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Safety of Hydrogen as an Energy Carrier

Report on PIRT Update

D85

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EXECUTIVE SUMMARY

This document reports on the results of the update of the PIRT (Phenomena Identification and Ranking Table) exercise. A first exercise was conducted during the first 18 months of the HYSAFE project, and this exercise was updated during the last year of the network in order to monitor the progress performed during the five years of the network and identify priorities for further developments. The report first recalls the results of the so called Macro PIRT providing an overview of safety issues, then the results of safety-oriented votes or scenario ranking, and then the results of phenomena-oriented votes, i.e. the ranking of the phenomena which reflects the current knowledge and state of the art.
Evolutions between results of the first PIRT (2005) and the current PIRT are highlighted.

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1. INTRODUCTION

In the framework of the HYSAFE project, a PIRT (Phenomena Identification and Ranking Table) exercise is being conducted with the objective of identifying R&D needs in the area of H2 safety, and to prioritize them.

A first PIRT exercise was performed during the first 18 months of the HYSAFE project, and this exercise was updated during the last year of the network in order to monitor the progress performed and identify priorities for further developments.

The PIRT update exercise consists of three steps. The first step, named macro PIRT providing a general overview of safety issues was performed during the WP7 meeting in September 2008, the second step which deals with the identification and ranking of accidental events (safety-oriented vote) and the third step, which focuses on the phenomena associated with the most important accidental events (phenomena-oriented vote) were conducted over the period September-November 2008.

This document reports on the results of these three votes, provides comparison with results obtained in 2005 and details the topics of R&D which require the most efforts to close gaps in knowledge and thereby help better understand, model and mitigate accident scenarios.

2. MACRO ANALYSIS

2.1. Identification of events

During the WP7 meeting in Berghausen (Karlsruhe) on September 2008 the 19th, 13 partners of HySafe were invited to prioritize potential hazards related with the use of hydrogen as an energy carrier. In order to allow comparing the current perception of hazards and control with the one existing in 2005, the same matrix of hazards and application was used (see Figure 1).

For each element of the matrix, the partners were invited to evaluate:

The current knowledge available on the hazards, the votes ranging from 0 (no knowledge available) to 5 (all is known), noted Xij.

The importance of the hazards, the votes ranging from 0 (not important at all) to 5 (most important), noted Yij.

Then a prioritization is proposed by combining both results for each partner; Zij = (5-Xij)*Yij so that the highest priority is given to a hazard considered important for which only poor knowledge is available and the lowest priority is given to a hazard considered as less important and/or for which precise knowledge is available. The rates given by the 13 partners are then averaged to obtain a global rate.

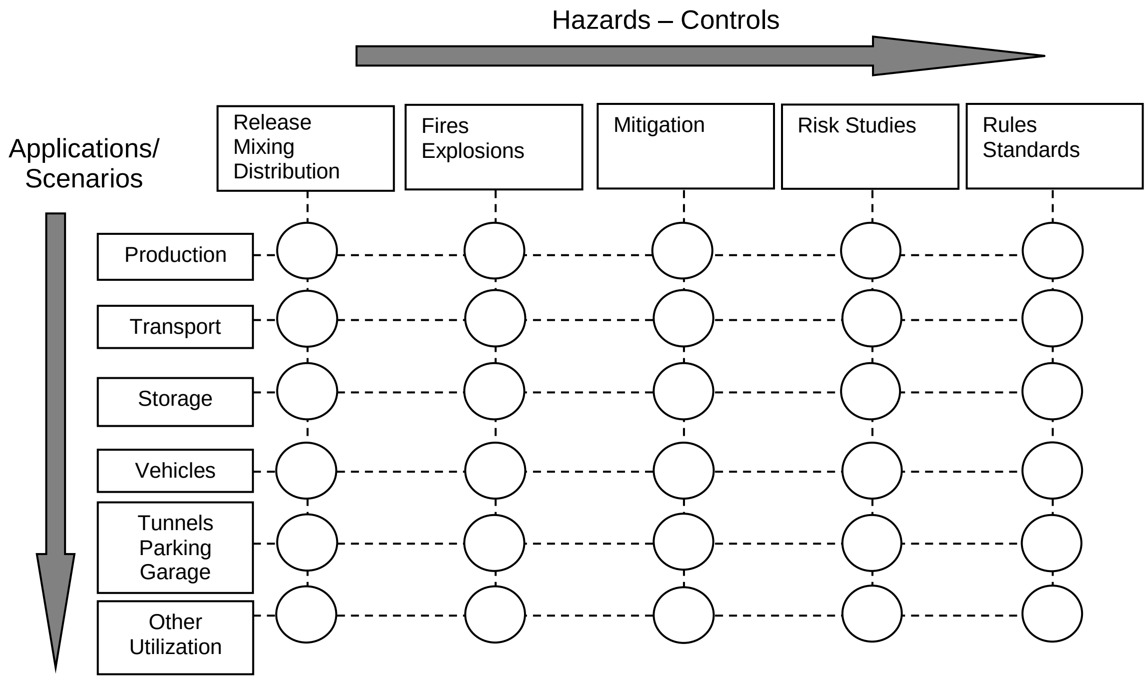

Figure 1 : Matrix of hazard/control vs applications for the Macro PIRT

2.2. Results of votes

Results obtained for the Macro PIRT update are reported in Figure 2 below. The highest priority is given to hazards related with the use of hydrogen powered vehicles in tunnels, parking and garages.

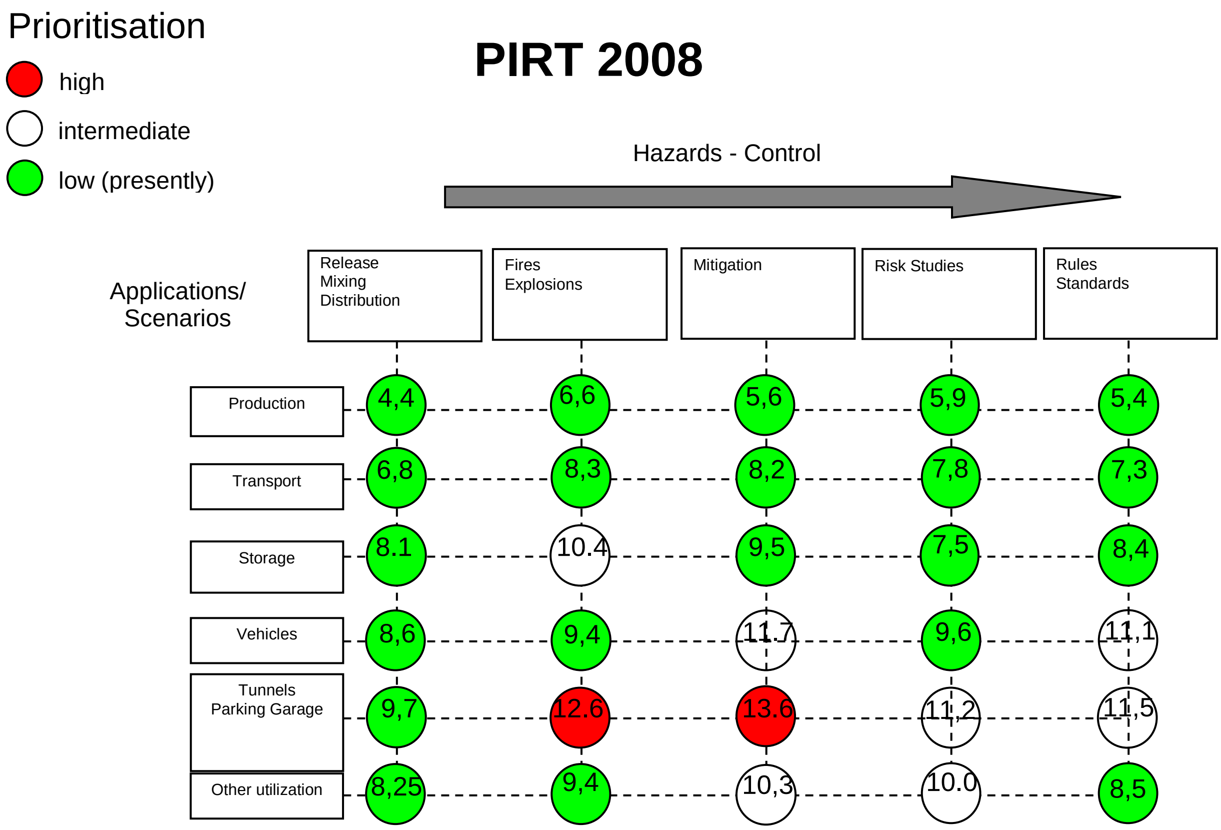

Figure 2 : Result matrix for the Macro PIRT update

Then, for each application, and each hazard, we can compare the overall ranking obtained during the update to the one obtained during first PIRT. This comparison is provided in the following Figure 3 to Figure 8.

2.3. Conclusion

This MACRO PIRT provides a rapid overview of the areas where attention should be focused. The general trend is the reduction of priority all hazards, but it should be noted that through these figures, it cannot be identified whether the reduction is due to an increase of knowledge, a decrease of the importance of each hazard or an increased of control on the hazard. The highest priority is given to **fires and explosions related to parking and tunnels** and **mitigation in parking and tunnels**

The two following steps, namely the safety ranking and phenomena ranking provides more detailed results.

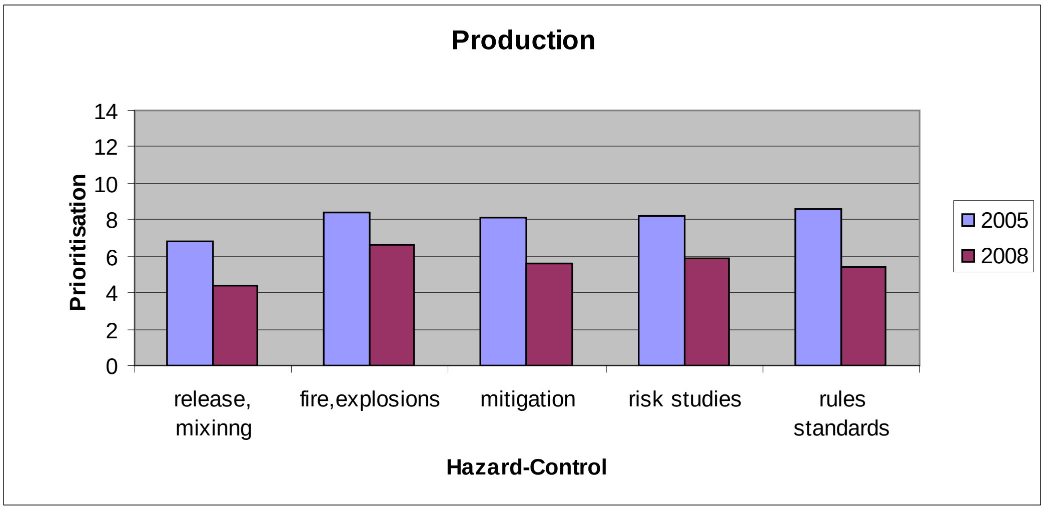

Figure 3 : Result of Macro PIRT update; production scenario

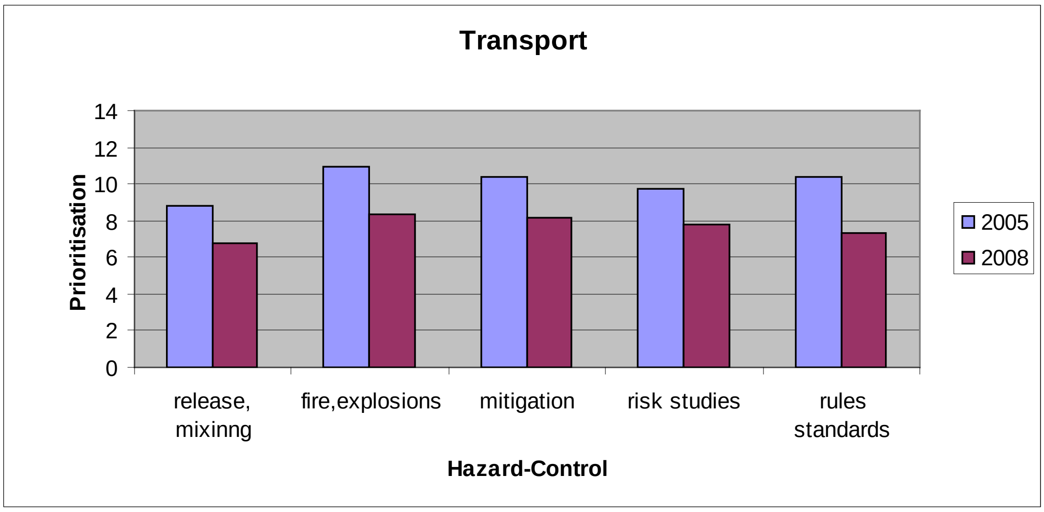

Figure 4 : Result of Macro PIRT update; transport scenario

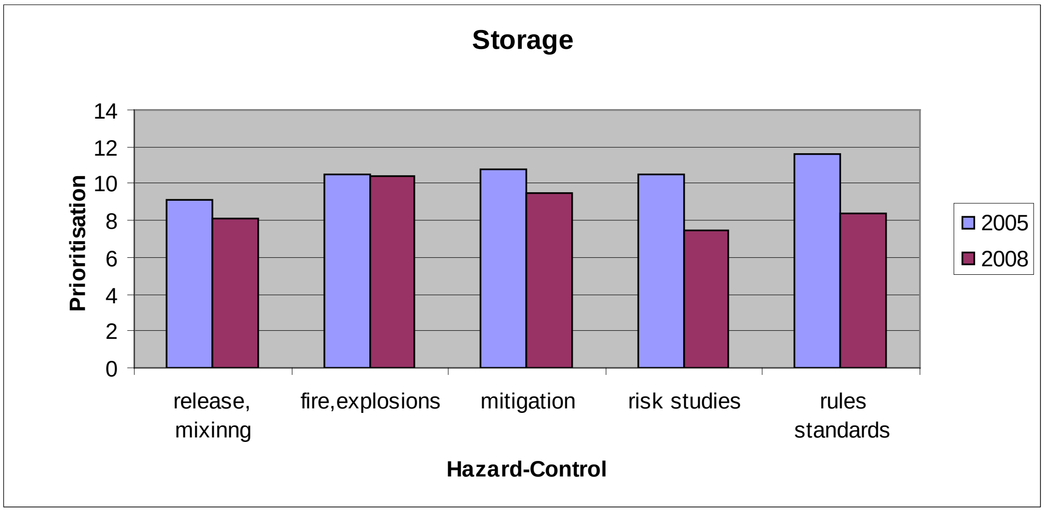

Figure 5 : Result of Macro PIRT update; storage scenario

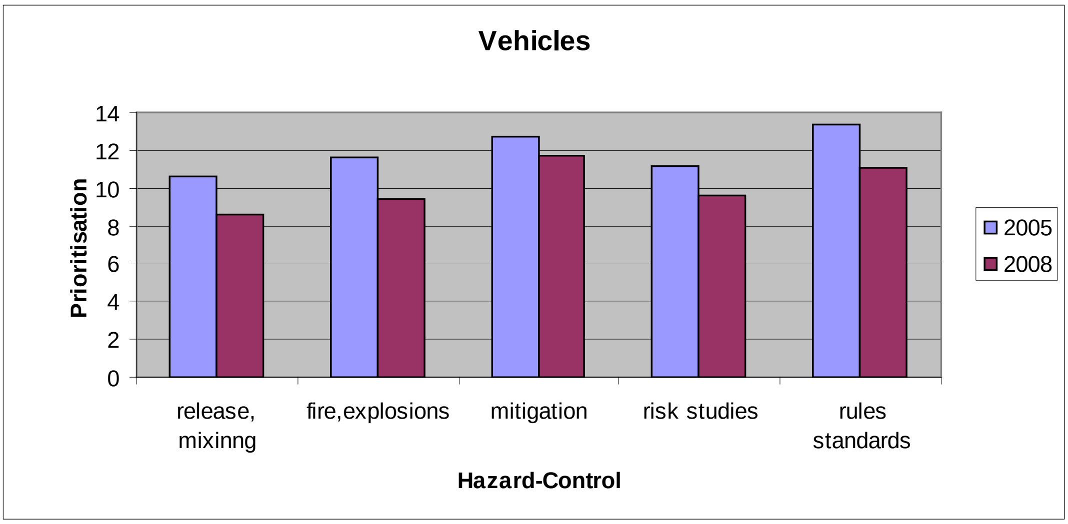

Figure 6 : Result of Macro PIRT update; vehicle scenario

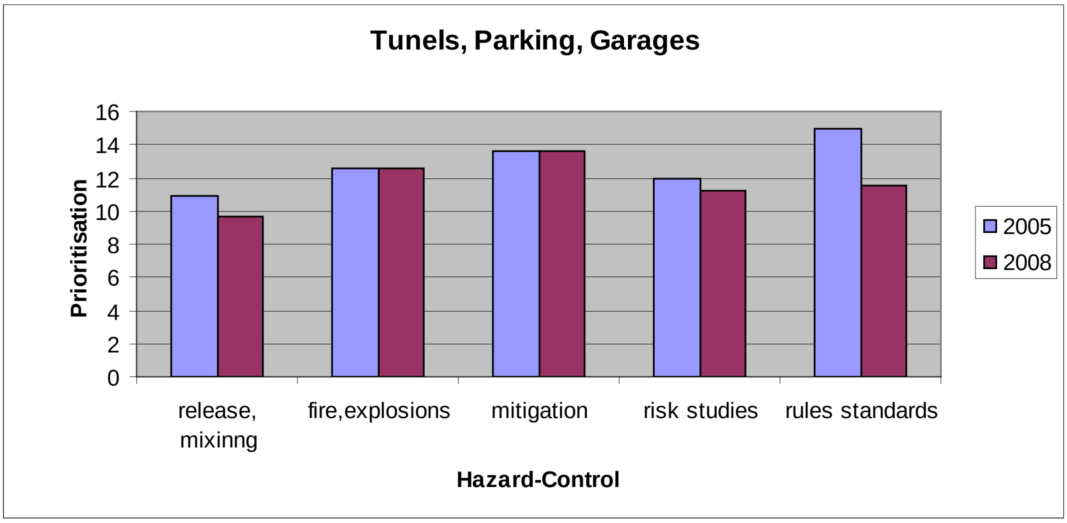

Figure 7 : Result of Macro PIRT update; tunnel, parking, garages scenario

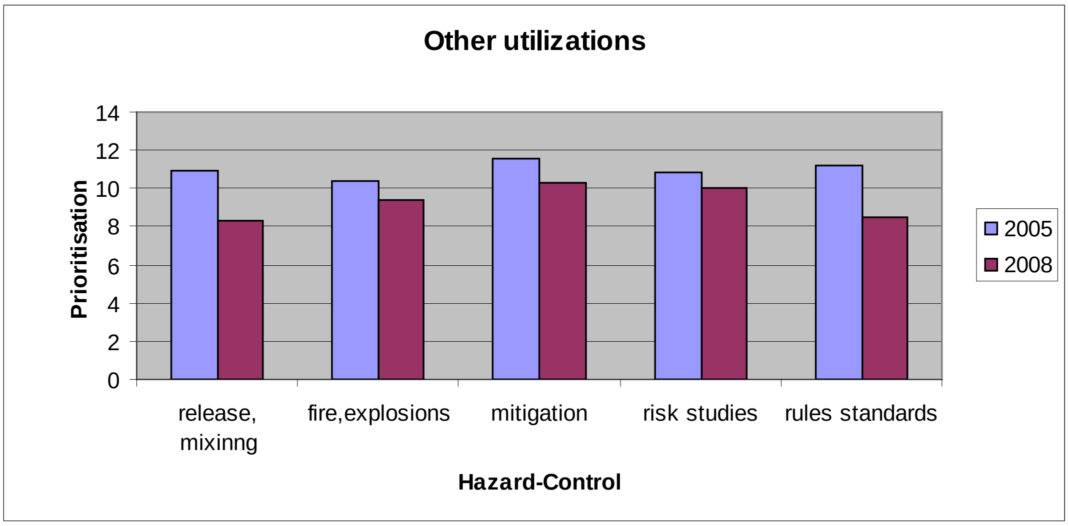

Figure 8 : Result of Macro PIRT update; other utilization scenario

3. SAFETY ANALYSIS

3.1. Identification of events

The list of accidental events used in the first PIRT analysis is unchanged and covers the following topics:

- H1: issues related to production (8 events)
- H2: issues related to transport and distribution (23 events)
- H3: issues related to large scale storage, refuelling stations and stationary applications (50 events)
- H4: issues related to H2-powered vehicles (commercial and private) (70 events)
- H5: issues related to other propulsion systems (3 events)
- H6: issues related to portable applications. (12 events)

Thus a total of 166 events were identified, spanning 6 application fields. Since many of the events were provided by the industrial partners, it is not surprising to see that the final list and distribution of events according to the horizontal activities reflects the main area of activities that they represent. Some application fields are under-represented (H1: production, H2: transport and distribution, H5: other propulsion systems and H6: portable applications), whereas some applications field (H4: commercial and private vehicles) are better represented.

3.2. Ranking of events

To rank events, a voting procedure was followed, based on expert scientific and engineering judgment. Accidental events are ranked according to their importance for safety, using the following scale:

- High importance (vote Level 3): the consequences can be severe (fatal injuries to people) and the probability of occurrence is high, medium or unknown. Uncertainties associated with this event must be reduced to the minimum possible.
- Medium importance (vote Level 2): the consequences can be important (severe injuries to people, significant material damage), and the probability of occurrence is high, medium or unknown.
- Low importance (vote Level 1): the consequences are not very important (minor injuries, slight material damage), or the probability that such an event happens is low.
- No opinion (Vote Level 0 or abstention): in the case when the person participating in the PIRT vote has no knowledge of the event or its consequences, or simply no opinion, then he or she should abstain or cast a Level 0 vote. Those votes are not processed in the statistical operations.

3.3. Who voted?

The table of events was sent to all the members of the HYSAFE project (25 partners), and to the Advisory Committee. One answer per partner was expected, eventually resulting from internal discussions between the partner's experts. The total number of votes received was 15. It should be noted that some partners provided answer for only a limited of events, so the total number of votes is less than 15 and ranges from 5 to 14 (see Figure 9).

A concern was expressed that the update would be biased if people voting for the update were different from those who voted in 2005. To circumvent this difficulty, it was advised whenever possible that the same experts would vote for the update.

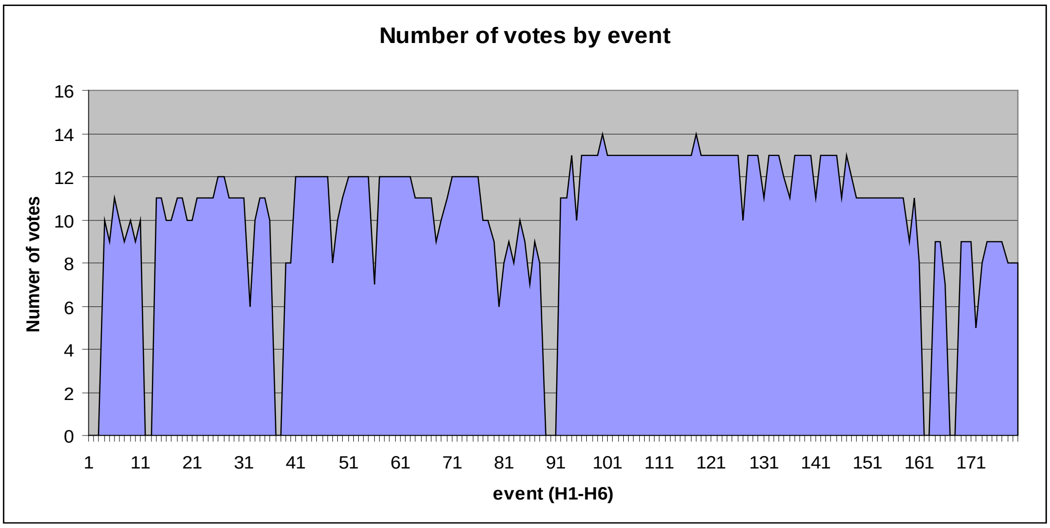

Figure 9 : Safety votes: number of votes by event

3.4. Results of safety votes

Since only non-zero votes are processed, the average vote for each event lies between 1 (all votes equal to 1) and 3 (all votes equal to 3).
It was proposed to classify the accidental events in the following categories:

- Group 1: events which have an average greater or equal to 2.25
- Group 2: events which have an average between 2.0 and 2.25
- Group 3: events which have an average smaller than 2.0

One should also examine events which exhibit a bimodal vote (a high number of “1” and “3” votes) or a near uniform distribution (nearly equal numbers of “1”, “2” and “3” votes). Here we will consider as bimodal, votes for which Level 1 and Level 3 votes have received each at least 25% of the total number of votes for that particular event. Near uniform votes also fall into that category. These bimodal events need to be examined closely, since they indicate a lack of consensus between the HYSAFE experts, or possibly, that the event itself is not well defined and leads to confusion.

One should also examine closely events for which the average lies near the threshold, and examine how the value is affected by an individual vote. For example, if an event has an average of 2.23 out of n votes, and if one vote were shifted from 1 to 2 or 2 to 3, then the average would increase by 1/n. Depending on n, this could move the event into Group 1.
In the following sections, we will examine the results of the “safety-oriented” PIRT voting exercise for the different horizontal applications of hydrogen. We will focus especially here on the events which fall into Group 1 (high priority) and Group B (bimodal – lack of consensus).

3.4.1. Production (H1)

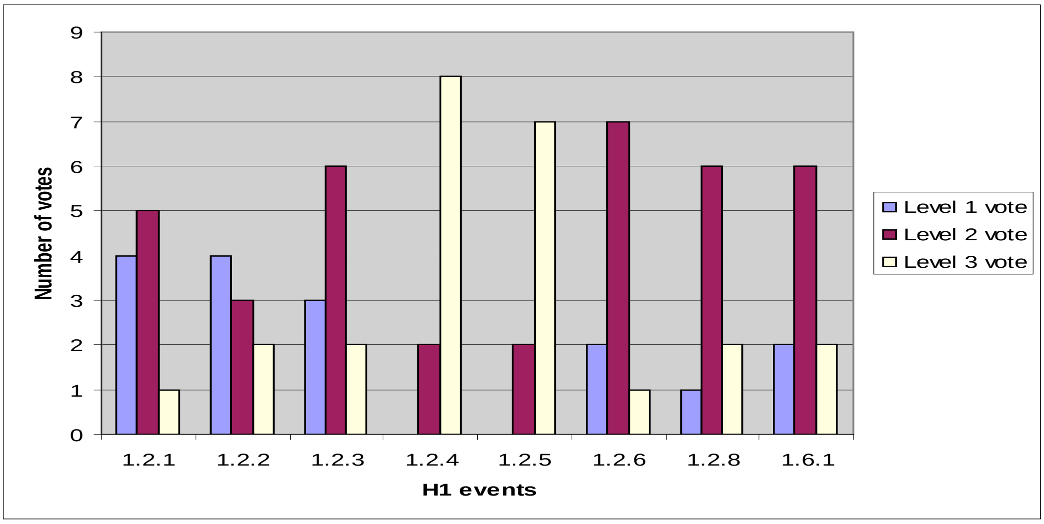

Figure 10 : Distribution of votes for H1 events

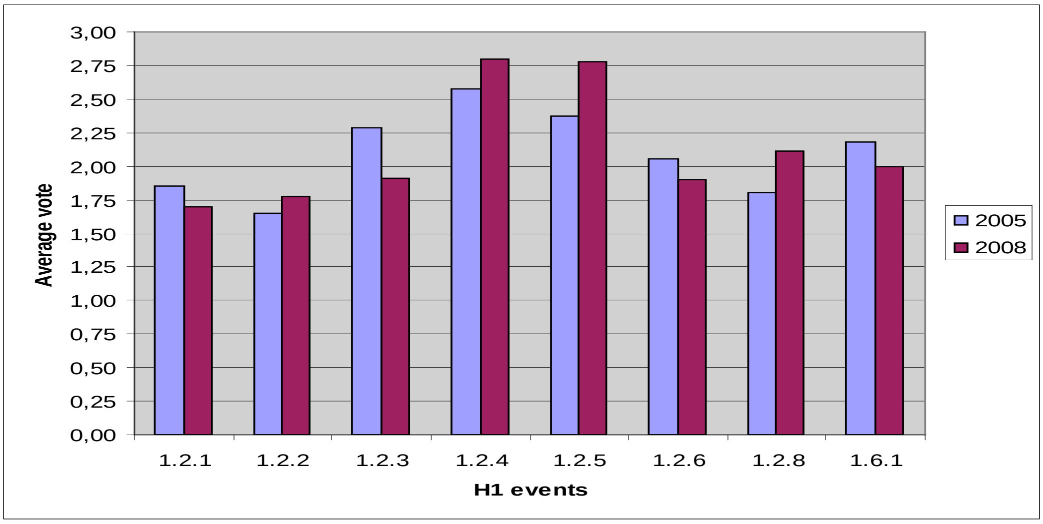

Figure 11 : Evolution of average vote for H1 events from 2005 to 2008

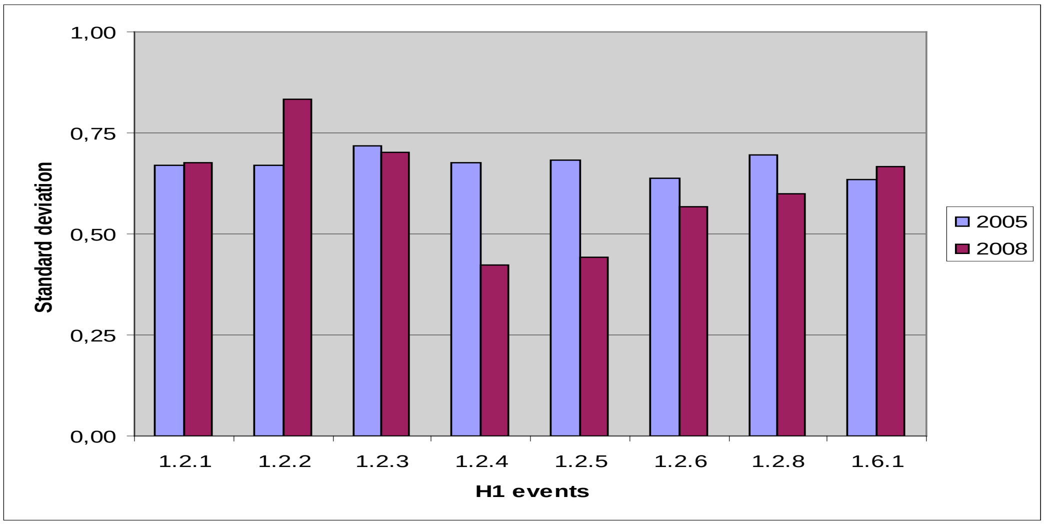

Figure 12 : Evolution of standard deviation for H1 events from 2005 to 2008

Only 8 accidental events were identified for H2 production systems, and a clear majority for electrolysis systems. This is clearly not exhaustive, does not include any massive production system and a more in-depth analysis will be needed in the future. The number of votes for each event ranged from 8 to 11. The distribution of votes is:

- Group 1: 2 events
- Group 2: 2 events
- Group 3: 4 events
- Group B: no events (0%)

The 2 events which belong to the 1st group of issues are:

- **Application 1.2 Electrolysis (small scale production at refuelling station situated in an urban location),**
    - Event 1.2.4 large leaks due to equipment rupture, inside container (2.80)
    - Event 1.2.5 large leak or equipment rupture leading to reverse flow from downstream high pressure section (**2.78**)

These 2 events (1.2.4 and 1.2.5) were already identified in Group 1 in 2005 analysis, their ranking has increased and their standard deviation has strongly decreased
The event 1.2.3 (small hydrogen leak in confined space) was in Group 1 in 2005 and is now in Group 2 (**1.91**).

<u>Conclusions for H1 votes:</u>
Events associated with **small or large leaks of H2** from electrolysis systems **into confined volumes** have been ranked as the most important safety issues.

3.4.2. Transport and distribution (H2)

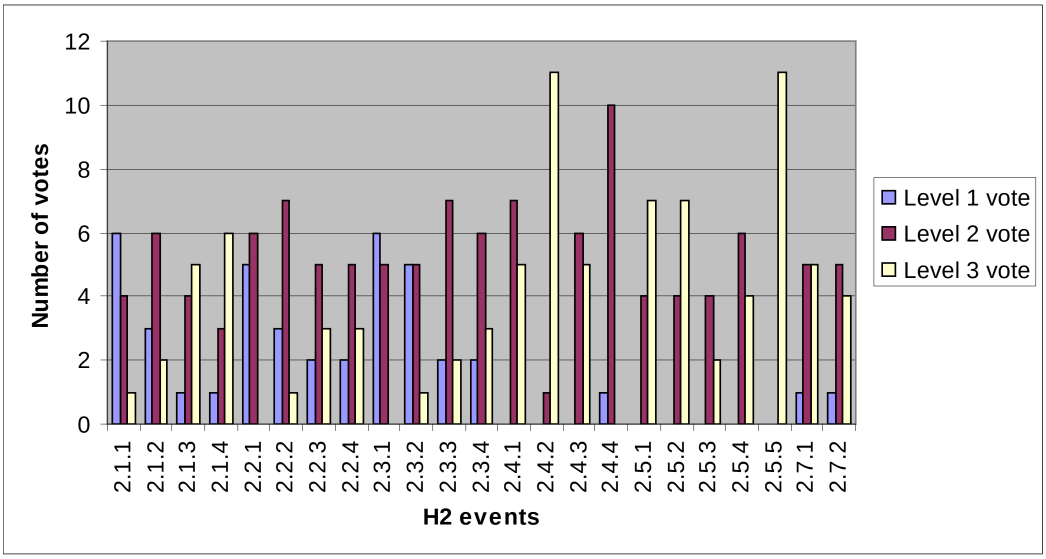

Figure 13 : Distribution of votes for H2 events

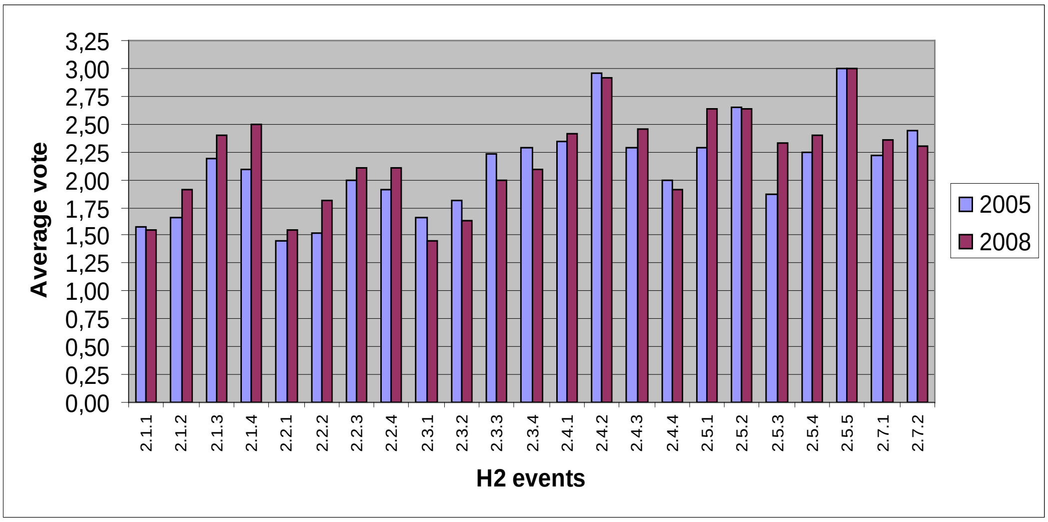

Figure 14 : Evolution of average vote for H2 events from 2005 to 2008

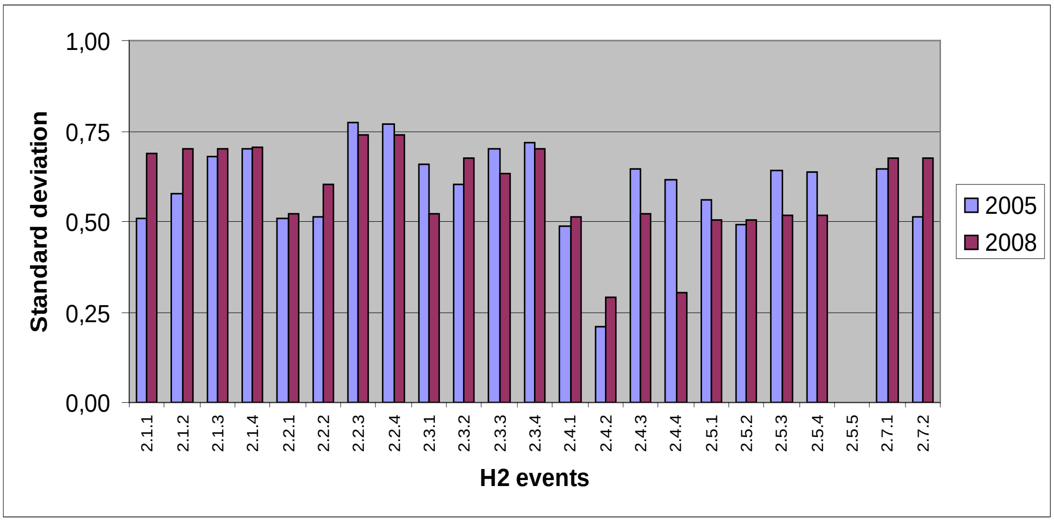

Figure 15 : Evolution of standard deviation for H2 events from 2005 to 2008

23 events were identified for the area of H2 transport and distribution, with events for pipeline transport of GH2, LH2 or mixtures of GH2 and natural gas (studied in the NATURALHY project), truck transport of GH2 or LH2 and sea transport of GH2 or LH2. The number of votes for each event ranged from 6 to 12.
Among the 23 events, 12 are ranked in the first group, with averages above 2.25, this has to be compared to the 9 events identified in previous PIRT.
Events in group 1 are:

Application 2.1 GH2 pipeline:

- event 2.1.3: instantaneous release from pipeline **(2.40)**
- event 2.1.4: instantaneous release compression station **(2.50)**

Application 2.3 pipeline carrying mixtures of NG and H2:

- event 2.3.4: instantaneous release from compression station **(2.09)**

Application 2.4 truck transport of compressed GH2

- event 2.4.1 crash of GH2 tanker on roads **(2.42)**
- event 2.4.2 crash of GH2 tanker in tunnels (**2.92)**
- event 2.4.3 discharge hose failure from GH2 tanker at refuelling station (**2.45**)

Application 2.5 truck transport of LH2

- event 2.5.1 line rupture (caused by a road accident) (**2.64**)
- event 2.5.2 tank rupture (caused by a road accident) (**2.64**)
- event 2.5.4 discharge hose failure from LH2 tanker at refuelling station (**2.40**)
- event 2.5.5 crash of LH2 tanker in tunnels (**3.0**)

Application 2.7 sea transport of LH2

- event 2.7.1 burst of tank aboard ship (**2.36**)
- event 2.7.2 line or tank rupture at a harbour location (**2.30**)

The event 2.2.3 (instantaneous release from LH2 pipeline) had a bimodal vote in 2005 (29% Level 1 votes and 29% Level 3 votes) is no more bimodal in 2008 (20% Level 1 votes and 30% Level 3 votes).

<u>Conclusions for H2 votes:</u>
Events 2.4.2 (crash of GH2 tanker in tunnel) and 2.5.5 (crash of LH2 tanker in tunnel) scored the highest averages (resp. 2.92 and 3.0) of all events – over all applications, underlying the importance of addressing **tunnel safety issues**, especially with vehicles transporting large quantities of H2 such as tankers. More generally, high votes were awarded for accidental issues involving accidental discharges via ruptures of line or dispenser hose, or even tank rupture situations for **road tankers involved in traffic accidents**.
Although **instantaneous release of GH2 from pipeline**, and **instantaneous release of GN/H2 mixtures from pipeline** show a higher score than 2005, the general appreciation is very similar to the PIRT 2005.

3.4.3. *Large scale storage, refuelling station and stationary applications (H3)*

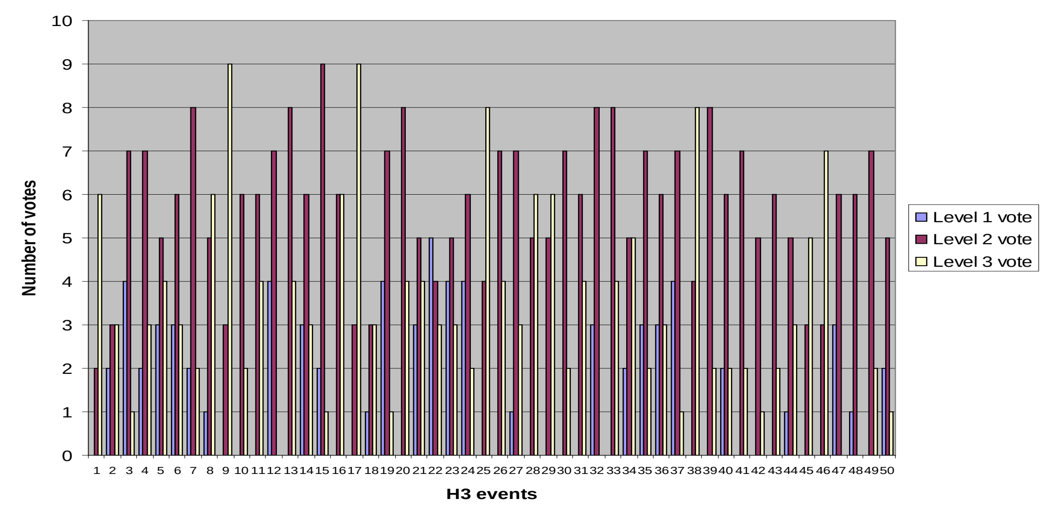

Figure 16 : Distribution of votes for H3 events

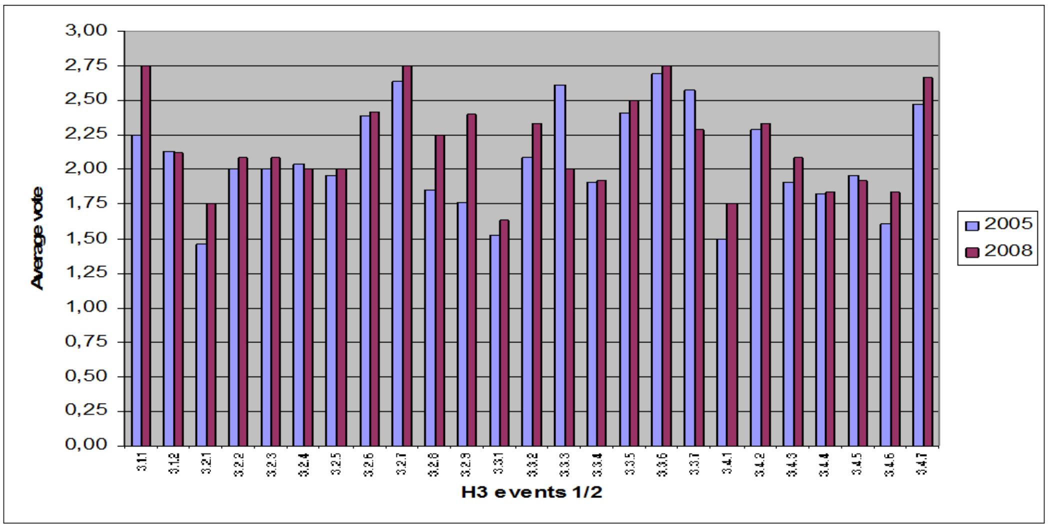

Figure 17 : Evolution of average vote for H3 events from 2005 to 2008 (1/2)

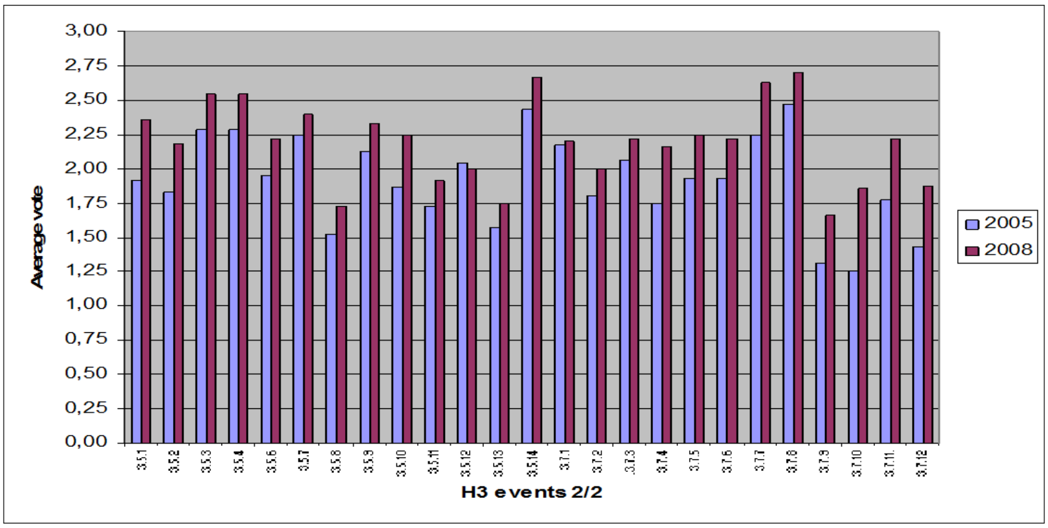

Figure 18 : Evolution of average vote for H3 events from 2005 to 2008 (2/2)

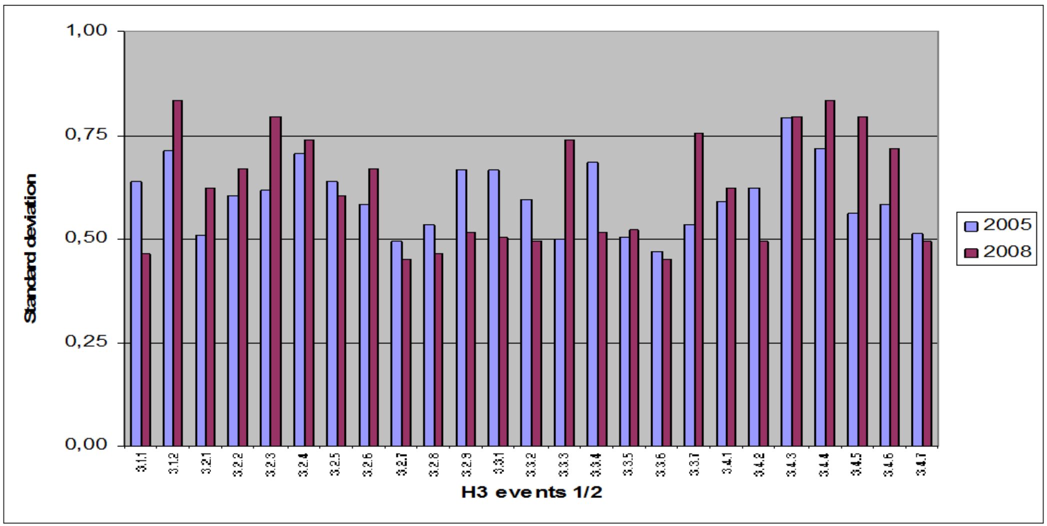

Figure 19 : Evolution of standard deviation for H3 events from 2005 to 2008 (1/2)

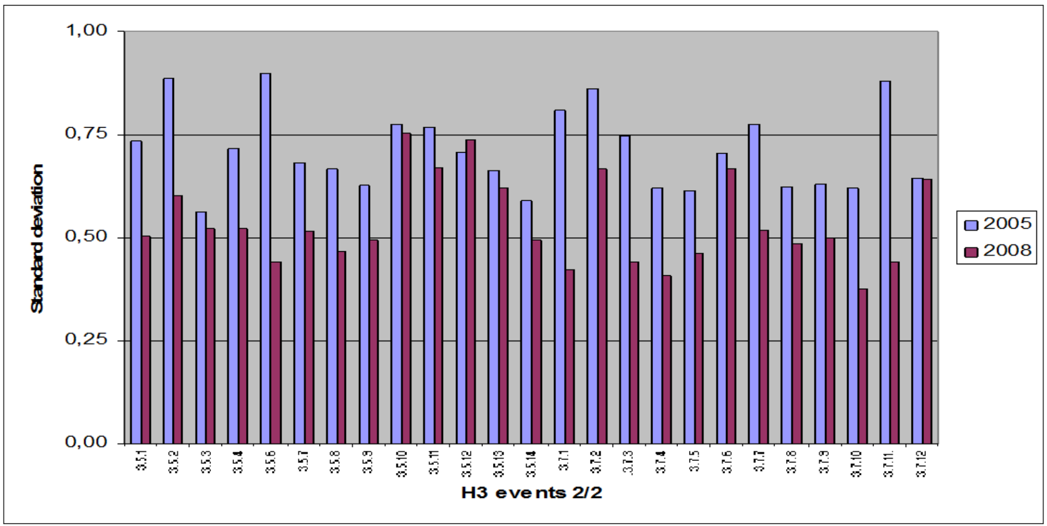

Figure 20 : Evolution of standard deviation for H3 events from 2005 to 2008 (2/2)

50 events were identified for the H3 application (large scale storage, refuelling stations and stationary applications). The number of votes ranged from 6 to 12. 18 of the events have been ranked into group 1 (average greater or equal to 2.25). There is no bimodal vote in 2008 compared to 5 in 2005.

Events in group 1 are:

Application 3.1 Hydride beds

- Event 3.1.1 Burst of tank inside building (**2.75**)

Application 3.2 LH2 tanks

- Event 3.2.6 Continuous release in partially confined or totally confined atmosphere (**2.42**)
- Event 3.2.7 Instantaneous release in partially confined or totally confined atmosphere (**2.75**)

Application 3.3 GH2 tanks

- Event 3.3.2 Continuous release in partially confined atmosphere (**2.33**)
- Event 3.3.3 Continuous release in open atmosphere (**2.0**)
- Event 3.3.5 Instantaneous release in partially confined atmosphere (**2.50**)
- Event 3.3.6 Instantaneous release in confined atmosphere (**2.75**)
- Event 3.3.7 Reverse flow of air into tank after release of H2 (**2.29**)

Application 3.4 Refuelling station LH2

- Event 3.4.2 Continuous release in partially confined atmosphere (**2.33**)
- Event 3.4.7 Instantaneous release in partially confined atmosphere (**2.67**)

Application 3.5 Refuelling station GH2

- Event 3.5.1 Release during refuelling of vehicle (**2.36**)
- Event 3.5.3 Fire exposing high pressure storage tank (**2.50**)
- Event 3.5.4 Hose or pipe rupture in dispenser (**2.50**)
- Event 3.5.7 Releases in containers (**2.40**)
- Event 3.5.9 Continuous release in partially confined area (**2,33**)
- Event 3.5.14 Instantaneous release in partially confined atmosphere (**2.67**)

Application 3.7 Stationary application: Auxiliary Power Unit (inside building)

- Event 3.7.7 Feeding line rupture (**2.63**)
- Event 3.7.8 High release rate leading to explosive mixture in room (**2.70**)

Conclusions for H3 votes:

Events concerning accidental releases (**small or large scale release rates**) from LH2 or GH2 **storage tanks** (through faulty or leaking connections, or, in the case of **refuelling stations**, at the level of the dispenser hose) **into confined or partially confined atmospheres** have received a high priority vote. The accidental release from an **APU inside a building** due to a leak or the opening of a safety valve has also been considered a very important safety issue (confinement aspect).

3.4.4. Commercial vehicles and passenger car (H4)

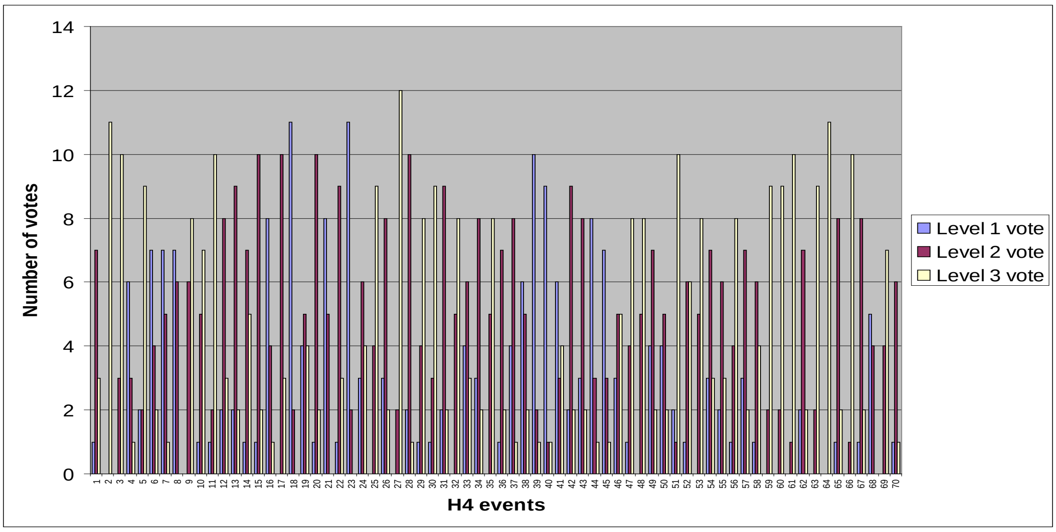

Figure 21 : Distribution of votes for H4 events

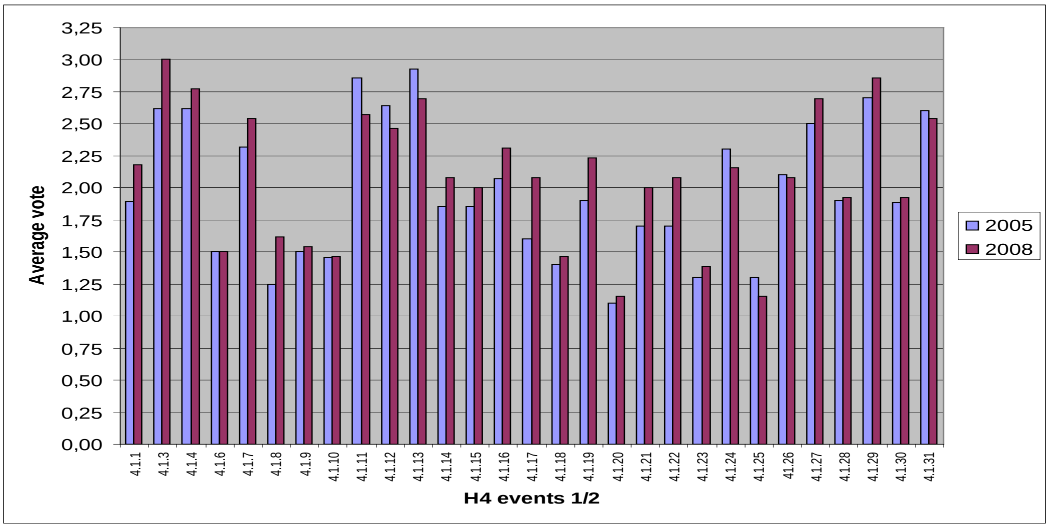

Figure 22 : Evolution of average vote for H4 events from 2005 to 2008 (1/2)

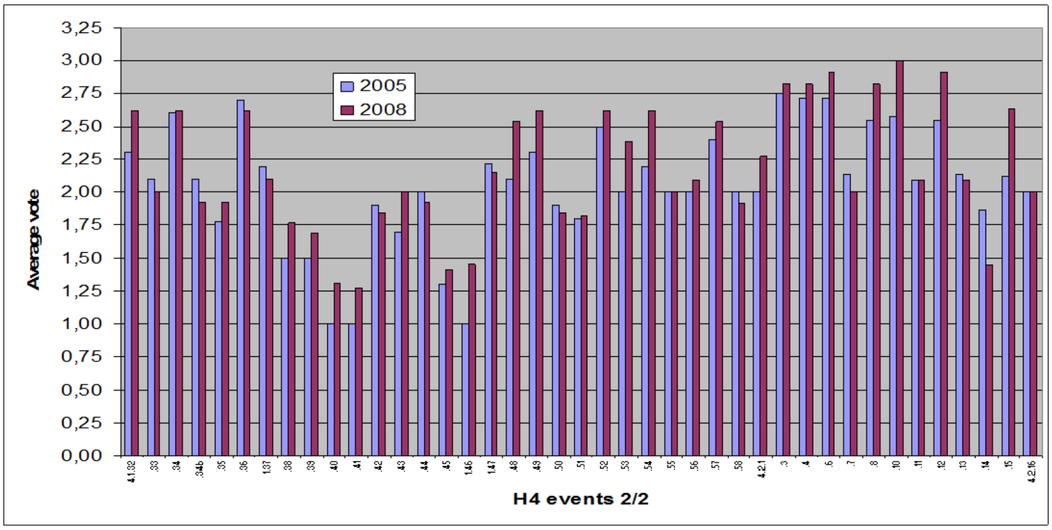

Figure 23 : Evolution of average vote for H4 events from 2005 to 2008 (2/2)

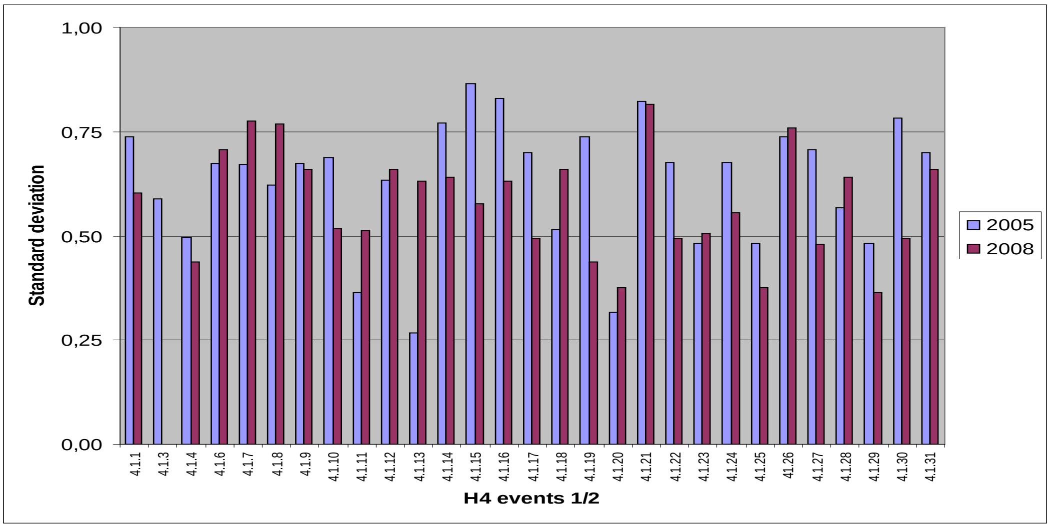

Figure 24 : Evolution of standard deviation for H4 events from 2005 to 2008 (1/2)

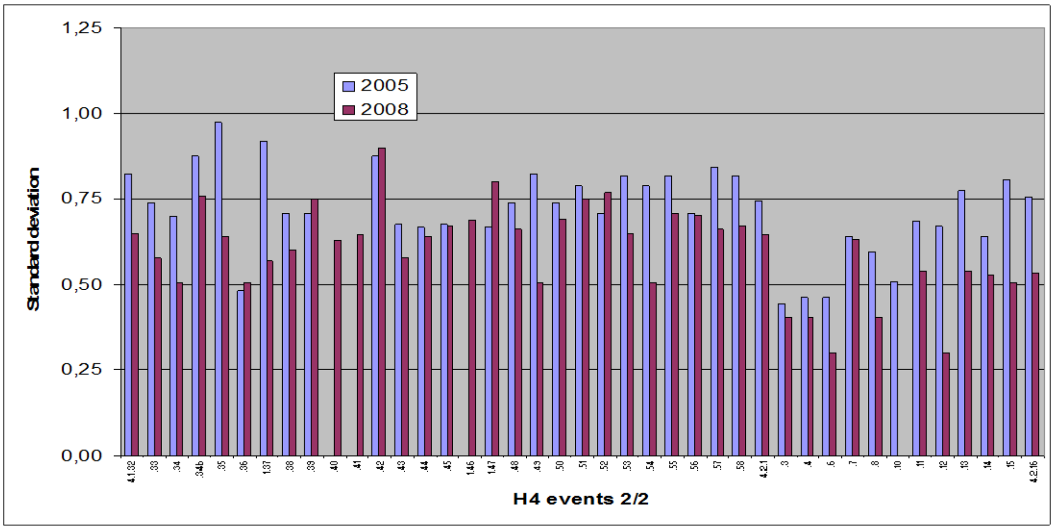

Figure 25 : Evolution of standard deviation for H4 events from 2005 to 2008 (2/2)

70 events have been identified for commercial vehicle and passenger car applications. The number of votes ranged from 8 to 14. Of the 70 events, 28 were ranked in the first category (average above 2.25 or close enough to the threshold to be affected by a single vote). 2 bimodal votes were identified (whereas there were 11 bimodal votes in 2005).

Events in Group 1 are:

Application 4.1 Commercial vehicles

- Event 4.1.3 vehicle accident in tunnel with tank damage (**3.00**)
- Event 4.1.4 fire in tunnel leading to strong heat flux on tank (**2.77**)
- Event 4.1.7 accident or failure leading to tank damage in maintenance workshop (**2.54**)
- Event 4.1.11 accidental release from high pressure tank in tunnel or under overbridge (**2.58**)
- Event 4.1.12 failure of tank due to fatigue crack while in tunnel or overbridge (**2.46**)
- Event 4.1.13 catastrophic failure of storage system in tunnel or overbridge (**2.69**)
- Event 4.1.16 catastrophic failure of storage system on road (**2.31**)
- Event 4.1.24 release due to system/component failure in urban environment (**2.15**)
- Event 4.1.27 release via the PRD (accidental or intentional) while in tunnel (**2.69**)
- Event 4.1.29 release due to system/component failure in tunnel (**2.89**)
- Event 4.1.31 container failure while in tunnel or overbridge (**2.54**)
- Event 4.1.32 release via the PRD (accidental or intentional) in a car park or maintenance workshop (**2.62**)
- Event 4.1.34 large rate release due to system damage or component failure (**2.62**)
- Event 4.1.36 container failure in car park or maintenance workshop (**2.62**)
- Event 4.1.48 release via safety device in tunnel (**2.54**)
- Event 4.1.49 release due to system damage or failure of component while in tunnel or overbridge (**2.62**)
- Event 4.1.52 container failure in a tunnel or overbridge (**2.62**)
- Event 4.1.53 release via safety device in car park (**2.38**)

- Event 4.1.54 release due to system damage or component failure in car park or maintenance workshop (**2.62**)
- Event 4.1.57 container failure in a car park or maintenance workshop (**2.54**)

Application 4.2 Passenger cars

- Event 4.2.1 car accident crash/overturn on road (2.27)
- Event 4.2.3 car accident leading to tank failure while in tunnel (**2.82**)
- Event 4.2.4 fire in tunnel, leading to thermal loading on tank (**2.82**)
- Event 4.2.6 car accident leading to tank failure in car park (high release rate case) (**2.91**)
- Event 4.2.8 fire in public car park, leading to thermal loading on tank (**2.82**)
- Event 4.2.10 car accident leading to tank failure in private car park (high release rate case) (**3.00**)
- Event 4.2.12 car accident leading to tank failure in maintenance workshop (high release rate case) (**2.92**)
- Event 4.2.15 scene of a car crash, accidental H2 line rupture by emergency services (**2,64**)

Conclusions for H4 votes:

H4 votes illustrate a number of safety concerns related to:

- Safety of H2 vehicles in **confined environments such as tunnels, public or private car parks, maintenance workshops**. Damage to systems or components including the tank (because of accidents or external causes such as fire) could lead **to releases of H2 and the formation of confined potentially explosive clouds**. For private cars with smaller quantities of H2 involved, small release rates have not been ranked in the first category, but high release rate issues have.
- The **performance and reliability of systems and components, including tanks**: in some case (PRD), even nominal behaviour (ie the device is functioning as intended) can have dangerous consequences, if for example the release happens in a confined environment.
- The performance of the H2 tanks under mechanical or thermal loads
- **Failure to follow "good practices"** (for car mechanics in maintenance activities (purging of systems), or for emergency crews on scenes of accidents).

3.4.5. Other propulsion systems (H5)

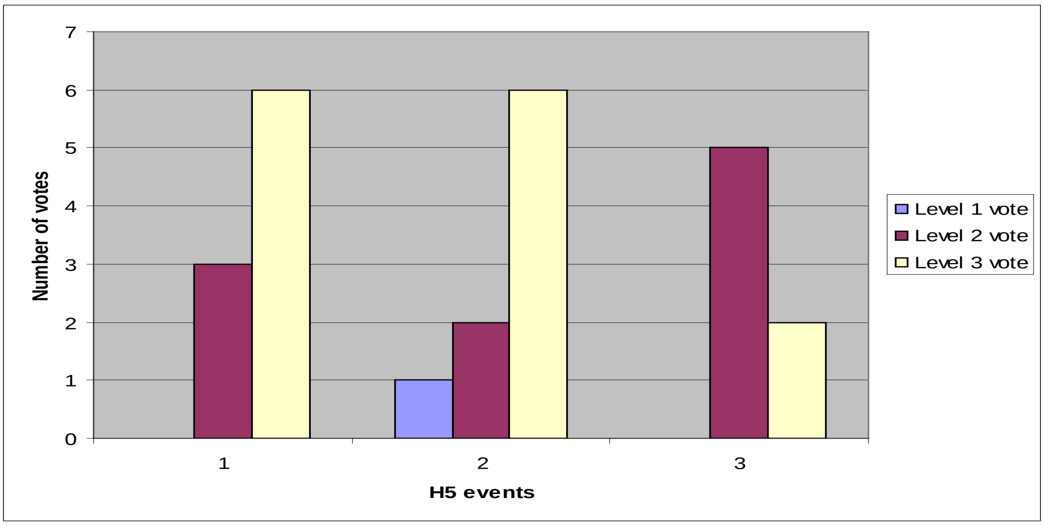

Figure 26 : Distribution of votes for H5 events

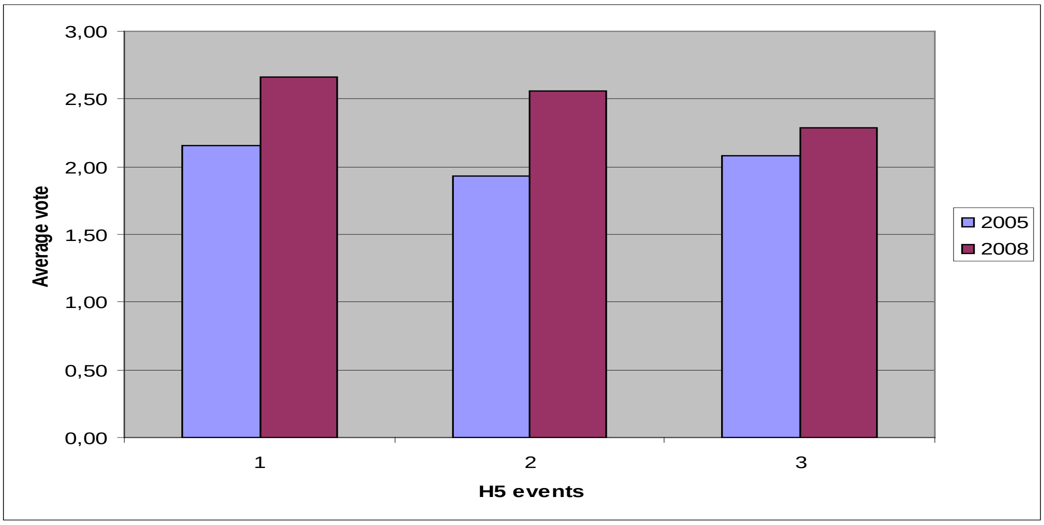

Figure 27 : Evolution of average vote for H5 events from 2005 to 2008

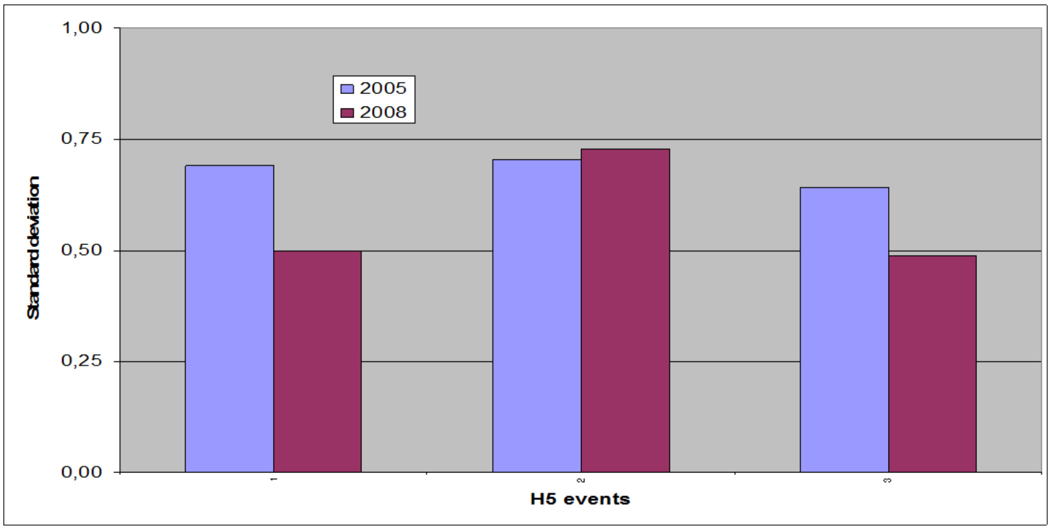

Figure 28 : Evolution of standard deviation for H5 events from 2005 to 2008

Very few accidental events (3) have been identified for this application; these events are ship overturn ship crash and ship rolling. These events are ranked in the first group. The number of votes ranges from 7 to 9, reflecting perhaps the lack of knowledge, expertise or interest of the HYSAFE consortium in propulsion systems other than cars or commercial vehicles. It may also reflect the fact that such systems are far less developed than cars and buses which are already being tested in several countries. This area will thus have to be examined closely in the future years to identify and prioritize safety issues and associated phenomena.

3.4.6. Portable applications (H6)

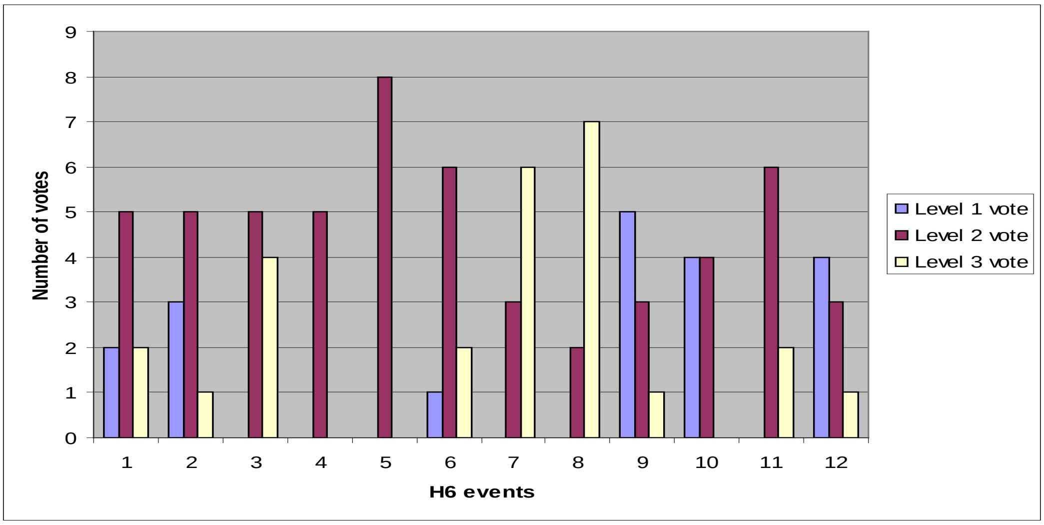

Figure 29 : Distribution of votes for H6 events

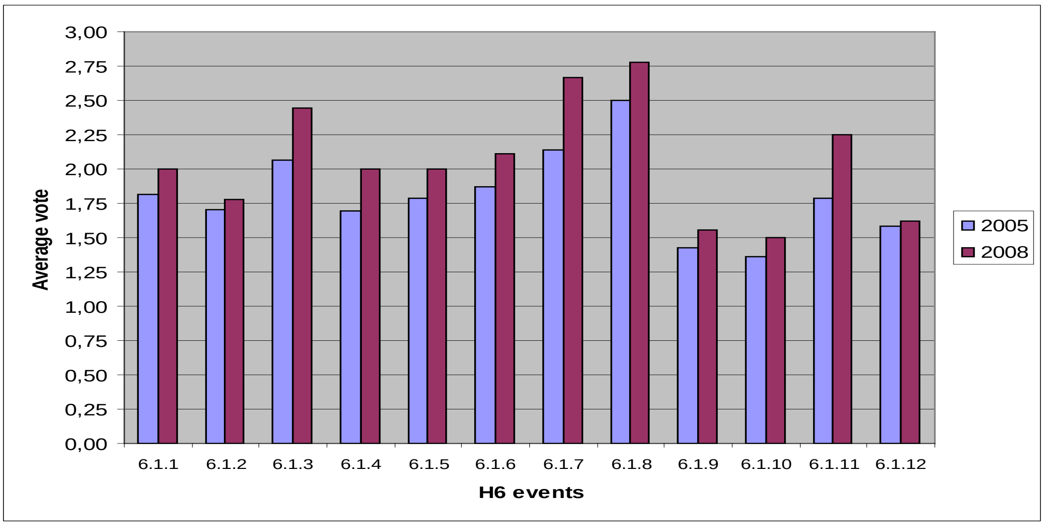

Figure 30 : Evolution of average vote for H6 events from 2005 to 2008

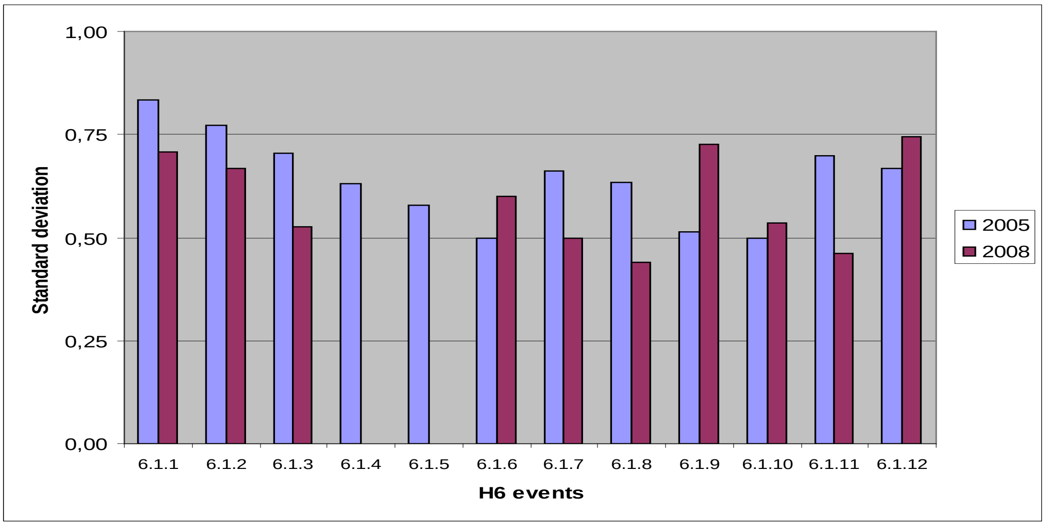

Figure 31 : Evolution of standard deviation for H6 events from 2005 to 2008

Only one application was identified as "portable application", namely a fuel cell system. 12 events were identified, 3 are ranked in Group 1 (only one in 2005). There was no bimodal vote (one in 2005 was Event 6.1.1 leaking from core, piping, etc. while inside building).

Events in Group 1 are:

- Event 6.1.3 Formation of explosive mixture outside stack, stack disassembly inside building (**2.44**)
- Event 6.1.7 Feed line rupture (**2.67**)
- Event 6.1.8 faulty connection or safety valve leading to release inside room and formation of an explosive atmosphere (**2.78**)

3.4.7. Conclusions for safety oriented votes

The step of the PIRT exercise, the update of safety-oriented vote, has highlighted a number of priorities among accidental events to be studied. These are:

- Any accident involving the release (small or large mass flow rate) of H2 into semi-confined or confined atmospheres, and this for many applications;
- Events that could lead to damage (thermal and mechanical loads) to tanks containing large quantities of H2 (road tankers, large scale storage at refuelling stations);
- Road safety and especially tunnel safety issues, for commercial vehicles as well as passenger cars
- Failure to follow "good practices" in maintenance workshops, refuelling stations, or scenes of accidents.

When one compares the results of this vote to the results of the previous exercise, for the six applications identified, it appears that the general trend is the same.
The number of votes is less in 2008 than 2005 (14 partners in 2008 compared to 20 in 2005) partners), many events received a slightly higher ranking in 2008 expressing that serious issues identified in 2005 are confirmed in 2008. It should be noticed that both the standard deviation and the number of bimodal votes decreased, reflecting a better agreement between the partner's evaluations.
The next step looks closely at the different phenomena which are relevant to the selected safety issues, and proposes a ranking of these phenomena according to our degree of knowledge.

4. PHENOMENA ANALYSIS

4.1. Identification of phenomena

The identification of phenomena was performed during the 2005 PIRT exercise. A list of phenomena corresponding to accident scenarios that were selected after the scenario ranking exercise was established, leading to the following categories:

- **P1: gaseous release:**
  - Permeation
  - Subsonic release
  - Choked flow (sonic) release
  - Full bore rupture (pipe), full vessel rupture
  - Turbulent flow in pipes, transport of H2
- **P2: liquid release and spill**
  - Liquid two-phase flow through orifice
  - Full bore liquid (pipelines), full vessel release
  - Formation of spill – pool spreading
  - Spill evaporation
  - Two-phase flow in liquid, including boiling
  - Heat transfer from ground
  - Condensation and evaporation of air
- **P3: explosion (related to liquid storage)**
  - Heat conduction in storage material
  - Boiling liquid Expanding Vapour Explosion (BLEVE)
- **P4: dispersion**
  - Impinged jets
  - Obstacle-generated turbulence
  - Effect of obstacles on flow patterns
  - Atmospheric conditions including wind
  - Heat transfer from environment
  - Natural ventilation (for partially confined atmospheres)
  - Forced ventilation
  - Buoyancy effects
  - Stable stratification
  - Turbulent mixing (in presence of large velocity gradients)
  - Turbulent mixing (decaying conditions)
  - Laminar diffusion
  - Compressible effects (shocks, under-expanded jets, contacts)
- **P5: ignition**
  - Autoignition
  - Shock ignition
  - Weak/mild ignition (including static electricity)
  - Strong ignition
  - Direct initiation of detonation
  - Jet ignition

- Radiative ignition
- Hot surface ignition
- Flammability limits

- **P6: combustion and explosion**
- o Laminar flame
- o Cellular flame
- Wrinkled flame
- Self turbulasing flame
- Flame acceleration / deceleration (due to obstacles, concentration gradients)
- Triple flame
- Turbulent deflagration
- DDT
- Detonation
- Quenching
- Standing flame – diffusion flame
- Jet fire
- Spill fire
- Multiphase combustion (for liq. H2)
- Heat radiation and absorbption

- **P7: mitigation**
- Natural ventilation
- Forced ventilation
- Post-accident inerting
- Recombiners
- Preventive ignition, ignitors
- Venting of deflagration
- Pressurisation of zone to avoir entry of H2
- Shut down systems
- Blast wave protective wall interaction

4.2. Ranking of phenomena

The objective of the phenomena-oriented vote is to establish, through expert ranking, what is the current state-of-the-art in terms of knowledge of physics, modelling and experimental data, and to identify knowledge gaps, and thereby to help focus R&D efforts on needed experimental and modelling work. The following scale was adopted for the votes:

- Vote **level 1**: the phenomenon is well understood. The processes are adequately modelled and well verified in general on an extended basis.

- Vote **level 2**: the phenomenon is on the whole understood but uncertainties remain for unexplored parameter ranges or extrapolation to application scale or conditions. The main processes are described by adequate models but the verification is not complete due to limited understanding and to limited amount of experimental data

- Vote **level 3**: the phenomenon is only partly understood. The models are rudimentary. The model verification is insufficient due to a significant lack of experimental data. R &D is needed!

- Vote **level 0** or no answer: no opinion, no expertise. These votes are discarded for statistical purposes.

Furthermore, to clarify as much as possible the status of knowledge, it was proposed to have 3 votes for each phenomenon:

- A vote on the level of understanding of the physics
- A vote on the level of modelling (for instance in CFD codes)
- A vote on the level of validation / existence of adequate experimental data.

Then, an average between the 3 categories is computed for each phenomenon.

4.3. Who voted?

The table of events was sent to all the members of the HYSAFE project (25 partners), and to the Advisory Committee. One answer per partner was expected, eventually resulting from internal discussions between the partner's experts. The total number of votes received was 15. It should be noted that some partners provided answer for only a limited of phenomena, so the total number of votes is less than 15 as it ranges from 5 to 14.
A concern was expressed that the update would be biased if people voting for the update were different from those who voted in 2005. To circumvent this difficulty, it was advised whenever possible that the same experts would vote for the update.

4.4. Results of phenomena oriented votes

Following the process used for the scenario ranking part of the PIRT, three categories of results were identified:

- The first group consists of phenomena for which the average vote is larger or equal to 2.25;
- The second group consists of phenomena for which the average vote lies between 2 and 2.25;
- And finally the third group for phenomena which have an average below 2.0.

Bimodal votes may also exist. We recall that these are votes are characterized by a high number of “1” votes and a high number of “3” votes – and this is worth investigating as it implies that for some experts, a phenomenon is well understood and modelled whereas for others, it is not. This discrepancy may originate from the lack of awareness of some recent research work, publications, etc. We will not examine these bimodal votes in this document.
In the next paragraphs, we review the results of the votes, and the main justifications for the results (for votes in the first and second group, i.e. which have averages greater than 2.0)

4.4.1. Gaseous releases

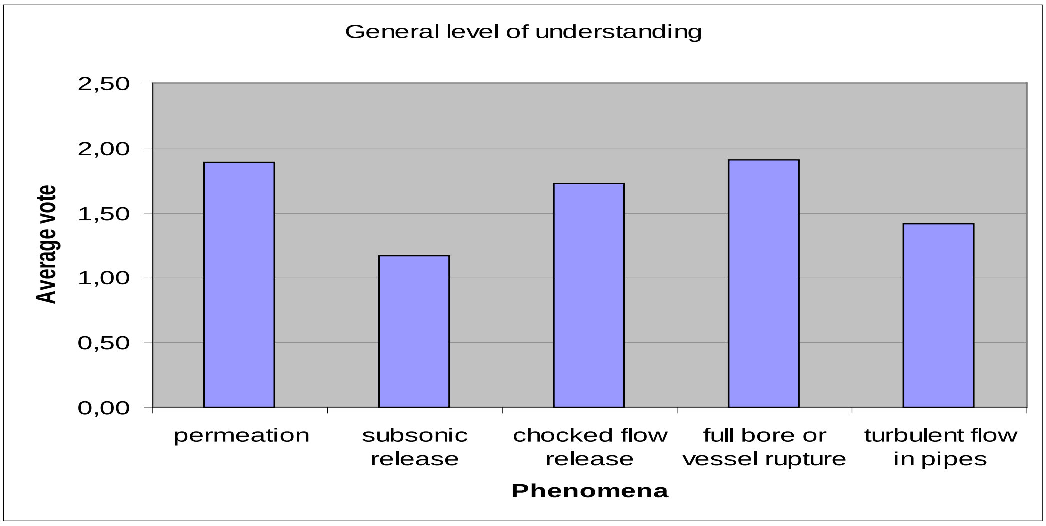

Figure 32 : General understanding for gaseous releases

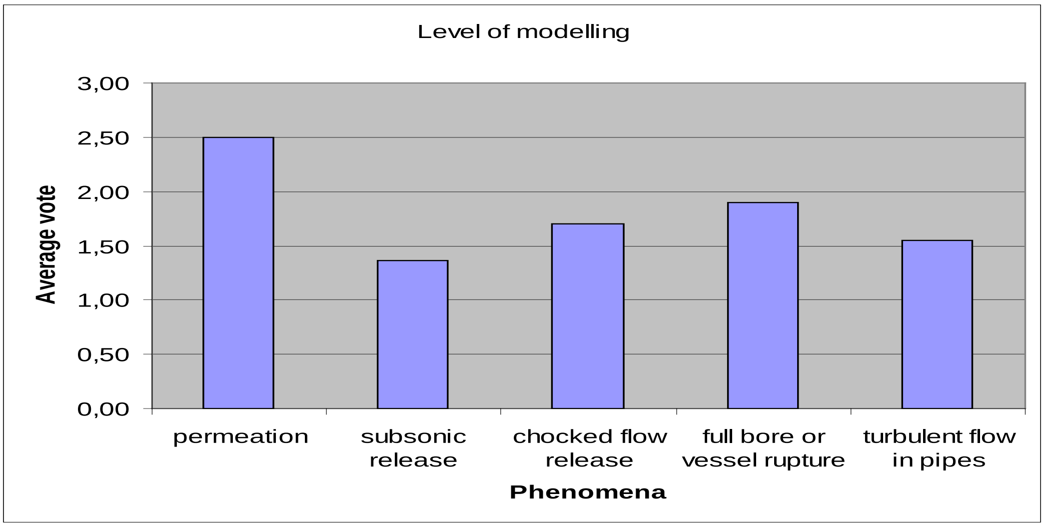

Figure 33 : Level of modelling for gaseous releases

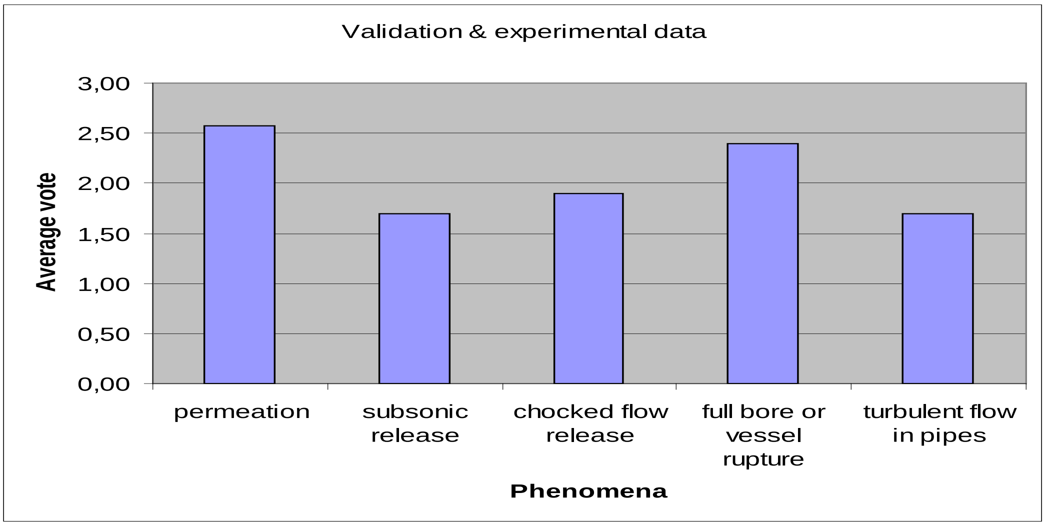

Figure 34 : Validation and experimental data for gaseous releases

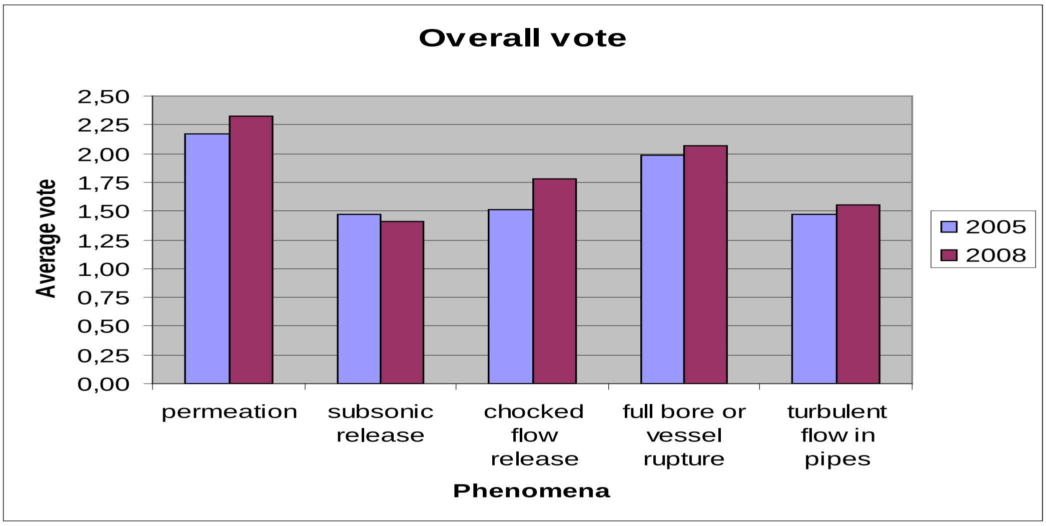

Figure 35 : Evolution of overall votes for gaseous releases from 2005 to 2008

Comments and justification proposed by experts are:

Permeation: Recent progress within HYSAFE // Preliminary UU results indicate no stratification
Subsonic releases: Boundary conditions for LES // There is a good knowledge for natural gas and He; maybe more experiments would be required for Hydrogen. // Cd coefficients for different situations.
Chocked (sonic) flow release: Experimental results are needed // Uncertainties are still remaining for natural gas; we think this is rather uncertain for hydrogen. // Cd coefficients for different situations, lack of detailed experimental datas because often difficult to make an adequate mass balance, see also recent work of [Hardstadt and Bellan] and [Houf and Schefer].
Full bore rupture or full vessel rupture: This issue is rather imprecise. The release can be either subsonic or choked depending on the gas conditions inside and on the break characteristics. A wide diversity of scenarios can be envisaged with very different behaviour… Some of them would require a deeper knowledge to be properly understood, with experiments under realistic conditions. // Transient issues, full vessel rupture is potentially very different from pipeline rupture. // Lack of experimenal datas, confidential datas from companies, published experiments in air
Turbulent flow in pipes, transport of H2: We think the physics is well understood and available models are satisfactory

Conclusion for gaseous releases:
In this category, only permeation phenomenon has an overall vote just above 2.25, although the general understanding of permeation process is found satisfactory, the votes show limited modelling capabilities and a lack of experimental data. Some recent work has been performed within Hysafe internal project INSHYDE and will be published at ICHS3.

4.4.2. Liquid releases and spills

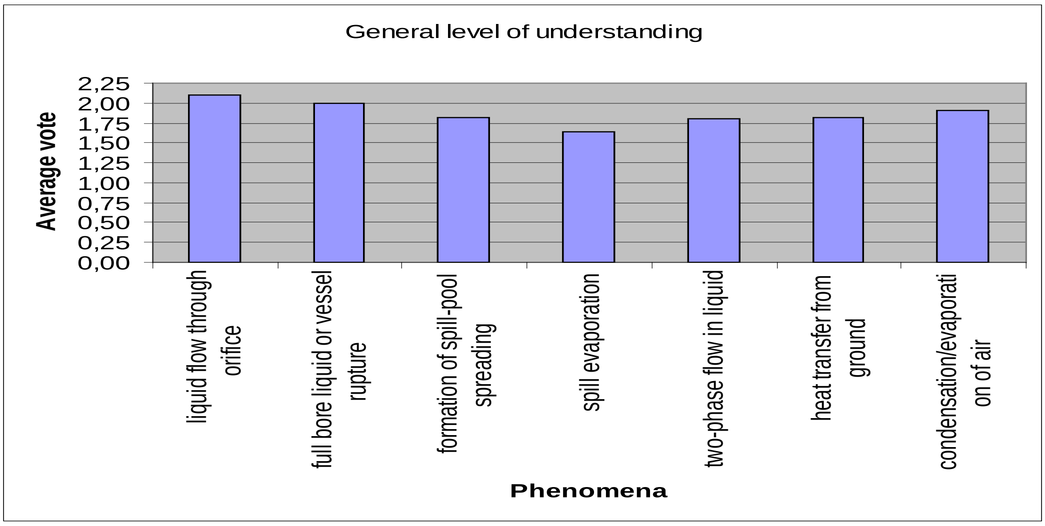

Figure 36: General understanding for liquid releases and spills

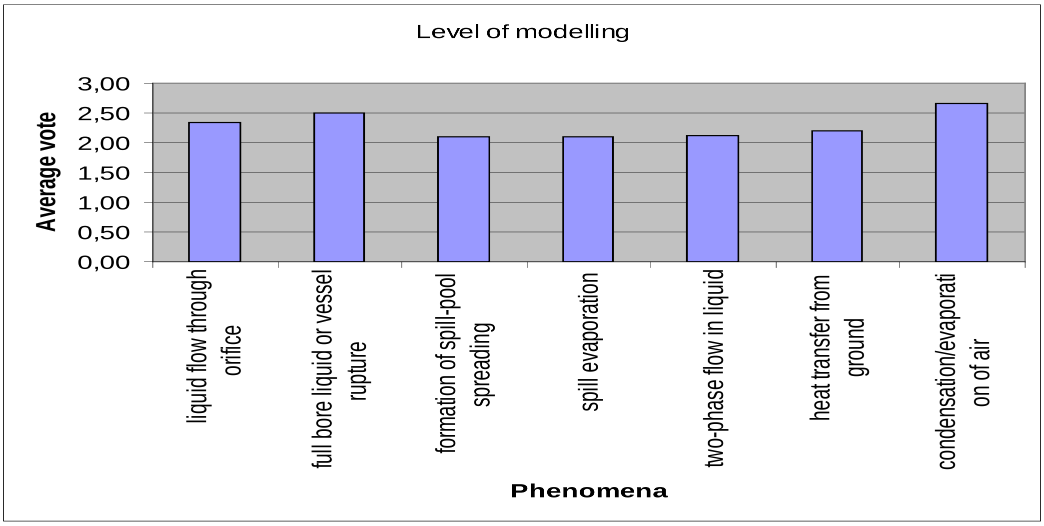

Figure 37 : Level of modelling for liquid releases and spills

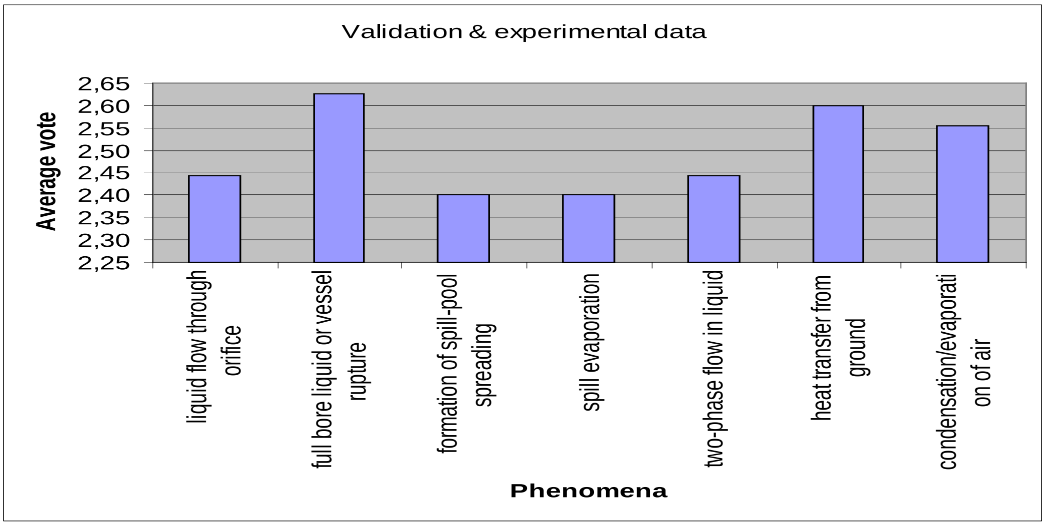

Figure 38 : Validation and experimental data for liquid releases and spills

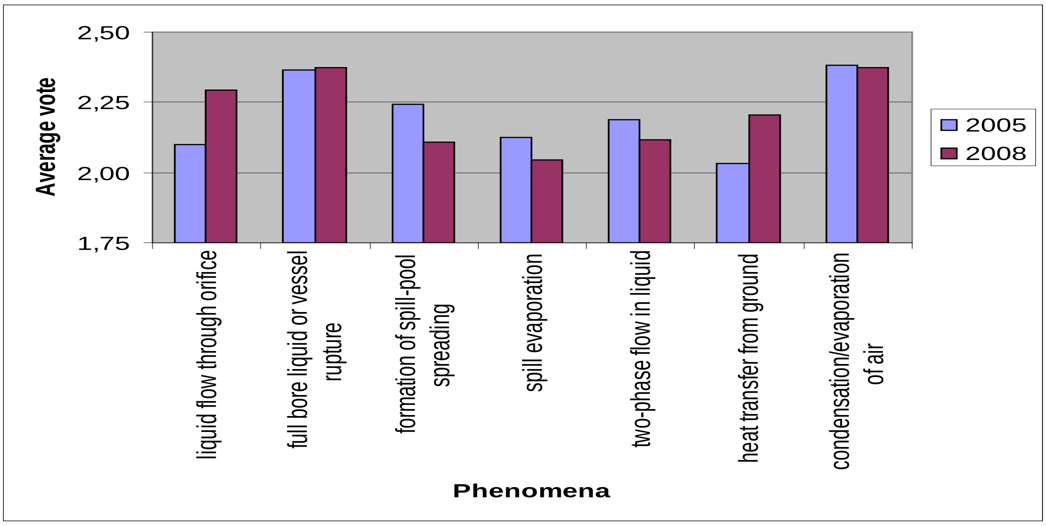

Figure 39 : Evolution of overall votes for liquid releases and spills from 2005 to 2008

Comments and justification proposed by experts are:

Liquid (two phase) flow through orifice: The level of understanding of the physics is good. However, for hydrogen, models should be adapted (calibrated) against specific experiments. The NASA experiments constitute a good reference // Very limited progress. More effort is needed

Full bore liquid or vessel rupture: This issue is rather imprecise. A wide diversity of scenarios can be envisaged with very different behaviour… Some of them would require a deeper knowledge to be properly understood, with experiments under realistic conditions // Very limited progress. More effort is needed

Formation of spill-pool spreading: Phenomena are well understood and can be modelled (numerous experiments to investigate the phenomena performed with LNG and LPG in the 70s and 80s). However, not all aspects have been modelled, e.g. influence of obstacles, only symmetrical spreading. The number of experiments dealing with pool spreading behaviour is small (e.g. FZJ Cottbus Experiment) and by far not sufficient for overall validation. // Some work in the EQHPP // The mechanical effects affecting pool spreading are well known for other fluids (examples are propane, natural gas, water, etc.). Probably, more experimental data for calibration of models is required for liquid hydrogen. // Very limited progress. More effort is needed

Spill evaporation: Phenomena are well understood, examined in detail by many authors. Experimental data may not cover all ranges, particularly for LH2. // For this group of phenomena, we can say that, although the physics maybe relative well identified, more experiments seem necessary to validate models. // Very limited progress. More effort is needed.

Heat transfer from ground: Phenomena are well understood (e.g. Nukiyama curve). Experimental data may not cover all ranges, particularly for LH2. // Very limited progress. More effort is needed.

Conclusion for liquid releases and spills:
In this category, three phenomena ranked above 2.25, these are **Liquid or two phase flow through orifice, full bore liquid or vessel rupture** and **condensation/evaporation of air**.

4.4.3. Explosion of liquid storage

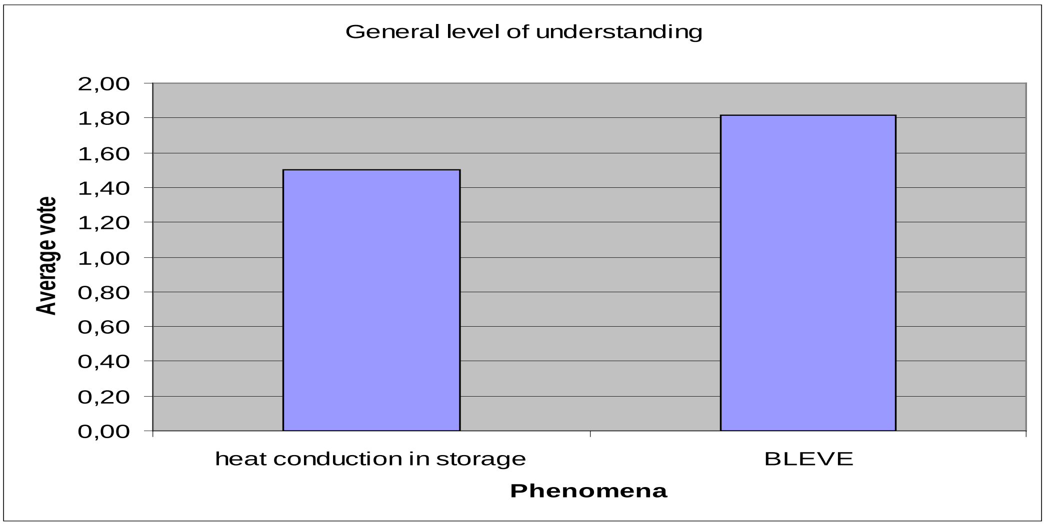

Figure 40 : General understanding for explosion of liquid storage

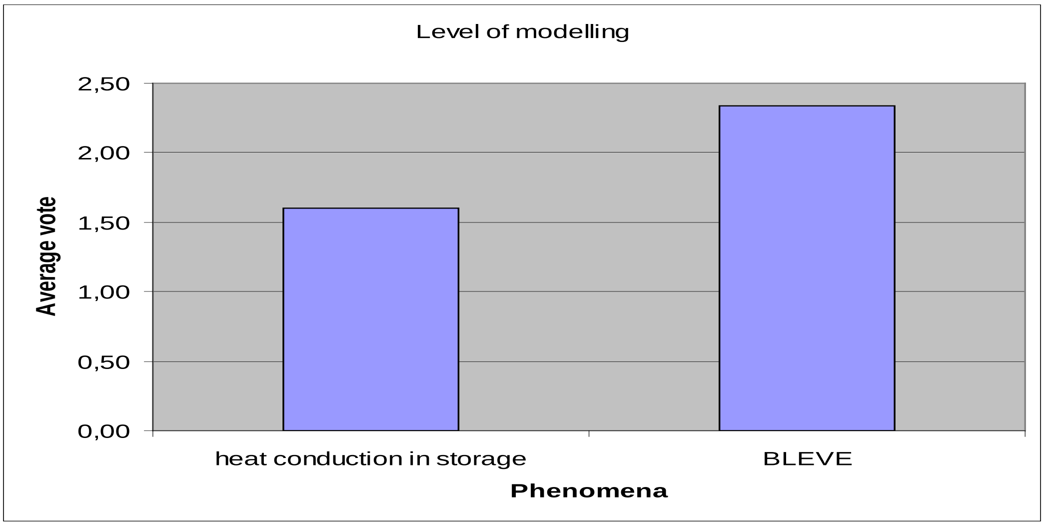

Figure 41 : Level of modelling for explosion of liquid storage

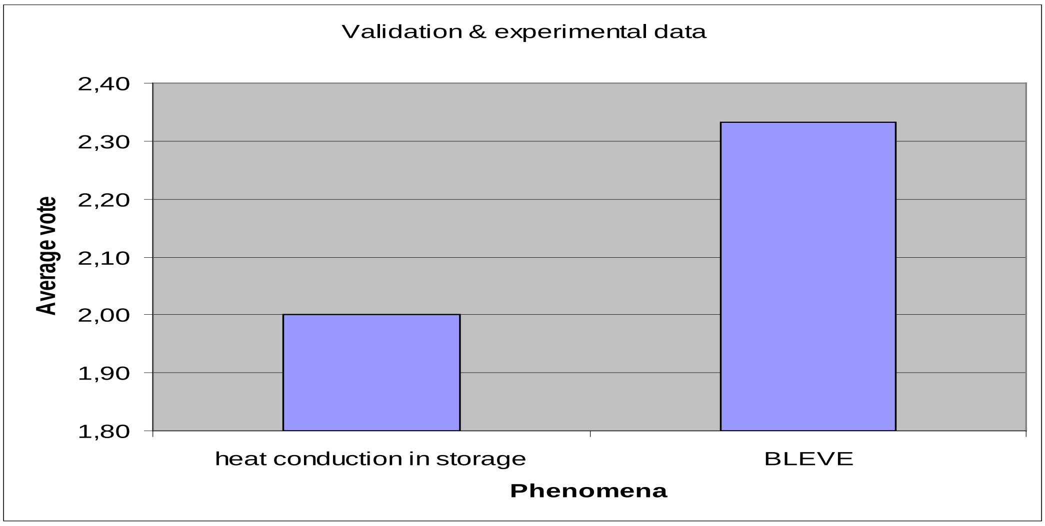

Figure 42 : Validation and experimental data for explosion of liquid storage

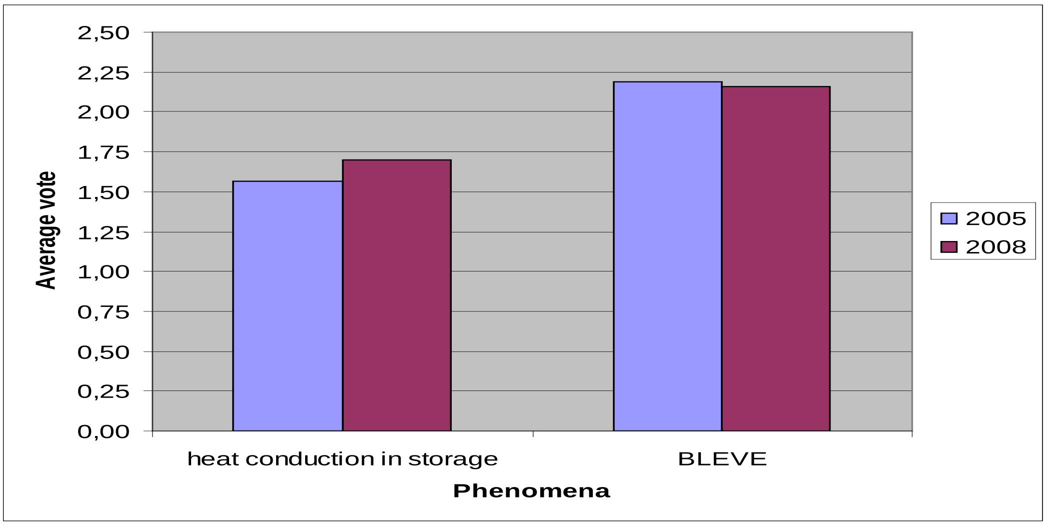

Figure 43 : Evolution of overall votes for explosion of liquid storage from 2005 to 2008

Comments and justification proposed by the partners are:

Heat conduction in storage: Heat conduction seems well known in general. There should be no difficulties on that, provided the storage material is duly tested to verify model predictions as it should be made in general.
BLEVE (Boiling Liquid Exploding Vapor Expansion): Experience and knowledge does exist for several liquid (liquified) fuels. The phenomena are well understood, but we do not know how far experimental information for hydrogen is available.

Conclusion for explosion of liquid storage:
In this category, one phenomenon BLEVE ranked in the second category. The results are very similar to those obtained in 2005.

4.4.4. Dispersion

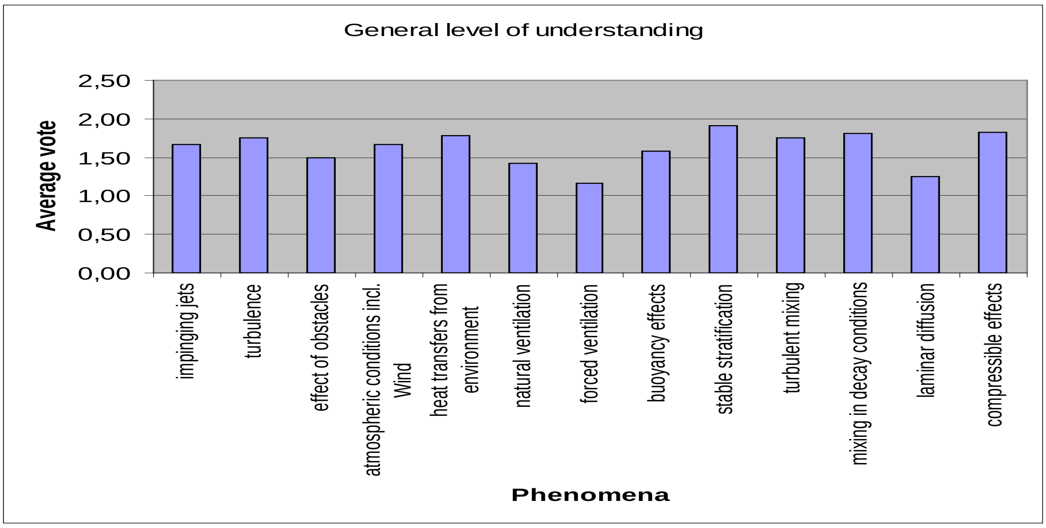

Figure 44 : General understanding for dispersion

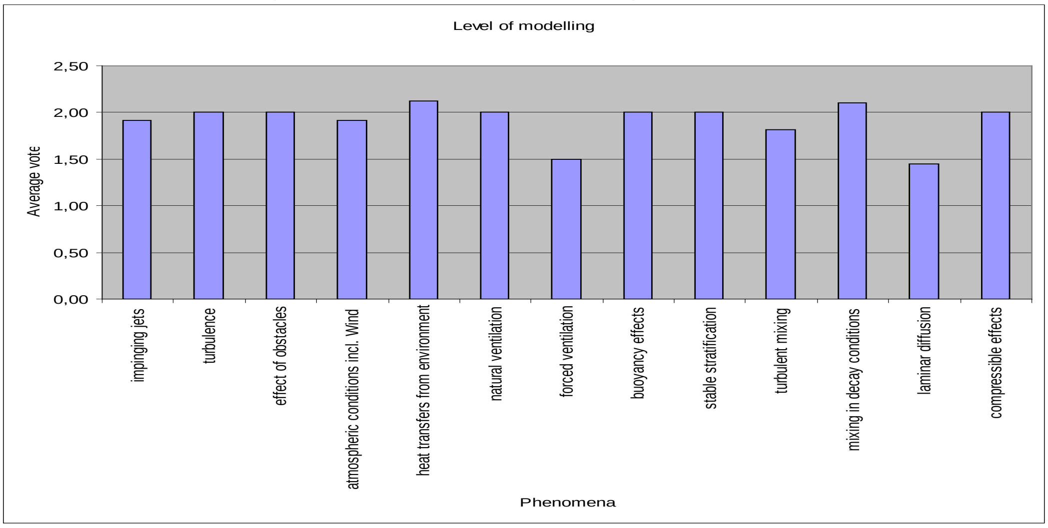

Figure 45 : Level of modelling for dispersion

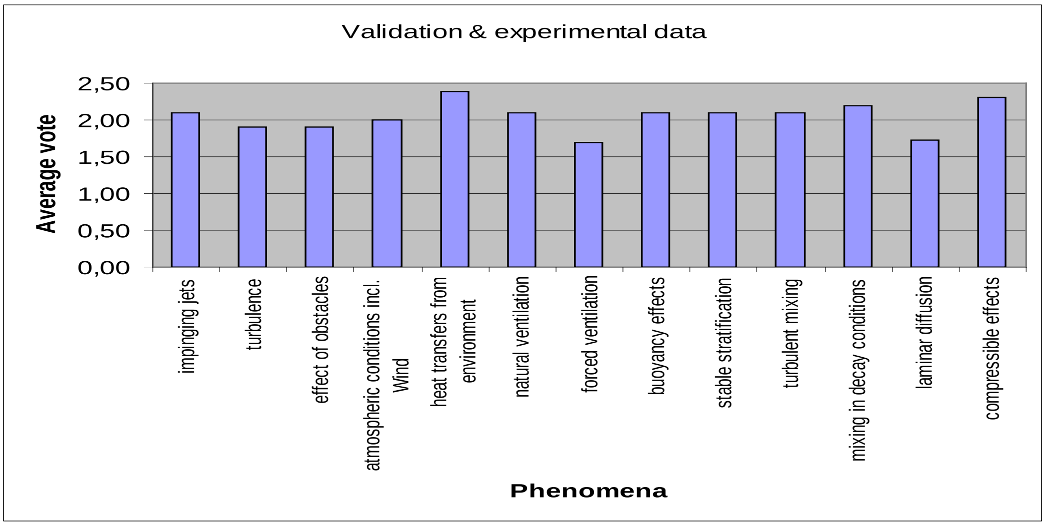

Figure 46 : Validation and experimental data for dispersion

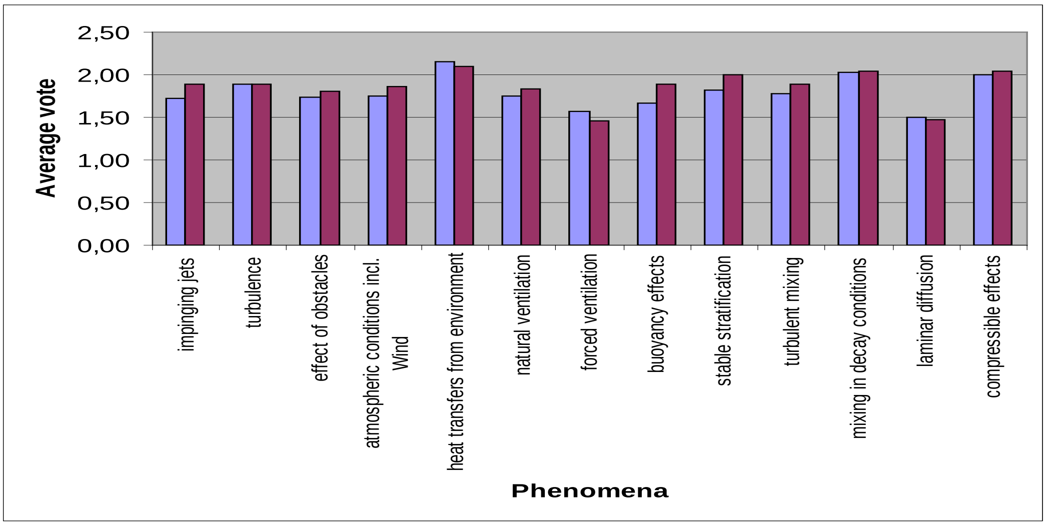

Figure 47 : Evolution of overall votes for dispersion from 2005 to 2008

Comments and justification proposed by experts are:

Impinging jets: Buoyancy-wall interaction. // Hydrogen jets may require more validation experiments to reduce the still existing uncertainties // Well known and documented fluid mechanics flow pattern, problem of wall functions, problem of large scale modelling (how to simulate with a coarse mesh the impinging zone ?) PhD under progress at IRPHE (Marseille) with detailed measurement techniques around the impinging zone // Recent progress within HYPER project by SANDIA

Turbulence: This is a well understood and modelled phenomenon for simple geometries. However, for complex geometries it may require further validation experiments // Challenging to reproduce experimental results in turbulence models // Coupling between turbulence and the mixing process, turbulent Schmidt number, transition to laminar flow (weak turbulence), depends on the region of interest // Recent progress through HYSAFE SBEPs (intercomparison exercises between various turbulence models)

Effect of obstacles: No generally valid simplified rules // Depending on the type of obstacles, it may require further validation experiments // h2 quite similar as other gases, large scale validation/exp missing // the question is resolved or unresolved obstacles by the model? For resolved obstacles, see impinging jet question. For unresolved ones, porosity concept?

Atmospheric conditions including wind: We are not aware of experiments on the influence of atmospheric conditions on the dispersion of H2; however, the general influence of weather conditions (wind, stability, rain,...) on the dispersion of other pollutants (including gases denser than air) is fairly well known. // part. Due to effects of atmospheric turbulence, and differing theories // Lack of detailed experimental data with hydrogen releases. Some are currently under progress at Pisa University, quality?

Heat transfer from environment: We think that heat transfer from the environment into the H2 cloud may be relevant in closed spaces, and probably not so much in open atmosphere. But it is not clear what type of phenomena is addressed in the question.

Natural ventilation: Good complex models, adequate simple models missing. // coupled with the question of buoyancy effect, lack of experimental data at large scale. Some interesting data have been obtained within the NaturalHy project for mixture of hydrogen and methane (unpublished at present time), problem of accurate measurement of ventilation flow for CFD code validation + velocity and turbulence measurements at different points for CFD code validation, published data in Fire science

Forced ventilation: Lack of experimental datas with well-defined boundary conditions, foreseen experiments in the CEA garage facility (DIMITHRY project)
Stable stratification: Break-down of a light gas stratified layer with different flows including jets and plumes (OECD project SETH II under progress), large scale facilities (PANDA and MISTRA), numerical benchmarks have to be organised
Turbulent mixing: There are new experiments available after HySafe...
Mixing in decay conditions: Additional efforts seem to be needed. Practical criteria to choose diffusion models and diffusion coefficients would be useful. // Recent progress through HYSAFE SBEPs (intercomparison exercises between various turbulence models)
Laminar diffusion: Large scale experiments for verification, transition from turbulent to laminar flow in models, control of numerical diffusion
Compressible effects: Mixing process close to a chocked flow release, detailed measurements (PIV+BOS or PLIF for gas concentration), important for the possible ignition of hydrogen release, recent papers from Dryer, Mogi.

Conclusion for dispersion:
In this category, there was no phenomenon in the first category and three phenomena were ranked in the 2nd category, heat transfer from the environment, mixing in decaying conditions, and compressible effects. The results are very similar to those obtained in 2005. From the comments of experts, accurate modelling of mixing at large scale and validation of results on experimental data still needs improvements.

4.4.5. Ignition

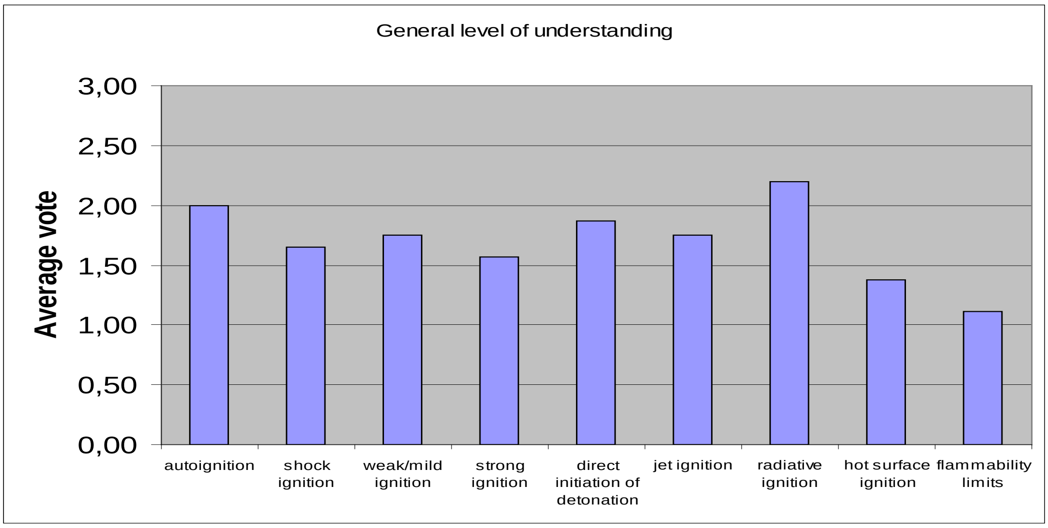

Figure 48 : General level of understanding for ignition

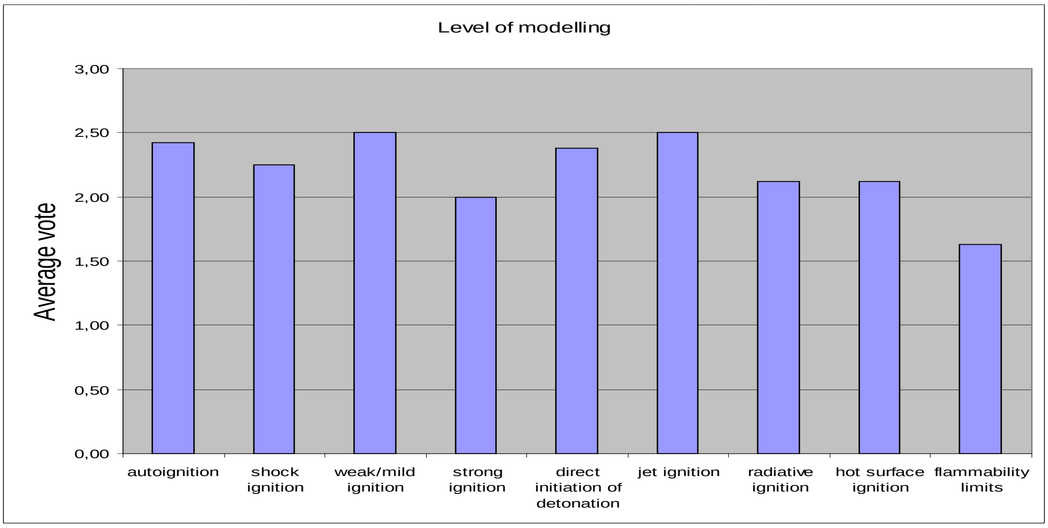

Figure 49 : level of modelling for ignition

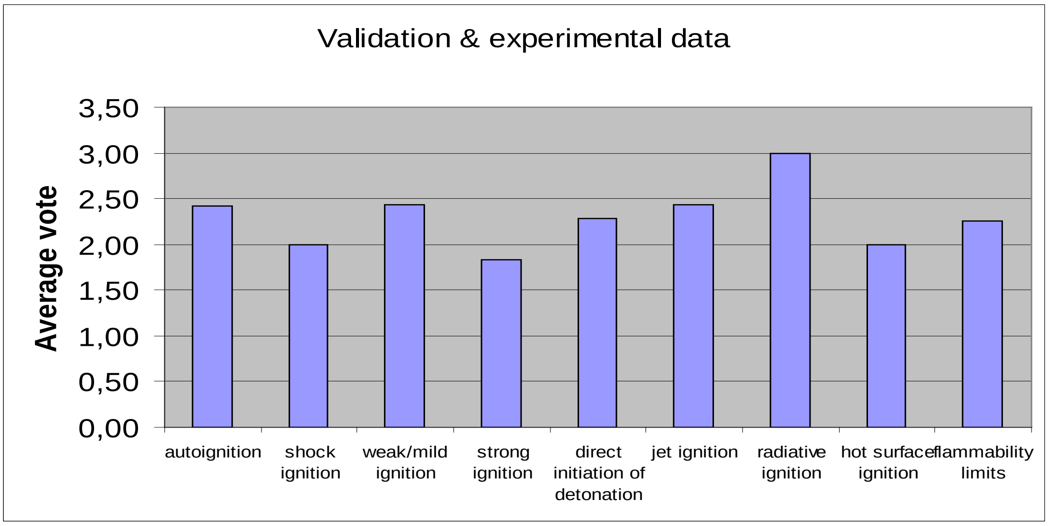

Figure 50 : Validation and experimental data for ignition

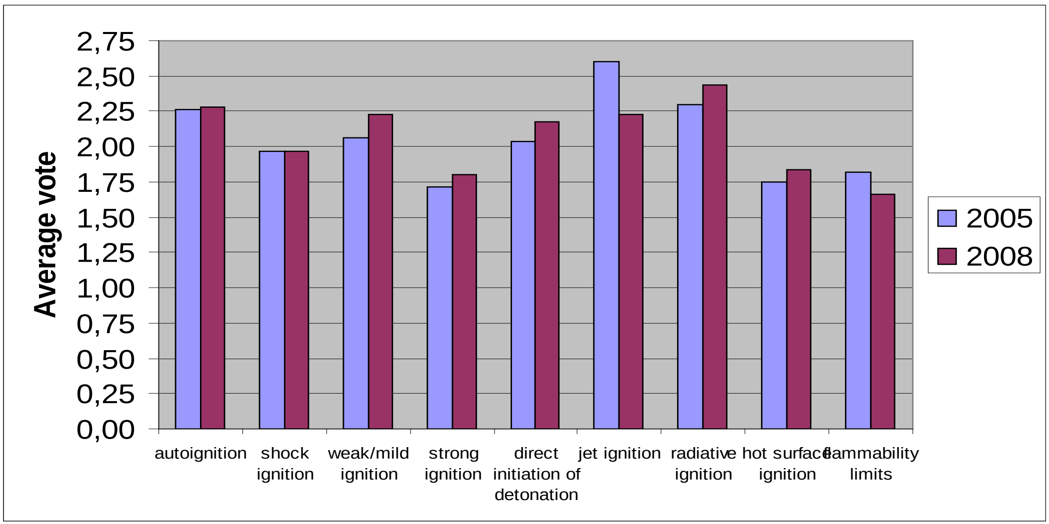

Figure 51 : Evolution of overall votes for ignition from 2005 to 2008

Conclusion for ignition:
In this category, there are two phenomena in the first category **autoignition** and **radiative ignition**. The results are very similar to those obtained in 2005, except for jet ignition which ranked 2.6 in 2005 and 2.2 in 2008. There was no justification provided for votes for ignition, only one comment "in general for ignition, good models lacking".

4.4.6. Combustion and explosion

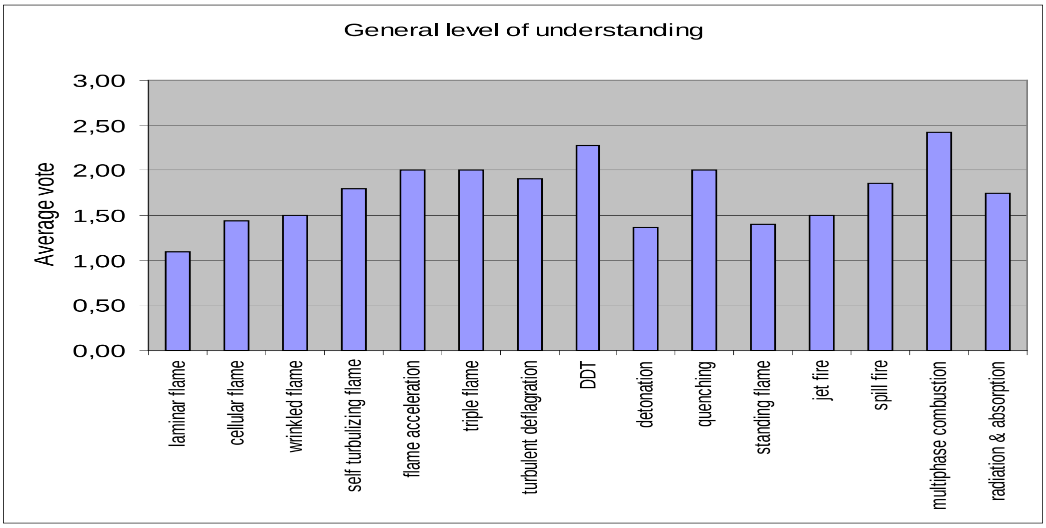

Figure 52 : General level of understanding for combustion and explosion

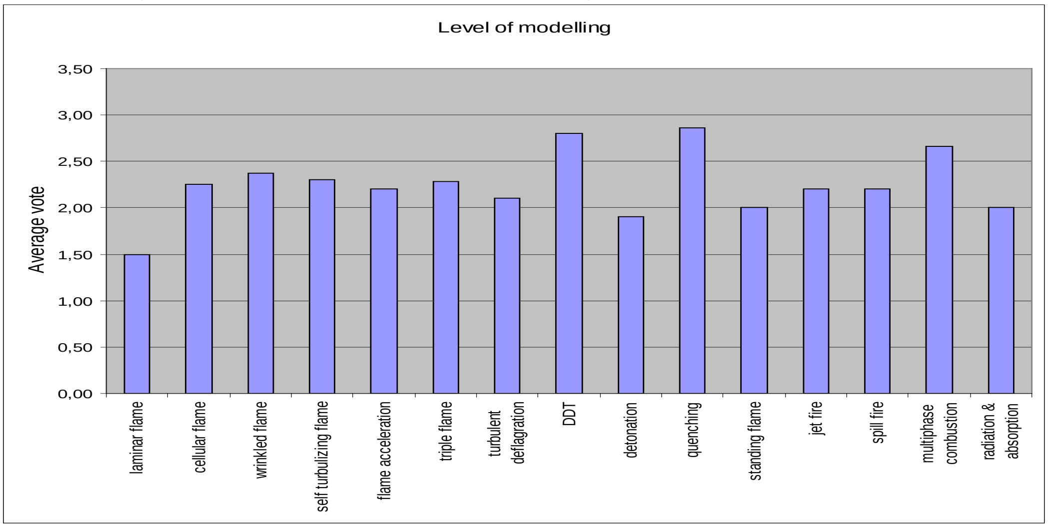

Figure 53: Level of modelling for combustion and explosion

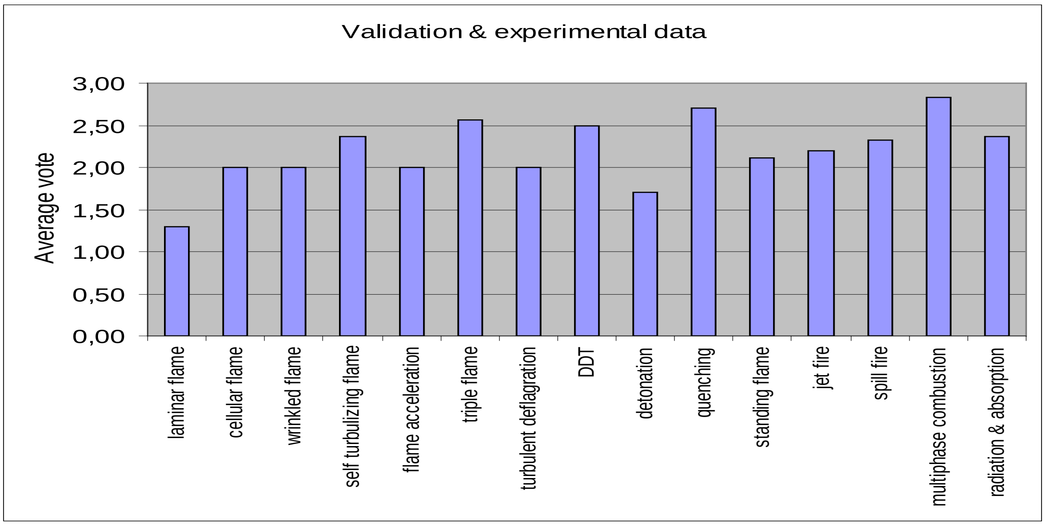

Figure 54: Validation and experimental data for combustion and explosion

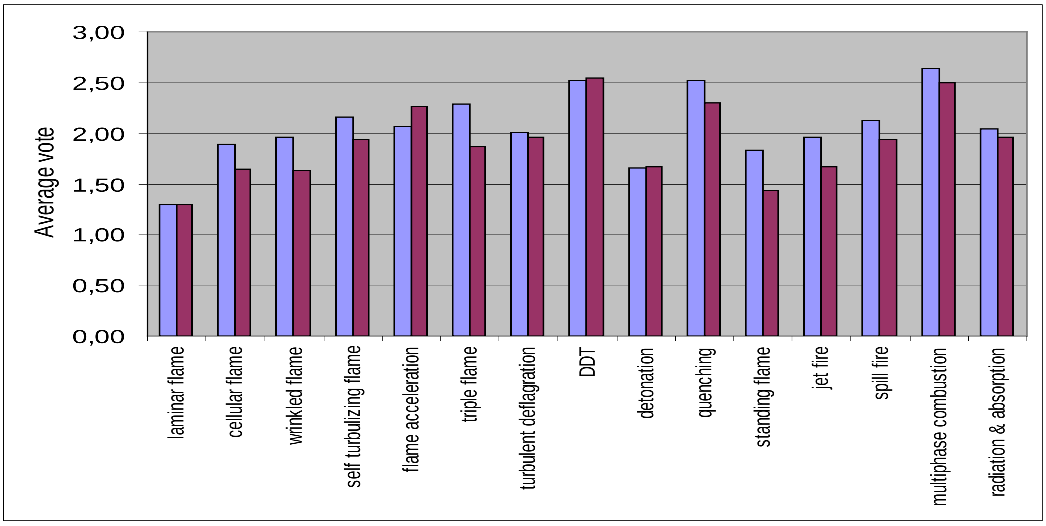

Figure 55 : Evolution of overall votes for combustion and explosion from 2005 to 2008

Comments and justification proposed by experts are:

Laminar flame: Generally well known; practical experience available. // Pb of scaling in large geometry: grid to recover the laminar flame velocity with a single step reaction
Cellular flame: Few experimental data available; additional experiments would be required. // Critical Peclet number see recent work of Leeds university (Bradley)
Wrinkled flame: Few experimental data available; additional experiments would be required // see "turbulent deflagration"
Self turbulizing flame: Few experimental data available; additional experiments would be required // see "cellular flame" because instabilities are responsible of self-turbulizing of flames
Flame acceleration: Direct simulation of these phenomena still offers some difficulties. Extrapolation of results from other flammable gases to H2 seems not directly possible. There is a lack of experiments on flame acceleration due to concentration gradients (non homogeneity) // see "turbulent deflagration" for concentration gradient, the recent work of ICARE lab
Triple flame: It would depend very much on the flammable gas properties. Existing or ongoing work for other gases may be not enough for H2.
Turbulent deflagration: It would depend very much on the flammable gas properties. Existing or ongoing work for other gases may be not enough for H2 // Phenomenological correlations exist in the literature to calculate Vf or St depending on mixture properties, temperature, pressure, geometry… these data are not universal but a large database exists (see S. dorofeev recent communications). CFD models exist where you provide Vf or St to compute premixed flame behaviour in complex geometry. At present time, no model exists where the feedback between fluid mechanics (dynamic and heat and mass transfer) and Vf or St is correctly modelled. Lack of predictive capabilities of CFD models. Few experiments in Hydrogen, scaling effect is very important especially in hydrogen combustion due to instabilities.

DDT: There is a lack of predictive models due to not well understood phenomena. Existing empirical correlations seem not to be enough for all the possible scenarios. // Scaling, 3D, only very simple configuration are modelled at present time see papers of Oran, Gamezo…
Detonation: It is relatively well understood and simulated if one does not want too fine details // for hydrogen combustion at large scale where the inner structure of the detonation wave is not very important

Quenching: Not well understood phenomena; a wide variety of effect can influence. More experiments would be required

Heat radiation & absorption: It could be difficult to model for complex geometrical conditions. // e.g. issue of impurities // integral models available (work of Houf, Schefer and Molina) - Few CFD models applied for standing flames or jet fire

Conclusion for combustion and explosion:
In this category, there are four phenomena in the first category **triple flame, transition from deflagration to detonation, quenching and multiphase combustion.** The overall ranking of combustion phenomena has slightly decreased for 2005 to 2008. The lack of predictive capabilities of CFD tools is pointed by the partners especially for DDT and turbulent combustion at large scale.

4.4.7. Mitigation

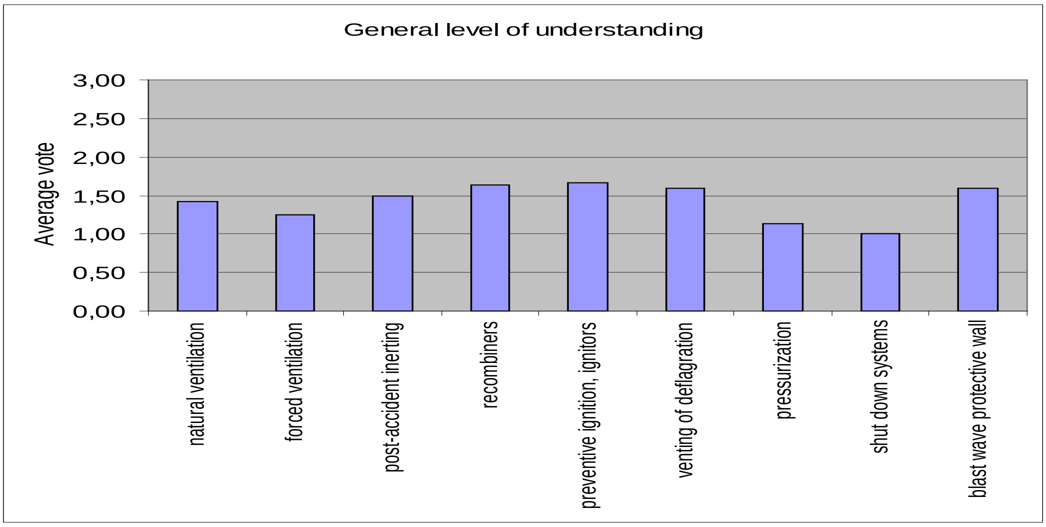

Figure 56 : General level of understanding for mitigation

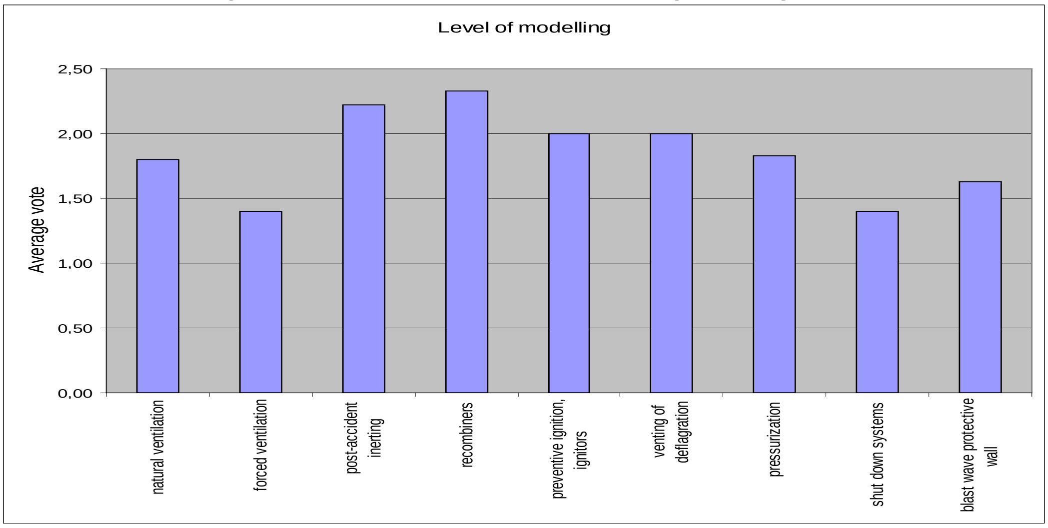

Figure 57 : Level of modelling for mitigation

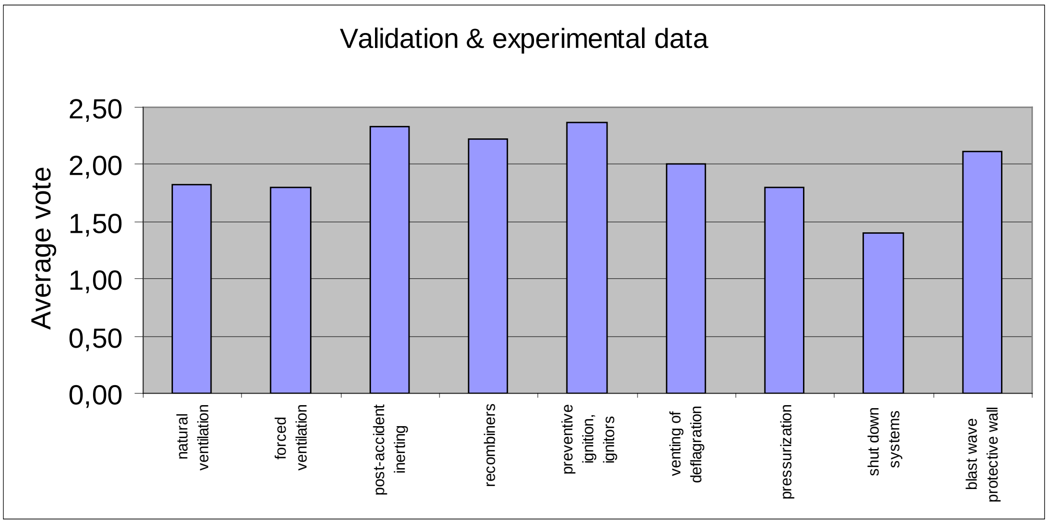

Figure 58 : Validation and experimental data for mitigation

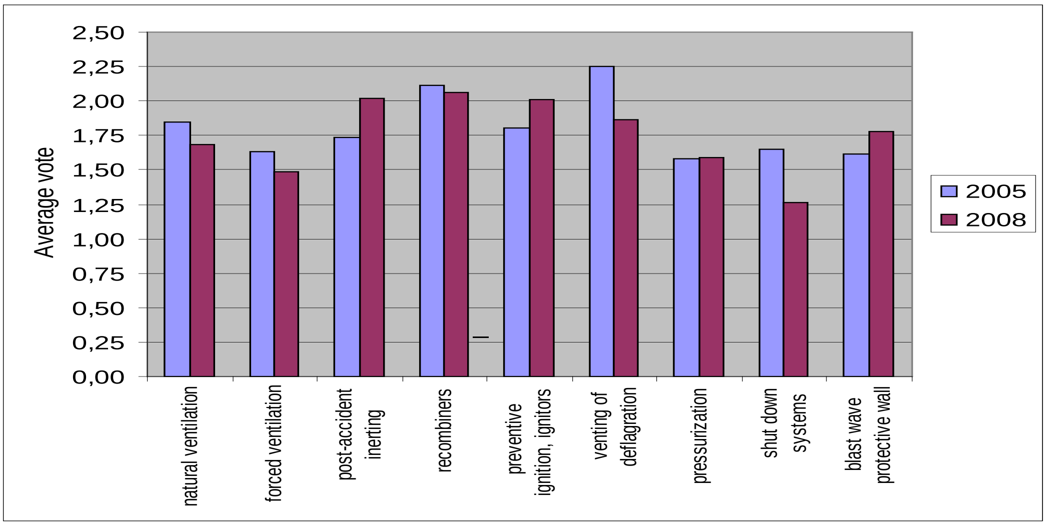

Figure 59 : Evolution of overall votes for mitigation from 2005 to 2008

Comments and justification proposed by the partners are:

Natural ventilation: Some work in Hyper // Recent progress within Hyper project and ICHS-2 // Coupled with the question of buoyancy effect, lack of experimental data at large scale. Some interesting data have been obtained within the NaturalHy project for mixture of hydrogen and methane (unpublished at present time), problem of accurate measurement of ventilation flow for CFD code validation + velocity and turbulence measurements at different points for CFD code validation, published data in Fire science
Forced ventilation: Lack of experimental datas with well-defined boundary conditions, foreseen experiments in the CEA garage facility (DIMITHRY project)
Post accident inerting: We think this is requiring additional research, including experiments
Recombiners: Recently, significant progress has been achieved in understanding phenomena and modelling the 'stand-alone' operational behaviour of recombiners. However, the interaction of recombiners with the surrounding atmosphere needs additional research efforts. This is an on-going research topic in NoE SARNET-2 (7th FP EURATOM). Numerous publications exist in the nuclear field, experimental data is mostly not public available. // We think this is requiring additional research, including experiments. // design dependent, lack of detailed experiment for CFD models
Venting of deflagrations: Not enough knowledge for obstructed enclosures. // It could result in the opposite effect if the flame is reanimated
Blast wave protective walls: Similarities to protective walls for other explosive materials // Large scale validation missing

Conclusion for mitigation:
In this category, no phenomenon was ranked in the first category; the highest score is for recombiners which scores 2.06. The general understanding of mitigation phenomena is considered as good, however, the lack of experimental data for models validation is emphasized by experts, especially for natural ventilation, forced ventilation, recombiners and venting of deflagrations. Despite the low ranking of these phenomena, it should be noted that this area of research is still very active (NATURALHY, HYSAFE, SARNET, DRIVE (French project), and several new projects are starting (SARNET2, DIMITRHY).

4.4.8. Conclusion on phenomena oriented votes

This step of the PIRT exercise, has enabled to rank the 60 phenomena involved accidental events. For each phenomenon, an average (over the partners vote) vote was calculated for the **general level of understanding**, the **level of modelling**, the **validation and experimental data**, then the **average** of the three votes was calculated.

The phenomena for which the average of three votes is above 2.25 are classified in the first group:

	Phenomena	Average vote
Gaseous releases	**permeation**	2.32
Liquid releases and spills	**liquid flow through orifice**	2.29
	full bore liquid or vessel rupture	2.38
	condensation/evaporation of air	2.27
Ignition	**autoignition**	2.28
	radiative ignition	2.44
Combustion	**triple flame**	2.28
	DDT	2.52
	quenching	2.52
	multiphase combustion	2.64

It is clear from this table that **liquid hydrogen behaviour** and **combustion and explosion** of hydrogen group the largest uncertainties and lack of knowledge.

On the opposite, no phenomenon related with dispersion or mitigation was ranked in the first group, expressing that these processes are well known, however the comments made by partners express a lack of experimental results (natural ventilation, forced ventilation, recombiners and venting of deflagrations).

When one compares the results of this vote to the results of the 2005 PIRT, it appears that the general trends are the same. It is not obvious to quantify the influence of recent research results on the votes. For example, concerning dispersion, projects like HySafe/Inshyde, Drive, Naturalhy, Hyper and other international programs have provided very valuable results but do not seem to influence the votes.

The classification of phenomena established for the first PIRT exercise was kept unchanged to allow for comparisons, however, some phenomenon were proposed by UU and should be considered for future PIRT exercises. These are Burning velocity of H2-air at low temperatures, Effect of natural leaks in enclosure on stratification, Blowdown phenomena, Lift-off, blow-off, blow-out, Microflames, Effect of geometry on spontaneous ignition, Direction of releases and jet fires on safety distance, Impinging jet fires, Non-uniform mixtures on combustion.

5. CONCLUSION

The PIRT (Phenomena Identification and Ranking Table) update exercise consists of three steps. The first step, named macro PIRT provides a general overview of safety issues and was performed during the WP7 meeting in September 2008. The second step which deals with the identification and ranking of accidental events (safety-oriented vote) and the third step, which focuses on the phenomena associated with the most important accidental events (phenomena-oriented vote), for the different applications, were conducted over the period September-November 2008. This document reports on the results of these three votes and provides comparison with results obtained in 2005.

The MACRO PIRT provides a rapid overview of the areas where attention should be focused. The general trend is the reduction of priority for all hazards. The highest priority in the MACRO PIRT is given to:

- **Fires and explosions in parking and tunnels.**
- **Mitigation in parking and tunnels.**

The two following steps, namely the safety and phenomena ranking provides more detailed and results.

The update of safety-oriented vote has highlighted a number of priorities among accidental events to be studied. These are:

- **Any accident involving the release of H2 into semi-confined or confined atmospheres, and this for many applications;**
- **Events that could lead to damage to tanks containing large quantities of H2 (road tankers, large scale storage at refuelling stations);**
- **Road safety and especially tunnel safety issues, for commercial vehicles as well as passenger cars**
- **Failure to follow “good practices” in maintenance workshops, refuelling stations, or scenes of accidents.**

The next step looks closely at the different phenomena relevant to the selected safety issues, and proposes a ranking of these phenomena according to our degree of knowledge (phenomena-based ranking).

The update phenomena-oriented vote provides a ranking of the 60 phenomena involved accidental events. The highest rankings are:

- **Combustion phenomena, such as triple flame, DDT, quenching and multiphase combustion**
- **Ignition phenomena**
- **Liquid releases and spills**
- **Permeation**

When one compares the results of this vote to the results of the previous exercise performed in 2005 it appears that the general trends are the same. However, it is not obvious to quantify the influence of recent research results on the votes. From this analysis, needs for better understanding and further research work are identified in the area of:

- Releases of liquid or gaseous hydrogen in enclosed areas like tunnels, parking or private garages.
- Releases of large quantities of liquid or gaseous hydrogen from refuelling stations or road tankers.
- Ignition, combustion and mitigation following these releases.
- Generally, acquisition of accurate experimental data, possibly at large scale for model validation.

Appendices

Safety-oriented votes

	Application	Type of Fuel storage	Environment	Event	Average	Standard deviation	#1	#2	#3	Total #
1: H1 Production							Level 1 vote	Level 2 vote	Level 3 vote	
	1.2 electrolysis (small scale at refueling station)		Urban	1.2.1 Mixing of oxygen/hydrogen inside process equiment	1,70	0,67	4	5	1	10
			Urban	1.2.2 Oxygen leak inside container	1,78	0,83	4	3	2	9
			Urban	1.2.3 Small hydrogen leak in confined areas	1,91	0,70	3	6	2	11
			Urban	1.2.4 Large leaks, equipment rupture in confined areas	2,80	0,42	0	2	8	10
			Urban	1.2.5 Large leak or equiment rupture causing reverse flow from downstream high pressure sections	2,78	0,44	0	2	7	9
			Urban	1.2.6 Flow of hydrogen into container (confined area) from leak outside container	1,90	0,57	2	7	1	10
			Urban	1.2.8 Flow from safety valve/relied openings in unsafe areas	2,11	0,60	1	6	2	9
	1.6 steam/methane reforming		Industrial zone	1.6.1 Natural gas feeding line rupture - Rupture of steel tube inside furnace - Line rupture after reforming (synthesis gas) - CO shift burst - PSA line rupture (rich hydrogen mixture) - line rupture after PSA (pure hydrogen mixture) - PSA vessel burst - PSA purge vessel burst	2,00	0,67	2	6	2	10
2 : H2 Transport and distribution							Level 1 vote	Level 2 vote	Level 3 vote	
	2.1 Pipeline GH2	GH2	Open	2.1.1 Continuous release from pipeline	1,55	0,69	6	4	1	11
		GH2	Open	2.1.2 Continuous release from compression station's fitting and connections	1,91	0,70	3	6	2	11

		GH2	Open	2.1.3 Instantaneous release from pipeline	2,40	0,70	1	4	5	10
		GH2	Open	2.1.4 Instantaneous release from compression station	2,50	0,71	1	3	6	10
	2.2 Pipeline LH2	LH2	Open	2.2.1 Continuous release from pipeline	1,55	0,52	5	6	0	11
		LH2	Open	2.2.2 Continuous release from pumping station	1,82	0,60	3	7	1	11
		LH2	Open	2.2.3 Instantaneous release from pipeline	2,10	0,74	2	5	3	10
		LH2	Open	2.2.4 Instantaneous release from pumping station	2,10	0,74	2	5	3	10
	2.3 Pipeline mixture NG/H2	GH2/NG	Open	2.3.1 Continuous release from pipeline	1,45	0,52	6	5	0	11
		GH2/NG	Open	2.3.2 Continuous release from compression station's fitting and connections	1,64	0,67	5	5	1	11
		GH2/NG	Open	2.3.3 Instantaneous release from pipeline	2,00	0,63	2	7	2	11
		GH2/NG	Open	2.3.4 Instantaneous release from pumping station	2,09	0,70	2	6	3	11
	2.4 Truck transport of compressed H2	GH2	Roads and motorways	2.4.1 Crash of GH2 Tanker on roads	2,42	0,51	0	7	5	12
		GH2	Tunnels and overbridge	2.4.2 Crash of GH2 Tanker in tunnel	2,92	0,29	0	1	11	12
		GH2	Urban	2.4.3 Discharge hose failure from GH2 Tanker at refuelling station	2,45	0,52	0	6	5	11
		GH2	Urban	2.4.4 Continuous release through faulty connection	1,91	0,30	1	10	0	11
	2.5 Truck transport of liquid H2	LH2	Roads and motorways	2.5.1 line rupture	2,64	0,50	0	4	7	11
		LH2	Roads and motorways	2.5.2 tank rupture	2,64	0,50	0	4	7	11
		LH2	Roads and motorways	2.5.3 flow inside tank in case of roll over	2,33	0,52	0	4	2	6
		LH2	Urban	2.5.4 Discharge hose failure from LH2 Tanker at refuelling station	2,40	0,52	0	6	4	10
		LH2	Tunnels and overbridge	2.5.5 Crash of LH2 Tanker in tunnel	3,00	0,00	0	0	11	11
	2.7 Sea transport of liquid H2	LH2	Harbour	2.7.1 Burst	2,36	0,67	1	5	5	11

		LH2	Harbour	2.7.2 line / tank rupture	2,30	0,67	1	5	4	10
3 : H3 Large scale storage, refuelling station, stationary applications							Level 1 vote	Level 2 vote	Level 3 vote	
	3.1 Hybride beds		inside buildings	3.1.1 Burst of tank	2,75	0,46	0	2	6	8
			inside buildings	3.1.2 Continuous relase of tank	2,13	0,83	2	3	3	8
	3.2 LH2 Tanks	LH2	Urban	3.2.1 Continuous release of tank in open atmosphere	1,75	0,62	4	7	1	12
		LH2	Urban	3.2.2 Instantaneous release of tank content in open atmosphere	2,08	0,67	2	7	3	12
		LH2	Urban	3.2.3 Instantaneous release of tank content in open atmosphere	2,08	0,79	3	5	4	12
		LH2	Urban	3.2.4 Instantaneous release of tank content in open atmosphere	2,00	0,74	3	6	3	12
		LH2	Urban	3.2.5 Instantaneous release of tank content in open atmosphere	2,00	0,60	2	8	2	12
		LH2	Urban	3.2.6 Continuous release in partially or totally confined atmosphere	2,42	0,67	1	5	6	12
		LH2	Urban	3.2.7 Instantaneous release in partially or totally confined atmosphere	2,75	0,45	0	3	9	12
		LH2	Roads and mototways	3.2.8 Overpressure in tank due to flow motion	2,25	0,46	0	6	2	8
		LH2	Urban	3.2.9 Overpressure in tank due to external heat release	2,40	0,52	0	6	4	10
	3.3 GH2 Tanks	GH2	Urban	3.3.1 Continuous release through valve in open atmosphere	1,64	0,50	4	7	0	11
		GH2	Urban	3.3.2 Continuous release in partially confined atmosphere	2,33	0,49	0	8	4	12

		GH2	Urban	3.3.3 Continuous release in open atmosphere	2,00	0,74	3	6	3	12
		GH2	Urban	3.3.4 Instantaneous release in open atmosphere	1,92	0,51	2	9	1	12
		GH2	Urban	3.3.5 Instantaneous release in partially confined atmosphere	2,50	0,52	0	6	6	12
		GH2	Urban	3.3.6 Instantaneous release in confined atmosphere	2,75	0,45	0	3	9	12
		GH2	Urban	3.3.7 Reverse flow of air into tank after release of H2	2,29	0,76	1	3	3	7
	3.4 Refueling station of cryogenic H2	LH2	Urban	3.4.1 Continuous release in open atmosphere	1,75	0,62	4	7	1	12
		LH2	Urban	3.4.2 Continuous release in partially confined atmosphere	2,33	0,49	0	8	4	12
		LH2	Urban	3.4.3 Instantaneous release in open atmosphere	2,08	0,79	3	5	4	12
		LH2	Urban	3.4.4 Instantaneous release in open atmosphere	1,83	0,83	5	4	3	12
		LH2	Urban	3.4.5 Instantaneous release in open atmosphere	1,92	0,79	4	5	3	12
		LH2	Urban	3.4.6 Instantaneous release in open atmosphere	1,83	0,72	4	6	2	12
		LH2	Urban	3.4.7 Instantaneous release in partially confined atmosphere	2,67	0,49	0	4	8	12
	3.5 Refueling station GH2	GH2	Urban	3.5.1 Release during refueling of vehicle	2,36	0,50	0	7	4	11
		GH2	Urban	3.5.2 Vehicle drives away during refueling	2,18	0,60	1	7	3	11
		GH2	Urban	3.5.3 Fire exposing high pressure storage tank	2,55	0,52	0	5	6	11
		GH2	Urban	3.5.4 Hose or pipe rupture in dispenser	2,55	0,52	0	5	6	11
		GH2	Urban	3.5.6 Overfilling of vehicle storage tank	2,22	0,44	0	7	2	9
		GH2	Urban	3.5.7 Releases in container (i.g. compressor container)	2,40	0,52	0	6	4	10
		GH2	Urban	3.5.8 Continuous release in open atmosphere	1,73	0,47	3	8	0	11
		GH2	Urban	3.5.9 Continuous release in partially confined atmosphere	2,33	0,49	0	8	4	12
		GH2	Urban	3.5.10 Instantaneous release in open atmosphere	2,25	0,75	2	5	5	12

		GH2	Urban	3.5.11 Instantaneous release in open atmosphere	1,92	0,67	3	7	2	12
		GH2	Urban	3.5.12 Instantaneous release in open atmosphere	2,00	0,74	3	6	3	12
		GH2	Urban	3.5.13 Instantaneous release in open atmosphere	1,75	0,62	4	7	1	12
		GH2	Urban	3.5.14 Instantaneous release in partially confined atmosphere	2,67	0,49	0	4	8	12
	3.7 Stationary application, Auxiliary power unit	GH2	inside buildings	3.7.1 Leaking from core, piping, ecc	2,20	0,42	0	8	2	10
		GH2	inside buildings	3.7.2 Release from cell purging	2,00	0,67	2	6	2	10
		GH2	inside buildings	3.7.3 Formation of explosive mixture outside the stack, small release rate	2,22	0,44	0	7	2	9
		GH2	inside buildings	3.7.4 Reverse electrolysis	2,17	0,41	0	5	1	6
		GH2	inside buildings	3.7.5 Membrane rupture	2,25	0,46	0	6	2	8
		GH2	inside buildings	3.7.6 Formation of explosive mixture inside the stack	2,22	0,67	1	5	3	9
		GH2	inside buildings	3.7.7 Feeding line rupture (from indoor gas storage)	2,63	0,52	0	3	5	8
		GH2	inside buildings	3.7.8 Explosive atmosphere in room; high release rate	2,70	0,48	0	3	7	10
		GH2	Urban	3.7.9 Release from cell purging	1,67	0,50	3	6	0	9
		GH2	Urban	3.7.10 Leaking from core, pipig, gasket	1,86	0,38	1	6	0	7
		GH2	Urban	3.7.11 Formation of explosive atmosphere outside the stack	2,22	0,44	0	7	2	9
		GH2 or LH2	inside buildings	3.7.12 Production of unconsumed H2 when FC is stopped. Process to neutralize the residual H2 (evacuate, inert)	1,88	0,64	2	5	1	8

4 : H4 Hydrogen Powerd vehicles							Level 1 vote	Level 2 vote	Level 3 vote	

	4.1 Commercial vehicles	GH2 or LH2	Roads and motorways	4.1.1 Vehicle crash / overturn / failure in car / stray bullet	2,18	0,60	1	7	3	11
		GH2 or LH2	Tunnels and overbridges	4.1.3 Vehicle accident/failure leading to damage of tank in tunnel	3,00	0,00	0	0	11	11
		GH2 or LH2	Tunnels and overbridges	4.1.4 Fire in tunnel	2,77	0,44	0	3	10	13
		GH2	Car parks and maintenance workshop	4.1.6 Process to neutralize residual H2 produced by FC when vehicle is stopped (evacuation, inerting) see 4.2.12 and	1,50	0,71	6	3	1	10
		GH2 or LH2	Car parks and maintenance workshop	4.1.7 car accident/failure leading to damage to tank in maintenance workshop	2,54	0,78	2	2	9	13
		GH2	Car parks and maintenance workshop	4.1.8 Permeation through the surface of pressure vessels and other components	1,62	0,77	7	4	2	13
		GH2	Car parks and maintenance workshop	4.1.9 Small leaks from components at joints, leaks	1,54	0,66	7	5	1	13
		GH2	Car parks and maintenance workshop	4.1.10 Relases from low pressure sections or almost empty storage systems	1,46	0,52	7	6	0	13
		GH2	Tunels and overbridge	4.1.11 Relases from high pressure	2,57	0,51	0	6	8	14
		GH2	Tunels and overbridge	4.1.12 Failure of vessel	2,46	0,66	1	5	7	13
		GH2	Tunels and overbridge	4.1.13 Catastrophic failure of storage system	2,69	0,63	1	2	10	13
		GH2	Roads and motorways	4.1.14 Release from high pressure storage	2,08	0,64	2	8	3	13
		GH2	Roads and motorways	4.1.15 Failure of vessel	2,00	0,58	2	9	2	13
		GH2	Roads and motorways	4.1.16 Catastrophic failure of storage system	2,31	0,63	1	7	5	13

		GH2	Open	4.1.17 Release via PRD	2,08	0,49	1	10	2	13
		GH2	Open	4.1.18 Release due to system damage or component failure (low pressure/small quantity)	1,46	0,66	8	4	1	13
		GH2	Open	4.1.19 Release due to system damage or component failure (high pressure/high quantity)	2,23	0,44	0	10	3	13
		GH2	Open	4.1.20 Small leak from components, joints, etc…	1,15	0,38	11	2	0	13
		GH2	Open	4.1.21 Container failure	2,00	0,82	4	5	4	13
		GH2	Urban	4.1.22 Release via PRD	2,08	0,49	1	10	2	13
		GH2	Urban	4.1.23 Release due to system damage or component failure (low pressure/small quantity)	1,38	0,51	8	5	0	13
		GH2	Urban	4.1.24 Release due to system damage or component failure (high pressure/high quantity)	2,15	0,55	1	9	3	13
		GH2	Urban	4.1.25 Small leak from components, joints, etc…	1,15	0,38	11	2	0	13
		GH2	Urban	4.1.26 Container failure	2,08	0,76	3	6	4	13
		GH2	Tunnels and overbridges	4.1.27 Release via PRD	2,69	0,48	0	4	9	13
		GH2	Tunnels and overbridges	4.1.28 Release due to system damage or component failure (low pressure/small quantity)	1,92	0,64	3	8	2	13
		GH2	Tunnels and overbridges	4.1.29 Release due to system damage or component failure (high pressure/high quantity)	2,86	0,36	0	2	12	14
		GH2	Tunnels and overbridges	4.1.30 leak from components	1,92	0,49	2	10	1	13
		GH2	Tunnels and overbridges	4.1.31 Container failure	2,54	0,66	1	4	8	13
		GH2	Car parks and maintenance workshop	4.1.32 Release via PRD	2,62	0,65	1	3	9	13
		GH2	Car parks and maintenance workshop	4.1.33 Release due to system damage or component failure (low pressure/small quantity)	2,00	0,58	2	9	2	13
		GH2	Car parks and maintenance workshop	4.1.34 Release due to system damage or component failure (high pressure/high quantity)	2,62	0,51	0	5	8	13

		GH2	Car parks and maintenance workshop	4.1.34 b leak from components	1,92	0,76	4	6	3	13
		GH2	Car parks and maintenance workshop	4.1.35 Permeation through pressure vessel walls	1,92	0,64	3	8	2	13
		GH2	Car parks and maintenance workshop	4.1.36 Container failure	2,62	0,51	0	5	8	13
		GH2	Car parks and maintenance workshop	4.1.37 System not purged before maintenance	2,10	0,57	1	7	2	10
		LH2	Open	4.1.38 Release via safety device	1,77	0,60	4	8	1	13
		LH2	Open	4.1.39 Release due to system damage or component failure	1,69	0,75	6	5	2	13
		LH2	Open	4.1.40 Small leaks from components, joints, etc… Probably gaseous downstream of container	1,31	0,63	10	2	1	13
		LH2	Open	4.1.41 Boil off	1,27	0,65	9	1	1	11
		LH2	Open	4.1.42 Container failure	1,85	0,90	6	3	4	13
		LH2	Urban	4.1.43 Release via safety device	2,00	0,58	2	9	2	13
		LH2	Urban	4.1.44 Release due to system damage or component failure	1,92	0,64	3	8	2	13
		LH2	Urban	4.1.45 Small leaks from components, joints, etc… Probably gaseous downstream of container	1,42	0,67	8	3	1	12
		LH2	Urban	4.1.46 Boil off	1,45	0,69	7	3	1	11
		LH2	Urban	4.1.47 Container failure	2,15	0,80	3	5	5	13
		LH2	Tunnels and overbridges	4.1.48 Release via safety device	2,54	0,66	1	4	8	13
		LH2	Tunnels and overbridges	4.1.49 Release due to system damage or component failure	2,62	0,51	0	5	8	13
		LH2	Tunnels and overbridges	4.1.50 Small leaks from components, joints, etc… Probably gaseous downstream of container	1,85	0,69	4	7	2	13
		LH2	Tunnels and overbridges	4.1.51 Boil off	1,82	0,75	4	5	2	11

		LH2	Tunnels and overbridges	4.1.52 Container failure	2,62	0,77	2	1	10	13
		LH2	Car parks and maintenance workshop	4.1.53 Release via safety device	2,38	0,65	1	6	6	13
		LH2	Car parks and maintenance workshop	4.1.54 Release due to system damage or component failure	2,62	0,51	0	5	8	13
		LH2	Car parks and maintenance workshop	4.1.55 Leaks from components	2,00	0,71	3	7	3	13
		LH2	Car parks and maintenance workshop	4.1.56 Boil off	2,09	0,70	2	6	3	11
		LH2	Car parks and maintenance workshop	4.1.57 Container failure	2,54	0,66	1	4	8	13
		LH2	Car parks and maintenance workshop	4.1.58 Sytem not purged before opening for maintenance	1,92	0,67	3	7	2	12
	4.2 Passenger car	GH2 or LH2	Roads and motorways	4.2.1 Car crash / overturn / failure in car / stray bullet	2,27	0,65	1	6	4	11
		GH2 or LH2	Tunnels and overbridges	4.2.3 Car accident/failure leading to damage of tank in tunnel	2,82	0,40	0	2	9	11
		GH2 or LH2	Tunnels and overbridges	4.2.4 Fire in tunnel	2,82	0,40	0	2	9	11
		GH2 or LH2	Car parks and maintenance workshop	4.2.6 Car accident/failure leading to damage to tank in public car park; high flow rate discharge	2,91	0,30	0	1	10	11
		GH2 or LH2	Car parks and maintenance workshop	4.2.7 car accident/failure leading to damage to tank in public car park; small flow rate leakage	2,00	0,63	2	7	2	11
		GH2 or LH2	Car parks and maintenance workshop	4.2.8 Fire in public car park	2,82	0,40	0	2	9	11
		GH2 or LH2	Car parks and maintenance workshop	4.2.10 Car accident/failure leading to damage to tank in private car park; high flow rate discharge	3,00	0,00	0	0	11	11
		GH2 or LH2	Car parks and maintenance workshop	4.2.11 car accident/failure leading to damage to tank in private car park; small flow rate leakage	2,09	0,54	1	8	2	11
		GH2 or LH2	Car parks and maintenance workshop	4.2.12 Car accident/failure leading to damage to tank in maintenance workshop; high flow rate discharge	2,91	0,30	0	1	10	11
		GH2 or LH2	Car parks and maintenance workshop	4.2.13 car accident/failure leading to damage to tank in maintenance workshop; small flow rate leakage	2,09	0,54	1	8	2	11

		GH2	Car parks and maintenance workshop	4.2.14 Process to neutralize residual H2 produced by FC when car is stopped (evacuation interting) (see 6.1.5)	1,44	0,53	5	4	0	9
		GH2 or LH2	Roads and motorways	4.2.15 Scene of a car crash, accidental rupture of H2 fuel lines by pneumatic pincer tools used by emergency services trying to free trapped passengers	2,64	0,50	0	4	7	11
		LH2	Car parks and maintenance workshop	4.2.16 boil-off	2,00	0,53	1	6	1	8
					14,00					

5 : H5 Other propulsion systems							Level 1 vote	Level 2 vote	Level 3 vote	
	5.1 Ships	All fuels	sea	5.1.1 Ship overturn	2,67	0,50	0	3	6	9
		All fuels	sea	5.1.2 Ship crash	2,56	0,73	1	2	6	9
		All fuels	sea	5.1.3 Ship rolling	2,29	0,49	0	5	2	7

6 : H6 Portable applications							Level 1 vote	Level 2 vote	Level 3 vote	
	6.1 Fuel cells	GH2	Inside buildings	6.1.1 leakings from core, piping, ecc	2,00	0,71	2	5	2	9
		GH2	Inside buildings	6.1.2 Release from cell purging	1,78	0,67	3	5	1	9
		GH2	Inside buildings	6.1.3 Formation of explosive mixture outside stack	2,44	0,53	0	5	4	9
		GH2	Inside buildings	6.1.4 Reverse electrolysis	2,00	0,00	0	5	0	5
		GH2	Inside buildings	6.1.5 Membrane rupture	2,00	0,00	0	8	0	8
		GH2	Inside buildings	6.1.6 formation of explosive mixture inside stack	2,11	0,60	1	6	2	9
		GH2	Inside buildings	6.1.7 Feed line rupture (from indoor gas storage)	2,67	0,50	0	3	6	9
		GH2	Inside buildings	6.1.8 Explosive mixture in room	2,78	0,44	0	2	7	9
		GH2	Urban	6.1.9 Release from cell purging	1,56	0,73	5	3	1	9
		GH2	Urban	6.1.10 Leaking from core, piping, gasket	1,50	0,53	4	4	0	8
		GH2	Urban	6.1.11 Formation of explosive atmosphere outside stack	2,25	0,46	0	6	2	8
		GH2 or LH2	Inside buildings	6.1.12 Production of unconsumed H2 when FC is stopped. Process to neutralize the residual H2 (evacuate, inert)	1,63	0,74	4	3	1	8

Phenomena-oriented votes

Gaseous releases

Phenomena	General level of understanding	Level of modelling	Validation & experimental data	Overall vote
permeation	1,89	2,50	2,57	2,32
subsonic release	1,17	1,36	1,70	1,41
chocked flow release	1,73	1,70	1,90	1,78
full bore or vessel rupture	1,91	1,90	2,40	2,07
turbulent flow in pipes	1,42	1,55	1,70	1,55

Liquid releases & spills

Phenomena	General level of understanding	Level of modelling	Validation & experimental data	Overall vote
liquid flow through orifice	2,10	2,33	2,44	2,29
full bore liquid or vessel rupture	2,00	2,50	2,63	2,38
formation of spill-pool spreading	1,82	2,10	2,40	2,11
spill evaporation	1,64	2,10	2,40	2,05
two-phase flow in liquid	1,80	2,11	2,44	2,12
heat transfer from ground	1,82	2,20	2,60	2,21
condensation/evaporation of air	1,90	2,67	2,56	2,37

Explosion of liquid storage

Phenomena	General level of understanding	Level of modelling	Validation & experimental data	Overall vote
heat conduction in storage	1,50	1,60	2,00	1,70
BLEVE	1,82	2,33	2,33	2,16

Dispersion

Phenomena	General level of understanding	Level of modelling	Validation & experimental data	Overall vote
impinging jets	1,66	1,91	2,10	1,89
turbulence	1,75	2,00	1,91	1,89
effect of obstacles	1,50	2,00	1,91	1,80
atmospheric conditions incl. Wind	1,67	1,91	2,00	1,86
heat transfers from environment	1,78	2,12	2,38	2,09
natural ventilation	1,42	2,00	2,10	1,84
forced ventilation	1,17	1,50	1,70	1,46
buoyancy effects	1,58	2,00	2,10	1,89
stable stratification	1,91	2,00	2,10	2,00
turbulent mixing	1,75	1,82	2,10	1,89
mixing in decay conditions	1,81	2,10	2,20	2,04
laminar diffusion	1,25	1,45	1,72	1,47
compressible effects	1,82	2,00	2,30	2,04

Ignition

Phenomena	General level of understanding	Level of modelling	Validation & experimental data	Overall vote
autoignition	2,00	2,42	2,42	2,28
shock ignition	1,65	2,25	2,00	1,97
weak/mild ignition	1,75	2,50	2,43	2,23
strong ignition	1,57	2,00	1,83	1,80
direct initiation of detonation	1,87	2,38	2,28	2,18
jet ignition	1,75	2,50	2,43	2,23
radiative ignition	2,20	2,12	3,00	2,44
hot surface ignition	1,38	2,12	2,00	1,83
flammability limits	1,11	1,63	2,25	1,66

Combustion et explosion

Phenomena	General level of understanding	Level of modelling	Validation & experimental data	Overall vote
laminar flame	1,10	1,50	1,30	1,30
cellular flame	1,44	2,25	2,00	1,90
wrinkled flame	1,50	2,37	2,00	1,96
self turbulizing flame	1,80	2,30	2,37	2,16
flame acceleration	2,00	2,20	2,00	2,07
triple flame	2,00	2,28	2,57	2,28
turbulent deflagration	1,91	2,10	2,00	2,00
DDT	2,27	2,80	2,50	2,52
detonation	1,36	1,90	1,70	1,65
quenching	2,00	2,86	2,71	2,52
standing flame (global or local)	1,40	2,00	2,11	1,84
jet fire	1,50	2,20	2,20	1,97
spill fire	1,86	2,20	2,33	2,13
multiphase combustion	2,42	2,66	2,83	2,64
heat radiation & absorption	1,75	2,00	2,37	2,04

Mitigation

Phenomena	General level of understanding	Level of modelling	Validation & experimental data	Overall vote
natural ventilation	1,42	1,80	1,82	1,68
forced ventilation	1,25	1,40	1,80	1,48
post-accident inerting	1,50	2,22	2,33	2,02
recombiners	1,64	2,33	2,22	2,06
preventive ignition, ignitors	1,67	2,00	2,37	2,01
venting of deflagration	1,60	2,00	2,00	1,87
pressurization	1,14	1,83	1,80	1,59
shut down systems	1,00	1,40	1,40	1,27
blast wave protective wall	1,60	1,63	2,11	1,78