Pre-normative REsearch for Safe use of Liquid Hydrogen (PRESLHY)

Project Deliverable

Phenomena Identification and Ranking Table (PIRT) Analysis

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Author:	Simon Jallais
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Approvals/ Modifications			
	Name	Organisation	Date
WP Leader	Simon Jallais	Air Liquide	10 December 2018
	Laurence Bernard	Air Liquide	10 December 2018
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Key words

Liquid Hydrogen, release, rainout, droplet, source term, pool, jet fire, pool fire, deflagration, detonation, flame acceleration, ignition, combustion, flame, BLEVE, RPT.

Abbreviations

BLEVE	Boiling Liquid Expansion Vapor Explosion
CFD	Computational Fluid Dynamics
CO_2	Carbon Dioxide
DDT	Deflagration to Detonation Transition
GS	Global Score
KS	Knowledge Score
LH_2	Liquid Hydrogen
O_2	Oxygen
PIRT	Phenomena Identification Ranking Table
RPT	Rapid Phase Transition
RPW	Research Priorities Workshop
R&D	Research and Development
UVCE	Unconfined Vapour Cloud Explosion
WP	Work Package

1 Methodology

To assess the knowledge gaps associated with LH_2 safety and update the experimental program, a Phenomena Identification and Ranking Table (PIRT) was performed in September 2018. The NoE HySafe applied the same methodology in 2005 to prioritise hydrogen safety research topic in general. The PRESLHY project performed again this exercise with a focus on LH_2.

The PIRT is a systematic way of gathering information from experts on a specific subject, and ranking the importance of the information, in order to meet some decision-making objectives, e.g., determining what are the highest priorities for research and development on that subject. The method was originally developed and applied in the late 80s to many nuclear technology issues.

Few weeks before the Research Priorities Workshop (RPW) in September 2018 (Buxton-UK) a PIRT questionnaire was prepared and widely distributed (via Google Forms) thanks to the large network from HYSAFE and PRESLHY members. At the workshop, the further processed answers of the questionnaire were presented and discussed.

For the 3 experimental and modelling Work Packages of PRESLHY (WP3 : Release and mixing phenomena - WP4 : Ignition phenomena and WP5 : Combustion phenomena) PRESLHY partners and others persons of good will developed a list (hopefully exhaustive) of associated physical phenomena.

For the WP3 (Release and mixing phenomena), the physical phenomena considered are listed below :

- Thermophysical properties for mixtures (including ortho / para conversion),
- Source term - discharge rate,
- Internal Heat Transfer flashing in pipes,
- Droplet size / distribution / evaporation,
- External Flashing,
- Rainout,
- Cold heavy gas atmospheric dispersion / transition to buoyant,
- Pool spreading on different surfaces including water,
- Cryogenic spillage interaction with materials (boats) : spillage & 2-phase jet,
- Pool evaporation on different surfaces including water,
- Condensation and freezing of air & CO_2 & humidity,
- Interaction with rain, water sprays & water curtains & foams,
- High pressure release : concentration decay (Conc fluctuations),

- High pressure release : Velocity, fluctuations & turbulence scale,
- High pressure release in complex environment : obstacles, impingement, surface,
- Buoyant low velocity release,
- H_2 build-up in confined / semi-confined areas (natural/forced ventilation).

For the WP4 (Ignition), the physical phenomena considered are listed below :

- Flammability limits at low temperatures (horizontal, upward and downward propagation),
- Ignition energy at low temperatures,
- Ignition in cryogenic jets,
- Ignition above pools,
- Shock Diffusion ignition at low temperatures,
- LH_2/ Condensed O_2 mixture ignition,
- Electrostatic properties of LH_2 releases,
- Electrostatic charging and ignition in cryogenic jets,
- Electrostatic charging and ignition above LH_2 pools.

For the WP5 (Combustion), the physical phenomena considered are listed below :

- Cryogenic free jet fire,
- Cryogenic impinging jet fire,
- Cryogenic surface jet fire,
- Pool fire,
- Laminar flame speed at low initial temperature including possible O_2 enrichment & deficiency,
- Quenching diameter and safe gap for cold mixtures,
- Turbulent flame speed at low initial temperature,
- Flame acceleration in tubes for cold mixtures,
- Critical expansion ratio of cold mixtures,
- Run-up distances and DDT for cold mixtures,
- Detonation cell size for cold mixtures,
- Unconfined Unobstructed Cold Vapour Cloud Explosion,
- Unconfined obstructed explosion of cold mixture (atmospheric vaporiser),
- Vented explosion for cold mixtures,
- LH_2 insulated vessel heat-up in fire,
- BLEVE (hot and cold),
- Rapid phase transition with water.

Concerning the scoring process, for each phenomenon identified, the user gives a value between 1 to 5 regarding :

- a : General level of understanding,
- b : Level of maturity of engineering modelling,
- c : Level of maturity of CFD modelling,
- d : Availability of experimental data,
- e : Criticality for enabling LH_2 in populated areas,
- f : Expert Level.

For the variables a, b, c : a score of 5 means well known and 1 means exploratory.
For the variable d : a score of 5 means many experiments and 1 means “no experiments”.
For the variable e : a score of 5 means very critical and 1 means “no criticality”.
For the variable f : it was self-evaluation. In the end, this was not used in the analysis because of its subjectivity. It is interesting to note that the lowest expert level is related to ignition phenomena.

Using all the questionnaires, a Knowledge Score (KS) was calculated as the product of a, b, c and d ⇒KS = a * b * c * d. The lower KS is and the lower is the knowledge of the phenomenon.

Finally, a Global Score is calculated by dividing the Knowledge Score by the criticality variable (e) ⇒GS = KS / e.

Globally 24 Risk and Safety experts (of 8 nationalities) answered the PIRT questionnaire.

2 Results for WP3 : Release and mixing phenomena

The knowledge score are listed in the table below. The lower the score means the lower knowledge on the phenomena.

Knowledge score	
Interaction with rain, water sprays & water curtains & foams	6
Condensation and freezing of air & CO_2 & humidity	17
Internal Heat Transfer flashing in pipes	18
High pressure release in complex environment : obstacles, impingement, surface…	21
Droplet size / distribution / evaporation	22
Cryogenic spillage interaction with materials (boats) : spillage & 2-phase jet	24
Rainout	25
External Flashing	28
Source term - discharge rate	42
Pool evaporation on different surfaces including water	46
Thermophysical properties for mixtures (including ortho / para conversion)	53
Pool spreading on different surfaces including water	60
Buoyant low velocity releases	68
High pressure release : Velocity, fluctuations & turbulence scale	76
Cold heavy gas atmospheric dispersion / transition to buoyant	77
High pressure release : concentration decay (Conc fluctuations)	88
H_2 build-up in confined / semi-confined areas (natural/forced ventilation)	132

The table shows that the less known phenomena are related to multiphasic release of a cryogenic material.

The table below summarises the criticality score. The higher this criticality score is and the more important the phenomena is regarding enabling LH_2 in the cities.

Criticality score	
Cold heavy gas atmospheric dispersion / transition to buoyant	4,2
Source term - discharge rate	4,1
High pressure release in complex environment : obstacles, impingement, surface	3,7
Thermophysical properties for mixtures (including ortho / para conversion)	3,6
External Flashing	3,6
High pressure release : concentration decay (Conc fluctuations)	3,6
High pressure release : Velocity, fluctuations & turbulence scale	3,6
Buoyant low velocity release	3,5
Droplet size / distribution / evaporation	3,4
Pool evaporation on different surfaces including water	3,4
Condensation and freezing of air & CO_2 & humidity	3,4
Pool spreading on different surfaces including water	3,4
Internal Heat Transfer flashing in pipes	3,3
H_2 build-up in confined / semi-confined areas (natural/forced ventilation)	3,2
Rainout	3,1
Interaction with rain, water sprays & water curtains & foams	3,1
Cryogenic spillage interaction with materials (boats): spillage & 2-phase jet	2,9

The source term and heavy to buoyant transition are considered the most important phenomena to study. It is sensible since they are crucial for an accurate consequence modelling and assessment of the safety distances..

Global score	
Interaction with rain, water sprays & water curtains & foams	2
Internal Heat Transfer flashing in pipes	5
Condensation and freezing of air & CO_2 & humidity	5
Droplet size / distribution / evaporation	6
High pressure release in complex environment : obstacles, impingement, surface	6
External Flashing	8
Rainout	8
Cryogenic spillage interaction with materials (boats) : spillage & 2-phase jet	8
Source term - discharge rate	10
Pool evaporation on different surfaces including water	13
Thermophysical properties for mixtures (including ortho / para conversion)	15
Pool spreading on different surfaces including water	17
Cold heavy gas atmospheric dispersion / transition to buoyant	18
Buoyant low velocity release	19
High pressure release : Velocity, fluctuations & turbulence scale	21
High pressure release : concentration decay (Conc fluctuations)	25
H_2 build-up in confined / semi-confined areas (natural/forced ventilation)	34

For the global score, the prioritised knowledge gaps are mainly related to :

- Multiphasic (high pressure) releases characterisation (flash, rainout, internal flashing, condensation…),
- Technical safety active barriers (foam, deluge, …).

3 Results for WP4 : Ignition

Knowledge score	
LH_2/ Condensed O_2 mixture ignition	5
Electrostatic charging and ignition above LH_2 pools	5
Electrostatic charging and ignition in cryogenic jets	6
Shock Diffusion ignition at low temperatures	8
Electrostatic properties of LH_2 releases	9
Ignition energy at low temperatures	16
Ignition above pools	18
Ignition in cryogenic jets	21
Flammability limits at low temperatures (horizontal, upward and downward)	26

In terms of knowledge, the less known phenomena are mainly the ignition of the LH_2/condensed oxygen mixture and the ignition of H_2/air mixture by electrostatic discharges. This is in good agreement with the LH_2 state of the art performed in the framework of the PRESLHY project.

Criticality score	
Flammability limits at low temperatures (horizontal, upward and downward)	3.6
LH_2/ Condensed O_2 mixture ignition	3.6
Ignition in cryogenic jets	3.4
Ignition above pools	3.4
Electrostatic properties of LH_2 releases	3.4
Electrostatic charging and ignition in cryogenic jets	3.4
Electrostatic charging and ignition above LH_2 pools	3.2
Ignition energy at low temperatures	3.1
Shock Diffusion ignition at low temperatures	2.9

For the criticality of ignition phenomena as for the release and mixing, the experts seem to privileged the phenomena influencing the separation and safety distances (for instance distance from the refueling station to the property line). The influence of low temperatures on the flammability limits becomes then of great importance.

Global score	
Electrostatic charging and ignition above LH_2 pools	1
LH_2/ Condensed O_2 mixture ignition	1
Electrostatic charging and ignition in cryogenic jets	2
Shock Diffusion ignition at low temperatures	3
Electrostatic properties of LH_2 releases	3
Ignition energy at low temperatures	5
Ignition above pools	5
Ignition in cryogenic jets	6
Flammability limits at low temperatures (horizontal, upward and downward)	7

For the global score, the prioritised knowledge gaps are mainly related to :

- Electrostatic charging and ignition in jet releases and above pools,
- Ignition of LH_2/ Condensed O_2 mixture.

4 Results for WP5 : Combustion

Knowledge score	
Run-up distances and DDT for cold mixtures	5
Quenching diameter and safe gap for cold mixtures	5
Detonation cell size for cold mixtures	6
Rapid phase transition with water	6
Turbulent flame speed at low initial temperature	7
Laminar flame speed at low initial temperature including possible O_2 enrichment & deficiency	8
Flame acceleration in tubes for cold mixtures	10
Critical expansion ratio of cold mixtures	10
Unconfined obstructed explosion of cold mixture (atmospheric vaporiser)	13
Cryogenic surface jet fire	15
BLEVE (hot and cold)	16
Cryogenic impinging jet fire	18
Vented explosion for cold mixtures	28
Unconfined Unobstructed Cold Vapour Cloud Explosion	31
LH_2 insulated vessel heat up in fire	33
Pool fire	39
Cryogenic free jet fire	57

In terms of knowledge in combustion science, the less known phenomena are mainly related to fundamental properties of deflagration (laminar and turbulent), detonation and DDT at low temperatures and rapid phase transition with water.

Criticality score	
Unconfined Unobstructed Cold Vapour Cloud Explosion	4
Unconfined obstructed explosion of cold mixture (atmospheric vaporiser)	3.9
Cryogenic free jet fire	3.9
Cryogenic impinging jet fire	3.8
LH_2 insulated vessel heat up in fire	3.7
Vented explosion for cold mixtures	3.6
BLEVE (hot and cold)	3.6
Pool fire	3.6
Cryogenic surface jet fire	3.4
Run-up distances and DDT for cold mixtures	3.4
Turbulent flame speed at low initial temperature	3.2
Laminar flame speed at low initial temperature including possible O_2 enrichment & deficiency	3
Flame acceleration in tubes for cold mixtures	3
Critical expansion ratio of cold mixtures	3
Quenching diameter and safe gap for cold mixtures	2.9
Detonation cell size for cold mixtures	2.9
Rapid phase transition with water	2.9

As explained before, the criticality score reflects the main hazardous phenomena for facility siting. As a consequence, UVCE and fire phenomena are considered as the most critical.

Global score	
Run-up distances and DDT for cold mixtures	1
Detonation cell size for cold mixtures	2
Critical gap size for cold mixtures	2
Turbulent flame speed at low initial temperature	2
Rapid phase transition with water	2
Flame acceleration in tubes for cold mixtures	3
Critical expansion ratio of cold mixtures	3
Laminar flame speed at low initial temperature including possible O_2 enrichment & deficiency	3
Unconfined obstructed explosion of cold mixture (atmospheric vaporiser)	3
BLEVE (hot and cold)	4
Cryogenic surface jet fire	4
Cryogenic impinging jet fire	5
Unconfined Unobstructed Cold Vapour Cloud Explosion	8
Vented explosion for cold mixtures	8
LH_2 insulated vessel heat-up in fire	9
Pool fire	11
Cryogenic free jet fire	15

For the global score, the prioritised knowledge gaps are mainly related to the influence of low temperature on :

- Deflagration fundamental properties,
- Detonation and DDT properties.

5 Conclusions

A PIRT analysis was performed on LH_2 hazards. The PIRT is a powerful tool to prioritise the needed R&D on a specific topic. This PIRT analysis will be used to adjust the PRESLHY experimental program.

Some conclusions need to be highlighted :

- WP3 : need of R&D on the physics of the liquid releases (internal flashing, droplets, rainout, condensation, external flashing, …),

- WP4 : need of R&D on electrostatic ignition and LH_2 / solid oxygen ignition,

- WP5 : need of R&D on deflagration, detonation and flame acceleration in cold conditions.