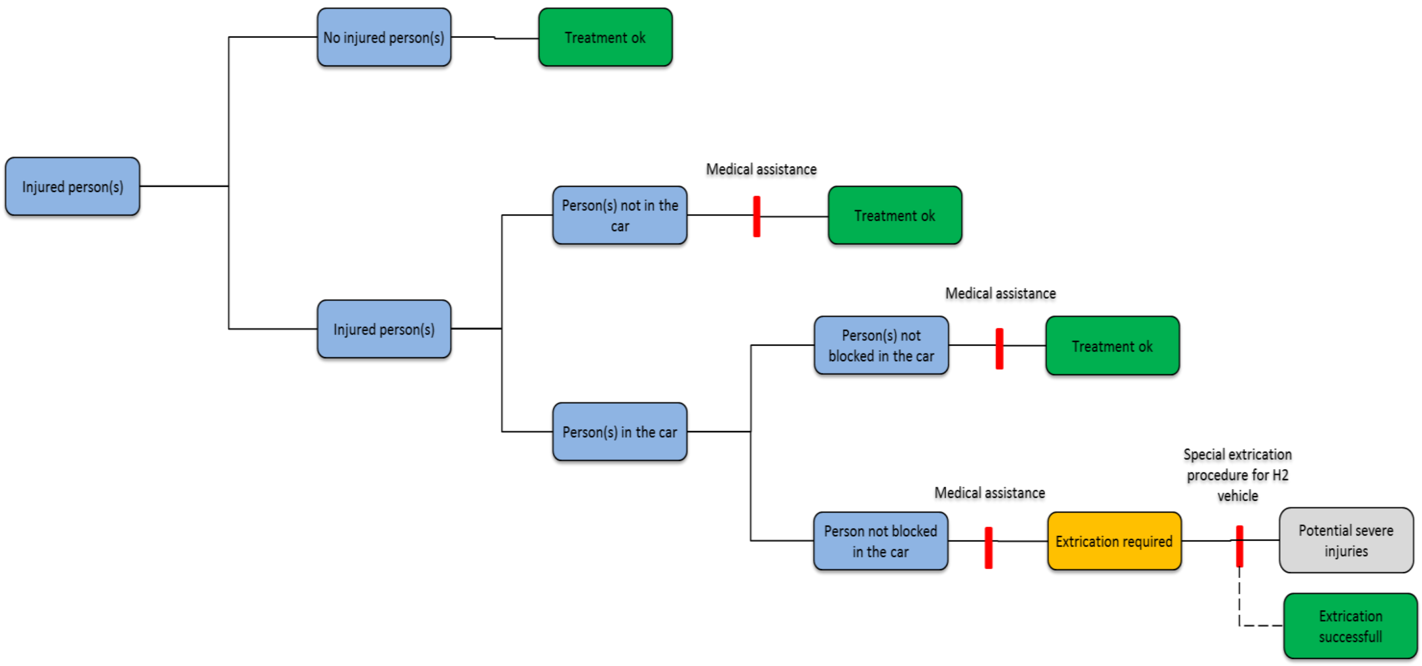
In this section of the document five flowcharts related to the chosen incidents are described. Please note that all the scenarios are available in Deliverable2.2.

2.4.1 Exercises involving FCH cars:

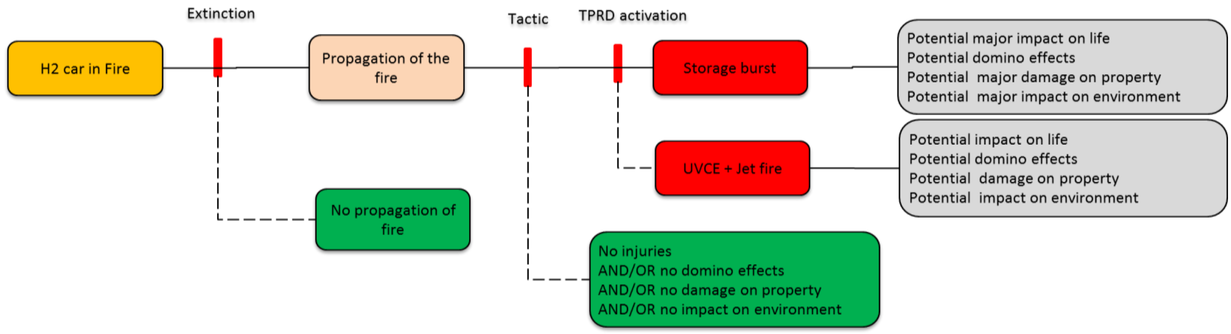
For exercises numbered 5 and 38, the beginning of the flow chart is common for the material part :



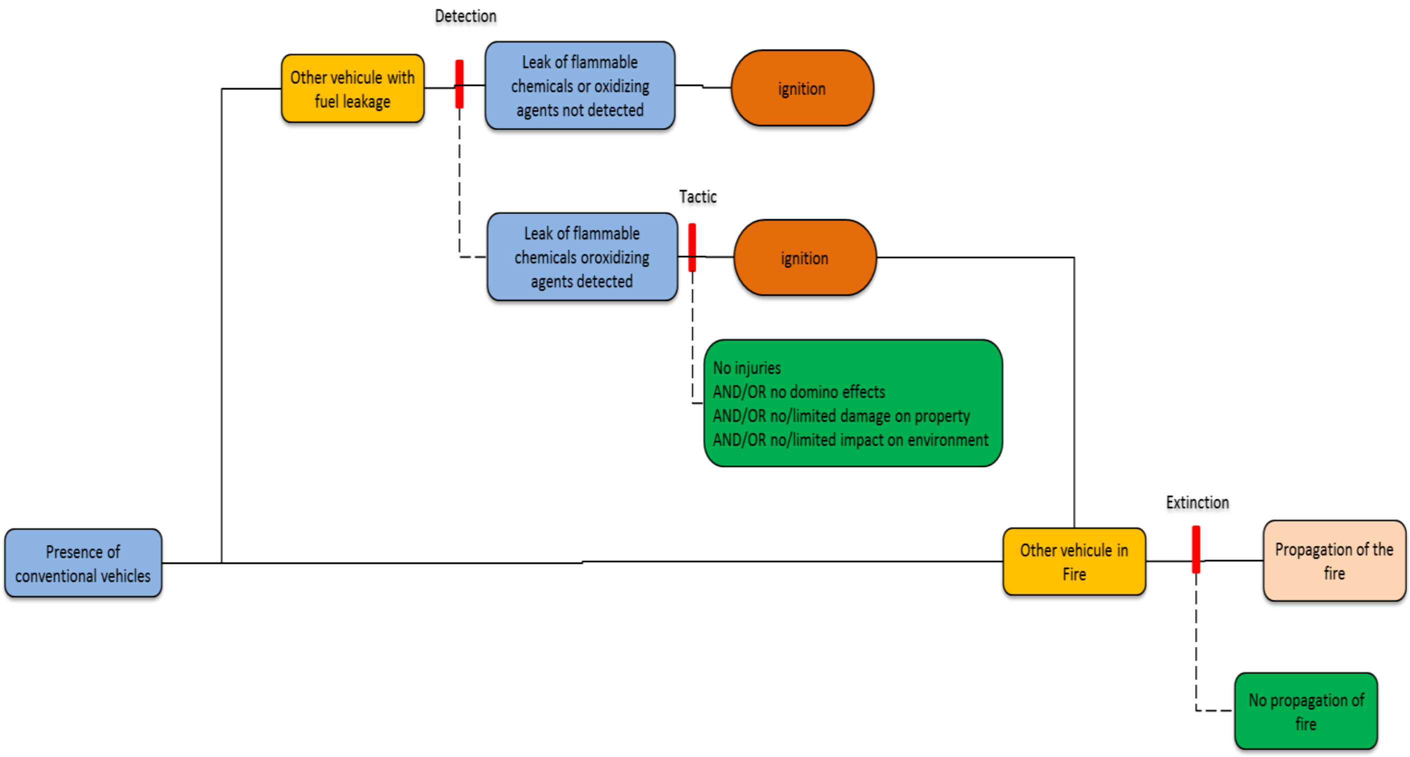
And for the human part:



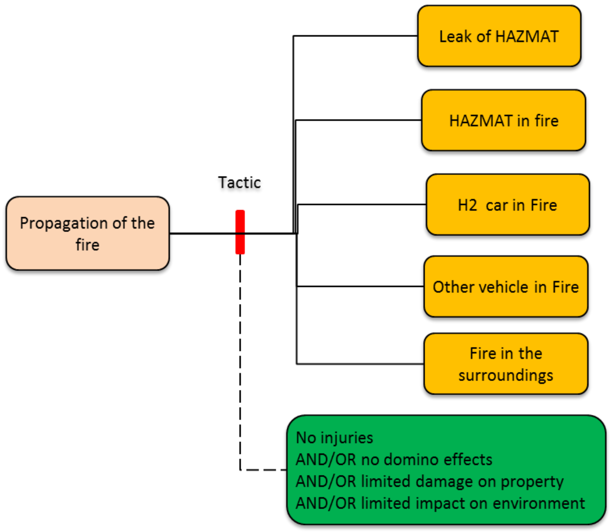
For the exercise No. 5, only a FCH car is involved in the accident, no injured person is identified and no risk of propagation from the car to anything else.



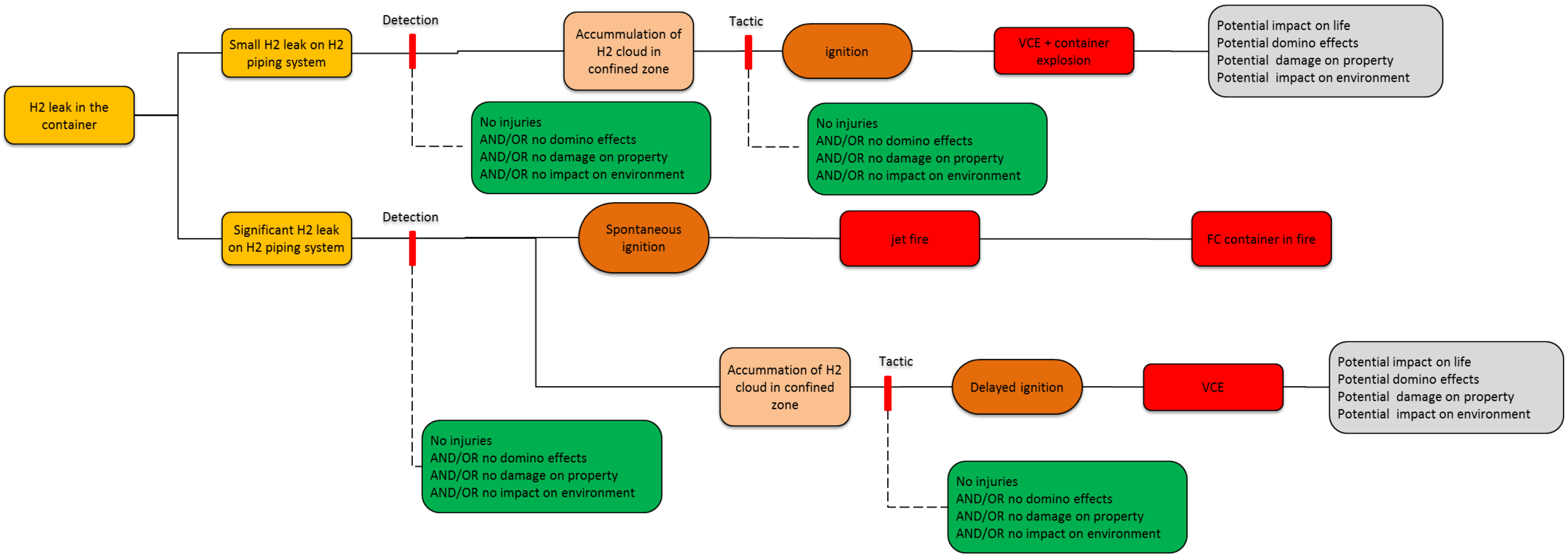
For the exercise No 38, other vehicles are added in the scenario. The incident can follow in parallel this flowchart, beginning with "presence of conventional vehicles."



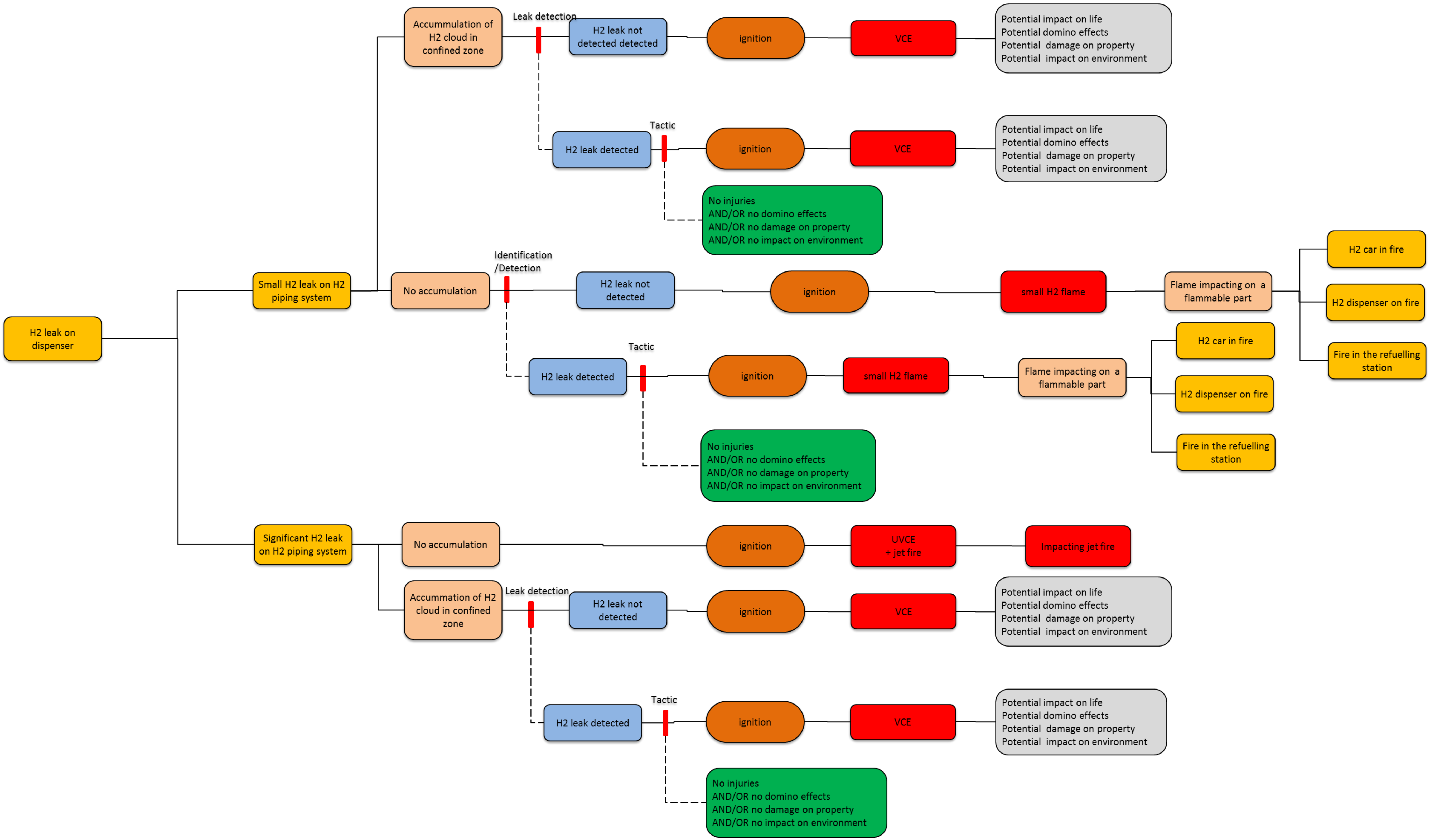
And after the step “Propagation of the fire “:



2.4.2 Exercises involving FC system, electrolyser, CHP systems, back-up power system, hydrogen-based energy storage systems

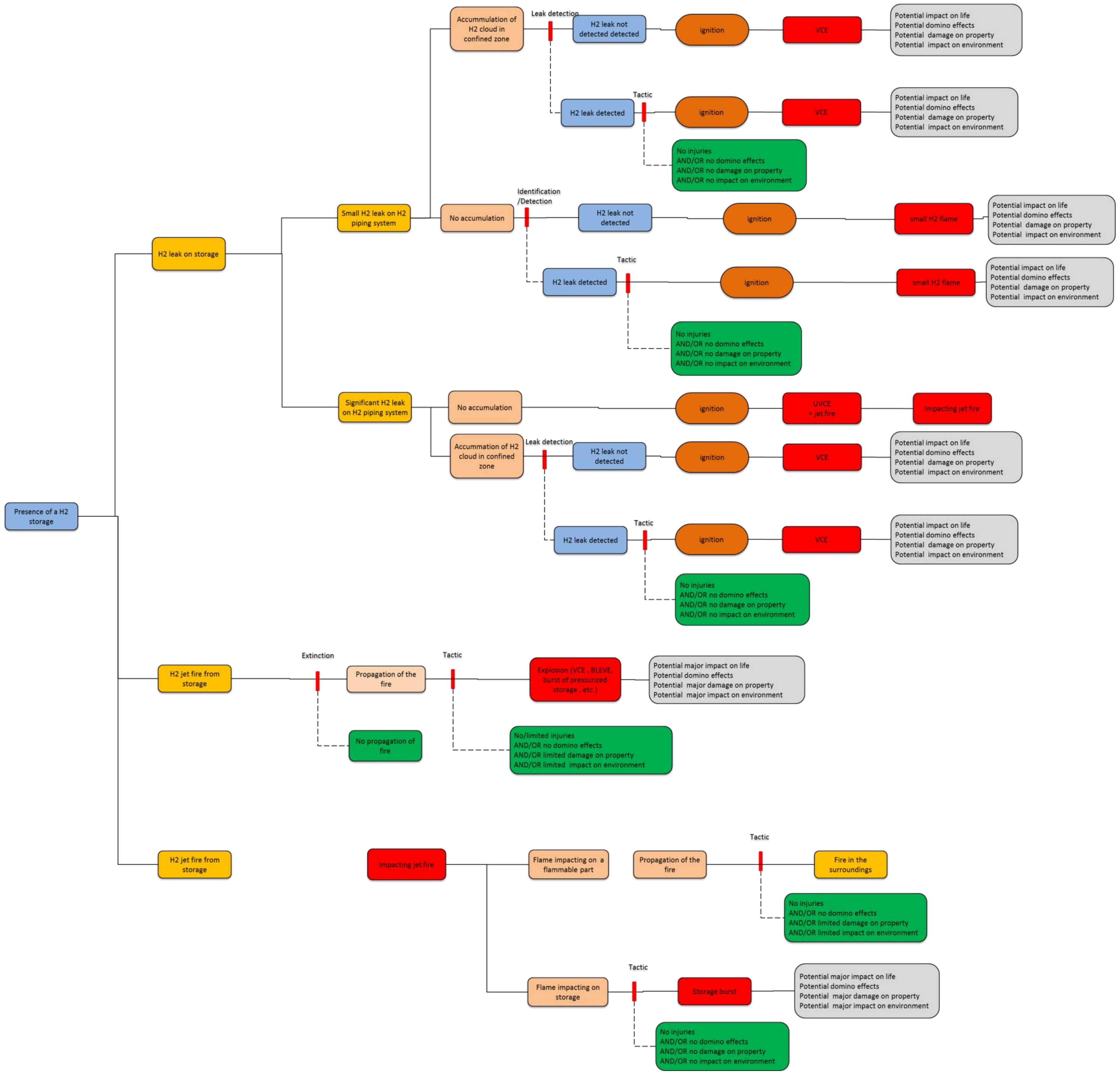


2.4.3 Exercise involving a refueling station



2.4.4 Exercise involving hydrogen trailers

2.4.5 Exercise involving hydrogen storages



3 Assessment of the operational training exercises

3.1 Assessment sheet

Table 3 contains a template of the assessment sheet that will be used for the pilot training sessions by the trainers. This sheet must be filled by the instructor at the end of each exercise. The assessment is on the individual basis. The instructor checks the items required in the related tactics and provide comments and improvement orientations.

Table 3. The exercise assessment sheet

EXERCISE ASSESMENT SHEET	Date :		HyResponse
Exercise identification :	Instructor name:		Student name : Team: - - - -
	CORRECT	FALSE	COMMENTS
AT THE FIRE STATION			
Check that the fire appliance is ready and operational			
Check every first reponder portection suit			
Take into account the informations about the incident (short brirefing for the team)			
Take weather conditions			
Choose a safe itinerary			
Take specific tools			
ARRIVAL ON SCENE			
Choose a safe way to get to the incident ground			
Stop the applicance a the required distance			
Set the required safety area			
Make the arrival radio call			
SIZE UP THE SCENE			
Collect informations about the situation			
Make a complete recognition of the incident scene			
Decide to engage immediate rescue if needed			
Complete the information collect			
Make the first report radio call (situation confirmation)			
RESCUE			
Engage rescue in the safest manner for first responders			
Make the paramedic requirement radio call (if needed)			

	CORRECT	FALSE	COMMENTS	
EXPOSURE PROTECTION				
Prevent exposure of persons				
Prevent exposure of properties				
Prevent exposure of environment				
Use personnel in a reasonable manner				
INCIDENT TREATMENT				
Engage incident treatment as required in the related tactic				
Use personnel in a reasonable manner				
Make the second report radio call (situation treatment information to authority)				
Make a permanent scene assessment				
OVERHAUL				
Control that no risk remains				
Stay on scene as long as needed				
Make the paramedic requirement radio call (if needed)				
Global assessment				
validation	YES		NO	
Instructor signature :				

4 Separation distances

The purpose of this section of the document is to provide an evaluation of separation distances for non-reacting releases (unignited jets) and reacting releases (jet fires) which should be taken into account for the implementation of multi-level operational training exercises. As stated in the DoW the challenge of this activity is to create a dynamic accidental environment as close to reality as possible while guarantying safety of trainees. The information presented below can also be considered during the installation and commissioning of HyResponse operating training facilities, which will allow First Responders to implement operational response strategies identified for selected scenarios (task 4.2). One type of the full-scale training exercises will take place on the existing portion of the road for a vehicle accident scene, and potentially in the urban area as well. With this in mind, we have calculated separation distances for unignited and ignited releases for an accident involving an FCH vehicles and an internal combustion engine (ICE) vehicle in the open, either on a portion of a highway or in an urban area near a building fitted with an air intake.

A separation (or safety) distance is defined, according to LaChance [1], as a minimum distance, which separates “specific targets (e.g. people, structures or equipment) from the consequences of potential accidents related to the operation a hydrogen facility” [1]. Another source, European Industrial Gases Association (EIGA), states that “the safety distance is the minimum separation between a hazard source and an object (human, equipment or environment) which will mitigate the effect of a likely foreseeable incident and prevent a minor incident escalating into a larger incident” [2]. Both definitions show the importance of defining the nature of the hazard, the operating conditions and the design of the analysed equipment, the type of target and the environment between the latter and the source of hazard. In this way, the harm potential for people or structures can be evaluated and compared with the harm criteria.

4.1 Definition of separation distances

Recommended separation distances for the installation of an FCH facility are considered as means of reducing the potential that an incident or a minor accident will propagate or have an effect on another part of a facility. A specified separation distance should account for any “foreseeable” accidents i.e. leaks, fires etc. but may not necessarily account for all possible scenarios. However, as described in [1], safety distances “generally should address likely events initiated by a hazard located on the facility and by external hazards (e.g. earthquakes or cars) some of which can occur outside the boundary of the facility (e.g. a fire at an adjacent building)”. At present, the way, in which separation distances are specified, varies from document to document and form country to country. While some documents (such as NFPA2) have been developed specifically with hydrogen technologies in mind, other existing codes have been updated to include hydrogen. In some cases the separation distances may have been based on criteria applicable to large industrial facilities making the realisation of public hydrogen infrastructures prohibitive in terms of distance requirements [3].

The nature of the hazard is related to the characteristics of hydrogen (e.g. flammability limits) and to the conditions such as storage pressure. The knowledge of the equipment design and operating conditions (i.e. storage pressures; maximum inventories; volumes and vent diameters) is very important for the evaluation of separation distances. In addition, it is crucial to establish harm criteria, i.e. prevention of hydrogen ignition; protection against specific value of heat flux or minimization of an overpressure. Finally, the chosen accident scenario and its consequences as well

as the assumptions made for each scenario will have a direct effect on the separation distances. For example, in NFPA 55 and NFPA 2 it was assumed that the size of hydrogen leaks is 3% of a cross-sectional area of a pipe, leading to the underestimation of the separation distances.

Before the evaluation of separation distances it is necessary to determine what we would like to protect against i.e. temperature, heat flux, overpressure etc. The main hazard associated with any hydrogen facility is uncontrolled combustion of accidently released hydrogen (gaseous or liquid). Possible modes of hydrogen combustion include jet fires, flash fires, deflagrations (unconfined vapour cloud explosions) and detonations. The other hazards are asphyxiation or cryogenic burns caused by liquid hydrogen but they are not relevant for the scenario discussed in this document.

In the case of hydrogen fire, people or objects may be exposed to flames or high levels of heat. Therefore in case of a fire it is necessary to know the temperature and the level of heat flux that can cause damage to people or structures. In the current document we use the temperature as a harm criterion. Considering the effect of fires on people and on fire-fighters in particular, the direct flame contact is generally assumed to cause third degree burns sufficient to have fatal consequences. Three temperatures are considered: 70 ^{o}C is taken as “no harm” criterion; 115 ^{o}C - as a “pain” limit, i.e. a threshold for pain from elevated temperatures from exposures longer than 5 minutes; and 309 ^{o}C as a “death” limit, i.e. third degree burns for 20 seconds [5].

For people, who are not in flames, there is a still a danger of being exposed to high radiation heat fluxes for prolonged periods of time which can lead to death. The heat fluxes can define the jet fire length and shape and ultimately effect the separation distances. The evaluation of separation from different levels of heat fluxes is currently underway and will be reported at the later stage of the project.

Although risk-based approach has been used elsewhere to evaluate the separation distances reported in NFPA 55 and NFPA 2, UU suggest deterministic approach, which is based on service pressures, leak diameters, hydrogen inventory and harm criteria. A deterministic analysis involves an evaluation of consequences for the most severe event possible with the intent of demonstrating that the facility meet harm criteria.

The initiating event considered is a collision between the FCH vehicle and the ICE vehicle on a road in urban area. First Responders can potentially face different situations following the collision and these depend predominantly on the nature of the collision, on the position of both vehicles after the impact and on the correct operation of the safety devices. The collision between two vehicles can potentially cause damage of hydrogen storage, hydrogen delivery systems and fuel cell (FC) or can lead to jet fires. The severity of the consequences will be influenced by several factors, such as an intensity of the impact, the state of the vehicles before the accident, the location of the impact etc. Generally, the damage of the FC and the fuel supply lines would have less severe consequences due to the smaller amount of hydrogen present in this part of the equipment. With this in mind, this section will focus on the storage system containing larger amounts of hydrogen in the tank.

The main safety device of the hydrogen storage system is a Thermal Pressure Relief Device (TPRD). Its purpose is to vent hydrogen from the storage vessel when it is exposed to high temperatures (usually above 110 °C) [4], thus avoiding excessive pressure build-up in the container. The TPRD diameter and the pressure in the storage tank are the most important parameters needed for the

evaluation of the separation distances. Unfortunately these parameters are not always known to first responders or some accident conditions do not allow full identification of the vehicles and their useful characteristics (e.g. in case of large fires). In the current document the separation distances are determined for a hypothetical storage tank fitted with a TPRD, diameter of which ranges from 2 to 6 mm. The hydrogen inventory depends on the make and model of the FCH vehicle. FCH vehicles usually have on-board hydrogen storage tanks with pressures of either 35 MPa or 70 MPa, which we have considered for our calculations. The assumptions regarding the environment are: temperature 293 K and pressure 101325 Pa.

4.2 Deterministic separation distances from non-reacting releases

Following the collision, damage to the hydrogen storage system in the FCH vehicle may occur thus leading to a release of compressed gaseous hydrogen. In this case, it is important to allow the dispersion of hydrogen, avoiding sparks or other sources of ignition in the path of the release. This section of the document reports the separation distances for non-reacting releases (i.e. when hydrogen is not involved in a combustion process) to the hydrogen concentration of interest useful to determine this area.

An unwanted release of gaseous hydrogen from its storage vessel is the main hazard for any FCH system. The release at high pressures creates a highly under-expanded (when the pressure at the nozzle exit is higher than the atmospheric pressure) turbulent jet, which "behaves differently from expanded jet (when the pressure at the nozzle exit is equal to the atmospheric pressure)" [5]. The leaks from hydrogen storage and/or equipment will be mostly in a form of under-expanded jets, at least at the beginning [5]. The jet fully expands to the atmospheric pressure at the location called notional nozzle as shown on Figure 4.

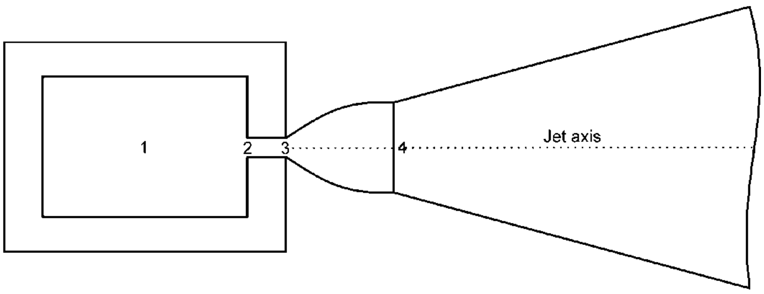


Figure 4. The scheme for under-expanded jet (1 – storage reservoir, 2 – nozzle entrance, 3 – nozzle exit, 4 – notional nozzle exit).

In an under-expanded jet a pressure at the nozzle exit has not fully dropped to the atmospheric pressure. For high pressures a velocity at the exit from the nozzle remains locally sonic, but the exit pressure rises above ambient value. As a result the expansion down to ambient conditions takes place outside the nozzle.

As mentioned earlier, the unscheduled hydrogen releases from high pressurised storage tanks will create highly under-expanded jets. This could lead to a formation of "a flammable hydrogen-air envelope, the size of which can be considered as the deterministic separation distance from the release source" [5]. Indeed, in the scenarios when the flammable envelope (i.e. hydrogen concentration in air equal to the lower flammability limit (LFL) of 4 vol. %) reaches an air intake of a building, the consequences both for occupants and a building structure can be catastrophic. "The

presence of an ignition source within the flammable envelope could initiate severe jet fires, deflagration, and potentially deflagration-to-detonation transition. It has to be noted that thermal effects of jet fires and pressure effects of deflagration or detonation could override the separation distance determined by the size of flammable envelope" [5]. The values of flammability limits LFL/UFL depends on temperature, pressure, diluents, ignition energy and direction of flame propagation in some cases. It also depends on a standard/code used [6]. For example, LFL value could be 6.2 vol. % for horizontally propagating flames and 8.9 vol. % for downward propagating flames [7]. The LFL and UFL of hydrogen-air mixtures at different temperatures for upward propagation are shown in Table 4 [8].

Table 4. Effect of temperature on the flammability limits of hydrogen-air mixtures at atmospheric pressures.

Temperature, ^{o}C	Lower Flammability Limit (LFL), vol. %	Upper Flammability Limit (UFL), vol. %
20	4.1	75.6
25	4.0	75.0
100	3.4	77.6
200	2.9	81.3
300	2.0	83.9
400	1.4	87.6

It is clear that the flammability range increases while LFL decreases at higher temperatures. Although a concentration of 4 vol. % of hydrogen in air is commonly used as a lower limit of an ignitable mixture under ideal conditions for burning, in other situations the concentrations of 2 or even 1 vol. % of gaseous hydrogen are used to provide a factor of safety and to account for uncertainties in the configuration that can affect the detection systems [9]. The flammability limits for hydrogen-air still mixtures are known (Table 4). For non-reacting high pressurised jets in the presence of well-established turbulent flow the ignition process will depend on the ignition point location. Veser et al [10] identified two regimes: a "fast" combustion regime and "slow" combustion regime. In the case of "fast" combustion regime, after an ignition the flame propagates upstream and downstream in relation to an ignition source. Even after the ignition source was stopped, the combustion zone was stabilised. In the case of "slow" unstable combustion regime, flame propagates only downstream compared to the location of the ignition source. The combustion zone was stable as long as an ignition source was active. It was determined that the threshold between stable and unstable regimes is at the axial hydrogen concentration of 11 vol. %. The "slow" regime was observed for the concentration ranging from 5 to 11 vol. % [10]. To summarise, the concentrations of interest for hydrogen-air mixtures are:

- 1 vol. % is a ¼ of the LFL of hydrogen in air;
- 2 vol. % is a ½ of the LFL of hydrogen in air;
- 4 vol. % is a LFL of hydrogen in air for an upward propagating flame at temperature 293.15 K and pressure 101325 Pa (NTP);
- 11 vol. % corresponds to the "fast" stable combustion regime when flame propagates both upwards and downwards (also corresponds to an average flame tip location)

The evaluation of the deterministic separation distances for non-reacting releases was carried using the similarity law for hydrogen concentration decay for round jets given by Chen and Rodi [11]:

$$x = \frac{5.4}{C_{ax}} \sqrt{\frac{\rho_N}{\rho_S}}\ D$$

where C_{ax} is the axial mass fraction of hydrogen, C_N is the mass fraction of hydrogen in the nozzle (in this case it is equal to 1), ρ_N is the density of the gas at the nozzle exit, ρ_S is the density of the surroundings air (1.204 kg/m^3), *D* is the diameter of the leakage and *x* is the distance to the axial concentration of interest.

The density of the gas at the nozzle exit, the diameter of the notional nozzle exit and the velocity of the gas in the same location were evaluated using the H2FC Cyber Laboratory engineering tool (http://sage.h2fc.eu/home/pub/12/). It was assumed that the temperature in the tank equal to 293 K; hydrogen pressure in the reservoir is either 35 or 70 MPa, and the orifice diameters was ranged between 2 and 6 mm in order to simulate different release sizes for different scenarios.

The calculated deterministic separation distances are reported in Table 5. Some assumptions behind the calculation of these distances are: the releases are steady state; the chosen orifices are round; the jets are oriented horizontally to vertically upwards; the jets are not attached to the ground; there were no obstacles; there are no consideration for losses [6]. The general trend is the larger the orifice diameter and the higher the storage pressure the longer the separation distance for the same concentration of hydrogen in air.

Table 5. Deterministic separation distances to axial hydrogen concentrations of interest

Pressure in hydrogen storage tank, MPa	Orifice diameter D, mm	Distances to 1 vol. %, m	Distances to 2 vol. %, m	Distances to 4 vol. %, m	Distance to 11 vol. %, m
35	2	53	26	13	4
35	3	80	40	20	7
35	4	107	53	26	9
35	5	133	66	33	11
35	6	160	79	39	13
70	2	69	34	17	6
70	3	103	51	25	9
70	4	138	68	34	11
70	5	172	85	42	14
70	6	206	102	51	17

The same approach can be implemented in an iterative way in order to obtain the concentration decay along the jet axis for the different value of orifice diameter and storage pressures (Figures 4 and 5).

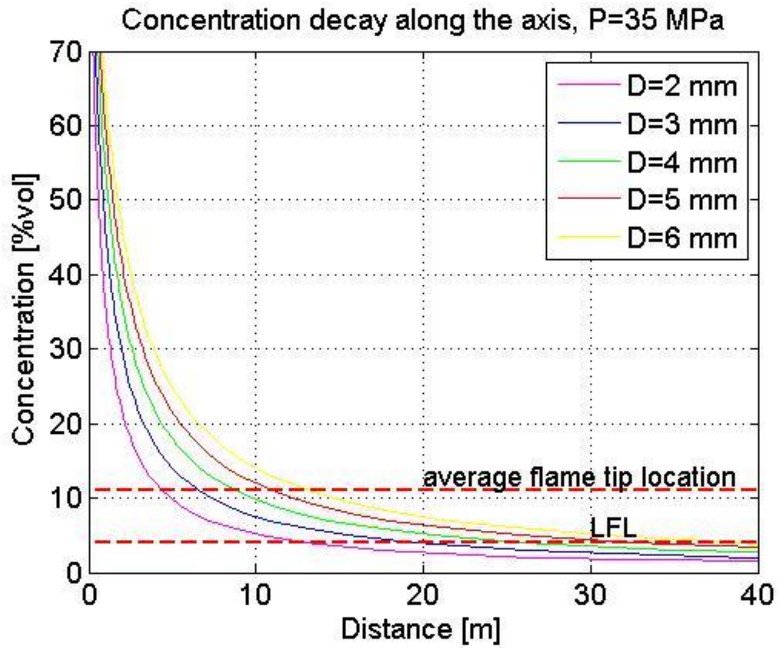


Figure 4. Concentration decay along the jet axis for a storage pressure of 35 MPa.

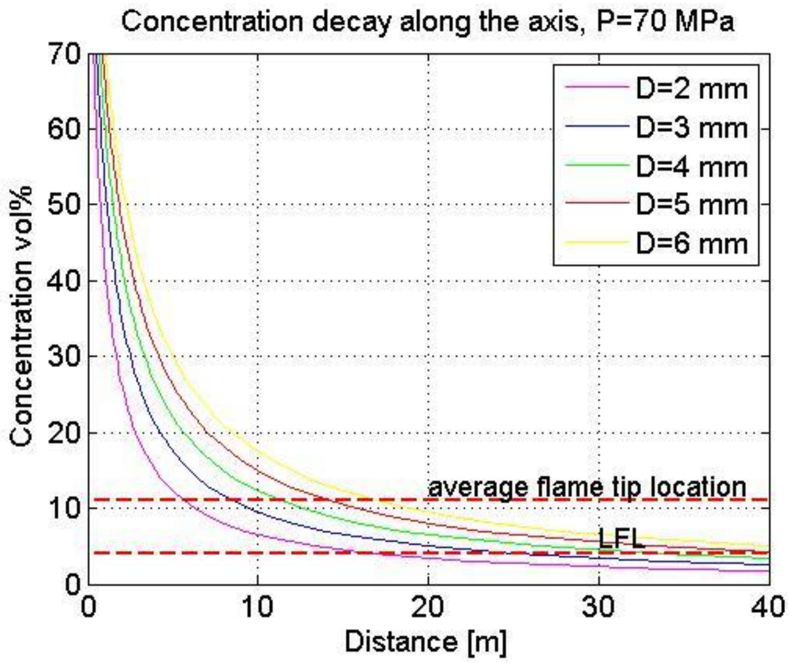


Figure 5. Concentration decay along the jet axis for a storage pressure of 70 MPa

It also important to know whether a leak is originally momentum- or buoyancy-controlled, or at which axial concentration the flow regime changes from momentum to buoyant part for the same jet. Buoyant jets (lower velocities) are always shorter compared to momentum-dominated jets (high velocities) from the same size nozzle. The simple technique used to distinguish between momentum and buoyancy-controlled flow is based in the work of Shevyakov et al. [14] described in detail by Molkov [5].

The pale blue cells highlighted in Table 5 correspond to the jets, where buoyancy occurs before the axial concentration decays to 4 vol. %. It means for horizontal jets the values of deterministic separation distances will be shorter. Almost all the unignited jets from fifth and six columns of Table 2 are in momentum-dominated regimes for concentrations of hydrogen in air above 4 vol. % and will become buoyant when they reach concentration values lower than 4 vol. %. Table 6 reports the distances corresponding to the transition from momentum-controlled to buoyancy-controlled jet, at hydrogen concentration above 4 vol. %. For instance, for storage pressure of 70 MPa and leak diameter of 6 mm the deterministic separation distance is reduced from 51 m (Table 5) to 33 m (Table 6) due to the buoyancy effect.

Table 6. Axial distance to buoyant part of the jet

Pressure in hydrogen storage tank, MPa	Axial distance to buoyant part of the jet, m	
	D=5 mm	D=6 mm
35	-	29
70	31	33

The separation distances given in third and fourth columns of Table 5 for concentrations of 1 and 2 vol. % of hydrogen are very over-estimated because it is very likely that the under-expanded jets will be buoyancy-controlled when they reach these values of concentration.

For a leak from a nozzle with diameter of 5 mm from a storage with internal pressure equal to 35 MPa and for a leak 4 mm in diameter from a tank at 70 MPa, the hydrogen concentration corresponding to the transition from momentum-controlled regime and buoyancy-controlled is slightly below 4 % by volume, so the transition will take place in the close proximity of the axial location corresponding to 4 vol. %.

4.3 Deterministic separation distances from reacting releases

Another possible scenario is associated with combustion of the FCH vehicle. It can be caused by an ignition source located inside the vehicle or by the spread of the fire from the adjacent conventional vehicle. If the fire involves the storage tank and it is fully established and/or continuous in time, TPRD will be activated to prevent catastrophic rupture of the storage tank. If TPRD activates correctly and in time, possible final effect will be a jet fire from TPRD release. If TPRD fails to activate, this can lead to a catastrophic rupture of the tank, producing fireball, blast waves and projectiles.

As it was mentioned earlier, in some scenarios a jet fire (i.e. reacting release involving the ignition of the hydrogen in air and resulting in the production of heat and combustion products) may occur. In this section we have calculated deterministic separation distances based on flame length. However, there also will be a radiation from the fire which can cause damage to people and structures at the distances beyond the flame length. The following harm criteria will be taken into account:

- 1.5 $\mathrm{kW/m^2}$: intensity safe for stationary personnel and members of the public;
- 6 $\mathrm{kW/m^2}$: intensity tolerable to escaping fire-fighting personnel;
- 9 $\mathrm{kW/m^2}$: threshold for equipment damage [12]. This work is currently ongoing.

As with non-reacting releases the extent of jet fire will depend on storage pressure and leak diameter. The following harm criteria for people were considered for the evaluation of the deterministic separation distances in this section:

- "no harm" separation: 70 °C for any duration (deterministic separation distance equal to 3.5 times the flame length $x=3.5\ L_f$);
- "pain" limit: 115 °C for 5 min exposure (deterministic separation distance equal to 3 times the flame length; $x=3L_f$);
- "death" limit: 309 °C, third degree burns for 20 seconds exposure (separation distance equal to 2 times the flame length $x=2L_f$) [5].

Three types of separation distances for jet fires were calculated and summarised in Table 7 Deterministic separation distances were evaluated using the H2FC engineering tool **"**Flame length and separation distance for jet fires" (http://sage.h2fc.eu/home/pub/6/). The calculations were performed for different TPRD orifice or leak diameters (from 2 to 6 mm).

Table 7. Deterministic separation distances for reacting releases

Pressure in storage tank, MPa	TPRD/leak diameter, mm	Flame length L_F, m	x (no harm), m	x (pain threshold), m	x (third degree burn), m
35	2	5	18	16	10
35	3	8	27	23	16
35	4	10	36	31	21
35	5	13	46	39	26
35	6	16	55	47	31
70	2	7	23	20	13
70	3	10	35	30	20
70	4	13	46	40	26
70	5	17	58	50	33
70	6	20	69	59	40

A further conservative analysis of deterministic separation distances could be done by considering the flame tip location to the concentration of 8 vol. % in unignited jets. Starting from this new assumption for the flame length, three new kinds of separation distances could be evaluated for the harm criteria "no harm" (70 °C), "pain" limit (115 °C), "death" limit (309 °C). The ratios of the separation distance to LFL to the separation distances based on harm criteria will have the following values:

$$x_{4\%}/x_{T=70\,°\mathrm{C}\,(8\%)} = 0.59$$

$$x_{4\%}/x_{T=115\,°\mathrm{C}\,(8\%)} = 0.69$$

$$x_{4\%}/x_{T=309\,°\mathrm{C}\,(8\%)} = 1.04$$

In the conservative case (i.e. for 8 vol. %) "all three separation distance for reacting releases (jet fires) are longer or equal to the separation distance based on the LFL (unignited release). In particular, the separation distance from a hydrogen leak source to a location with axial concentration equal to LFL, e.g. to prevent ingress of flammable mixture into a ventilation system of a building, is practically equal to the "death" separation distance for reacting release (exposure to 309 ^{o}C during 20 seconds). Two other separation distances for jet fires ("no harm" and "pain" limits) are longer than the separation distance to LFL (unignited release)" [5].

4.4 Consequences of a catastrophic failure of the tank

The case for safety published on h2safe.netresource (http://h2safe.net/case_safety.html) analysing relative frequencies of failure modes states that only about 10-27% of pressurised gas releases are classified as catastrophic. Nevertheless, it must be stressed that the malfunction of the tank safety device (TPRD) can lead to a catastrophic rupture of the hydrogen storage tank. UU is currently working on the catastrophic rupture consequences and effects, focusing on heat radiation and blast waves. At the moment we can suggest using as guidance the distances reported by Zalosh [13]. The experiments related to a catastrophic failure of hydrogen storage tank were carried out on a vessel (volume 88 L; storage pressure 31.8 MPa; no TPRD) installed underneath a sport utility vehicle. After approximately 4 minutes of exposure to the propane bonfire, flames and gases entered the passenger compartment. The catastrophic tank rupture occurred after 12 minutes 8 seconds of fire exposition, generating a fireball with maximum diameter of 24 m and lasting 4.5 seconds. Various parts of the test vehicle and storage tank were found at distances up to 107 m. It must be stressed the above mentioned distances can be even longer for the hydrogen storage tanks pressurized to 35 or 70 MPa.

Conclusions

Currents document reports on the elaboration of multi-level operational training exercises to be carried out during HyResponse pilot training sessions, on the operational training platform. The operational exercises have been identified based on the scenarios matrix developed earlier in D2.2. The pedagogic approach was applied in order to categorise the exercises as "Discovery level", "Advanced level", and "Expert level", depending on the difficulty of the chosen scenario. For each level, several scenarios are described for both the stationary and transport FCH applications. An assessment sheet was developed to check and validate by the instructors the trainees' achievements, practical skills and knowledge during the operational exercises. Three pilot sessions will also allow the assessment of the strategies and tactics developed in D2.3. During face-to-face training the way, in which the trainees assimilate them, will be evaluated in order to improve either content or pedagogy of the training. As the safety during the operational training is extremely important the deterministic separation distances calculated for non-reacting and reacting hydrogen releases are also presented in this document.

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