Consequence Assessment of the BBC Hydrogen Refueling Station, Using the ADREA-HF Code

E. Papanikolaou[1,3], A.G. Venetsanos[1], M. Schiavetti[2], A. Marangon[2], M. Carcassi[2] and N. Markatos[3]

[1] Environmental Research Laboratory, National Centre for Scientific Research Demokritos, 15310, Aghia Paraskevi Attikis, Greece, *venets@ipta.demokritos.gr*
[2] Università degli Studi di Pisa, Dipartimento di Ingegneria Meccanica Nucleare è della Produzione, Largo Lucio Lazzarino 1, 56126, Pisa, Italy
[3] National Technical University of Athens, School of Chemical Engineering, Department of Process Analysis and Plant Design, Heroon Polytechniou 9, 15780, Zografou, Greece

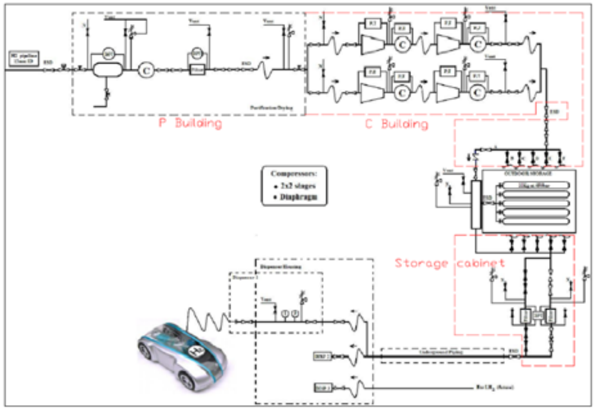
Outline

- Scope
- Description of the BBC Gaseous Hydrogen Refueling Station
- Quantitative Risk Analysis (QRA)
  - Consequence Assessment Using the Integral Code GAJET and the ADREA-HF CFD Code
    - Confined Scenarios
      - Release and Dispersion Calculations
      - Results
    - Open/Semi-confined Scenarios
      - Release and Dispersion Calculations
      - Results
- Evaluation of vulnerabilities
- Conclusions

Scope

- Overall aim of HYQRA
  - Quantitative Risk Analysis (QRA) studies of H_2 applications within internal project HyQRA of HYSAFE
  - A Benchmark Base Case (BBC) was selected
    - inter-comparison of various QRA approaches applied by partners on an agreed pre-defined hypothetical gaseous H_2 refueling station
    - identification of knowledge gaps on data and information used in the QRA steps specifically related to H_2
- NCSRD and UNIPI collaborated on a common QRA
  - UNIPI identified the hazards on site, selected the most critical ones, defined the events that could potentially cause an accident and prepared the scenarios in risk order
  - NCSRD performed quantitative analysis for the confined and open/semi-confined scenarios through numerical simulations using the integral code GAJET and the CFD code ADREA-HF. Results were provided to UNIPI
  - UNIPI performed quantitative analysis of open scenarios using the numerical code Effects 7.6 and compared the results with the ones by NCSRD
  - UNIPI evaluated the consequences in terms of overpressure and heat radiation to determine the distances of damage in the station

Description of the BBC H_2 Refueling Station



BBC Gaseous H_2 Refueling Station Flow Sheet

Layout of the BBC Gaseous H_2 Station and its Surroundings

<u>Flow Sheet</u>

Simplified Piping and Instrumentation Diagram of H_2 equipment

H_2 supply by pipeline at low pressure (4 barg) and 20°C temperature from external source

Purification and Compression: H_2 compressed in 2 stages (first to 150 and finally to 450 barg). Compression with 2 separated trains with only 1 operated each time. Train not in use was not purged.

H_2 storage: outdoors, 6 banks of 5 cylinders (0.5m^3) each (approximately 560 kg of H_2 in total)

3 Dispensers to deliver H2 to a car

<u>Layout</u>

Purification/drying building, Compression building, Storage bank, Storage cabinet, 3 dispensers underneath a canopy

<u>Surroundings</u>

School, Restaurant, Apartments, Shopping Mall, Offices, Trees

Personnel present on site: operators (continuously) and customers (during refueling time)

Quantitative Risk Assessment by UNIPI

- Identification of the hazards: analysis of all equipment on site and their functions, possible deviations, causes and consequences

  Risk = **L**ikelihood ^{x} **S**everity

  Likelihood: from literature, Severity: based on qualitative judgment

- Selection of most critical events/hazards through the **Fundamental Risk Matrix**

HAZID methodology

	Likelihood – L index			
	4	3	2	1
	$F \geq 10^{-2}$	$5 * 10^{-4} \leq F < 10^{-2}$	$5*10^{-6} < F < 5 * 10^{-4}$	$F \leq 5*10^{-6}$
Severity – S index	$F \geq 0.01$	$0.0005 \leq F < 0.01$	$0.000005 < F < 0.0005$	$F \leq 0.000005$
4	(red)	(red)	(red)	(yellow)
3	(red)	(red)	(yellow)	(white)
2	(red) 1.1.1.1;	(yellow)	(white)	(white)
1	(yellow)	(white)	(white)	(white)

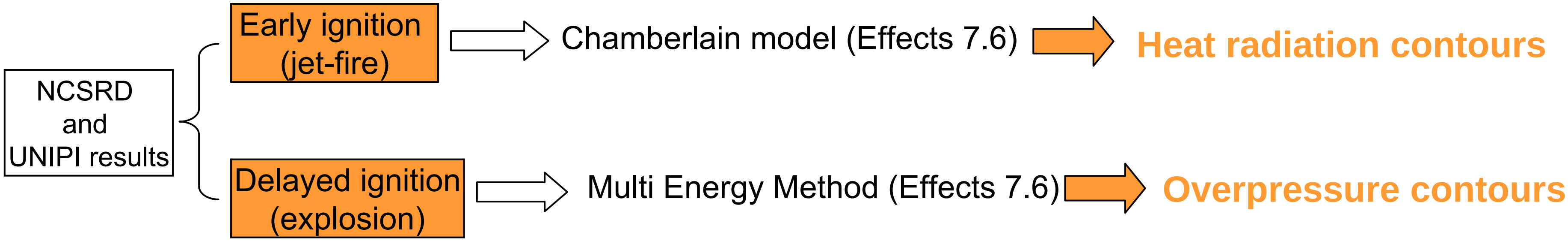
LEGEND:	
(red)	*NON ACCEPTABLE RISKS*: the events that fall in this region are non acceptable and more detailed analysis are recommended (see next paragraphs).
(yellow)	*ALMOST ACCEPTABLE RISKS* or *ALARP* (As Low As Reasonably Practicable) *REGION*: the events that fall in this region are almost; nevertheless a more detailed analysis is recommended (see next paragraphs).
(white)	*ACCEPTABLE RISKS*: for the events that fall in this region, the design and the management of the plant guarantee an adequate control of the risk. No need to proceed with more detailed analysis.

Quantitative Risk Assessment by UNIPI

- Revision of events located in the red & yellow zones of the Fundamental Risk Matrix done by taking into account the effectiveness of emergency/detection systems → quantitative fault tree analysis using the frequencies of the failures of H_2 detection systems, PT transducers and emergency shut down systems.
- Re-evaluation of frequencies of accidental occurrences → quantitative event tree analysis

information from literature

- **Compensated Risk Matrix**
- Scenarios still in the red & yellow zones → quantitative evaluation of the consequences → NCSRD simulations for all scenarios, UNIPI calculations for open scenarios



Consequence Assessment

UNIPI prepared 15 scenarios to be simulated by NCSRD

- Confined scenarios: Compression and Purification/Drying Buildings
- Open/semi-confined scenarios: Storage Cabinet, Storage Bank, Dispensers

NCSRD Simulations

- Integral code GAJET for release calculations
  - Transient application of the Birch approach to represent the time decreasing fictitious source diameter at expanded conditions in case of time varying release
- CFD code ADREA-HF for dispersion calculations
  - Solution of the transient 3d fully compressible conservation equations for mixture mass, mixture momentum and hydrogen mass fraction
  - For all simulations turbulence was modeled with the k-ε model extended for buoyant flows
  - Cartesian grids with porosity formulation

Dispersion results given to UNIPI

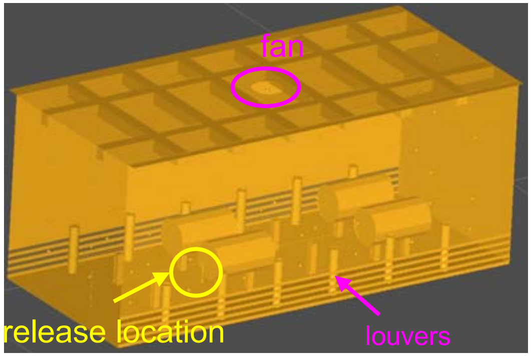
- Risk assessments parameters: Flammable (4-75% concentration) H2 mass and mixture volume histories, Maximum horizontal and vertical distances from source to LFL cloud
- Physical behavior: Time evolution of LFL clouds (4% iso-surfaces)

UNIPI calculated overpressure and heat radiation contours for the open scenarios

NCSRD simulations – Confined scenarios

- Compression building
  - Small leak (C1 scenario), large leak (C2 scenario), pipeline capture (C3 scenario)

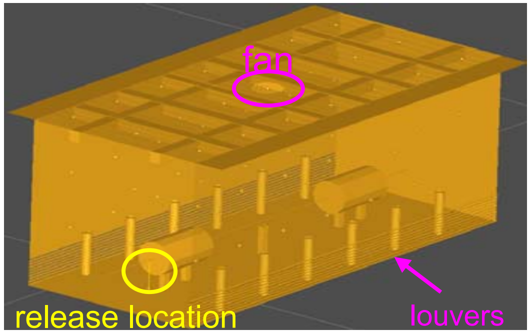
Scenario	Diameter of leak (mm)	Leak position (m)	Leak direction	Stored H2 (m^3)	Temperature (K) and pressure (bar)
C1	0.8	(72, 63.15, 0.56)	downwards	0.25	313.15, 450
C2	1.6	(72, 63.15, 0.56)	downwards	0.25	313.15, 450
C3	8	(72, 63.19, 0.67)	horizontal	0.25	313.15, 450



Compression building

- Purification/Drying building
  - Small leak (P1 scenario), pipeline rupture (P2 scenario)

Scenario	Diameter of leak (mm)	Leak position (m)	Leak direction	Stored H2 (m^3)	Temperature (K) and pressure (bar)
P1	0.8	(71.5, 68.9, 0.55)	downwards	0.5	293.15, 4
P2	1.2	(71.5, 68.9, 0.54)	horizontal	0.5	293.15, 4

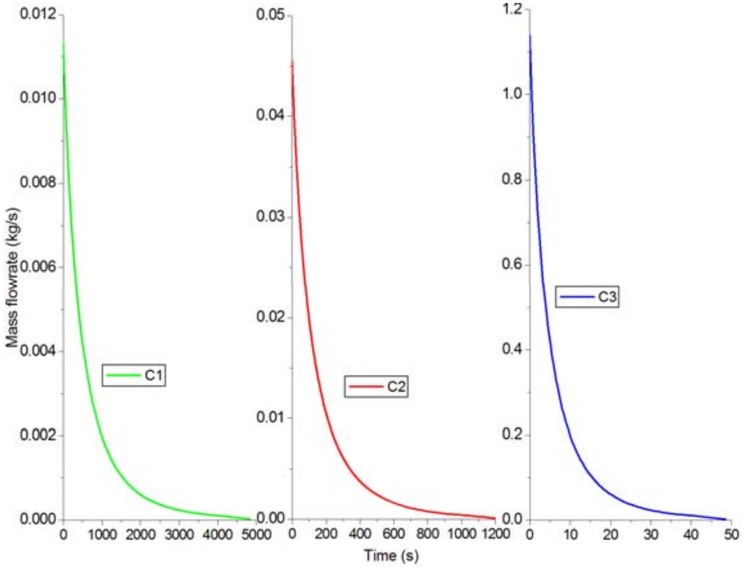


Purification/Drying building

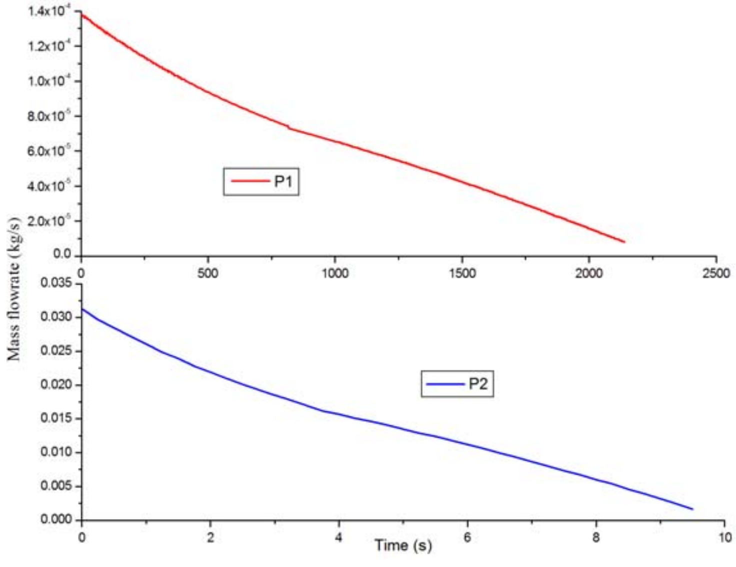
Dimensions of both buildings (in m): 3 × 7 × 3
Natural Ventilation (louvers), Mechanical Ventilation (fan in the middle of the ceiling, 150 ACH)

NCSRD simulations – Confined scenarios

- Release calculations with GAJET: isentropic expansion of H_2 from storage through the nozzle, assuming real H_2 gas properties
- Source modeling: Birch approach for fictitious area calculation, H_2 jet modeled as circular source with varying in time area based on the fictitious area and sonic velocity, atmospheric temperature and pressure



Compression building scenarios

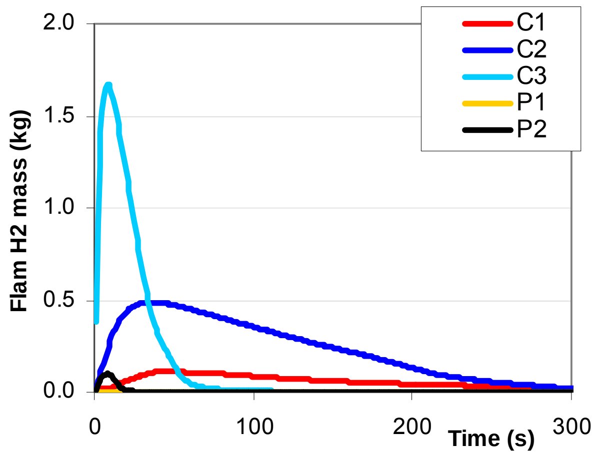


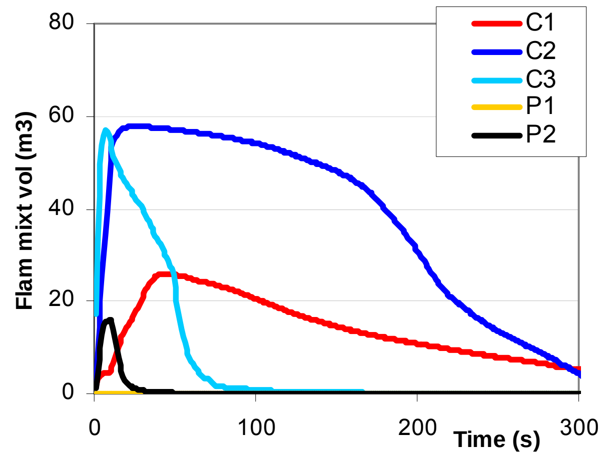
Purification/Drying building scenarios

For C1 and P1 scenarios the release was constant until the H_2 concentration at the fan exceeded 20% of LFL. Initial simulations showed that for C1 this time was 5 seconds whereas for P1, H_2 concentration did not reach 20% of LFL for 1000 seconds. The EDS was assumed to be activated 10 seconds after 20% of LFL at the fan. Release conditions were adjusted accordingly.

Confined Scenarios - Results

Scenario	Nozzle diameter (mm)	Initial release rate (g/s)	Release direction	Stored H_2 (m^3)	Pressure (bar)	Ventilation (ach)	Max. flammable mixture volume (m^3)	Max. H2 mass in flammable cloud (kg)
C1	0.8	11	Down	0.25	450	150	26	0.1
C2	1.6	45	Down	0.25	450	150	58	0.5
C3	8	1100	Horizontal	0.25	450	150	57	1.6
P1	0.8	0.14	Down	0.5	4	150	$1.68\ 10^{-3}$	$8.3\ 10^{-6}$
P2	1.2	32	Horizontal	0.5	4	150	16	$9.8\ 10^{-2}$

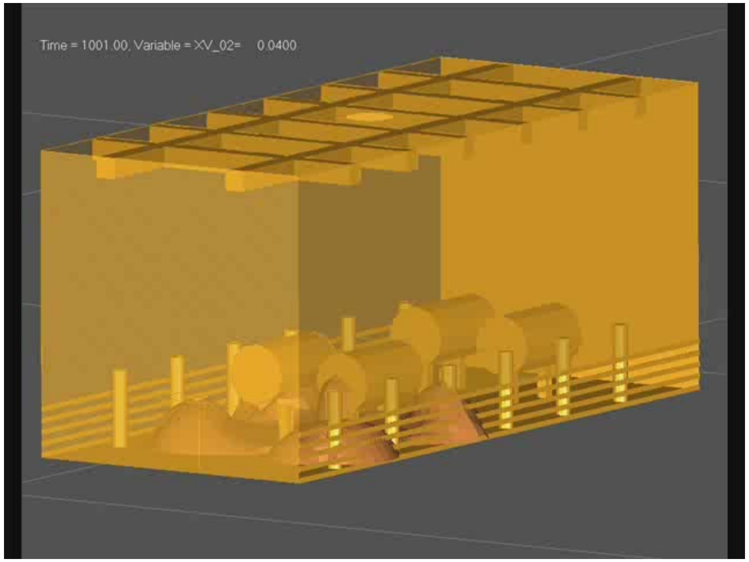




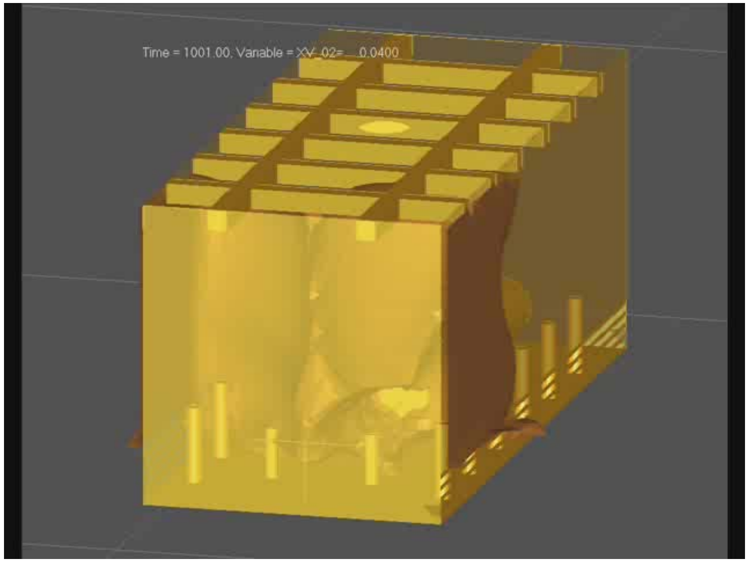
- increase of release diameter or storage pressure increases maximum values of flammable mass and mixture volume
- residence time of flammable volume depends on the release flow-rate and duration
- ventilation was sufficient for P1 scenario

Confined Scenarios - Results

LFL (4% by volume) H_2 cloud



C1 Scenario

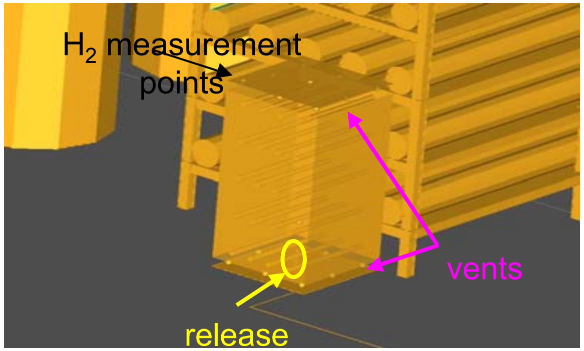


C3 Scenario

NCSRD simulations – Open/Semi-confined scenarios

- Storage Cabinet Scenarios
  - Small leak (ST1, ST2 scenarios), pipeline capture (ST3, ST4 scenarios)

Scenario	Diameter of leak (mm)	Leak direction	Stored H2 (m^3)	Temperature (K) and pressure (bar)	Wind velocity (m/s)
ST1	0.8	downwards	0.1	293.15, 450	1.5
ST2	0.8	downwards	0.1	293.15, 450	5
ST3	8	horizontal	0.1	293.15, 450	1.5
ST4	8	horizontal	0.1	293.15, 450	5

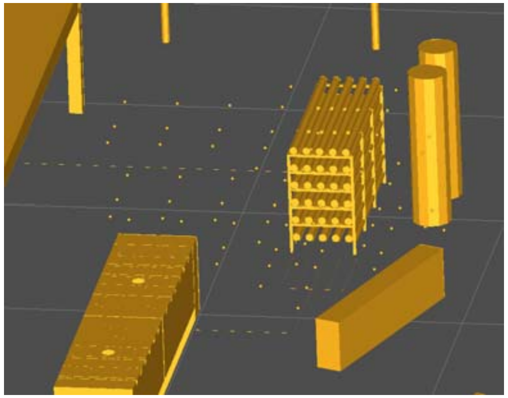


Storage Cabinet

Dimensions (in m): 1×1×2, Vents of 0.1m height at the bottom and top

- Storage Bank Scenarios
  - Large leak from 1 bank (S1, S2 scenarios) or 1 storage vessel (S3, S4 scenarios)

Scenario	Diameter of leak (mm)	Leak direction	Stored H2 (m^3)	Temperature (K) and pressure (bar)	Wind velocity (m/s)
S1	1.6	downwards	12.5	293.15, 450	1.5
S2	1.6	downwards	12.5	293.15, 450	5
S3	1.6	downwards	2.5	293.15, 450	1.5
S4	1.6	downwards	2.5	293.15, 450	5



Storage Bank

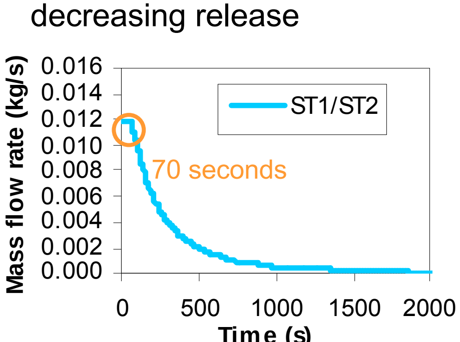
NCSRD simulations – Open/Semi-confined scenarios

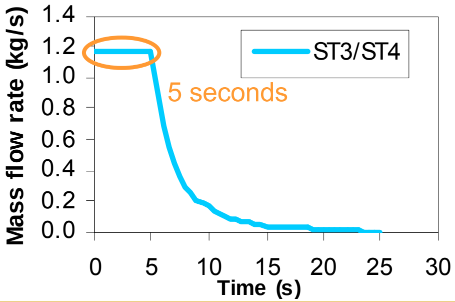
- Dispensers
  - Large leak from refueling hose (RF1, RF2 scenarios)

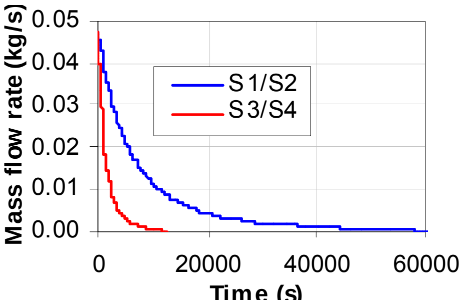
Scenario	Diameter of leak (m)	Leak direction	H2 inventory (m^3)	Temperature (K) and pressure (bar)	Wind velocity (m/s)
RF1	0.0016	downwards	0.15	293.15, 450	1.5
RF2	0.0016	downwards	0.15	293.15, 450	5

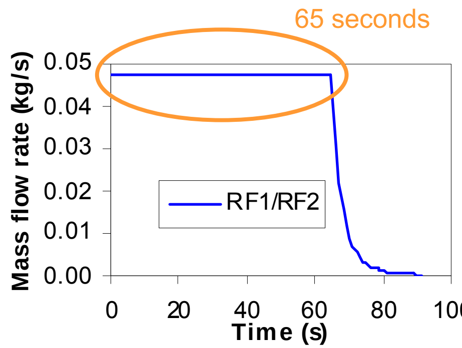
Dispensers

- Some approach for release calculations as in confined scenarios
- ST1, ST2 scenarios: H_2 released smaller than maximum expected in pipeline → constant release for necessary time to refill a car (70 sec) and then the pressure drop inside the filter was assumed enough to be detected → decreasing release
- ST3, ST4 scenarios: pressure drop assumed to activate the ESD after 5 sec → constant release for 5 sec followed by decreasing release
- RF1/RF2 scenarios: 60 sec needed from the operator to activate the ESD system, line closes 5 sec after activation → constant release for 65 sec followed by a decreasing release



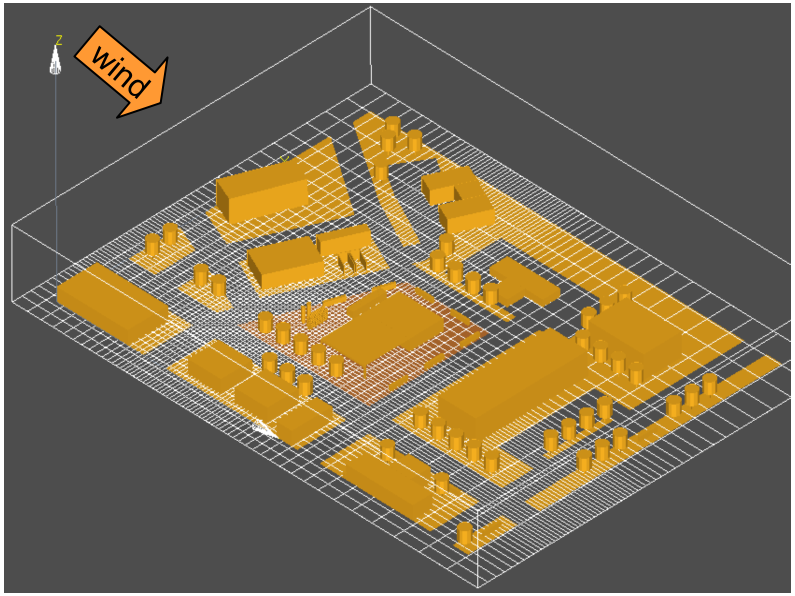




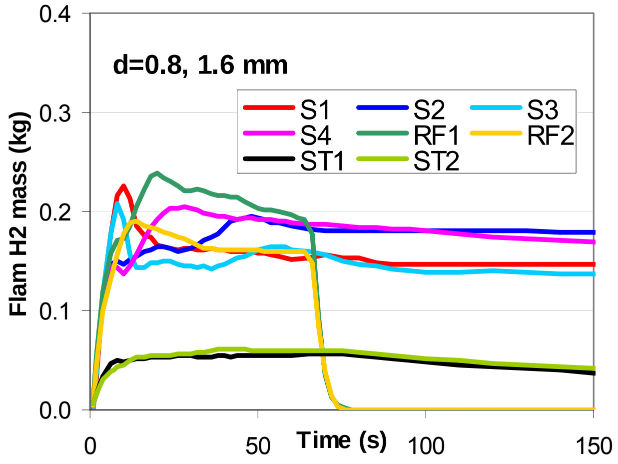


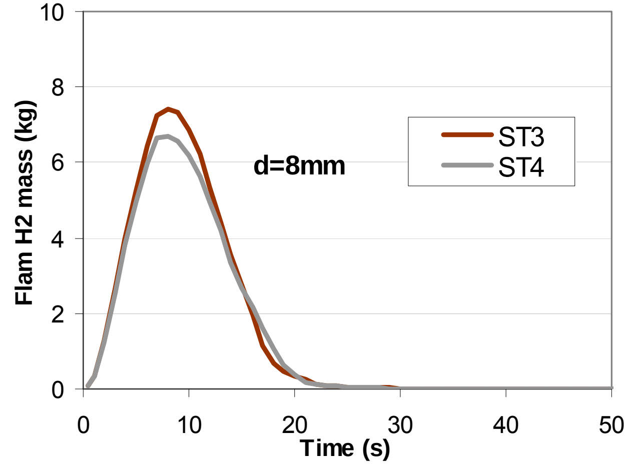
NCSRD simulations – Open/Semi-confined scenarios

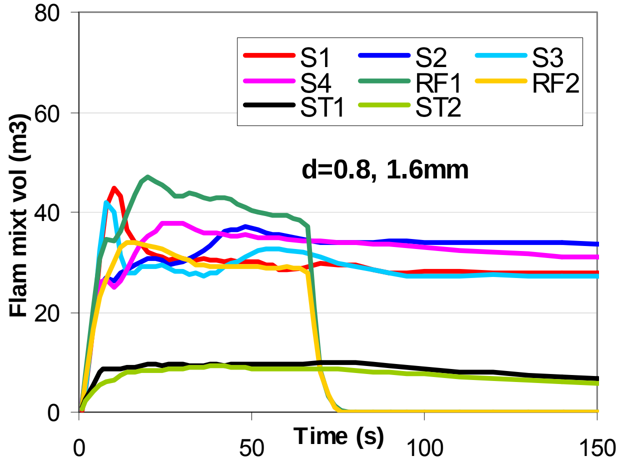
- Dispersion calculations:
  - 3 consecutive modeling steps, each one providing initial conditions for the next
    - 1d (vertical) problem for undisturbed wind field
    - 3d steady state wind field
    - 3d transient dispersion

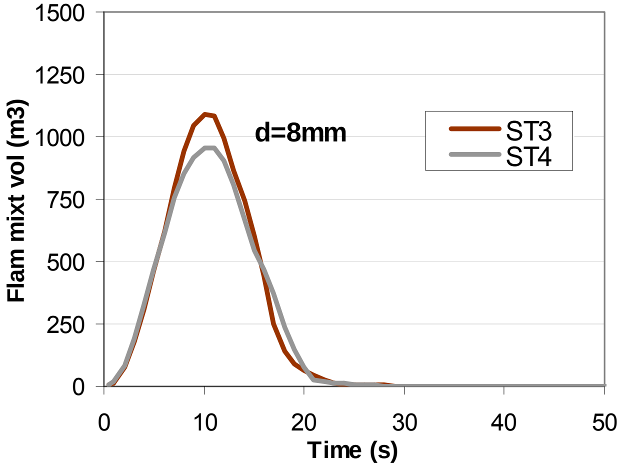


Open/Semi-confined scenarios - Results

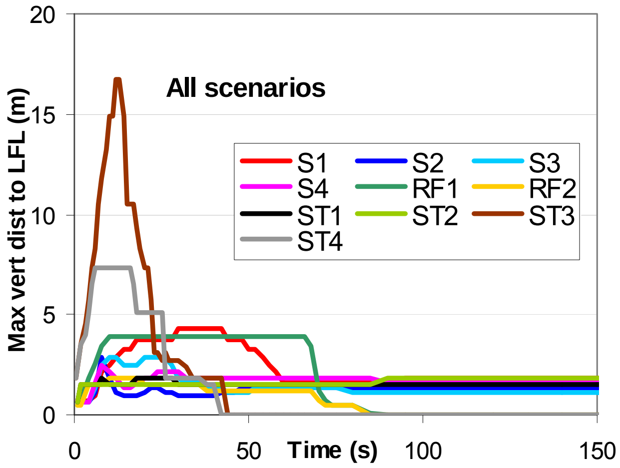


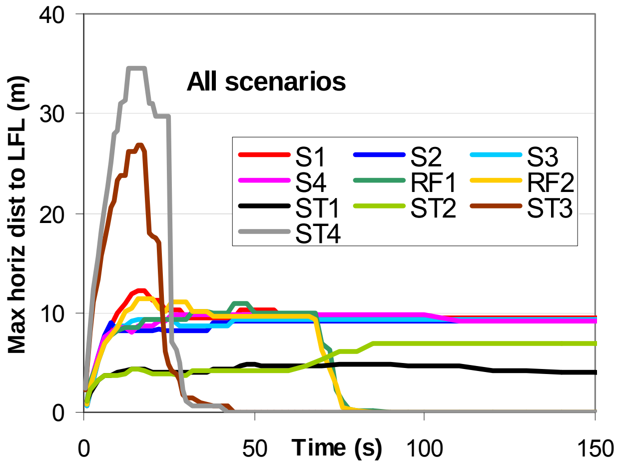






Open/Semi-confined scenarios - Results

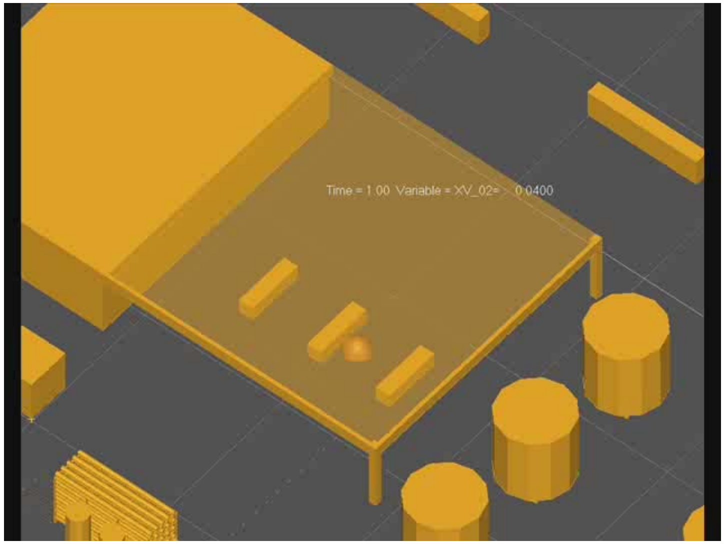




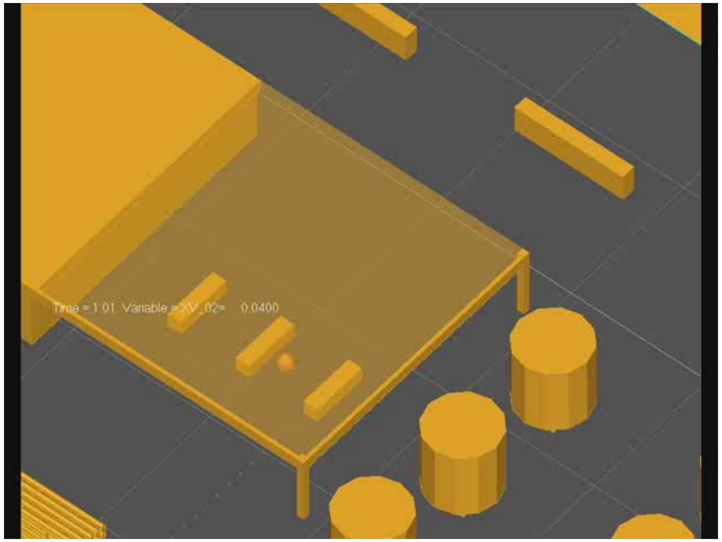
Nozzle diameter (mm)	Scenarios	Maximum flammable H_2 mass (kg)	Maximum flammable mixture volume (m3)	Maximum horizontal distance to LFL (m)	Maximum vertical distance to LFL (m)
8	ST3, ST4	7	1000	35	17
1.6	S1, S2, S3, S4, RF1, RF2	0.2	40	10	<5
0.8	ST1, ST2	0.05	10	<10	<5

Open/Semi-confined Scenarios - Results

LFL (4% by volume) H_2 cloud



RF1 Scenario (1.5 m/s wind)



RF2 Scenario (5 m/s wind)

Evaluation of vulnerabilities

	UVCE	Jet Fire
Distance 1	Pressure 30kPa (100% mortality)	Thermal radiation 35kW/m^2 (100% mortality)
Distance 2	Pressure 10kPa (2.5% mortality)	Thermal radiation 4.1kW/m^2 (1% 1st degree burns)

ID	SIMULATED SEQUENCES	Phenomenon	Frequency	Distance 1 (m)	Distance 2 (m)
S1	Large leak from the manifold of one storage bank.	UVCE	3 E-6	25.3	37.5
		Jet fire	1.5 E-5	4.5	5.55
S2	Large leak from the manifold of one storage bank.	UVCE	3 E-6	8.6	18.4
		Jet fire	1.5 E-5	3.4	4.4
S3	Large leak from one bottle.	UVCE	3 E-4	25	37
		Jet fire	1.5 E-3	4.44	5.45
S4	Large leak from one bottle.	UVCE	3 E-4	5	9.5
		Jet fire	1.5 E-3	3.5	4.38
S5	Rupture in the valve of one bottle	UVCE	3 E-5	42	81
		Jet fire	1.5 E-4	22.5	24.4
ST1	Small leak in the storage cabinet	UVCE	4.9 E-3	5.2	9.5
		Jet fire	6.5 E-2	--	--
ST2	Small leak in the storage cabinet	UVCE	4.9 E-3	6	11.5
		Jet fire	6.5 E-2	--	--
ST3	Rupture in the storage cabinet	UVCE	3 E-5	26.6	44.7
		Jet fire	2.2 E-6	--	--
ST4	Rupture in the storage cabinet	UVCE	3 E-5	34	54
		Jet fire	2.2 E-6	--	--
RF1	Large leak in the refuelling hose	UVCE	1 E-5	26	39
		Jet fire	5 E-5	4.5	5.55
RF2	Large leak in the refuelling hose	UVCE	1 E-5	8	16.7
		Jet fire	5 E-5	3.45	4.4

Conclusions

- A joint UNIPI-NCSRD effort was undertaken for the risk assessment of the BBC-HyQRA HRS
- ADREA-HF for release and dispersion calculations was successfully applied for consequence assessment of the scenarios earlier identified by UNIPI
- Risk assessment parameters were found mainly increasing functions of release rate (nozzle diameter size and storage pressure) as expected

Acknowledgements

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THANK YOU FOR YOUR ATTENTION !