WP4 PIRT: Results of « Safety Oriented » Vote

(Deliverable D12)

Thursday, 13 January 2005

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, has been conducted over the period August – December 2004. The second step, which will focus on the phenomena associated with the most important accidental events (*phenomena-oriented vote*), will be conducted over the period January – May 2005.

2. 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).

3. 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.

4. WHO VOTED ?

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.

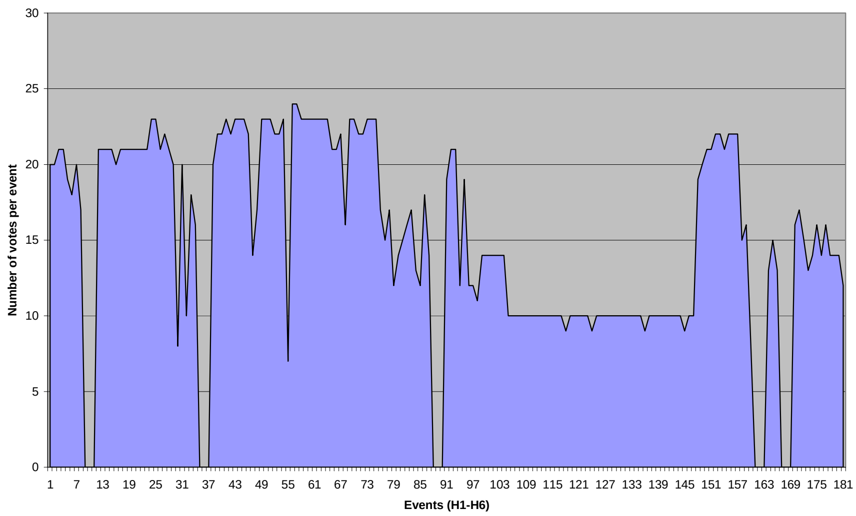

Fig. 1: Distribution of non-zero votes according to the different events (H1-H6): events received from 3 to 24 votes.

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.

5. OVERALL 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

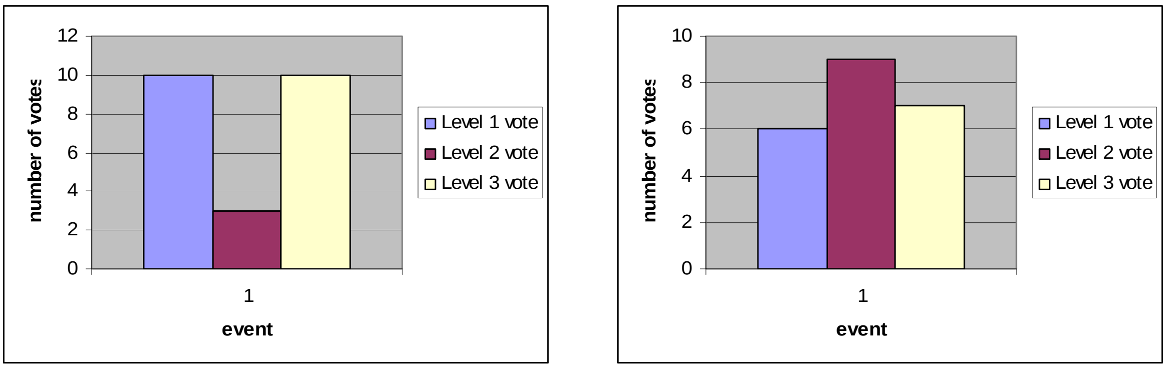

Fig. 2: Example of bimodal distributions which require a close analysis: strongly bimodal vote distribution (left) and near-uniform vote distribution (right)

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)

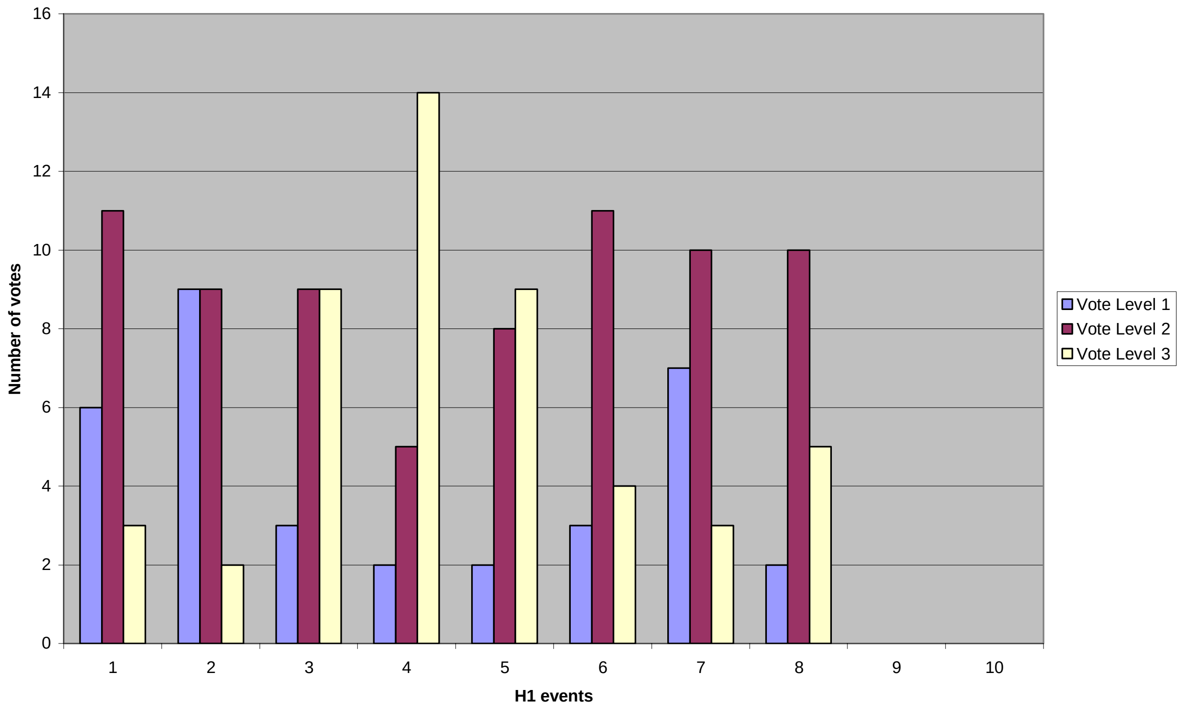

Fig. 3: Distribution of votes for H1 events

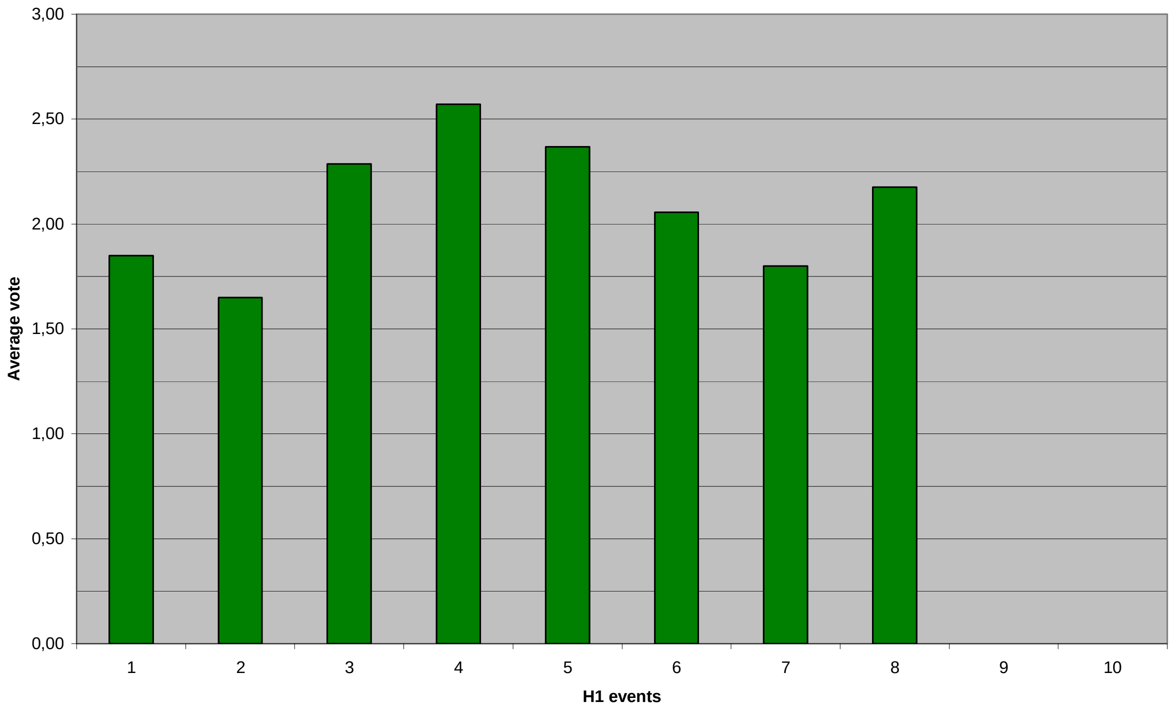

Fig. 4: Average votes for H1 events

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)

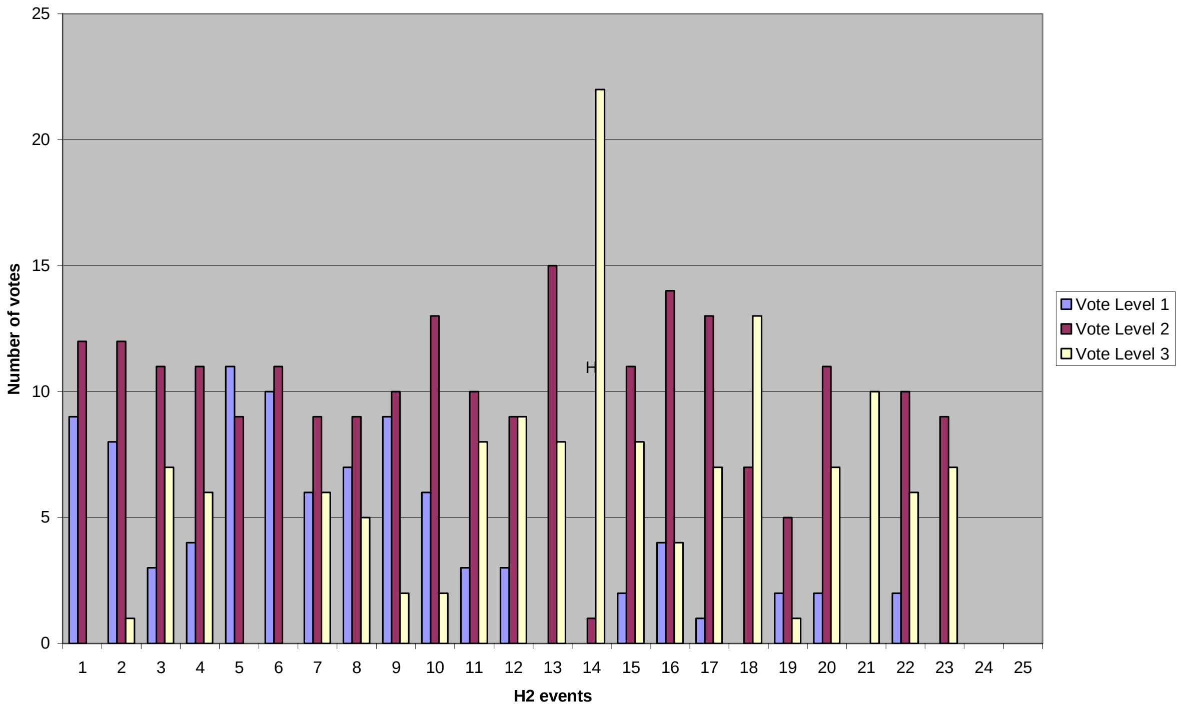

Fig. 5: Distribution of votes for H2 events

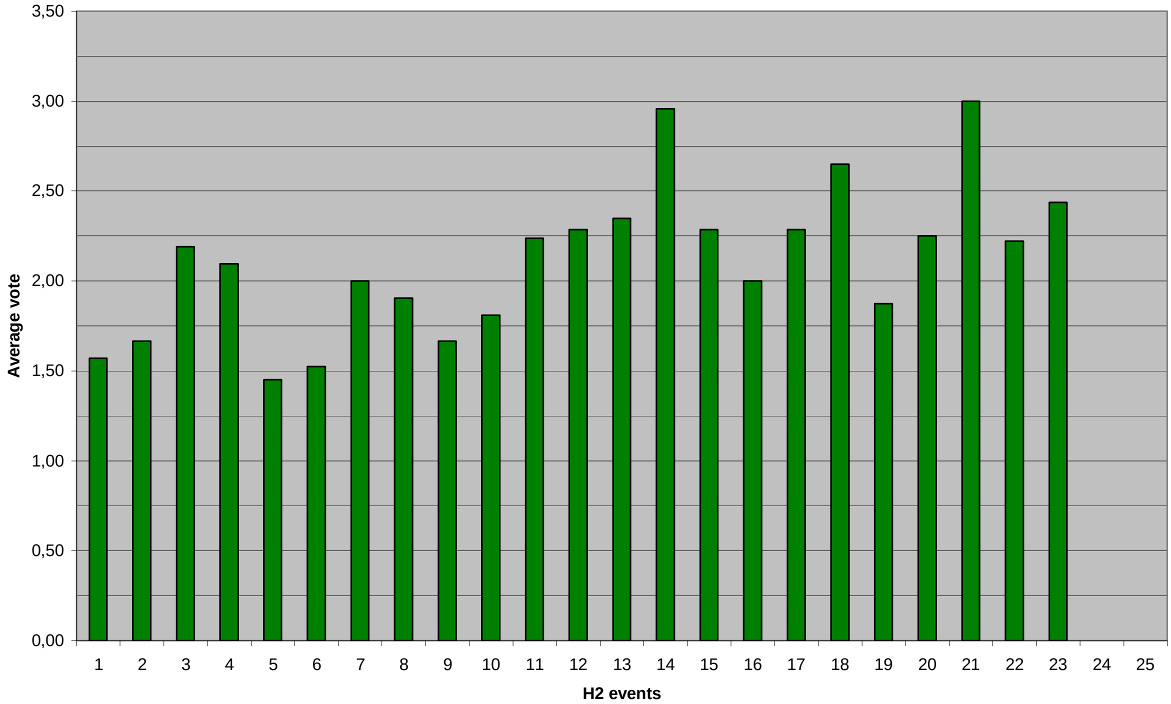

Fig. 6: Average votes for H2 events

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.

Conclusions for H2 votes:

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, REFUELLING STATIONS AND STATIONARY APPLICATIONS (H3)

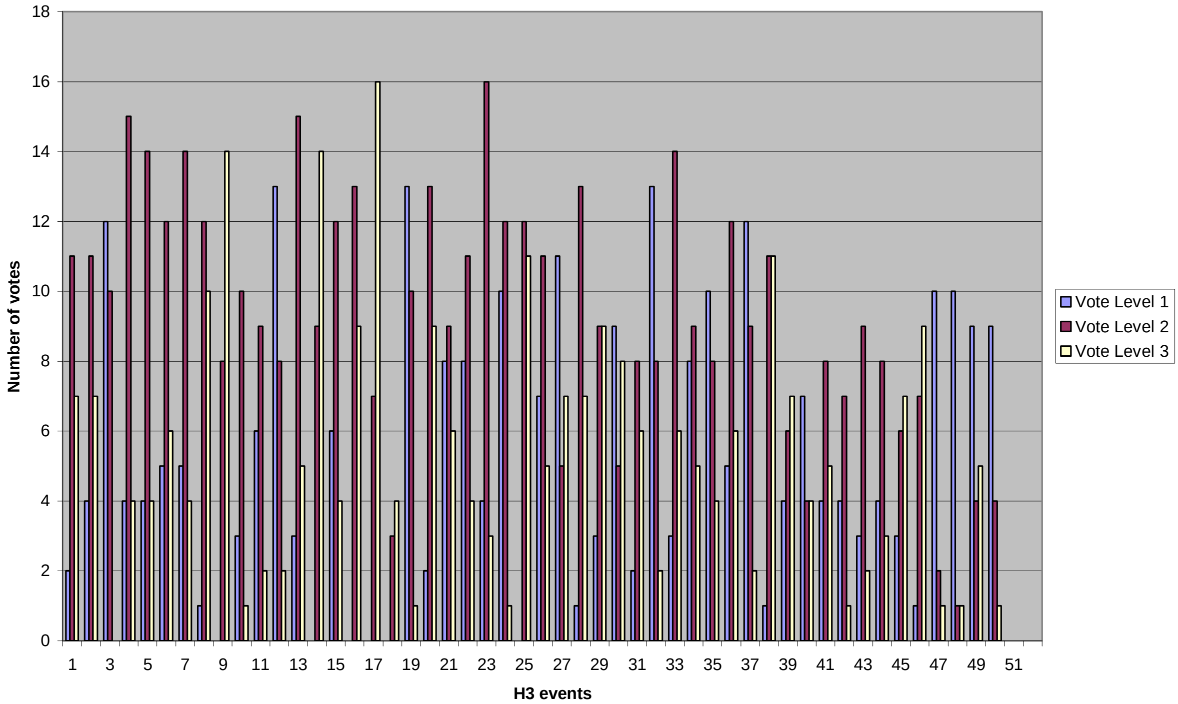

Fig. 7: Distribution of votes for H3 events

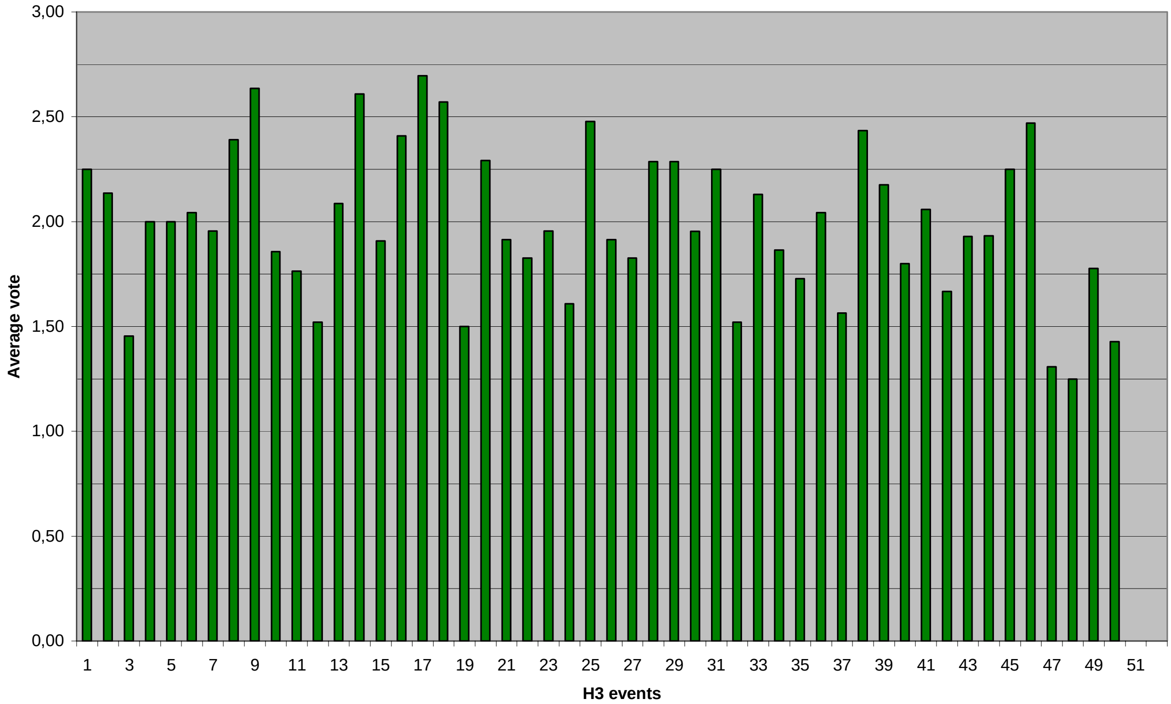

Fig. 8: Average votes for H3 events

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)

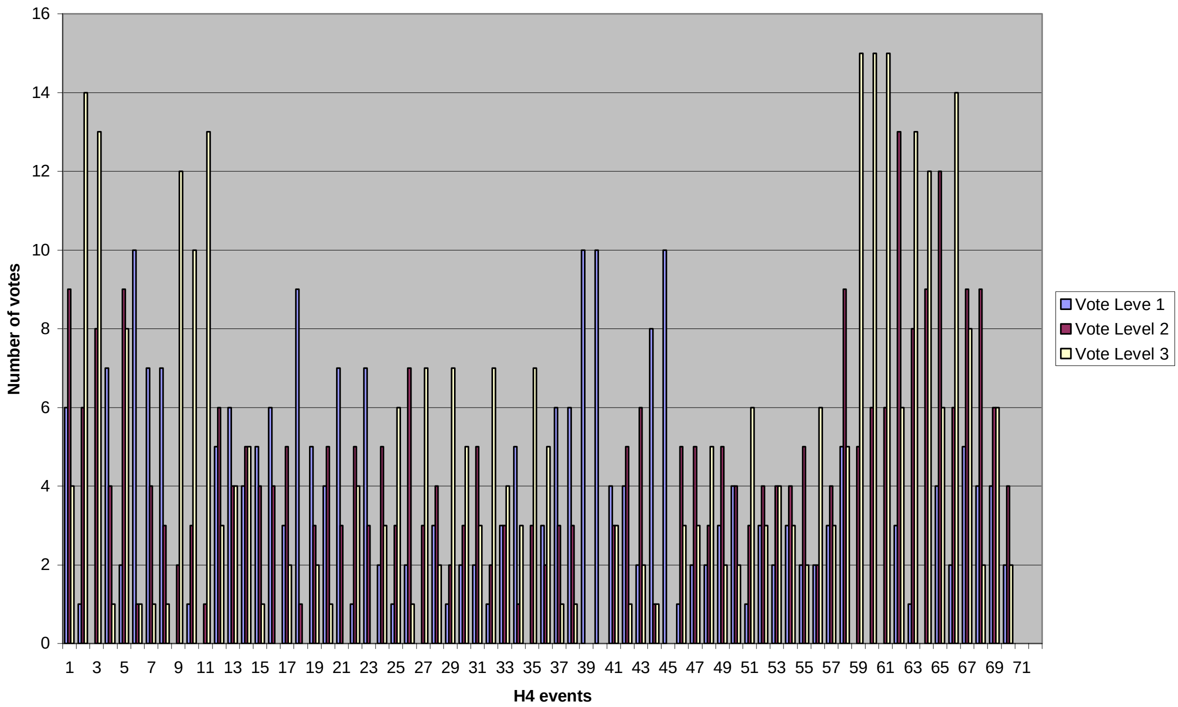

Fig. 9: Distribution of votes for H4 events

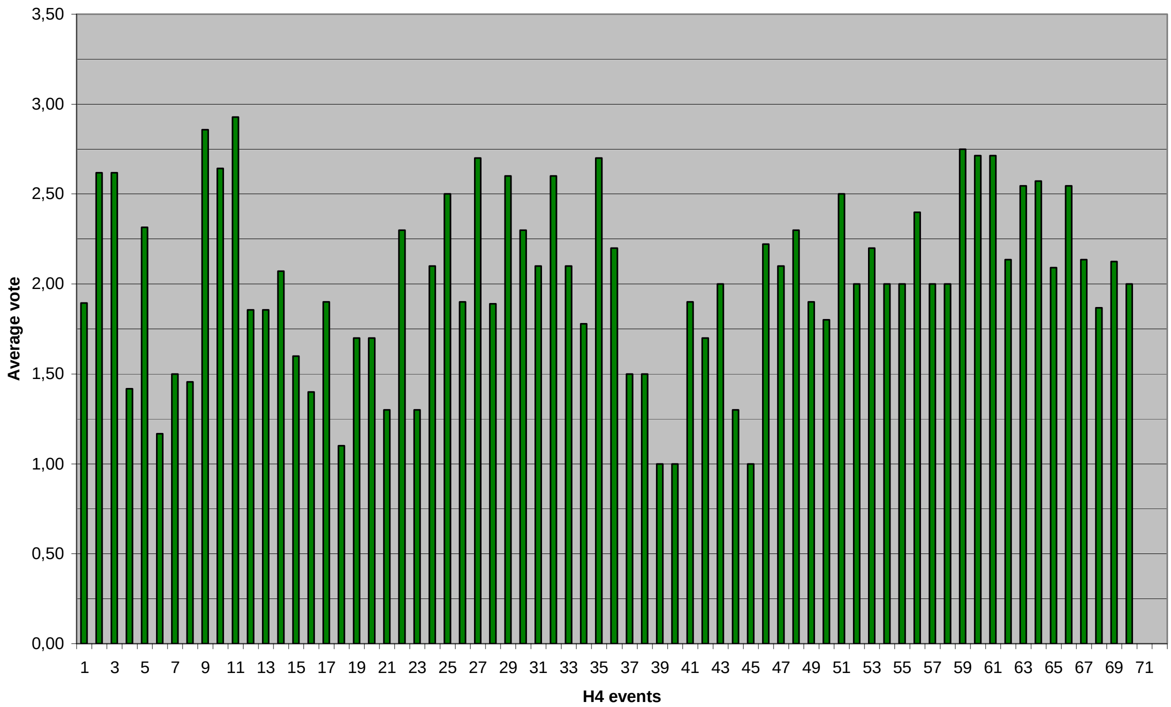

Fig. 10: Average votes for H4 events

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

Conclusions for H4 votes:

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)

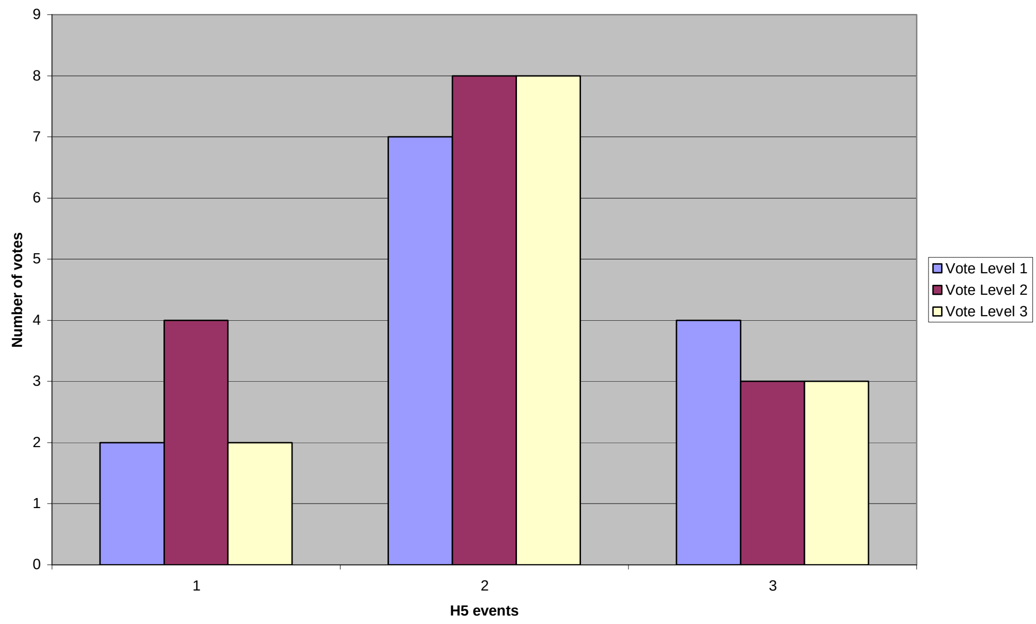

Fig. 11: Distribution of votes for H5 events

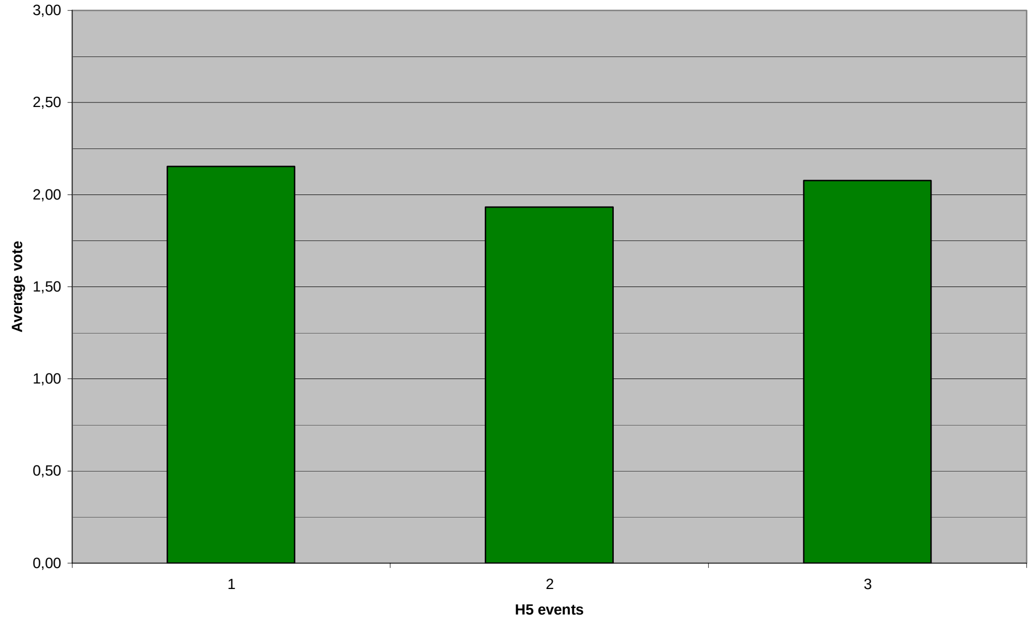

Fig. 12: Average votes for H5 events

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)

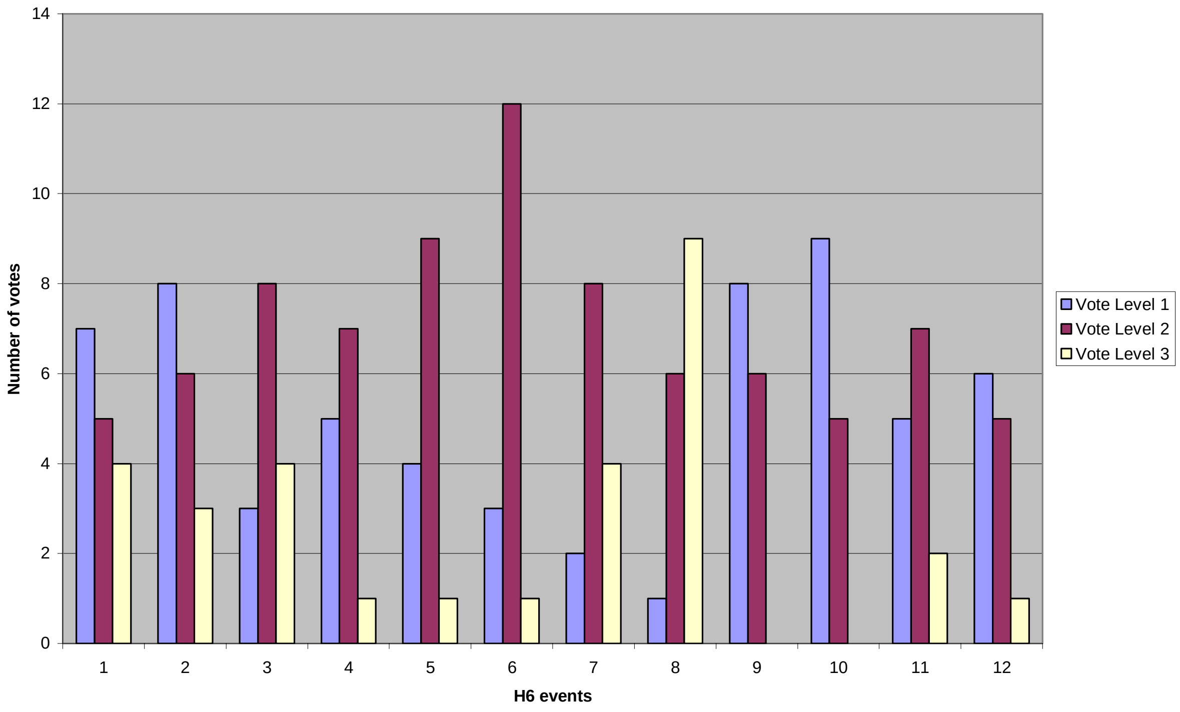

Fig. 13: Distribution of votes for H6 events

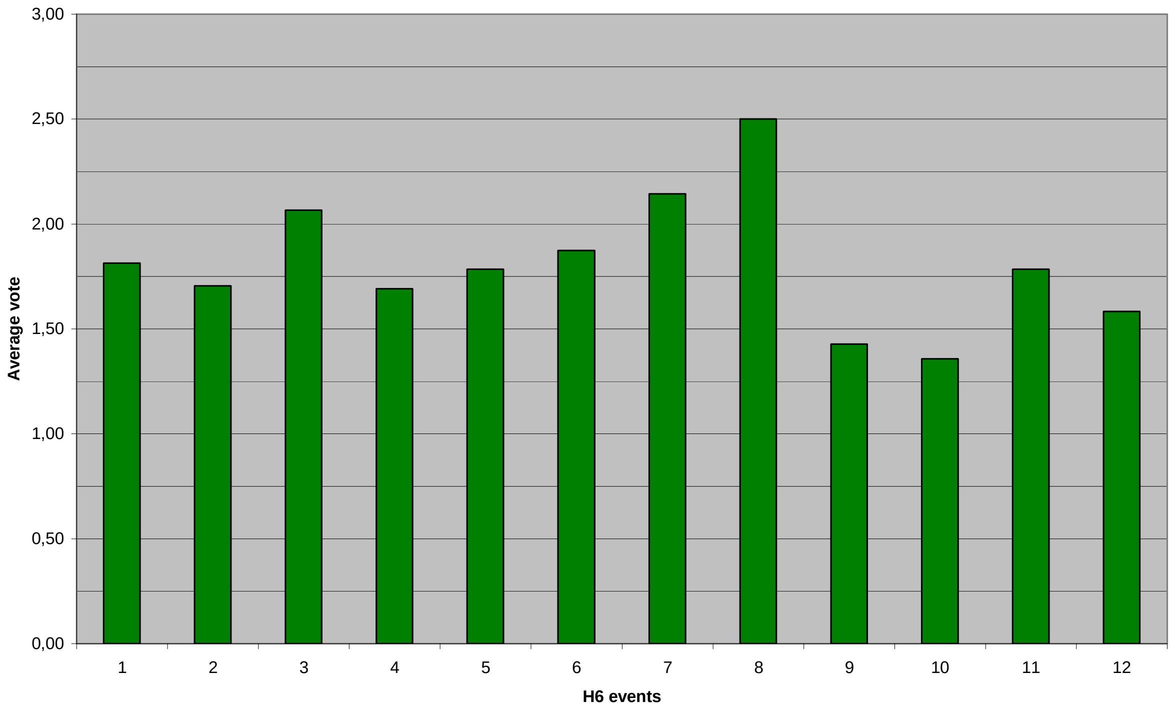

Fig. 14: Average votes for H6 events

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

6. 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.

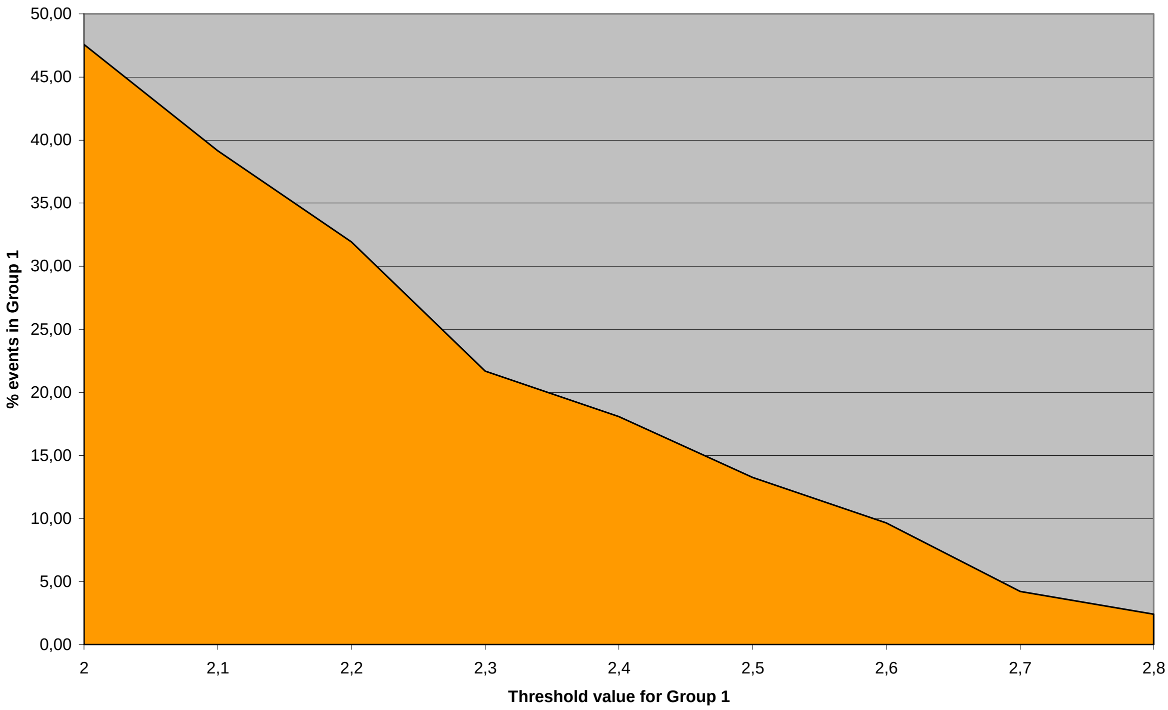

Fig. 15: Effect of threshold on number of events selected in Group 1 (high priority).

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%).

7. OVERALL CONCLUSIONS

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.

Before finalizing the “safety oriented” vote and ranking, more discussions are needed to resolve the lack of consensus for the bimodal votes (18 events are concerned).

The next step will look closely at the different phenomena which are relevant to the selected safety issues, and will rank these phenomena according to our degree of knowledge (phenomena-based ranking).

WP4- PIRT - Phenomena Identification and Ranking Table: Safety Oriented Vote

APPLICATION		TYPE OF FUEL STORAGE	ENVIRONMENT	EVENT	DESCRIPTION OF EVENT / CAUSE	SAFETY ORIENTED VOTE AVERAGE	STANDARD DEVIATION							
1. H1: PRODUCTION								#1	#2	#3	Total #	% Level 1	% Level 2	% Level 3
	1.2 electrolysis (small scale at refilling station)		Urban	1.2.1 mixing of oxygen/hydrogen inside process equipment	1) Failure in control system for separation of gases. 2) material failure	1,85	0,67	6	11	3	20	30	55	15
			Urban	1.2.2 Oxygen leak inside container	material failure, valve, fitting leak	1,65	0,67	9	9	2	20	45	45	10
			Urban	1.2.3 small hydrogen leaks, in confined areas	Hydrogen is difficult to contain inside process equiopment, often diffuse leaks from valves, fittings etc. May be difficult to discover	2,29	0,72	3	9	9	21	14	43	43
			Urban	1.2.4 Large leaks, equipment rupture in confined areas (inside container)	Material failure, human failures during inspection or maintenance operations, failure in process design	2,57	0,68	2	5	14	21	10	24	67
			Urban	1.2.5 large leak or equipment rupture causing reverse flow from downstream high pressure sections		2,37	0,68	2	8	9	19	11	42	47
			Urban	1.2.6 Flow of hydrogen into container (confined area) from leak outside container	External leak flowing into the container through ventialtion inlet openings or other openings	2,06	0,64	3	11	4	18	17	61	22
			Urban	1.2.8 Flow from safety valves/relief openings to unsafe location	Wrong design/location of relief point from	1,80	0,70	7	10	3	20	35	50	15
	1.6 steam/methane reforming		Industrial zone	1.6.1 Natural gaz feeding line rupture - Rupture of steel tubes inside the furnace - Line rupture after reforming (synthesis gas) - CO shift reactor burst - PSA line rupture (rich hydrogen mixture) - line rupture after PSA (pure hydrogen mixture) - PSA vessel burst - PSA purge vessel burst - CO shift reactor burst	mechanical / chemical / thermal agression of equipments	2,18	0,64	2	10	5	17	12	59	29
2. H2:TRANSPORT AND DISTRIBUTION														
	2.1 pipeline GH2	GH2	Open	2.1.1 continuous release from pipeline	leaking from pipeline	1,57	0,51	9	12	0	21	43	57	0
		GH2	Open	2.1.2 continuous release from compression station's fittings and connections	leaking from compression station's fittings and connections	1,67	0,58	8	12	1	21	38	57	5
		GH2	Open	2.1.3 instantaneous release from pipeline	catastrophic rupture of pressure relief devices or mechanical agression (construction work) or thermal agression (welding) or chemical agression (corrosion, incompatibility)	2,19	0,68	3	11	7	21	14	52	33
		GH2	Open	2.1.4 instantaneous release from compression station	catastrophic rupture of pressure relief devices	2,10	0,70	4	11	6	21	19	52	29
	2.2 pipeline LH2	LH2	Open	2.2.1 continuous release from pipeline	leaking fittings or connections	1,45	0,51	11	9	0	20	55	45	0
		LH2	Open	2.2.2 continuous release from pumping station	leaking fittings or connections	1,52	0,51	10	11	0	21	48	52	0
		LH2	Open	2.2.3 instantaneous release from pipeline	catastrophic rupture of pressure relief devices or mechanical agression (construction work) or thermal agression (welding) or chemical agression (corrosion, incompatibility)	2,00	0,77	6	9	6	21	29	43	29
		LH2	Open	2.2.4 instantaneous release from pumping station	catastrophic rupture or pressure relief devices	1,90	0,77	7	9	5	21	33	43	24
	2.3 pipeline mixture NG/H2 (NATURALHY)	GH2 / NG	Open	2.3.1 continuous release from pipeline		1,67	0,66	9	10	2	21	43	48	10
			Open	2.3.2 continuous release from compression station's fittings and connections		1,81	0,60	6	13	2	21	29	62	10
			Open	2.3.3 instantaneous release from pipeline	Mechanical agression (construction work) - Thermal agression (welding work) - Chemical agression (corrosion, incompatibility)	2,24	0,70	3	10	8	21	14	48	38
			Open	2.3.4 instantaneous release from compression station	Mechanical agression (construction work) - Thermal agression (welding work) - Chemical agression (corrosion, incompatibility)	2,29	0,72	3	9	9	21	14	43	43
	2.4 truck transport of compressed GH2	GH2	roads and motorways	2.4.1 crash of GH2 tanker on roads		2,35	0,49	0	15	8	23	0	65	35
		GH2	Tunnels and overbridges	2.4.2 crash of GH2 tanker in tunnel		2,96	0,21	0	1	22	23	0	4	96
		GH2	Urban	2.4.3 discharge hose failure from GH2 tanker at refuelling station		2,29	0,64	2	11	8	21	10	52	38
		GH2	Urban	2.4.4 Continuous release through faulty connections		2,00	0,62	4	14	4	22	18	64	18
	2.5 truck transport of LH2	LH2	roads and motorways	2.5.1 line rupture	overturn - crash - lorry on fire	2,29	0,56	1	13	7	21	5	62	33
		LH2	roads and motorways	2.5.2 tank rupture	overturn, crash, internal explosion (mixture LH2 and LO2 / incompatibility between tank material and hydrogen) - Lorry on fire	2,65	0,49	0	7	13	20	0	35	65
		LH2	roads and motorways	2.5.3 flow inside tank in case of roll over		1,88	0,64	2	5	1	8	25	63	13
		LH2	Urban	2.5.4 discharge hose failure from LH2 tanker at refuelling station		2,25	0,64	2	11	7	20	10	55	35
		LH2	Tunnels and overbridges	2.5.5 crash of LH2 truck in tunnel		3,00	0,00	0	0	10	10	0	0	100
	2.7 sea transport of LH2	LH2	harbour	2.7.1 burst	Chemical agression (corrosion, incompatibility) - Internal explosion	2,22	0,65	2	10	6	18	11	56	33
		LH2	harbour	2.7.2 line / tank rupture		2,44	0,51	0	9	7	16	0	56	44
3. H3: LARGE SCALE STORAGE, REFUELLING STATIONS, STATIONARY APPLICATIONS														
	3.1 Hydride beds		Inside buildings	3.1.1 Burst of tank	Thermal agression - Mechanical agression - Chemical agression	2,25	0,64	2	11	7	20	10	55	35
			Inside buildings	3.1.2 Continuous release of tank ~~in open atmosphere~~	leaking fittings or connections	2,14	0,71	4	11	7	22	18	50	32
	3.2 LH2 tanks	LH2	Urban	3.2.1 Continuous release of tank in open atmosphere	leaking fittings or connections	1,45	0,51	12	10	0	22	55	45	0
		LH2	Urban	3.2.2 instantaneous release of tank content in open atmosphere	(a) break-off of connecting lines between tank and shut-off device	2,00	0,60	4	15	4	23	17	65	17
			Urban	3.2.3 instantaneous release of tank content in open atmosphere	(b) rupture of tank due to mechanical loading (impact)	2,00	0,62	4	14	4	22	18	64	18
			Urban	3.2.4 instantaneous release of tank content in open atmosphere	(c) excessive pressure build-up caused by total loss of insulating vacuum	2,04	0,71	5	12	6	23	22	52	26
			Urban	3.2.5 instantaneous release of tank content in open atmosphere	(d) boil off and overpressure	1,96	0,64	5	14	4	23	22	61	17
			Urban	3.2.6 continuous release in partially confined or totally confined atmosphere	leaking fittings or connections	2,39	0,58	1	12	10	23	4	52	43
			Urban	3.2.7 instantaneous release in partially confined or totally confined atmosphere		2,64	0,49	0	8	14	22	0	36	64
		LH2	roads and motorways	3.2.8 overpressure in tank due to flow motion (in case of turn-over)		1,86	0,53	3	10	1	14	21	71	7
		LH2	Urban	3.2.9 overpressure in tank due to external heat release	caused by neighbouring fire	1,76	0,66	6	9	2	17	35	53	12
	3.3 GH2 tanks	GH2	Urban	3.3.1 continuous release (through valves) in open atmosphere		1,52	0,67	13	8	2	23	57	35	9
		GH2	Urban	3.3.2 continuous release in partially confined atmosphere		2,09	0,60	3	15	5	23	13	65	22
		GH2	Urban	3.3.3 continuous release in confined atmosphere		2,61	0,50	0	9	14	23	0	39	61
		GH2	Urban	3.3.4 instantaneous release in open atmosphere		1,91	0,68	6	12	4	22	27	55	18
		GH2	Urban	3.3.5 instantaneous release in partially confined atmosphere		2,41	0,50	0	13	9	22	0	59	41
		GH2	Urban	3.3.6 instantaneous release in confined atmosphere		2,70	0,47	0	7	16	23	0	30	70
		GH2	Urban	3.3.7 reverse flow of air into tank after release of H2		2,57	0,53	0	3	4	7	0	43	57
	3.4 refueling station cryogenic H2	LH2	Urban	3.4.1 Continuous release in open atmosphere	leaking fittings or connections	1,50	0,59	13	10	1	24	54	42	4

		LH2	Urban	3.4.2 continuous release in partially confined atmosphere	leaking fittings or connections	2,29	0,62	2	13	9	24	8	54	38
		LH2	Urban	3.4.3 instantaneous release in open atmosphere	(a) crash of vehicle against dispenser	1,91	0,79	8	9	6	23	35	39	26
			Urban	3.4.4 instantaneous release in open atmosphere	(b) break-away of the flexible filling tube's coupling	1,83	0,72	8	11	4	23	35	48	17
			Urban	3.4.5 instantaneous release in open atmosphere	(c) piping catastrophic rupture	1,96	0,56	4	16	3	23	17	70	13
			Urban	3.4.6 instantaneous release in open atmosphere	(d) pressure relief devices	1,61	0,58	10	12	1	23	43	52	4
		LH2	Urban	3.4.7 instantaneous release in partially confined atmosphere	piping catastrophic rupture	2,48	0,51	0	12	11	23	0	52	48
	3.5 refueling station GH2	GH2	Urban	3.5.1 Release during refuelling of vehicle	Human failure, material failures, driver present	1,91	0,73	7	11	5	23	30	48	22
		GH2	Urban	3.5.2 Vehicle drives away while refuelling	Brakes not activated	1,83	0,89	11	5	7	23	48	22	30
		GH2	Urban	3.5.3 Fire exposing high pressure storage tank	invisible H2 fire, noisy area, not easy to detect, exposing storage tanks	2,29	0,56	1	13	7	21	5	62	33
		GH2	Urban	3.5.4 hose or pipe rupture in dispenser	vehicle collision with dispenser	2,29	0,72	3	9	9	21	14	43	43
		GH2	Urban	3.5.6 Overfilling of vehicle storage tank	failure in control system	1,95	0,90	9	5	8	22	41	23	36
		GH2	Urban	3.5.7 Releases in containers (e.g compressor containers)	see releases in confined areas for electrolysis under H1	2,25	0,68	2	8	6	16	13	50	38
		GH2	Urban	3.5.8 Continuous release in open atmosphere	leaking fittings or connections	1,52	0,67	13	8	2	23	57	35	9
		GH2	Urban	3.5.9 Continuous release in partially confined atmosphere	leaking fittings or connections	2,13	0,63	3	14	6	23	13	61	26
		GH2	Urban	3.5.10 Instanataneous release in open atmosphere	(a) crash of vehicle against dispenser	1,86	0,77	8	9	5	22	36	41	23
			Urban	3.5.11 Instanataneous release in open atmosphere	(b) break-away of the flexible filling tube's coupling	1,73	0,77	10	8	4	22	45	36	18
			Urban	3.5.12 Instanataneous release in open atmosphere	(c) piping catastrophic rupture	2,04	0,71	5	12	6	23	22	52	26
			Urban	3.5.13 Instanataneous release in open atmosphere	(d) pressure relief devices	1,57	0,66	12	9	2	23	52	39	9
		GH2	Urban	3.5.14 instantaneous release in partially confined atmosphere	piping catastrophic rupture	2,43	0,59	1	11	11	23	4	48	48
	3.7 Stationary application: Auxiliary Power Unit	GH2	Inside buildings	3.7.1 leakings from core, piping, ecc.		2,18	0,81	4	6	7	17	24	35	41
		GH2	Inside buildings	3.7.2 release from cell purging	downstream valve failure	1,80	0,86	7	4	4	15	47	27	27
		GH2	Inside buildings	3.7.3 formation of explosive mixture outside the stack: small release rate	stack gasket rupture, stack disassembly	2,06	0,75	4	8	5	17	24	47	29
		GH2	Inside buildings	3.7.4 reverse electrolysis	cell flooding	1,67	0,78	4	7	1	12	33	58	8
		GH2	Inside buildings	3.7.5 membrane rupture	overpressure, reverse pressure, ageing	1,93	0,62	3	9	2	14	21	64	14
		GH2	Inside buildings	3.7.6 formation of explosive mixtures inside the stack	due tu membrane rupture	1,93	0,70	4	8	3	15	27	53	20
		GH2	Inside buildings	3.7.7 feeding line rupture (from indoor gas storage)		2,25	0,77	3	6	7	16	19	38	44
		GH2	Inside buildings	3.7.8 explosive atmosphere in room: high release rate	expand valve, connecting leak. Safety valve opening	2,47	0,62	1	7	9	17	6	41	53
		GH2	Urban	3.7.9 release from cell purging	downstream valve failure	1,31	0,63	10	2	1	13	77	15	8
		GH2	Urban	3.7.10 leakings from core, piping, gasket		1,25	0,62	10	1	1	12	83	8	8
		GH2	Urban	3.7.11 formation of explosive atmosphere outside the stack		1,78	0,88	9	4	5	18	50	22	28
		GH2 or LH2	Inside buildings	3.7.12 production of unconsumed H2 when FC is stopped. Processes to "neutralize" the residual H2 (evacuate, inert)		1,43	0,65	9	4	1	14	64	29	7
4. H4: VEHICLES POWERED WITH H2														
	4.1 commercial vehicle	GH2 or LH2	roads and motorways	4.1.1 vehicle crash / overturn / failure in car / stray bullet	No need to distinguish between ICE- and fuel cell powered vehicles. All issues could lead to the same phenomena. However, there is a need to distinguish between GH2 & LH2, as the behaviour of the released hydrogen in the early stages of the release will be very different, i.e buoyant gas from a GH2 release and much denser gas in the early stages of a LH2 release. The quantity of hydrogen involved in commercial vehilces will be significantly larger than passenger cars by up to an order of magnitude, and different release points may affect the behaviour of release especially in confined environments, e.g. garages and tunnels.	1,89	0,74	6	9	4	19	32	47	21
		GH2 or LH2	Tunnels and overbridges	4.1.3 vehicle accident/failure leading to damage to tank in Tunnel		2,62	0,59	1	6	14	21	5	29	67
		GH2 or LH2	Tunnels and overbridges	4.1.4 fire in tunnel	may be caused by other accident not involving H2 car, but provides thermal loading on H2 vehicle	2,62	0,50	0	8	13	21	0	38	62
		GH2	car parks and maintenance workshops	4.1.6 process to "neutralize" residual H2 produced by FC when vehicle is stopped (evacuation, inerting, …) [see 4.2.12, 6.1.5]		1,42	0,79	7	4	1	12	58	33	8
		GH2 or LH2	car parks and maintenance workshops	4.1.7 car accident/failure leading to damage to tank in Maintenance workshop		2,32	0,67	2	9	8	19	11	47	42
		GH2	car parks and maintenance workshops	4.1.8 permeation through the surfaces of the pressure vessels and other components		1,17	0,72	10	1	1	12	83	8	8
		GH2	car parks and maintenance workshops	4.1.9 small leaks from components at joints, seals,	No system can be 100% leak tight, and legal requirements will certainly allow a very small amount of leakage	1,50	0,67	7	4	1	12	58	33	8
		GH2	car parks and maintenance workshops	4.1.10 releases from low pressure sections or almost empty storage systems	due to vents, broken pipes, loose or damaged fittings, trapped foreign bodies	1,45	0,69	7	3	1	11	64	27	9
		GH2	Tunnels and overbridges	4.1.11 releases from high pressure storage	due to vents, broken pipes, loose or damaged fittings, trapped foreign bodies	2,86	0,36	0	2	12	14	0	14	86
		GH2	Tunnels and overbridges	4.1.12 failure of vessel	due to fatigue crack	2,64	0,63	1	3	10	14	7	21	71
		GH2	Tunnels and overbridges	4.1.13 catastrophic failure of storage system		2,93	0,27	0	1	13	14	0	7	93
		GH2	roads and motorways	4.1.14 releases from high pressure storage	same as 4.1.11 but different environment	1,86	0,77	5	6	3	14	36	43	21
		GH2	roads and motorways	4.1.15 failure of vessel	same as 4.1.12 but different environment	1,86	0,86	6	4	4	14	43	29	29
		GH2	roads and motorways	4.1.16 catastrophic failure of storage system	same as 4.1.13 but different environment	2,07	0,83	4	5	5	14	29	36	36
New events proposed by Volvo		GH2	Open	4.1.17 Release via PRD	Release may be unintentional, i.e. component failure, or intentional, i.e. in the event of a fire to avoid failure of the pressure vessels	1,60	0,70	5	4	1	10	50	40	10
		GH2	Open	4.1.18 Release due to system damage or component failure (low pressure/small quantity)	Traffic accident, component failure, vandalism, etc., or routine FC purging Draft regs require shut-off system limiting released hydrogen	1,40	0,52	6	4	0	10	60	40	0
		GH2	Open	4.1.19 Release due to system damage or component failure (high pressure/large quantity)	Traffic accident, component failure, bullet, vandalism,	1,90	0,74	3	5	2	10	30	50	20
		GH2	Open	4.1.20 Small leaks from components, joints etc	Open env. assumes vehicle in traffic and is unlikely to enter traffic with major leaks.	1,10	0,32	9	1	0	10	90	10	0
		GH2	Open	4.1.21 Container failure	Low probability due to various design features and safeguards, but high consequence	1,70	0,82	5	3	2	10	50	30	20
		GH2	Urban	4.1.22 Release via PRD	Release may be unintentional, i.e. component failure, or intentional, i.e. in the event of a fire to avoid failure of the pressure vessels	1,70	0,67	4	5	1	10	40	50	10
		GH2	Urban	4.1.23 Release due to system damage or component failure (low pressure/small quantity)	Traffic accident, component failure, vandalism, etc., or routine FC purging Draft regs require shut-off system limiting released hydrogen	1,30	0,48	7	3	0	10	70	30	0
		GH2	Urban	4.1.24 Release due to system damage or component failure (high pressure/large quantity)	Traffic accident, component failure, bullet, vandalism, etc	2,30	0,67	1	5	4	10	10	50	40
		GH2	Urban	4.1.25 Small leaks from components, joints etc	Open env. assumes vehicle in traffic and is unlikely to enter traffic with major leaks.	1,30	0,48	7	3	0	10	70	30	0
		GH2	Urban	4.1.26 Container failure	Low probability due to various design features and safeguards, but high consequence	2,10	0,74	2	5	3	10	20	50	30

WP4- PIRT - Phenomena Identification and Ranking Table: Safety Oriented Vote

		GH2	Tunnels and overbridges	4.1.27 Release via PRD	Release may be unintentional, i.e. component failure, or intentional, i.e. in the event of a fire to avoid failure of the pressure vessels	2,50	0,71	1	3	6	10	10	30	60
		GH2	Tunnels and overbridges	4.1.28 Release due to system damage or component failure (low pressure/small quantity)	Traffic accident, component failure, vandalism, etc., or routine FC purging Draft regs require shut-off system limiting released hydrogen	1,90	0,57	2	7	1	10	20	70	10
		GH2	Tunnels and overbridges	4.1.29 Release due to system damage or component failure (high pressure/large quantity)	Traffic accident, component failure, bullet, vandalism, etc	2,70	0,48	0	3	7	10	0	30	70
		GH2	Tunnels and overbridges	4.1.30 Leaks from components	-	1,89	0,78	3	4	2	9	33	44	22
		GH2	Tunnels and overbridges	4.1.31 Container failure	Low probability due to various design features and safeguards, but high consequence	2,60	0,70	1	2	7	10	10	20	70
		GH2	car parks and maintenance workshops	4.1.32 Release via PRD	Release may be unintentional, i.e. component failure, or intentional, i.e. in the event of a fire to avoid failure of the pressure vessels	2,30	0,82	2	3	5	10	20	30	50
		GH2	car parks and maintenance workshops	4.1.33 Release due to system damage or component failure (low pressure/small quantity)	Accident, component failure, vandalism, etc., or routine FC purging Draft regs require shut-off system limiting released hydrogen	2,10	0,74	2	5	3	10	20	50	30
		GH2	car parks and maintenance workshops	4.1.34 Release due to system damage or component failure (high pressure/large quantity)	Traffic accident, component failure, bullet, vandalism, etc	2,60	0,70	1	2	7	10	10	20	70
		GH2	car parks and maintenance workshops	4.1.34 Leaks from components	For example, leaks from loose, untightened connections, failure to follow test procedures etc	2,10	0,88	3	3	4	10	30	30	40
		GH2	car parks and maintenance workshops	4.1.35 Permeation through pressure vessel walls	-	1,78	0,97	5	1	3	9	56	11	33
		GH2	car parks and maintenance workshops	4.1.36 Container failure	Low probability due to various design features and safeguards, but high consequence	2,70	0,48	0	3	7	10	0	30	70
		GH2	car parks and maintenance workshops	4.1.37 System not purged before opening for maintenance	Severity depends on point in the system where it is opened	2,20	0,92	3	2	5	10	30	20	50
		LH2	Open	4.1.38 Release via safety device	Release may be unintentional, i.e. component failure, or intentional, e.g. in the event of a fire to avoid failure of the cryogenic vessel	1,50	0,71	6	3	1	10	60	30	10
		LH2	Open	4.1.39 Release due to system damage or component failure	Traffic accident, component failure, vandalism, etc., or routine FC purging Draft regs require shut-off system limiting released hydrogen, depending where the release is	1,50	0,71	6	3	1	10	60	30	10
		LH2	Open	4.1.40 Small leaks from components, joints etc Probably gaseous downstream of container	Open env. assumes vehicle in traffic and is unlikely to enter traffic with major leaks.	1,00	0,00	10	0	0	10	100	0	0
		LH2	Open	4.1.41 Boil-off	Draft regs require boil-off management system	1,00	0,00	10	0	0	10	100	0	0
		LH2	Open	4.1.42 Container failure	Low probability due to various design features and safeguards, but high consequence	1,90	0,88	4	3	3	10	40	30	30
		LH2	Urban	4.1.43 Release via safety device	Release may be unintentional, i.e. component failure, or intentional, i.e. in the event of a fire to avoid failure of the cryogenic vessels	1,70	0,67	4	5	1	10	40	50	10
		LH2	Urban	4.1.44 Release due to system damage or component failure	Traffic accident, component failure, vandalism, etc., or routine FC purging Draft regs require shut-off system limiting released hydrogen, depending where the release is	2,00	0,67	2	6	2	10	20	60	20
		LH2	Urban	4.1.45 Small leaks from components, joints etc Probably gaseous downstream of container	Urban env. assumes vehicle in traffic and is unlikely to enter traffic with major leaks.	1,30	0,67	8	1	1	10	80	10	10
		LH2	Urban	4.1.46 Boil-off	Draft regs require boil-off management system	1,00	0,00	10	0	0	10	100	0	0
		LH2	Urban	4.1.47 Container failure	Low probability due to various design features and safeguards, but high consequence	2,22	0,67	1	5	3	9	11	56	33
		LH2	Tunnels and overbridges	4.1.48 Release via safety device	Release may be unintentional, i.e. component failure, or intentional, i.e. in the event of a fire to avoid failure of the cryogenic vessels	2,10	0,74	2	5	3	10	20	50	30
		LH2	Tunnels and overbridges	4.1.49 Release due to system damage or component failure	Traffic accident, component failure, vandalism, etc., or routine FC purging Draft regs require shut-off system limiting released hydrogen, depending where the release is	2,30	0,82	2	3	5	10	20	30	50
		LH2	Tunnels and overbridges	4.1.50 Small leaks from components, joints etc Probably gaseous downstream of container	Urban env. assumes vehicle in traffic and is unlikely to enter traffic with major leaks.	1,90	0,74	3	5	2	10	30	50	20
		LH2	Tunnels and overbridges	4.1.51 Boil-off	Draft regs require boil-off management system	1,80	0,79	4	4	2	10	40	40	20
		LH2	Tunnels and overbridges	4.1.52 Container failure	Low probability due to various design features and safeguards, but high consequence	2,50	0,71	1	3	6	10	10	30	60
		LH2	car parks and maintenance workshops	4.1.53 Release via safety device	Release may be unintentional, i.e. component failure, or intentional, i.e. in the event of a fire to avoid failure of the cryogenic vessels	2,00	0,82	3	4	3	10	30	40	30
		LH2	car parks and maintenance workshops	4.1.54 Release due to system damage or component failure	Accident, component failure, vandalism, etc., or routine FC purging Draft regs require shut-off system limiting released hydrogen, depending where the release is	2,20	0,79	2	4	4	10	20	40	40
		LH2	car parks and maintenance workshops	4.1.55 Leaks from components	For example, leaks from loose, untightened connections, failure to follow test procedures etc	2,00	0,82	3	4	3	10	30	40	30
		LH2	Tunnels and overbridges	4.1.56 Boil-off	Draft regs require boil-off management system	2,00	0,71	2	5	2	9	22	56	22
		LH2	car parks and maintenance workshops	4.1.57 Container failure	Low probability due to various design features and safeguards, but high consequence	2,40	0,84	2	2	6	10	20	20	60
		GH2	car parks and maintenance workshops	4.1.58 System not purged before opening for maintenance	Severity depends on point in the system where it is opened	2,00	0,82	3	4	3	10	30	40	30
	4.2 passenger car	GH2 or LH2	roads and motorways	4.2.1 car crash / overturn / failure in car / stray bullet	No need to distinguish between ICE- and fuel cell powered vehicles. All issues could lead to the same phenomena.	2,00	0,75	5	9	5	19	26	47	26
		GH2 or LH2	Tunnels and overbridges	4.2.3 car accident/failure leading to damage to tank in Tunnel		2,75	0,44	0	5	15	20	0	25	75
		GH2 or LH2	Tunnels and overbridges	4.2.4 fire in tunnel	may be caused by other accident not involving H2 car, but provides thermal loading on H2 car	2,71	0,46	0	6	15	21	0	29	71
		GH2 or LH2	car parks and maintenance workshops	4.2.6 car accident/failure leading to damage to tank in public car park : high flow rate discharge		2,71	0,46	0	6	15	21	0	29	71
		GH2 or LH2	car parks and maintenance workshops	4.2.7 car accident/failure leading to damage to tank in public car park : small flow rate leakage		2,14	0,64	3	13	6	22	14	59	27
		GH2 or LH2	car parks and maintenance workshops	4.2.8 fire in public car park	may be caused by other accident not involving H2 car, but provides thermal loading on H2 car	2,55	0,60	1	8	13	22	5	36	59
		GH2 or LH2	car parks and maintenance workshops	4.2.10 car accident/failure leading to damage to tank in Private car park : high flow rate discharge		2,57	0,51	0	9	12	21	0	43	57
		GH2 or LH2	car parks and maintenance workshops	4.2.11 car accident/failure leading to damage to tank in Private car park : small flow rate leakage		2,09	0,68	4	12	6	22	18	55	27
		GH2 or LH2	car parks and maintenance workshops	4.2.12 car accident/failure leading to damage to tank in Maintenance workshop: high flow rate discharge		2,55	0,67	2	6	14	22	9	27	64
		GH2 or LH2	car parks and maintenance workshops	4.2.13 car accident/failure leading to damage to tank in Maintenance workshop: small flow rate leakage		2,14	0,77	5	9	8	22	23	41	36
		GH2	car parks and maintenance workshops	4.2.14 process to "neutralize" residual H2 produced by FC when car is stopped (evacuation, inerting, …) [see 6.1.5]		1,87	0,64	4	9	2	15	27	60	13
		GH2 or LH2	roads and motorways	4.2.15 scene of car crash: accidental rupture of H2 fuel lines by pneumatic pincer tools used by emergency services trying to free trapped passengers		2,13	0,81	4	6	6	16	25	38	38
		LH2	car parks and maintenance workshops	4.2.16 Boil off		2,00	0,76	2	4	2	8	25	50	25

WP4- PIRT - Phenomena Identification and Ranking Table: Safety Oriented Vote

5. H5: OTHER PROPULSION SYSTEMS														
	5.1 ships	All fuel	sea	5.1.1 ship overturn	(a) hull overturned and hydrogen leakings towards the cabin, (b) boiloff and pressurization of LH2 tank	2,15	0,69	2	7	4	13	15	54	31
		All fuel	sea	5.1.2 ship crash	rupures of hydrogen components	1,93	0,70	4	8	3	15	27	53	20
		All fuel	sea	5.1.3 ship rolling	boiloff and pressurization of LH2 tank	2,08	0,64	2	8	3	13	15	62	23
6. H6: PORTABLE H2 APPLICATIONS														
	6.1 fuel cells	GH2	Inside buildings	6.1.1 leakings from core, piping, ecc.		1,81	0,83	7	5	4	16	44	31	25
		GH2	Inside buildings	6.1.2 release from cell purging	downstream valve failure	1,71	0,77	8	6	3	17	47	35	18
		GH2	Inside buildings	6.1.3 formation of explosive mixture outside the stack	stack gasket rupture, stack disassembly	2,07	0,70	3	8	4	15	20	53	27
		GH2	Inside buildings	6.1.4 reverse electrolysis	cell flooding	1,69	0,63	5	7	1	13	38	54	8
		GH2	Inside buildings	6.1.5 membrane rupture	overpressure, reverse pressure, ageing	1,79	0,58	4	9	1	14	29	64	7
		GH2	Inside buildings	6.1.6 formation of explosive mixtures inside the stack	due tu membrane rupture	1,88	0,50	3	12	1	16	19	75	6
		GH2	Inside buildings	6.1.7 feeding line rupture (from indoor gas storage)		2,14	0,66	2	8	4	14	14	57	29
		GH2	Inside buildings	6.1.8 explosive atmosphere in room	expand valve, connecting leak. Safety valve opening	2,50	0,63	1	6	9	16	6	38	56
		GH2	Urban	6.1.9 release from cell purging	downstream valve failure	1,43	0,51	8	6	0	14	57	43	0
		GH2	Urban	6.1.10 leakings from core, piping, gasket		1,36	0,50	9	5	0	14	64	36	0
		GH2	Urban	6.1.11 formation of explosive atmosphere outside the stack		1,79	0,70	5	7	2	14	36	50	14
		GH2 or LH2	Inside buildings	6.1.12 production of unconsumed H2 when FC is stopped. Processes to "neutralize" the residual H2 (evacuate, inert)		1,58	0,67	6	5	1	12	50	42	8

GROUP 1
GROUP 2
GROUP 3
GROUP B - Bimodal