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NETWORK OF EXCELLENCE

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Report on Phenomena / Scenario Ranking: Results of the PIRT (Phenomena Identification and Ranking Table) exercise

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EXECUTIVE SUMMARY

This document reports on the results of the PIRT (Phenomena Identification and Ranking Table) exercise conducted during the first 18 months of the HYSAFE project. The report first recalls the results of the safety-oriented votes or scenario ranking, and then on the phenomena-oriented votes, i.e. the ranking of the phenomena which reflects the current knowledge and state of the art.

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.

The PIRT exercise consists of two steps. The first step, which deals with the identification and ranking of accidental events (*safety-oriented vote*) for the different applications, was conducted over the period August – December 2004. The second step, which focusses on the phenomena associated with the most important accidental events (*phenomena-oriented vote*), was conducted over the period January – October 2005.

This document will report on the results of both votes, 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. IDENTIFICATION OF EVENTS AND PHENOMENA

2.1 Identification of accidental events

The first task of the PIRT exercise was to establish a list of accidental events. This was performed in an iterative manner, with additional input being provided continuously. The list was organised in terms of applications – the horizontal lines of the so-called HYSAFE matrix. These were actually modified to better account for the evaluation of risks and consequences, and lead to 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. This list is by no means final – and will be updated in the next years, with hopefully, more input in the application fields which were under-represented (H1: production, H2: transport and distribution, H5: other propulsion systems and H6: portable applications).

2.2 Identification of phenomena

The identification of phenomena was performed during the second step of the PIRT exercise, during a WP4 meeting organised in Warsaw, June 2005. 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**
  - Laminar flame
  - 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

3. RANKING

3.1 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; It was asked to justify each Level 3 vote.
- 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 and with limited consequences.
- 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.

3.2 Ranking of phenomena

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

- Vote **level 1**: the phenomenon is well understood. The processes are adequately modeled 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 phenomemon 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 modeling (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. WHO VOTED ?

4.1 Safety-oriented votes (Scenario ranking)

The table of events was sent to all the members of the HYSAFE project (25 partners), and to the Advisory Committee, which provided two independent votes (V. Tam of BP, and A. Tchouvalev of Stuart Energy). Among the HYSAFE partners, BAM and JST did not participate. JRC chose not to participate, and expressed several concerns, among which the fact that votes should only be cast by experts in the field, since "non-expert" votes could affect the results by artificially averaging the result. Actually, the choice of casting a vote was left to each organisation (Level 0 vote or abstention), and in many cases, this was done, with the number of votes per event ranging from 3 to 24. This is illustrated in figure 1.

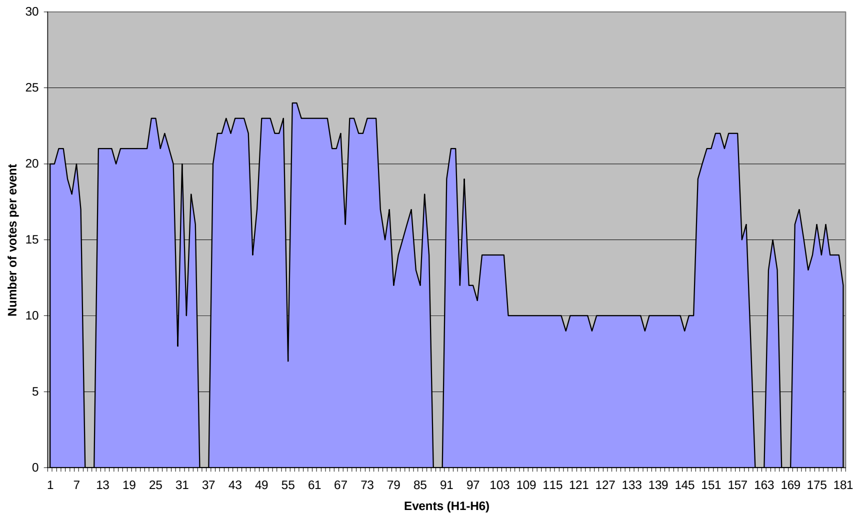

Fig. 1: Distribution of non-zero votes according to the different events (H1-H6): events received from 3 to 24 votes.

Another concern of JRC was that the ranking of events should not only be based on the average of the votes but on the distributions between Level 1, Level 2 and Level 3 votes: important events can indeed be overlooked if they have bimodal vote patterns (a high number of Level 1 and Level 3 votes which "cancel" each other). Actually, as was presented at the Paris meeting in December 2004, bimodal events were also identified and singled out for further discussions and ranking. This is explained in the following section.

4.2 Phenomena-oriented votes

For the phenomena-oriented votes, votes were received from 13 HYSAFE members, BMW, BRE, CEA, Fh-ICT, FZK, FZJ, GexCon, NCSRD, U. Calgary, UPM, U. Ulster and WUT. Comments were also received from UNIPI. Thus, mainly universities and research organizations responded. In addition, 4 members of the Advisory Council, Dr. Dorofeev, Dr. Tchouvalev, Prof. Bjerkevedt and Dr. Hirano, provided votes. Thus up to 17 votes were received to rank phenomena.

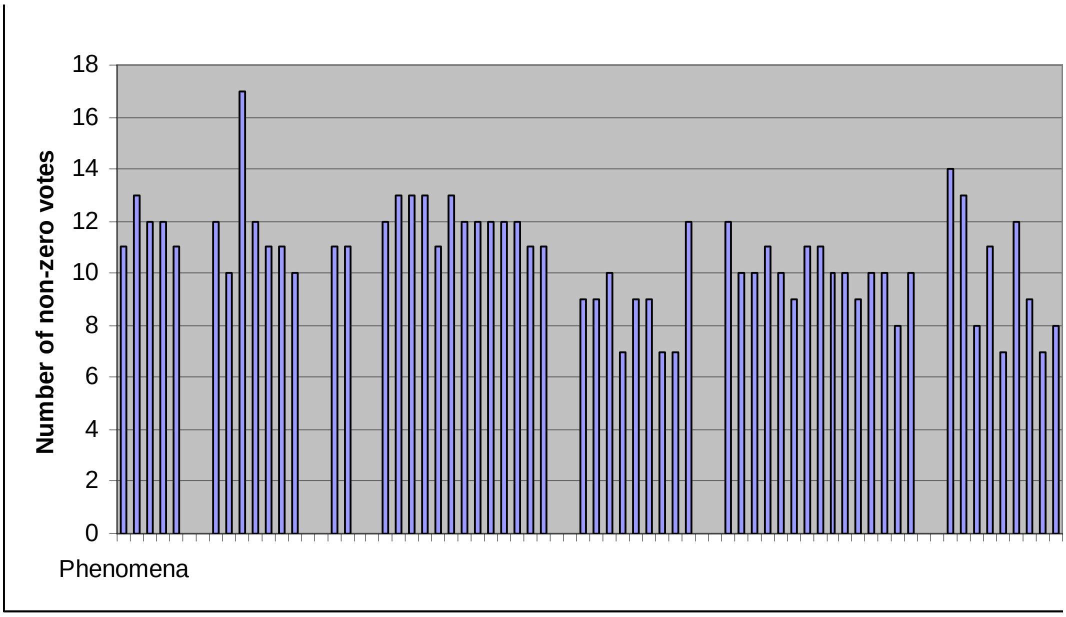

Fig. 2: Distribution of non-zero votes for the phenomena.

Fig. 2 shows the distribution of votes received for the phenomena ranking. Phenomena received between 7 and 17 votes, and on average, about 10 votes.

5. RESULTS OF SAFETY-ORIENTED VOTE

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). A minimum number of votes per event are also required. It is proposed therefore to discard events which have received less than a third of all possible votes. Here, with 24 organisations or individual experts participating in the safety ranking, the threshold for considering events is therefore set at 8. All events which received fewer than 8 votes were therefore discarded.

For the rest of the events, 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[1]
- 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.

- Group B: events which have a bimodal vote

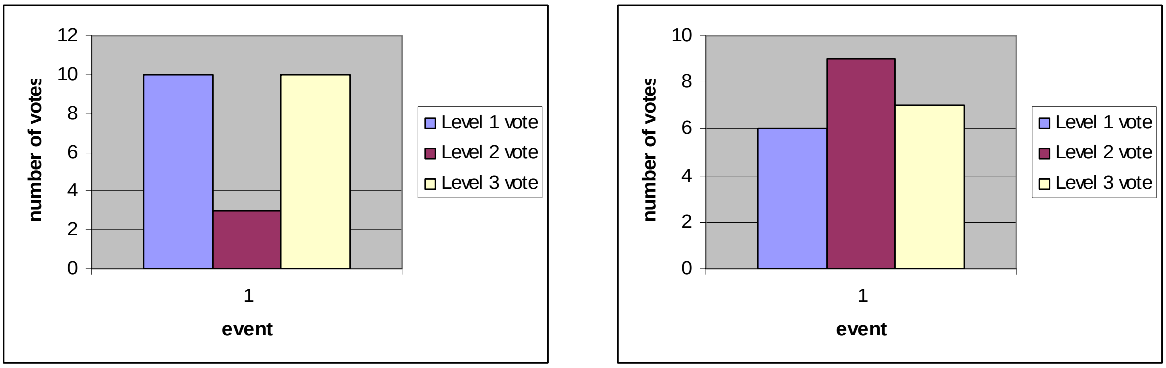

Fig. 3: Example of bimodal distributions which require a close analysis: strongly bimodal vote distribution (left) and near-uniform vote distribution (right)

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).

[1] The limit of 2.25 is artificial. A higher limit will lead to fewer selected events, a lower value to a higher number of events. The effect of the threshold is examined in section 6 of the present document.

5.1 Production (H1)

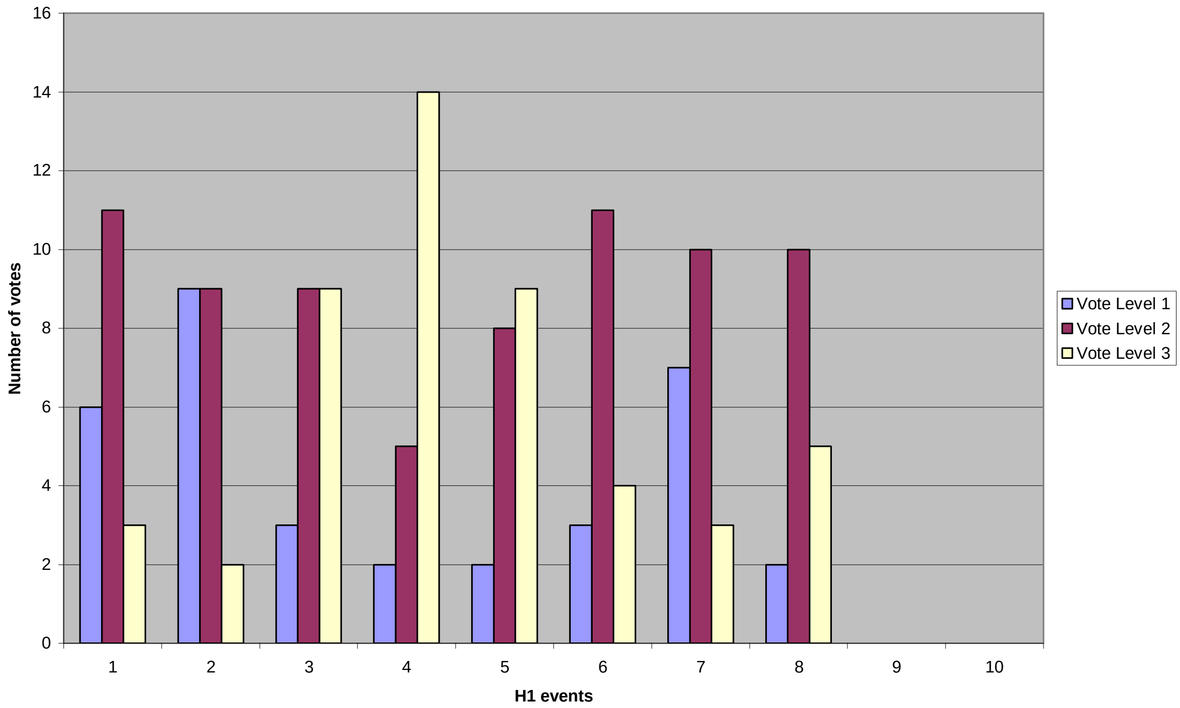

Fig. 3: Distribution of votes for H1 events

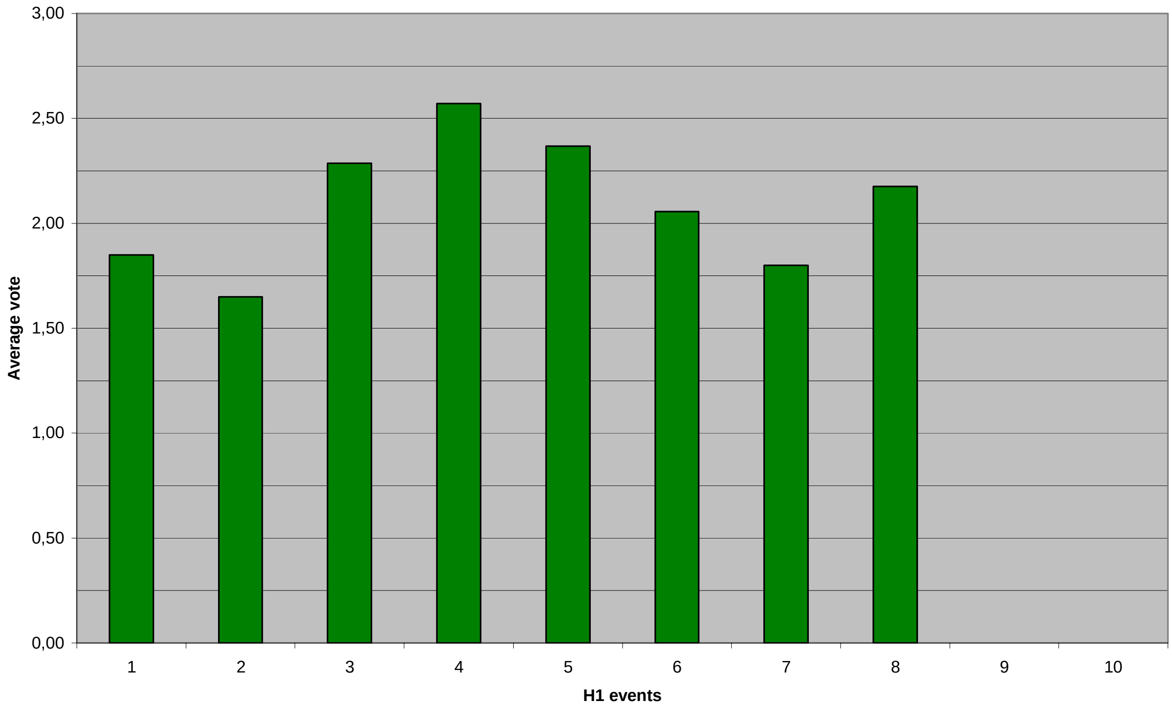

Fig. 4: Average votes for H1 events

Only 8 accidental events were identified for H2 production systems, and a clear majority for electrolysis systems. This is clearly not exhaustive, and a more in-depth analysis of production systems and associated accident scenarios will have to be performed in the future. A high number of votes (between 17 and 21) were received for the 8 events. The results are:

- Group 1: 3 events (37.5%)
- Group 2: 2 events (25%)
- Group 3: 3 events (37.5%)
- Group B: no events (0%)

The 3 events (37.5%) 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 1.2.3 small hydrogen leak in confined areas (**2.29**)
    - Event 1.2.4 large leaks due to equipment rupture, inside container (**2.57**)
    - Event 1.2.5 large leak or equipment rupture leading to reverse flow from downstream high pressure section (**2.37**)

Justifications for the Level 3 votes in Group 1 were given as:

Event 1.2.3:

- accumulation of H2 with time resulting in destructive overpressures in case of ignition
- might lead to explosive atmosphere
- High probability .Might lead to gas accumulation, dependent on detection, ventilation and shutdown system
- if not good ventilation and hydrogen monitoring equipment installed
- Due to presence of people, relatively small effects have large consequences; Frequency of occurrence could be very significant
- high probability; confined areas, so not dispersion; damage are dependent on the accumulation

Event 1.2.4:

- Vote 3 due to conjonction of confined area in urban area.
- potentially high release rate of H2 and large amount of fuelmass leads to a large cloud of H2/air mixture
- High probability of catastrophic consequences. Special safety measures should be taken.
- Might lead to explosive atmosphere
- Confined area, persons present, high release rate
- Proximity human to source

Event 1.2.5:

- Vote 3 due to conjonction of confined area in urban area.
- High probability of catastrophic consequences. Special safety measures should be taken.
- Might lead to explosive atmosphere
- Very high trelease rate in confined area. Measures to prevent this has to be installed (and often are)
- Jet fire, transition to detonation

<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.

5.2 Transport and distribution (H2)

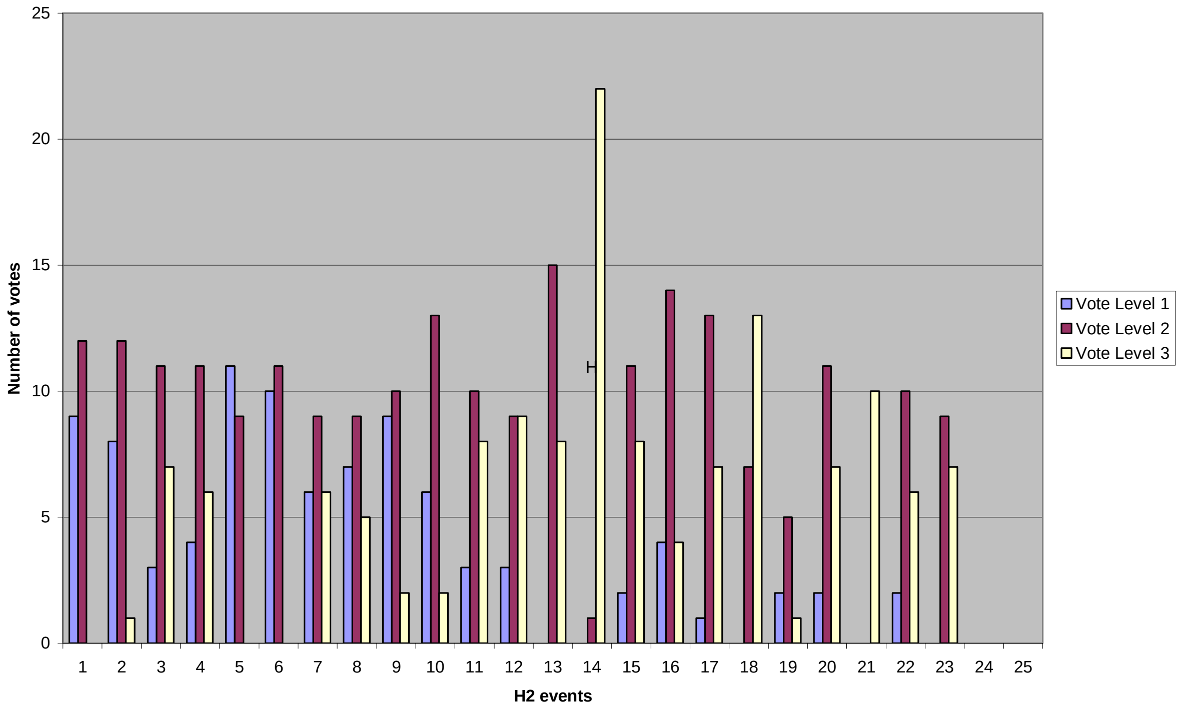

Fig. 5: Distribution of votes for H2 events

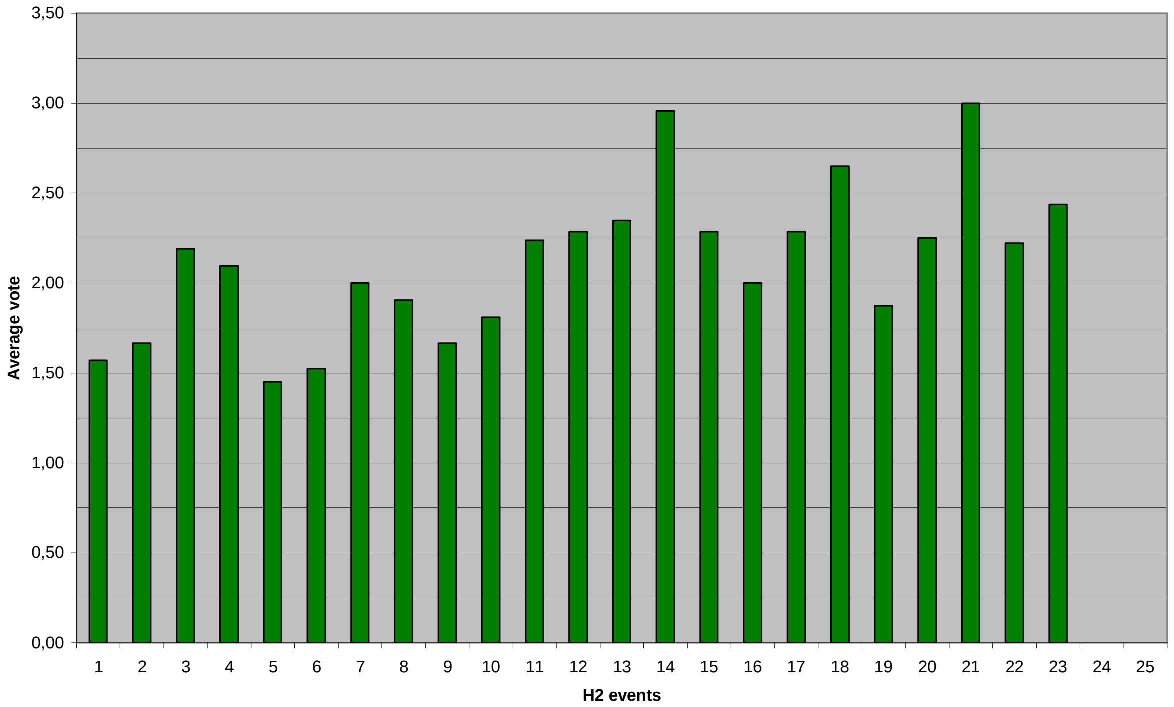

Fig. 6: Average votes for H2 events

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 (to be studied in the NATURALHY

project), truck transport of GH2 or LH2 and sea transport of GH2 or LH2. Generally, a high number of votes were expressed, from 18 to 23. Two events which were incorporated recently received a fewer number of votes (organisations did not always vote on those), between 8 and 10. Among the 23 events, 9 are ranked in the first group, with averages above 2.25. These are:

- Application 2.3 pipeline carrying mixtures of NG and H2:
  - event 2.3.4: instantaneous release from compression station (**2.29**)
- Application 2.4 truck transport of compressed GH2
  - event 2.4.1 crash of GH2 tanker on roads (**2.35**)
  - event 2.4.2 crash of GH2 tanker in tunnels (**2.95**)
  - event 2.4.3 discharge hose failure from GH2 tanker at refuelling station (**2.29**)
- Application 2.5 truck transport of LH2
  - event 2.5.1 line rupture (caused by a road accident) (**2.29**)
  - event 2.5.2 tank rupture (caused by a road accident) (**2.65**)
  - event 2.5.4 discharge hose failure from LH2 tanker at refuelling station (**2.25**)
  - event 2.5.5 crash of LH2 tanker in tunnels (**3.0**)
- Application 2.7 sea transport of LH2
  - event 2.7.2 line or tank rupture at a harbour location (**2.44**)

An additional event, 2.3.3 (instantaneous release from pipeline carrying a mixture of NG and H2) score **2.24**, extremely close to the threshold of 2.25, so that it should also be considered. Likewise, event 2.7.1 (burst of tank aboard LH2 transport ship) scored **2.22** and should also be considered. Thus, 11 events fall into the first group of events (48% of all events). There are 3 events in Group 2, 8 events in Group 3 and 1 bimodal vote,

- Application 2.2 LH2 pipeline
  - event 2.2.3 (instantaneous release from LH2 pipeline) (29% Level 1 votes and 29% Level 3 votes).

Justifications for the Level 3 votes in Group 1 were:

Events 2.3.3 and 2.3.4:
- consequences similar to Belgian accident in Summer 2004
- High probability of catastrophic consequences. Special safety measures should be taken.
- Jet fire, fireball, detonation
- hydrogen in confined geometry may form explosive mixture with air
- Important to know whether current design standard is adequate. This could determine how much hydrogen could be accommodated in current pipeline network.

Event 2.4.1:
- potentially high release rate of H2 and large amount of fuelmass leads to a large cloud of H2/air mixture
- Fire may occur leading to overpressures, PRD activation and large H2 release. H2 deflagration and possible DDT depending on local confinement
- Large consequences in case of tank rupture
- in the case of release with istant ignition the consequences can be severe (fatal injuries to people)
- Jet fire, fireball, detonation

Event 2.4.2 :

- Due to the confinement
- scope of consequences
- large amounts of H2 in confined area. Risk of deflagration or DDT
- potentially high release rate of H2 and large amount of fuel mass leads to a large cloud of H2/air mixture with DDT potential
- possibility of explosion with fatal injuries to people
- High probability of catastrophic consequences. Special safety measures should be taken.
- Fire may occur leading to overpressures, PRD activation and large H2 release. H2 deflagration and possible DDT
- Large consequences in case of tank rupture
- semi-confined places, so accumulation, so very severe event; all other means of transport could be an ignition source
- Medium probability (1/year), partial confinement, risk of fatalities
- Detonation
- hydrogen in confined geometry may form explosive mixture with air

Event 2.4.3:
- Large release rate inside the RS. Possible deflagration and DDT depending on local confinement
- Urban area, high probability, potentially large release rate
- the consequences can be severe (fatal injuries to people)
- Jet fire

Event 2.5.1
- High probability of catastrophic consequences.
- Large release rate. Possible BLEVE
- High tank pressure, large release rate
- in the case of release with instant ignition the consequences can be severe (fatal injuries to people)
- Deflagration likely to be followed by DDT

Event 2.5.2:
- scope of consequences
- High probability of catastrophic consequences.
- Very large leak. Possible BLEVE
- High tank pressure, large release rate
- the consequences can be severe (fatal injuries to people)
- Deflagration likely to be followed by DDT

Event 2.5.4:
- Large release rate inside the RS. Possible BLEVE
- the consequences can be severe (fatal injuries to people)
- Pool fire, possibly followed by fireball

Event 2.7.1:
- Projectiles
- the consequences can be severe (fatal injuries to people)
- Pool fire, possibly followed by fireball

Event 2.7.2:
- Pool fire, possibly followed by fireball
- if the ignition happens, the consequences can be severe (fatal injuries to people)

- Very large release. Possible BLEVE
- High probability of catastrophic consequences. Special safety measures should be taken.

<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 tunel) scored the highest averages (resp. 2.96 and 3.0) of all events – over all applications, underlying the importance of addressing tunnel safety issues (this is done under H4 for commercial vehicles and passenger cars), especially with vehicles transporting large quantities of H2 such as tankers (probably those vehicles would not be allowed in tunnels anyway). 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**.
Issues related to pipeline transport generally scored less, expressing perhaps that this is an industrial practice with high safety records, or that these pipelines are situated in less populated areas than those through which H2 tankers would circulate. There is one exception, namely **instantaneous release of H2 from pipeline**, which score 2.19 in for GH2 pipelines (Group 2) and which had a bimodal distribution with an average of 2.0 for LH2 pipeline (Group B). These issues need to be investigated further.

5.3

Large scale storage, refueling stations and stationary applications(H3)

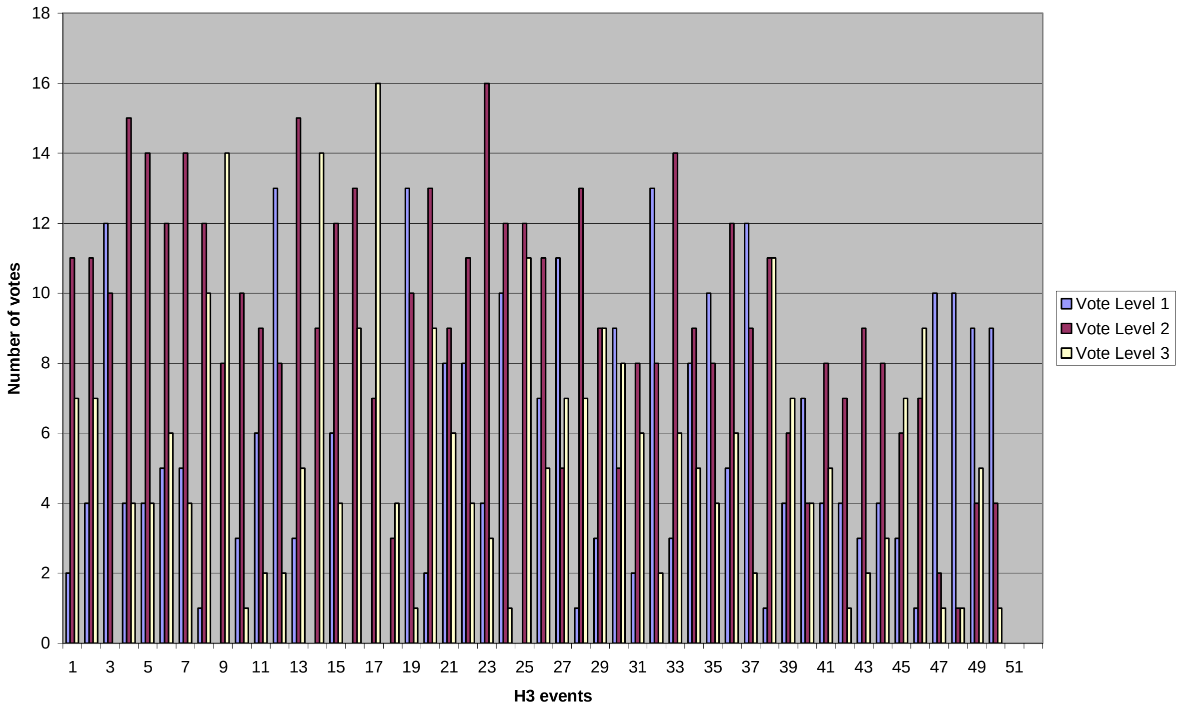

Fig. 7: Distribution of votes for H3 events

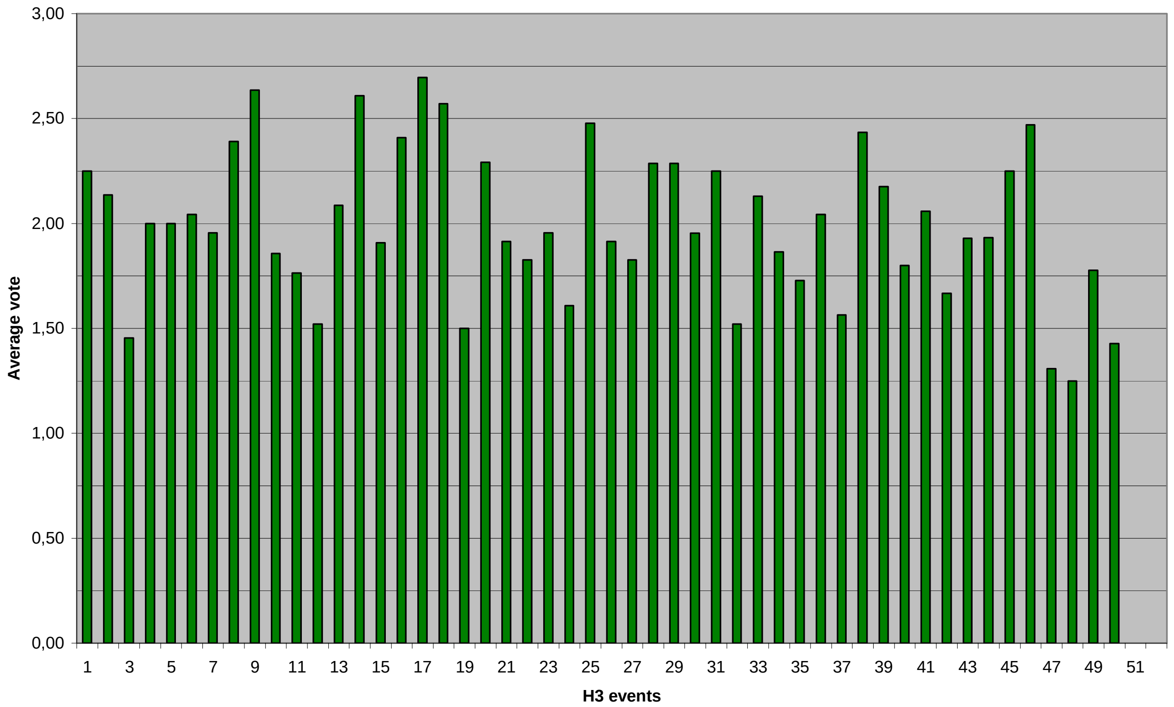

Fig. 8: Average votes for H3 events

50 events were identified for the H3 application (large scale storage, refuelling stations and stationary applications). The number of votes ranged from 7 (an event which was identified at

the PIRT meeting on December 3, 2004 – and which consequently did not receive a high number of votes) to 24. 15 of the events have been ranked into group 1 (average greater or equal to 2.25), 9 events fall in Group 2, and 21 events fall in Group 3. There are also a number of bimodal votes (5) that need to be examined more closely.

Events in Group 1 are:

- Application 3.1 Hydride beds
    - Event 3.1.1 Burst of tank inside building (**2.25**)
- Application 3.2 LH2 tanks
    - Event 3.2.6 Continuous release in partially confined or totally confined atmosphere (**2.39**)
    - Event 3.2.7 Instantaneous release in partially confined or totally confined atmosphere (**2.64**)
- Application 3.3 GH2 tanks
    - Event 3.3.3 Continuous release in confined atmosphere (**2.61**)
    - Event 3.3.5 Instantaneous release in partially confined atmosphere (**2.41**)
    - Event 3.3.6 Instantaneous release in confined atmosphere (**2.70**)
    - Event 3.3.7 Reverse flow of air into tank after release of H2 (**2.57**)
- Application 3.4 Refuelling station LH2
    - Event 3.4.2 Continuous release in partially confined atmosphere (**2.29**)
    - Event 3.4.7 Instantaneous release in partially confined atmosphere (**2.48**)
- Application 3.5 Refuelling station GH2
    - Event 3.5.3 Fire exposing high pressure storage tank (**2.29**)
    - Event 3.5.4 Hose or pipe rupture in dispenser (**2.29**)
    - Event 3.5.7 Releases in containers (**2.25**)
    - Event 3.5.14 Instantaneous release in partially confined atmosphere (**2.43**)
- Application 3.7 Stationary application: Auxiliary Power Unit (inside building)
    - Event 3.7.7 Feeding line rupture (**2.25**)
    - Event 3.7.8 High release rate leading to explosive mixture in room (**2.47**)

Events in Group B are:

- Application 3.4 Refuelling station LH2
    - Event 3.4.3 Instantaneous release in open atmosphere (35% Level 1 votes, 26% Level 3 votes)
- Application 3.5 Refuelling station GH2
    - Event 3.5.2 Vehicle drives away while refuelling (48% Level 1 votes and 30% Level 3 votes)
    - Event 3.5.6 Overfilling of vehicle storage tank (41% Level 1 votes and 36% Level 3 votes)
- Application 3.7 Stationary application: Auxiliary Power Unit (inside building)
    - Event 3.7.2 Release from cell purging (47% Level 1 votes and 27% Level 3 votes)
    - Event 3.7.11 Formation of explosive atmosphere outside stack (50% Level 1 votes and 28% Level 3 votes)

The justifications for the Level 3 votes for the events in Group 1 are:

Event 3.1.1:

Event 3.2.6:

- accumulation of H2 in confined area can cause explosion, DDT
- Might lead to explosive atmosphere
- if in confined area
- if not venting & detection measures established
- Due to presence of people, relatively small effects have large consequences; Frequency of occurrence could be very significant
- due to accumulation, the probability of flammable atmosphere generation is higher; if ignition occurs, the consequences can be severe

Event 3.2.7:
- due to accumulation, the probability of flammable atmosphere generation is higher; if ignition occurs, the consequences can be severe
- scope of consequences
- accumulation of H2 in confined area can cause explosion, DDT
- potentially high release rate of H2 and large amount of fuel mass leads to a large cloud of H2/air mixture
- possibility of explosion with fatal injuries to people in an urban surrounding
- BLEVE or explosive atmosphere
- if not venting & detection measures established
- (confinement/local accumulation, low probability, major-damage, badly mitigable)
- Jet fire, fireball, detonation

Event 3.3.3:
- Jet fire, fireball,possibly DDT due to object generated turb.
- scope of consequences
- risk of accumulation in confined area
- accumulation of H2 with time resulting in destructive overpressures in case of ignition
- possibility of explosion with fatal injuries to people in an urban surrounding
- Possible explosive atmosphere
- Confined atmosphere, accumulation of gas
- if not venting & detection measures established
- Due to presence of people, relatively small effects have large consequences; Frequency of occurrence could be very significant
- due to accumulation, the probability of flammable atmosphere generation is higher; if ignition occurs, the consequences can be severe
- hydrogen in confined geometry may form explosive mixture with air

Event 3.3.5:
- scope of consequences
- risk of accumulation in confined area
- potentially high release rate of H2 and large amount of fuel mass leads to a large cloud of H2/air mixture with DDT potential
- Possible explosive atmosphere
- Jet fire, fireball,possibly DDT due to object generated turb.

Event 3.3.6:
- scope of consequences
- risk of accumulation in confined area
- potentially high release rate of H2 and large amount of fuel mass leads to a large cloud of H2/air mixture with DDT potential
- Possible explosive atmosphere
- Jet fire, fireball,possibly DDT due to object generated turb.
- possibility of explosion with fatal injuries to people in an urban surrounding

- High safety risk
- due to accumulation, the probability of flammable atmosphere generation is higher; if ignition occurs, the consequences can be severe
- (confinement/local accumulation, low probability, major-damage, badly mitigable)
- hydrogen in confined geometry may form explosive mixture with air

Event 3.3.7:

Event 3.4.2:
- Vote 3 due to conjonction of confined area in urban area.
- Possible fire and explosion
- Due to presence of people, relatively small effects have large consequences; Frequency of occurrence could be very significant
- Cryogenic H2 could disperse a long way similar to LNG, also if it flows into drains, etc. The effect could be un-predictable. We have a fair amount of data on LNG. Useful to know how different LH2 is from LNG wrt to dispersion and flow behaviour.

Event 3.4.7:

Event 3.5.3:
- How much comes out and the consequence of fire and explosion is important for emergency planning. H2 fire is nearly invisible which makes detection by human difficult. This could mean that we need to have a standard specifically for H2 operations -- this could affect operation of the H2 business.
- Jet fire, fireball
- the consequences can be very severe
- high risk if not detected and shutdown
- Possible explosion

Event 3.5.4 :
- How much comes out and the consequence of fire and explosion is important for emergency planning. H2 fire is nearly invisible which makes detection by human difficult. This could mean that we need to have a standard specifically for H2 operations -- this could affect operation of the H2 business.
- Jet fire, fireball
- the consequences can be very severe, although the probability is low
- High probability of catastrophic consequences. Special safety measures should be taken.
- worst case scenario
- Possible fire and explosion
- high release rate, ignition source present, persons present

Event 3.5.7:
- accumulation of H2 with time resulting in destructive overpressures in case of ignition
- Possible fire and explosion
- confined areas, so not dispersion; damage are dependent on the accumulation;
- Deflagration/detonation followed by missile effects
- How much comes out and the consequence of fire and explosion is important for emergency planning. H2 fire is nearly invisible which makes detection by human difficult. This could mean that we need to have a standard specifically for H2 operations -- this could affect operation of the H2 business.

Event 3.5.14:

- Jet fire, fireball,possibly DDT due to object generated turb.
- if possibility for gas accumulation
- Possible fire and explosion
- Special safety measures should be taken.
- worst case scenario
- Vote 3 due to conjonction of confined area in urban area.

Event 3.7.7:

Event 3.7.8:

- Deflagration, DDT, detonation
- confined environment; if ignition occurs the damage can be high
- Possible explosion
- possibility of explosion with fatal injuries to people

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). A number of safety issues specific to refuelling stations have either received a high priority or bimodal votes – (overfilling, car drives away, fire), so that these issues need to be looked at closely.

5.4

Commercial vehicles and passenger cars (H4)

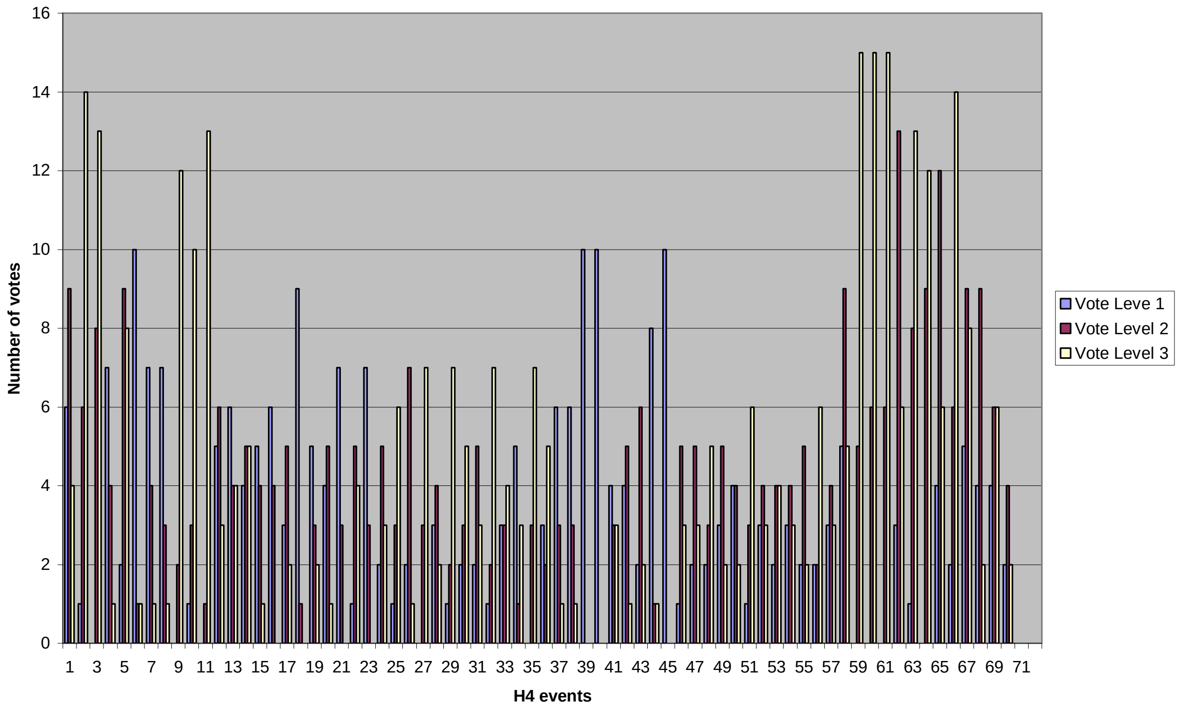

Fig. 9: Distribution of votes for H4 events

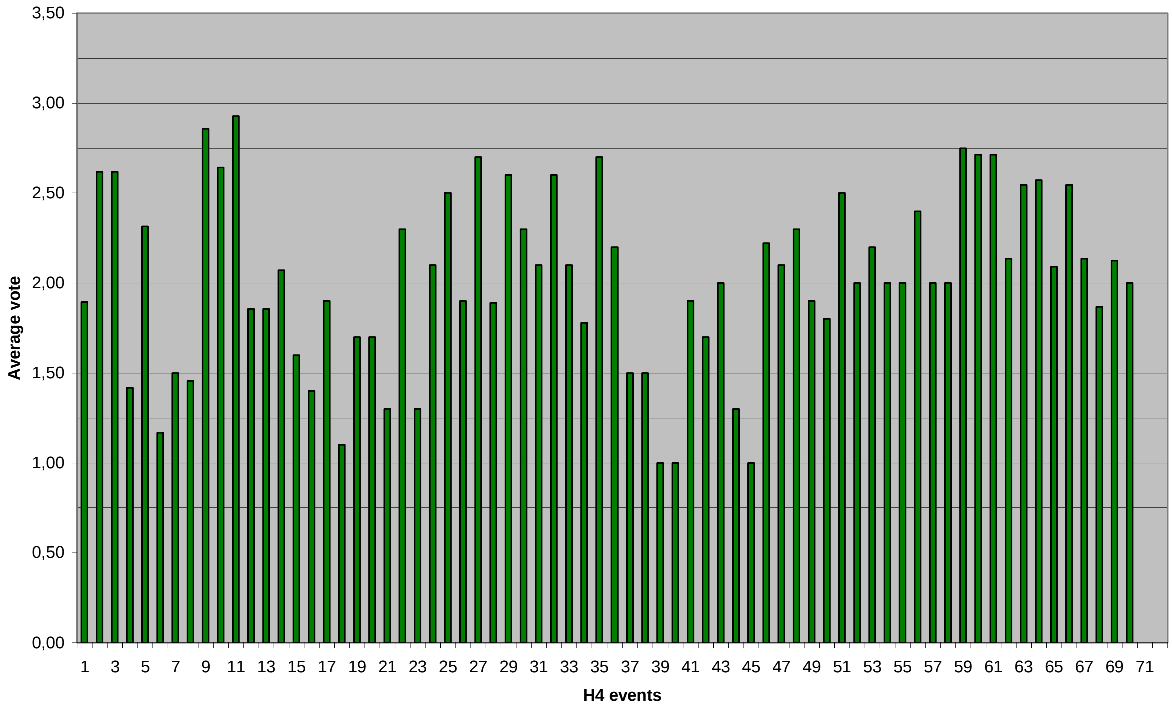

Fig. 10: Average votes for H4 events

70 events have been identified for commercial vehicle and passenger car applications. A large number of issues related to commercial vehicles were identified late in the year 2004,

so that not all partners had time to vote on them (about 10 votes were received). For all other events, the number of votes ranged from 8 to 22. Of the 70 events, 25 were ranked in the first category (average above 2.25 or close enough to the threshold to be affected by a single vote), representing 34% of the total number of events, 8 events in Group 2, 26 events in Group 3 and 11 in Group B. Events in Group 1 are:

- Application 4.1 Commercial vehicles
    - Event 4.1.3 vehicle accident in tunnel with tank damage (**2.62**)
    - Event 4.1.4 fire in tunnel leading to strong heat flux on tank (**2.62**)
    - Event 4.1.7 accident or failure leading to tank damage in maintenance workshop (**2.32**)
    - Event 4.1.11 accidental release from high pressure tank in tunnel or under overbridge (**2.86**)
    - Event 4.1.12 failure of tank due to fatigue crack while in tunnel or overbridge (**2.64**)
    - Event 4.1.13 catastrophic failure of storage system (**2.93**)
    - Event 4.1.24 release due to system/component failure in urban environment (**2.30**)
    - Event 4.1.27 release via the PRD (accidental or intentional) while in tunnel (**2.50**)
    - Event 4.1.29 release due to system/component failure in tunnel (**2.70**)
    - Event 4.1.31 container failure while in tunnel or overbridge (**2.60**)
    - Event 4.1.32 release via the PRD (accidental or intentional) in a car park or maintenance workshop (**2.30**)
    - Event 4.1.34 large rate release due to system damage or component failure (**2.60**)
    - Event 4.1.36 container failure in car park or maintenance workshop (**2.70**)
    - Event 4.1.37 accident due to lack of purge of system before opening for maintenance (in workshop) (**2.70**)
    - Event 4.1.47 container failure in an urban environment (**2.22**)
    - Event 4.1.49 release due to system damage or failure of component while in tunnel or overbridge (**2.30**)
    - Event 4.1.52 container failure in a tunnel or overbridge (**2.50**)
    - Event 4.1.54 release due to system damage or failure of component while in car park or maintenance workshop (**2.20**)
    - Event 4.1.57 container failure in a car park or maintenance workshop (**2.40**)
- Application 4.2 Passenger cars
    - Event 4.2.3 car accident leading to tank failure while in tunnel (**2.75**)
    - Event 4.2.4 fire in tunnel, leading to thermal loading on tank (**2.71**)
    - Event 4.2.6 car accident leading to tank failure in car park (high release rate case) (**2.71**)
    - Event 4.2.8 fire in public car park, leading to thermal loading on tank (**2.55**)
    - Event 4.2.10 car accident leading to tank failure in private car park (high release rate case) (**2.57**)
    - Event 4.2.12 car accident leading to tank failure in maintenance workshop (high release rate case) (**2.55**)

Bimodal events (Group B) are:

- Application 4.1 Commercial vehicles
    - Event 4.1.15 failure of vessel (storage tank) while on the road (43% Level 1 votes and 29% Level 3 votes)

  - Event 4.1.16 catastrophic failure of storage system while on the road (29% Level 1 votes and 36 Level 3 votes)
  - Event 4.1.34 leaks from components while in car park or maintenance workshop (30% Level 1 votes and 40% Level 3 votes)
  - Event 4.1.35 permeation through pressure vessel walls (56% Level 1 votes and 33% Level 3 votes)
  - Event 4.1.42 container failure while in the open (40% Level 1 votes and 30% Level 3 votes)
  - Event 4.1.53 release via safety device while in car park or workshop (30% Level 1 votes and 30% Level 3 votes)
  - Event 4.1.55 release from components while in car park or workshop (30% Level 1 votes and 30% Level 3 votes)
  - Event 4.1.58 system not purged before opening for maintenance in workshop (30% Level 1 votes and 30% Level 3 votes)
- Application 4.2 passenger cars
  - Event 4.2.1 car crash on road (26% Level 1 votes and 26% Level 3 votes)
  - Event 4.2.15 rupture of H2 lines by emergency crew on scene of accident (25% Level 1 votes and 38% Level 3 votes)
  - Event 4.2.16 boil off while in car park or maintenance workshop (25% Level 1 votes and 25% Level 3 votes)

Justifications for Level 3 votes in Group 1 are:

Event 4.1.3:
- risk of explosion in tunnel
- potentially high release rate of H2 and large amount of fuel mass leads to a large cloud of H2/air mixture
- possibility of explosion with fatal injuries to people
- Possible fire and explosion
- Confined area
- the consequences can be severe (fatal injuries to people)
- Medium probability (1/year), partial confinement, risk of fatalities
- hydrogen in confined geometry may form explosive mixture with air

Event 4.1.4:
- Due to the confinement
- scope of consequences
- possibility of explosion with fatal injuries to people
- Possible explosion
- Confined area
- over pressure in hydrogen systems; release and ignition; the consequences can be severe (fatal injuries to people)
- hydrogen in confined geometry may form explosive mixture with air

Event 4.1.7:
- worst case scenario
- potentially high release rate of H2 and large amount of fuel mass leads to a large cloud of H2/air mixture
- possibility of explosion with fatal injuries to people
- Possible fire and explosion
- the consequences can be severe (fatal injuries to people)

Event 4.1.11:

Event 4.1.12:
Event 4.1.13:
Event 4.1.24:
Event 4.1.27:
Event 4.1.29:
Event 4.1.31:
Event 4.1.32:
Event 4.1.34:
Event 4.1.36:
Event 4.1.37:
Event 4.1.47:
Event 4.1.49:
Event 4.1.52:
Event 4.1.57:

Event 4.2.3:
- hydrogen in confined geometry may form explosive mixture with air
- Medium probability (1/year), partial confinement, risk of fatalities
- the consequences can be severe (fatal injuries to people)
- Explosion in tunnel is almost always fatal to all occupants.
- Possible fire and explosion
- possibility of explosion with fatal injuries to people
- potentially high release rate of H2 and large amount of fuel mass leads to a large cloud of H2/air mixture
- risk of explosion in tunnel
- Due to the confinement

Event 4.2.4:
- hydrogen in confined geometry may form explosive mixture with air
- over pressure in hydrogen systems; release and ignition; the consequences can be severe (fatal injuries to people)
- Possible explosion
- possibility of explosion with fatal injuries to people
- Due to the confinement

Event 4.2.6:
- hydrogen in confined geometry may form explosive mixture with air
- large quantities, dispersion could not avoid the formation of flammable atmosphere; the consequences can be severe (fatal injuries to people)
- Possible fire and explosion
- possibility of explosion with fatal injuries to people
- potentially high release rate of H2 and large amount of fuel mass leads to a large cloud of H2/air mixture

Event 4.2.8:
Event 4.2.10:
- hydrogen in confined geometry may form explosive mixture with air
- large quantities, dispersion could not avoid the formation of flammable atmosphere; the consequences can be severe (fatal injuries to people)
- Possible fire and explosion
- possibility of explosion with fatal injuries to people
- potentially high release rate of H2 and large amount of fuel mass leads to a large cloud of H2/air mixture

Event 4.2.12:
- hydrogen in confined geometry may form explosive mixture with air
- large quantities, dispersion could not avoid the formation of flammable atmosphere; the consequences can be severe (fatal injuries to people)
- Possible fire and explosion
- possibility of explosion with fatal injuries to people
- potentially high release rate of H2 and large amount of fuel mass leads to a large cloud of H2/air mixture

<u>Conclusions for H4 votes:</u>
The H4 votes (Group 1 but also Group B) 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).

5.5

Other propulsion systems (H5)

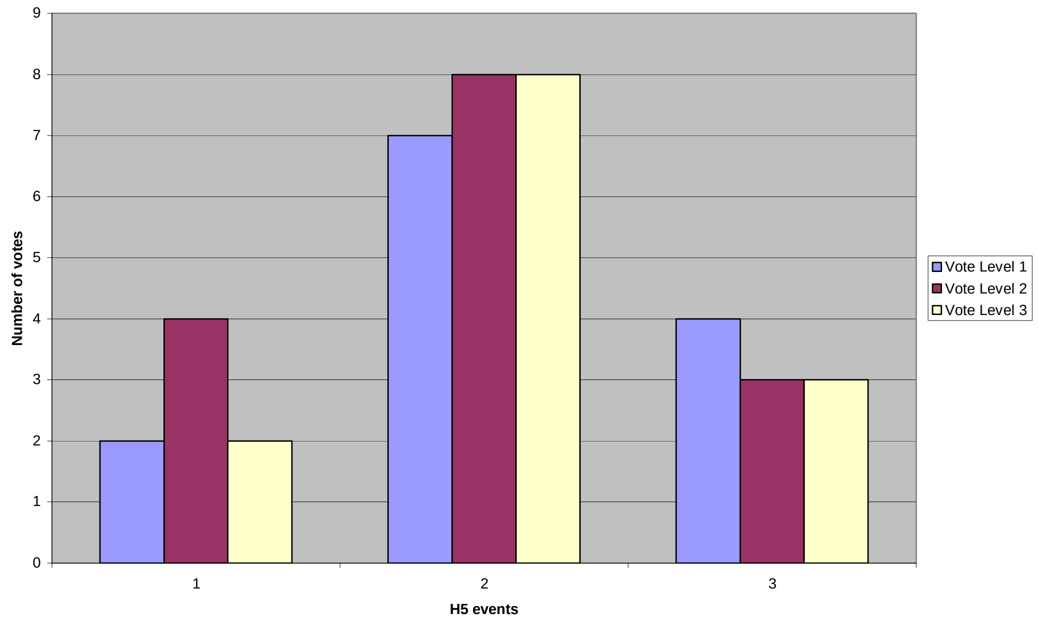

Fig. 11: Distribution of votes for H5 events

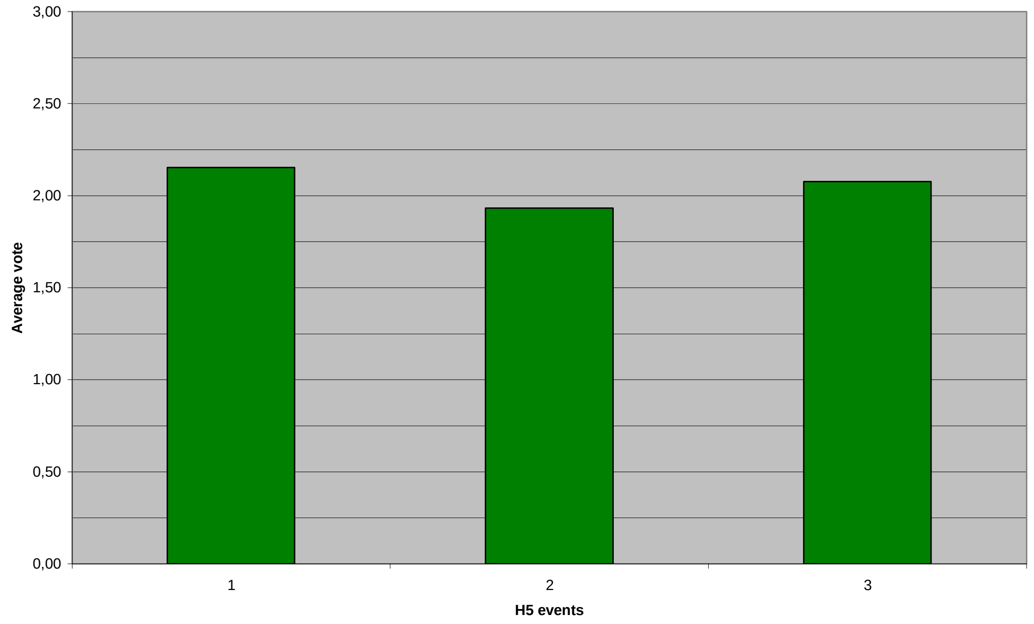

Fig. 12: Average votes for H5 events

Very few accidental events (3) have been identified for this horizontal application, 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.

5.6

Portable applications (H6)

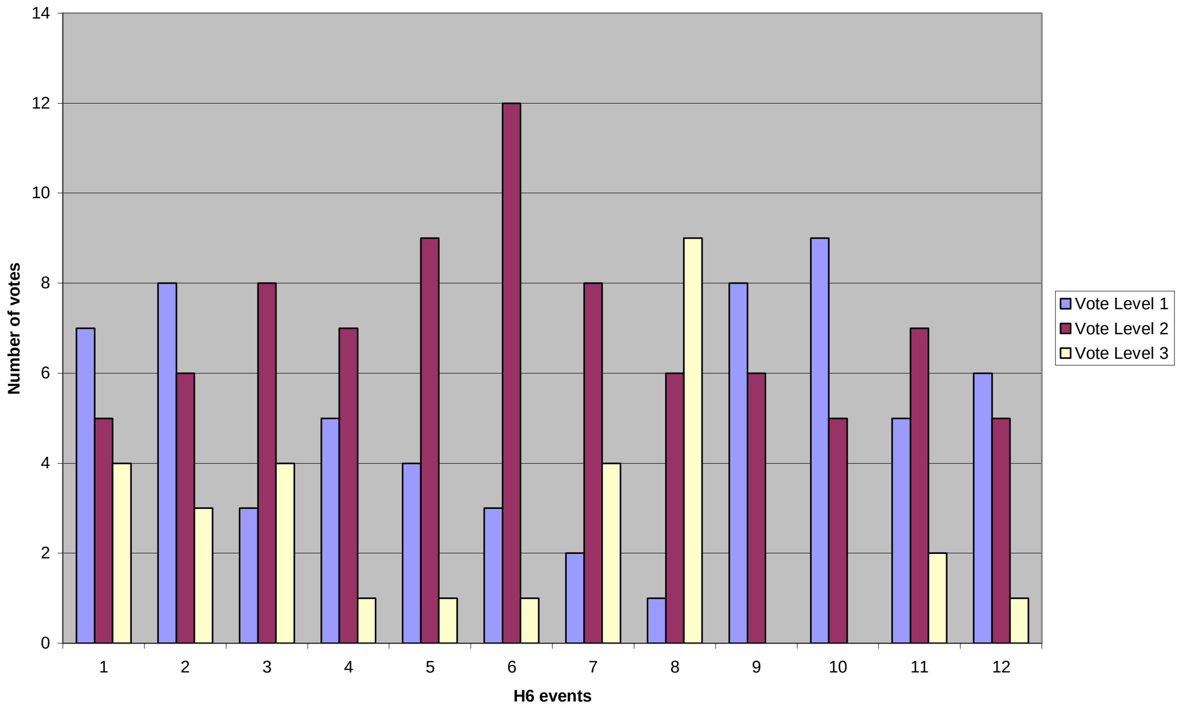

Fig. 13: Distribution of votes for H6 events

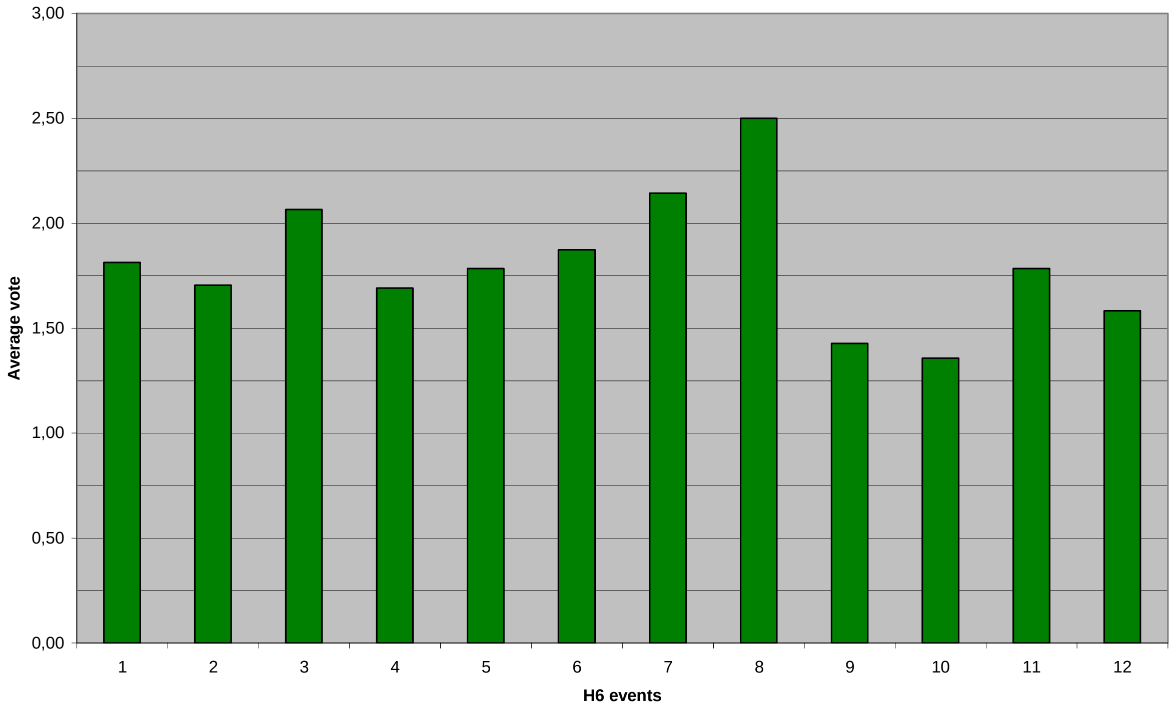

Fig. 14: Average votes for H6 events

Only one application was identified as "portable application", namely a fuel cell system. 12 events were identified, and only one was ranked in Group 1, two in Group 2 and 8 in Group

3. There was also one bimodal vote. Overall, there are too few events to make the PIRT exercise significative.

The event in Group 1 is:

- Application 6.1 fuel cells
    - Event 6.1.8 faulty connection or safety valve leading to release inside room and formation of an explosive atmosphere (2.50)

and the event in Group B is:

- Application 6.1 fuel cells
    - Event 6.1.1 leaking from core, piping, etc. while inside building, with 44% of Level 1 votes and 25% of Level 3 votes.

The justifications for the Level 3 votes of Group 1 are:

Event 6.1.8:

- Deflagration, detonation
- Might form explosive atmosphere
- confined environment, the consequences can be severe

5.7

Effect of threshold on number of events in Group 1

As explained previously, the ranking of events in Group 1 and Group 2 depend on the value of the threshold set for the average value of the votes. Here a value of 2.25 was used. A higher value leads of course to fewer selected events, while a lower value leads to a higher number of events in Group 1, as illustrated below.

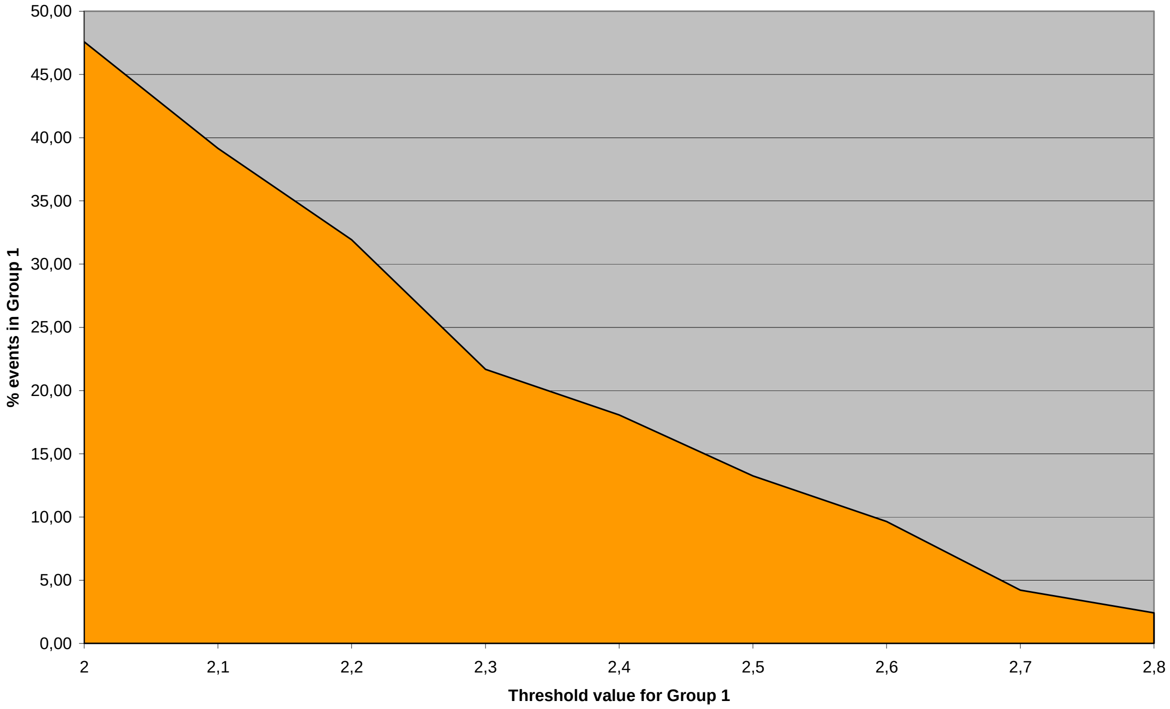

Fig. 15: Effect of threshold on number of events selected in Group 1 (high priority).

With the value of 2.25, the “safety-oriented vote” of the PIRT exercise has allowed us to prioritize the different accidental events (Group 1 and Group B):

- H1: 8 events initially: 3 events in Group 1 and 0 in Group B
- H2: 23 events initially : 11 events in Group 1 and 1 in Group B
- H3: 50 events initially: 15 events in Group 1 and 5 in Group B
- H4: 70 events initially: 25 events in Group 1 and 11 in Group B
- H5: 3 events initially: 0 event in Group 1 and 0 in Group B
- H6: 12 events initially: 1 event in Group 1 and 1 in Group B

with an overall result of 55 events (33%) selected (Group 1) out of an initial list of 166, and 18 bimodal events (11%).

6. CONCLUSIONS OF SAFETY-ORIENTED VOTES

The first step of the PIRT exercise, the 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.

More discussions are needed to resolve the lack of consensus for the bimodal votes (18 events are concerned).

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 (phenomena-based ranking).

7. RESULTS OF PHENOMENA ORIENTED VOTES

Juste as was done in the scenario ranking part of the PIRT, 3 categories of results were identified:

- The first group consists of phenomena for which the average of the votes is greater or equal to 2.25;
- The second group consists of phenomena for which the average of the votes 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 which 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 modeled 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, ie which have averages greater than 2.0)

7.1 Gaseous releases

Results of the votes of the gaseous release phenomena are given in the figures below.

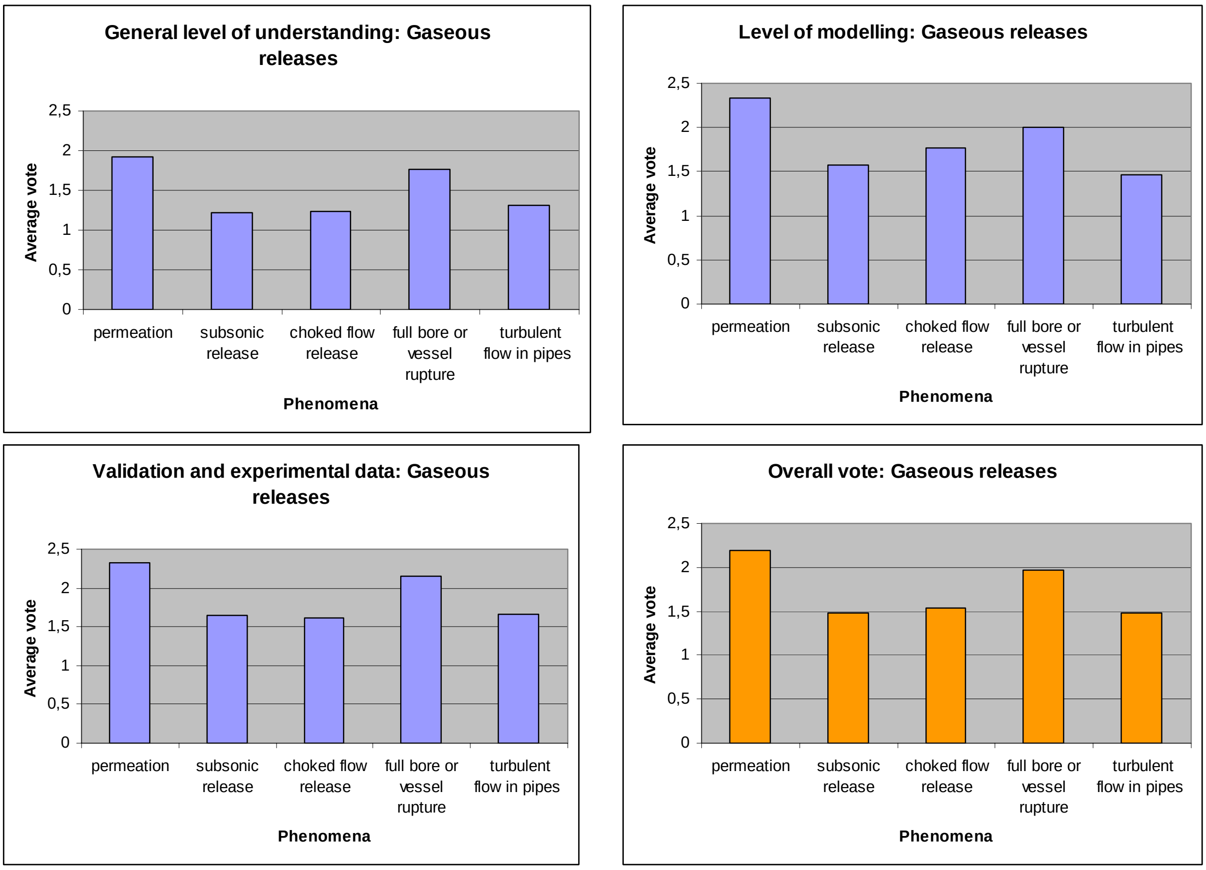

Fig. 17. Phenomena-oriented votes for the gasous release category.

In this category, there are no phenomena in the first group (average greater than 2.25) and only one in the second group, **permeation**:

Phenomena	Average	Justification
Permeation	2,20	Unclear whether it is brownian motion or continuum transport. // Porous media models can be used to calculate permeation rates. Validation is needed for new hydrogen storage materials. After hydrogen is released, which turbulence model should be applied? Laminar flow? // We are not adequately informed on the level of modelling and validation of the permeation phenomena to vote meaningfully // As long as the release can be controlled out of vehicle, this must be a very easy topic to control as rate is extremely low and any kind of ventilation system will be adequate. // Relies on empirical source terms for CFD (e.g. permeation rates)

Although the phenomena overall has a vote just below 2.0, the phenomenon of **full bore or full vessel rupture** has votes greater than 2.0 in terms of modelling and experimental data. Thus, it could be concluded that R&D work is needed also to further the knowledge for this kind of phenomenon.

7.2 Liquid releases and spills

Results of the votes on the liquid releases and spills phenomena are given in figure 18. In this category, there are two phenomena in the first category, **full bore and/or vessel rupture** and **condensation and evaporation**:

Phenomena	Average	Justification
full bore liquid (pipelines), full vessel rupture	2,36	No paper available (known) on catastrophic failure except BLEVE scenarios. // 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. // The conditions for BLEVE are not well established (see for BLEVE below). Modeling of slumping phase of cryogenic liquid is difficult. // Cryogenic releases may not be too violent, and can probably be modelled by gasous release assumptions. Vessel rupture due to fire/heat is more complicated(?) //
condensation (20-90K) and evaporation (>90K) of air	2,38	No publication available. // although the physics maybe relative well identified, more experiments seem necessary to validate models // Minor effects // Would not expect this to be too critical except for the very near zone, air aerosols formed will quickly evaporate with further mixing with air. //

And several phenomena in the 2nd category, liquid flow through orifice, spill formation and pool spreading, spill evaporation, two-phase flow in pool, and heat transfer from the ground:

Phenomena	Average	Justification
liquid (two-phase) flow through orifice	2,10	This should be considered together with pipe or enclosure where orifice exists. // 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. // Isentropic expansion to ambient pressure is often assumed to obtain the void fraction at the exit. // Expected difficult physics, but major simplifications will likely produce quite acceptable predictions. //
formation of spill - pool spreading	2,24	The NASA-6 SBEP has shown that the pool spreading with heat exchange with ground & atmosphere, two-phase flow processes, etc and the formation of the spill (radius as a function of time) is difficult to model; furthermore the experimental data is not sufficiently detailed or accurate to support the validation of the different models. // The mechanical effects affecting pool spreading are well known for other fluids (examples are propane, natural gas, water, the molten corium after a nuclear accident, etc.). Probably, more experimental data for claibration of models is required for liquid hydrogen. // More modeling and tests are necessary, see Venetsanos and Bartzis, ICHS-PISA, 2005 // Models exist but not (to our knowledge) validated for H2 // Difficult physics, depend on phenomena not so often modeled, like heat transfer mechanisms and phase changes. Not necessarily so difficult to obtain adequate results. Will depend on heat conduction, soil and a lot more which may not be well described in a general situation. An expected conservative approach will be to evaporate everything released with boiling point temperature (?) within a limited diameter, this will assumedly give reasonable results. // 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. // This is difficult for hydrocarbons, and even more so for hydrogen //
spill evaporation	**2,13**	Heat and mass tranfer at fluid at fluid-gas interface and effect of flow properties, and mode of boiling (convective boiling, boiling crisis, etc) have to be addressed. // although the physics maybe relative well identified, more experiments seem necessary to validate models // Depends strongly on ground heat transfer // Models exist but not (to our knowledge) validated for H2 // Depend on soil, pool diameter, wind, and more // Phenomena are well understood, examined in detail by many authors. Experimental data may not cover all ranges, particularly for LH2. //
two-phase flow in liquid, incl. Boiling	**2,19**	Too complicated to resolve with CFD, diffcult to model properly. // although the physics maybe relative well identified, more experiments seem necessary to validate models // Is the local equilibrium model (Venetsanos and Bartzis, ICHS-PISA, 2005) adequate or should one employ more complicated schemes as in Chitose et al., J. Energy Resources Technology-Transaction of ASME 124(4) pp 283-289, 2002 // Difficult physics, but may not be critical to conservative risk assessments //
heat transfer from ground	**2,03**	Effect of scale is not investigated. // although the physics maybe relative well identified, more experiments seem necessary to validate models // More modeling and tests are necessary, see Venetsanos and Bartzis, ICHS-PISA, 2005 // Small release => full evaporation, larger => pool forms, phenomena depend on previous phenomena. // Phenomena are well understood (e.g. Nukiyama curve). Experimental data may not cover all ranges, particularly for LH2. //

Thus, clearly, in the area of liquid releases and spills, the current state of the art is lacking and the HYSAFE NoE needs to perform more R&D work on this topic.

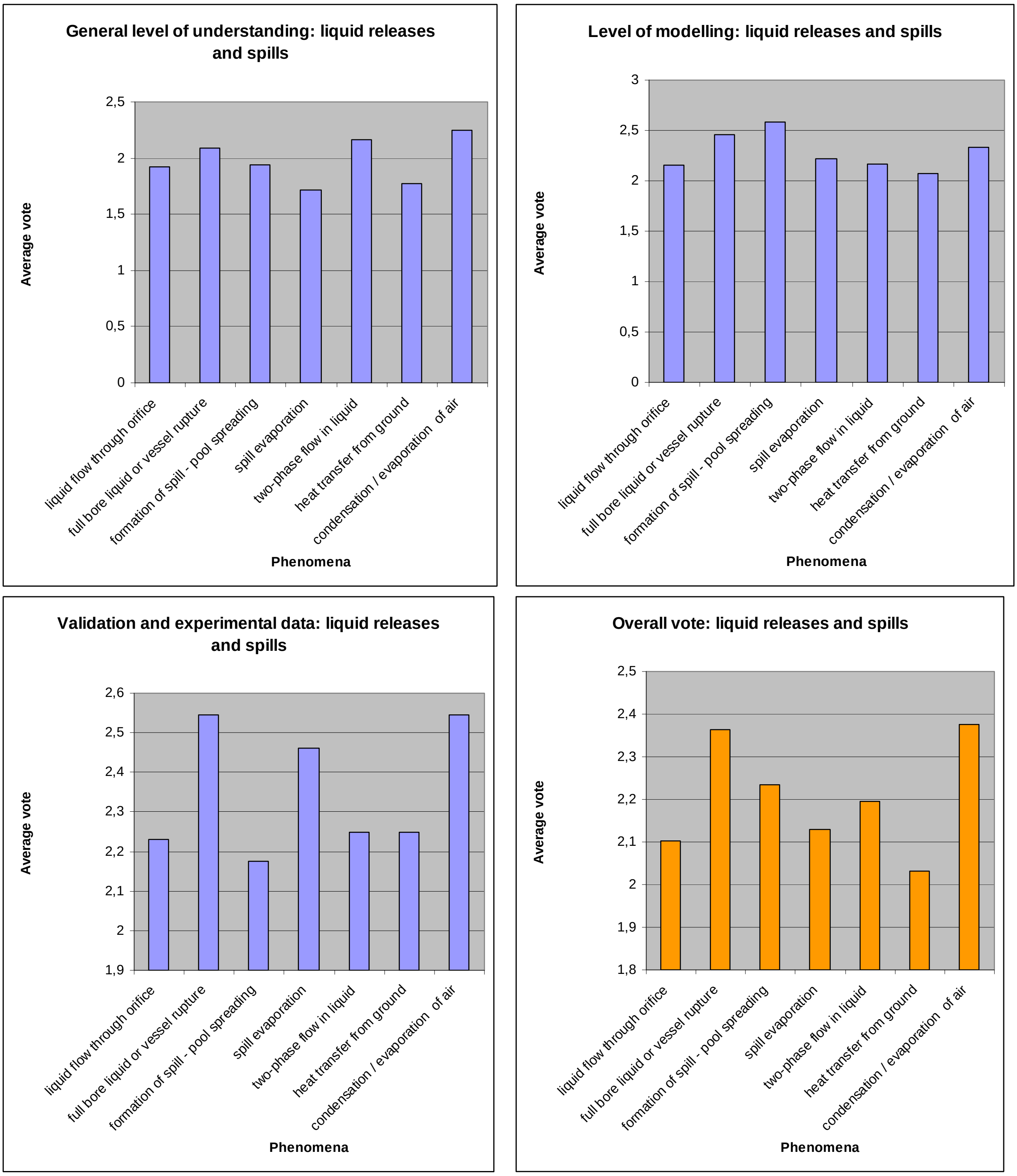

Fig. 18. Phenomena-oriented votes for the gasous release category.

7.3 Explosion of liquid storage

In this category, one phenomenon was ranked in the 2nd category, **BLEVE**:

Phenomena	Average	Justification
Boiling Liquid Expanding Vapour Explosion BLEVE	2.18	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 // So far appropriate methods for the calculation of the blast effects from an exploding pressure vessel of liquefied gas are not available.For lack of better, BLEVE blast effects are often approximated with methods that do not fully apply.The near-field effects are, for instance, calculated with methods for expansion of a pressurised perfect gas while the far-field effects are calculated with TNT-equivalency methods. Present knowledge of the conditions that allow explosive evaporation upon a vessel rupture is insufficient. In addition, the exact evaporation rate of flashing superheated liquids is unknown See A.C. Van den Berg et al., J. Loss Prevent. Proc. 17(6):431-436, 2004 // Good TNO numerical model for BLEVE blast, expansion controlled evaporation. Validation is difficult and not specfically done for H2 (propane validated) // Would be interested in experiments on strong fire exposure of tanks with failing vent device. //

The results of the vote are shown in the figure below:

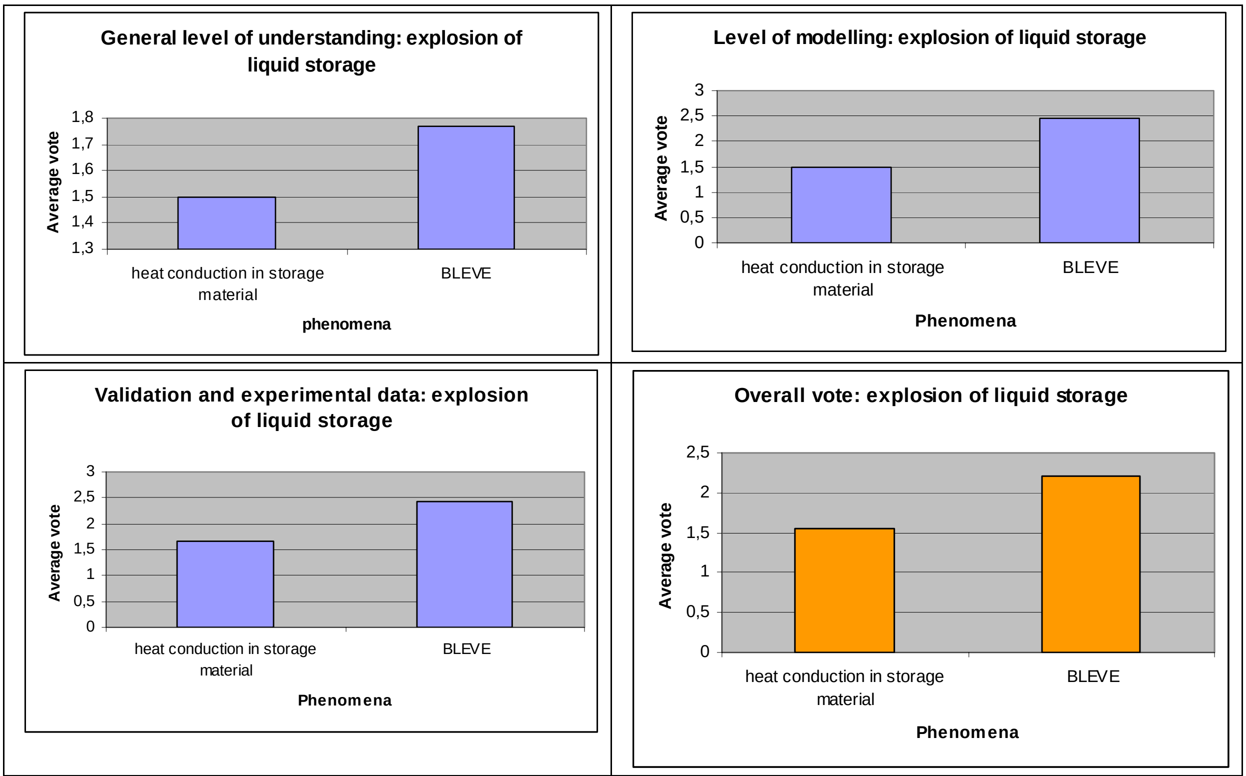

Fig. 18. Phenomena-oriented votes for the liquid storage explosion category

7.4 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.**

Phenomena	Average	Justification
heat transfer from environm.	2.15	Probably we do not understand this question well. 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 // Ground heat transfer for cryogenic releases // Nice to learn more, but not sure if this will be critical. CFD can be used in most situations without detailed knowledge on this. //
turbulent mixing (decaying conditions)	2,03	The SBEP-V1 has shown how complex these phenomena can result. Additional efforts seem needed. Practical criteria to choice diffussion models and diffussion coefficients would be useful. // Did the k-epsilon models applied in Russian-2 predict too fast turbulent mixing decay? Which model should be suggested? // In most situations not critical to safety //
compressible effects (shocks, under-expanded jets, contacts)	2,00	Should we use a pseudo-source approach or resolve the underexpanded jet region as in Xu B.P. et al., ICHS Pisa, 2005 // Don't consider this too difficult, current status is likely acceptable for risk assessments. //

Figure 19 illustrates the results of the votes for the dispersion category. It can be seen that although in the overall vote, there are only 3 phenomena that rank higher than 2.0, there are several phenomena which, from the point of view of the modeling capabilities of the current codes but also and mainly from the point of view of the quality or availability of suitable experimental data for validation purposes, get average votes higher than 2.0. These are:

- Impinged jets
- Turbulence
- Effect of obstacles (and generation of turbulence)
- Atmospheric conditions, wind
- Natural ventilation
- Buoyancy effects
- Stratification
- Turbulent mixing (in decaying conditions).

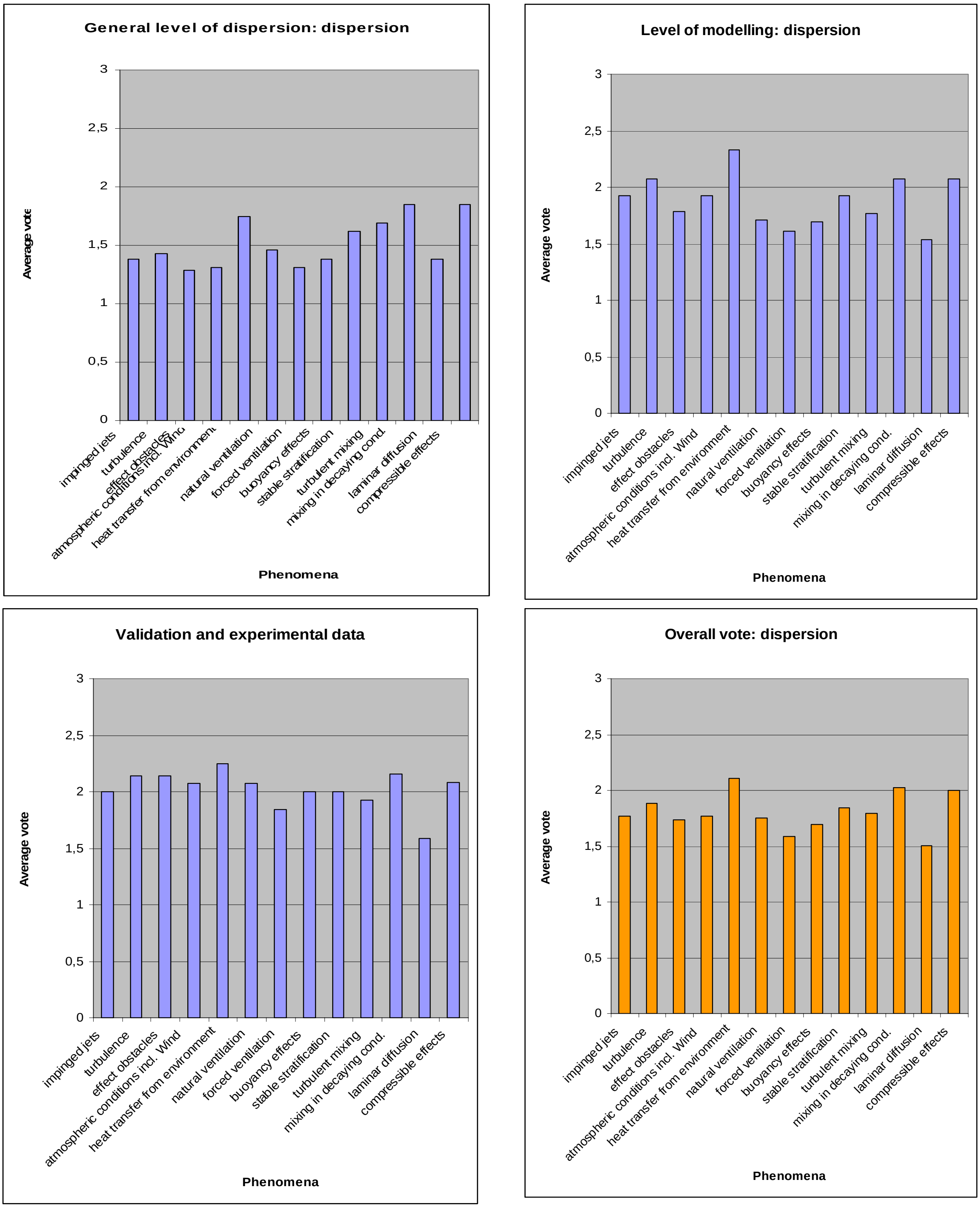

Fig. 19. Phenomena-oriented votes for the liquid storage explosion category

7.5 Ignition

The results of the votes for the ignition category are shown in figure 20. Three phenomena were ranked in the first category, **auto-ignition, jet ignition and radiative ignition**, and 2 in the second category, **weak ignition** (for instance from static electricity) and **direct initiation of detonation.**

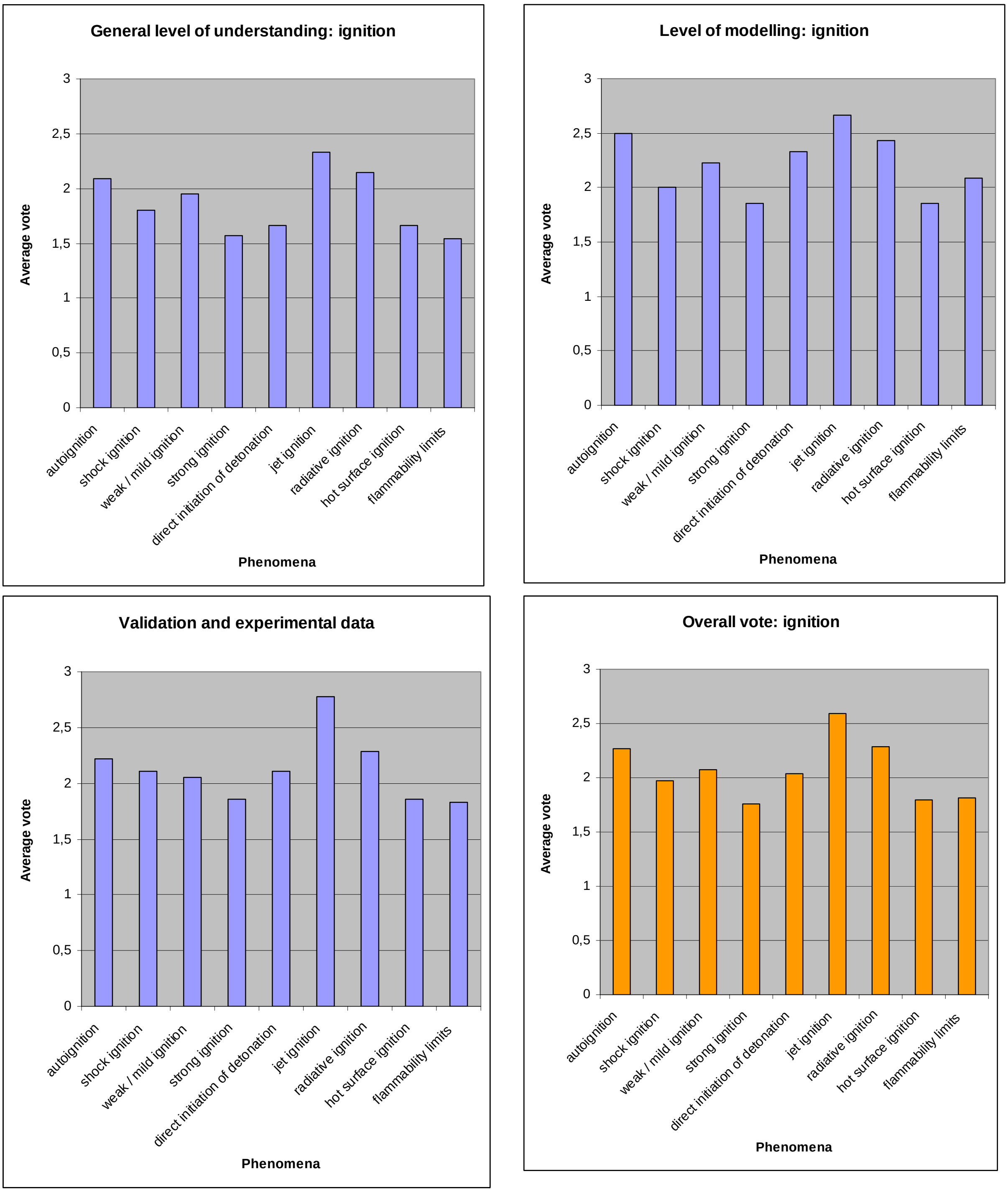

Fig. 20. Phenomena-oriented votes for the ignition category

Phenomena	Average	Justification
autoignition (effect of additives)	2,27	Uncertain how well modelled this is for practical situations // Difficulty in comparing with experimental results. There is strong interaction between chemical reactions, molecular and thermal diffusion, and thermal transport (ref. Comb and Flame, 128:22-37 (2002)) //
jet ignition (ignition by hot jet or combustion products)	2,59	Some work is in progress in Canada; Karim et al. // Fh-ICT experiments with jet ignition and partial confinement with 20 vol% H2 wrt DDT; lack of models, which are applicable for practical use, especially delivering criteria for DDT. Paper # 120018 ICHS conference PISA. // DDT potential could be better understood. //

radiative ignition	2,29	Believe understanding is there, but quantification and whether significant impact to safety unclear. // Difficulty in modelling several orders of magnitude in time of different processes (Int J of Hydrogen Energy, 30:319-326 (2005)) //

Phenomena	Average	Justification
weak / mild ignition (incl. Static electricity) [forced ignition]	2,07	MIE data are published. // Good knowledge, but difficult to measure, uncertain how critical exact knowledge is to safety since the MIE limits are extremely low. // Internal structures of the plasma core remain mostly unknown. Difficulty in experimental investigations due to very short process times, extremely high core temperatures and large gradients in the refractive index (Comb. and Flame, 128:74-87 (2002)) //
direct initiation of detonation	2,04	Experimental data are published // Believe this is well understood, uncertain how modeling is //

7.6 Combustion and explosion

The results of the votes for the combustion and explosion categories are shown in figure 21.

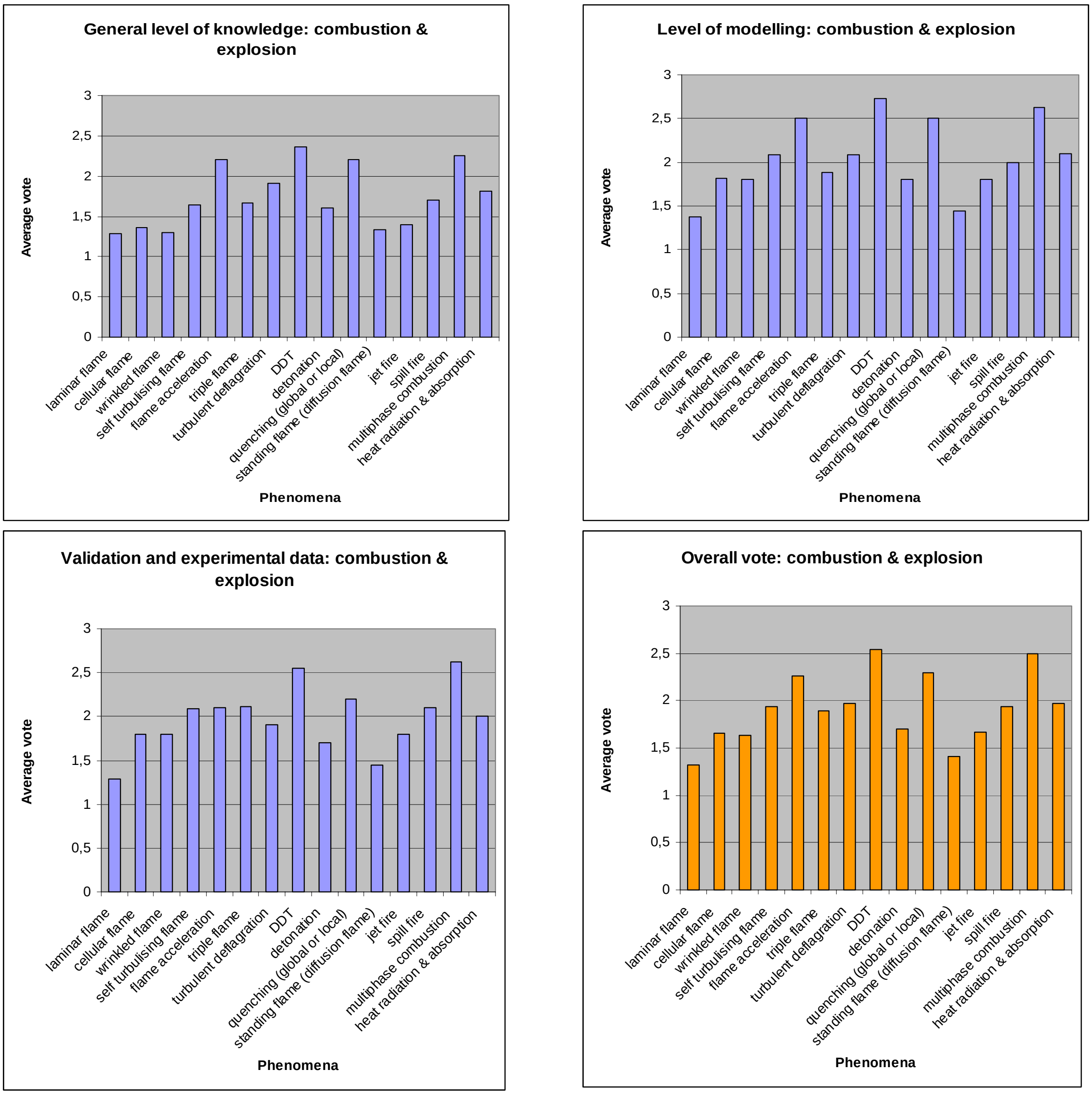

Fig. 21. Phenomena-oriented votes for the combustion/explosion category

In this category of phenomena, 4 phenomena were classified in the first category, flame acceleration and deceleration, DDT, quenching and multiphase combustion (for liquid H2 burns).

Phenomena	Average	Justification
flame acceleration / deceleration due to obstacles, conc. Gradients	2,27	Addressed by LES at Ulster. // Direct simulation of these phenomena still offers some difficulties. Extraplation 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) // acceptable understanding, not critical to improve for risk assessments //
DDT (to to flame acceleration, shock focussing, etc)	2,55	Too wide spectrum of scenarios (enough experiments). // 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 // Fh-ICT experiments with different turbulence levels and partial confinement. Correlation between turbulence level and DDT occurrence. Paper # 120018 ICHS conference PISA. No models for practical use available. //
quenching (global or local)	2,30	Not well understood phenomena; a wide variety of effect can influence. More experiments would be required // Difficult combination of turbulence, wall effects, … //
multiphase combustion (for liq. H2)	2,50	It seems there are no data. //

7.7 Mitigation

In this last category, one phenomenon was ranked in the first group, **venting of deflagration**, and one was ranked in the 2nd group, **recombiners**.

Phenomena	Average	Justification
venting of deflagration	2,25	DDT investigated by venting is not investigated at all. // It could result in the opposite effect if the flame is reanimated // Venting may have an opposite effect as desired, if ignition occurs within volume to be vented and unburnt mixture is expelled through the vent opening, forming a highly turbulent vortex outside of the volume; following flame and combustion products may trigger a detonation within this vortex because of SWACER effect. There seems to be a lower limit of the opening size where this effect could be suppressed, depending on sensitivity of the mixture. // Good enough understanding for adequate predictions // FLIP experiments question the isolation-compartment technique. Engineering approaches depend on the particularities of the enclosure and the expected efficiency. Most of the codes rely on lumped-parameter approach (Nucl Eng and Design, Article in Press (2005)) //

Phenomena	Average	Justification
recombiners	2,12	We think this is requiring additional research, including experiments // Most phenomena are relatively well known, gaps exist in questions like start-up behaviour, deactivation, hot catalyst surface ignition etc. Existing models are either of black-box type with a lack of flexibility with respect to boundary conditions or detailed models with a lack of suitable validation data. Numerous investigations/ publications exist in the nuclear field, experimental data often not public available // The effect of temperature difference across the plates is not modelled. The number of recombiners to be installed depends on the rates of hydrogen production, release and mixing and not only on the recombination rate of catalytic device (Nucl Eng and Design, 166:481-494 (1996)) //

Figure 22 shows the results of the votes for this category.

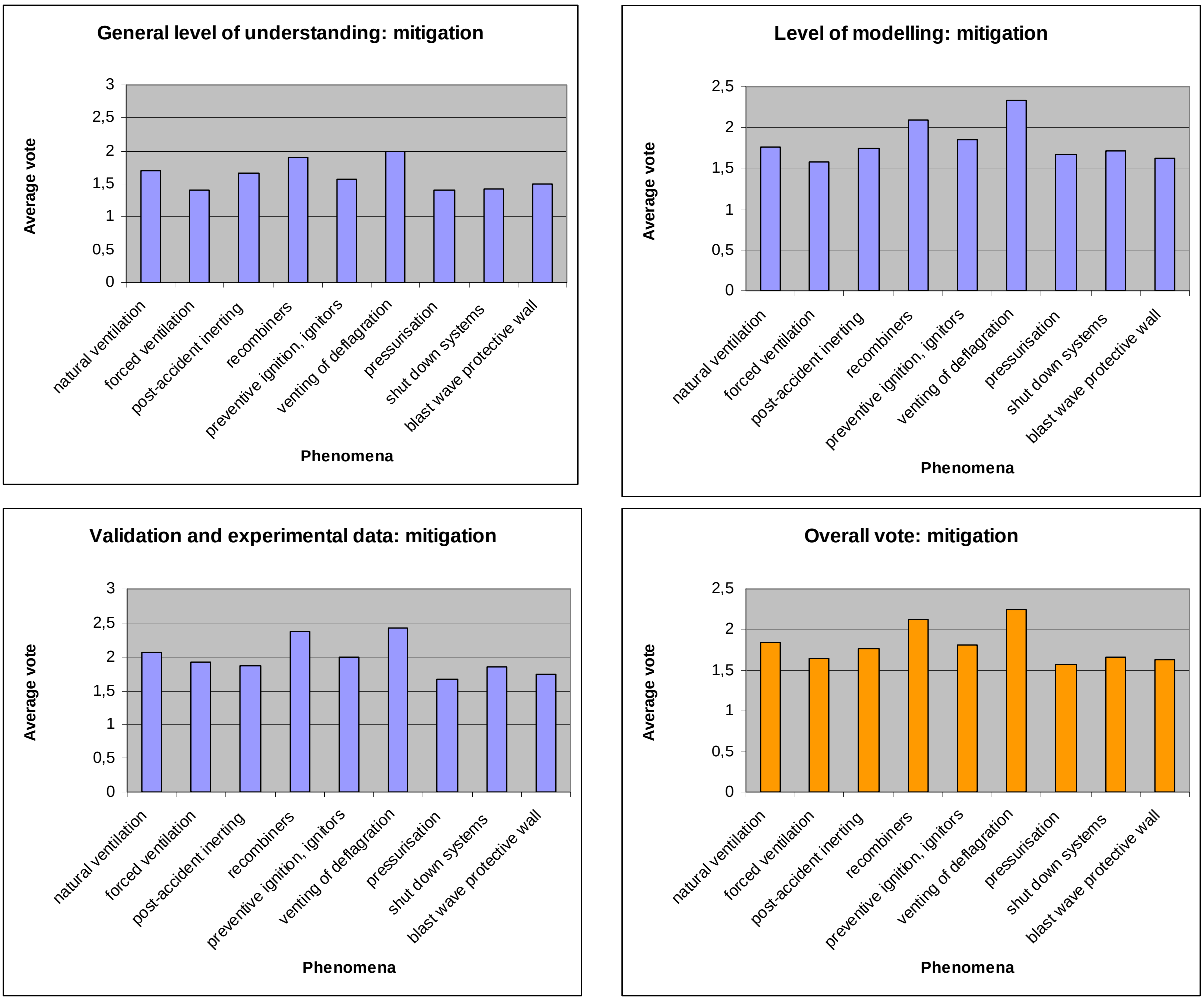

Fig. 22. Phenomena-oriented votes for the combustion/explosion category

8. CONCLUSIONS OF THE PHENOMENA-ORIENTED VOTES

9. OVERALL CONCLUSIONS

Technical appendices

- **A1. Safety-oriented votes**
- **A2. Phenomena-oriented votes**