WP4 PIRT: Results of « Safety Oriented » Vote

(Deliverable D12)

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1. INTRODUCTION

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

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.](image)

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
- 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)](image)

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).

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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)

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

Conclusions for H1 votes:

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)

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 instant 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 tunnel) 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)

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 3.7.2 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)

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
- (confinelement/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 conjunction 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 conjunction 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)

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
  o Event 4.1.3 vehicle accident in tunnel with tank damage (2.62)
  o Event 4.1.4 fire in tunnel leading to strong heat flux on tank (2.62)
  o Event 4.1.7 accident or failure leading to tank damage in maintenance workshop (2.32)
  o Event 4.1.11 accidental release from high pressure tank in tunnel or under overbridge (2.86)
  o Event 4.1.12 failure of tank due to fatigue crack while in tunnel or overbridge (2.64)
  o Event 4.1.13 catastrophic failure of storage system (2.93)
  o Event 4.1.24 release due to system/component failure in urban environment (2.30)
  o Event 4.1.27 release via the PRD (accidental or intentional) while in tunnel (2.50)
  o Event 4.1.29 release due to system/component failure in tunnel (2.70)
  o Event 4.1.31 container failure while in tunnel or overbridge (2.60)
  o Event 4.1.32 release via the PRD (accidental or intentional) in a car park or maintenance workshop (2.30)
  o Event 4.1.34 large rate release due to system damage or component failure (2.60)
  o Event 4.1.36 container failure in car park or maintenance workshop (2.70)
  o Event 4.1.37 accident due to lack of purge of system before opening for maintenance (in workshop) (2.70)
  o Event 4.1.47 container failure in an urban environment (2.22)
  o Event 4.1.49 release due to system damage or failure of component while in tunnel or overbridge (2.30)
  o Event 4.1.52 container failure in a tunnel or overbridge (2.50)
  o Event 4.1.54 release due to system damage or failure of component while in car park or maintenance workshop (2.20)
  o Event 4.1.57 container failure in a car park or maintenance workshop (2.40)

- Application 4.2 Passenger cars
  o Event 4.2.3 car accident leading to tank failure while in tunnel (2.75)
  o Event 4.2.4 fire in tunnel, leading to thermal loading on tank (2.71)
  o Event 4.2.6 car accident leading to tank failure in car park (high release rate case) (2.71)
  o Event 4.2.8 fire in public car park, leading to thermal loading on tank (2.55)
  o Event 4.2.10 car accident leading to tank failure in private car park (high release rate case) (2.57)
  o 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
  o Event 4.1.15 failure of vessel (storage tank) while on the road (43% Level 1 votes and 29% Level 3 votes)
  o 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

<table>
<thead>
<tr>
<th>Conclusions for H4 votes:</th>
</tr>
</thead>
<tbody>
<tr>
<td>The H4 votes (Group 1 but also Group B) illustrate a number of safety concerns related to:</td>
</tr>
<tr>
<td>- safety of H2 vehicles in <strong>confined environments such as tunnels, public or private car parks, maintenance workshops</strong>. Damage to systems or components including the tank (because of accidents or external causes such as fire) could lead to <strong>releases of H2 and the formation of confined potentially explosive clouds</strong>. 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.</td>
</tr>
<tr>
<td>- the <strong>performance and reliability of systems and components, including tanks</strong>: 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.</td>
</tr>
<tr>
<td>- the <strong>performance of the H2 tanks under mechanical or thermal loads</strong></td>
</tr>
<tr>
<td>- <strong>failure to follow “good practices”</strong> (for car mechanics in maintenance activities (purging of systems), or for emergency crews on scenes of accidents).</td>
</tr>
</tbody>
</table>
5.5 OTHER PROPULSION SYSTEMS (H5)

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)

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).
### APPLICATIONS

**STORAGE ENVIRONMENT EVENT DESCRIPTION OF EVENT / CAUSE AVERAGE**

<table>
<thead>
<tr>
<th>EVENT</th>
<th>DESCRIPTION OF EVENT / CAUSE</th>
<th>AVERAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1.1</td>
<td>Continuous release from pipeline</td>
<td>1,57 0,51 9 12 0 21 43 48 57 0</td>
</tr>
<tr>
<td>1.1.2</td>
<td>Continuous release from compressors and other equipment</td>
<td>1,67 0,58 8 12 1 21 38 57 6</td>
</tr>
<tr>
<td>1.1.3</td>
<td>Continuous release from valves</td>
<td>2,19 0,66 3 11 7 21 14 52 33</td>
</tr>
<tr>
<td>1.1.4</td>
<td>Continuous release from leakage, fittings and connections</td>
<td>1,90 0,77 7 9 5 21 33 43 24</td>
</tr>
<tr>
<td>1.1.5</td>
<td>Continuous release from burst in pipelines</td>
<td>2,00 0,77 6 9 6 21 29 43 29</td>
</tr>
<tr>
<td>1.1.6</td>
<td>Continuous release from pipeline break or loss of pressure</td>
<td>2,14 0,63 10 11 6 21 44 52 62 0</td>
</tr>
<tr>
<td>1.1.7</td>
<td>Continuous release from break or loss of pressure</td>
<td>2,20 0,72 3 9 9 21 14 43 43</td>
</tr>
<tr>
<td>1.1.8</td>
<td>Continuous release from leakage, fittings and connections</td>
<td>1,88 0,64 2 5 4 21 20 55 35</td>
</tr>
<tr>
<td>1.1.9</td>
<td>Continuous release from break in pipe</td>
<td>2,25 0,64 2 11 7 21 10 55 35</td>
</tr>
<tr>
<td>1.1.10</td>
<td>Continuous release from valve</td>
<td>2,26 0,64 2 11 7 21 10 55 35</td>
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<tr>
<td>1.1.11</td>
<td>Continuous release from break in pipe</td>
<td>2,35 0,49 0 15 8 23 0 65 35</td>
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<td>1.1.12</td>
<td>Continuous release from break in pipe</td>
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</tr>
<tr>
<td>1.1.13</td>
<td>Continuous release from break in pipe</td>
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<td>1.1.14</td>
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<td>1.1.15</td>
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<td>1.1.16</td>
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<td>1.1.17</td>
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<td>1.1.18</td>
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<td>1.1.19</td>
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<td>2,36 0,49 0 8 14 22 0 36 64</td>
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<td>1.1.21</td>
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<td>1,76 0,66 6 9 2 11 35 53 17</td>
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<td>1.1.22</td>
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<td>1.1.23</td>
<td>Continuous release from break in pipe</td>
<td>2,09 0,60 3 15 5 23 13 65 22</td>
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<tr>
<td>1.1.24</td>
<td>Continuous release from break in pipe</td>
<td>2,61 0,50 0 9 14 23 0 39 61</td>
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<td>1.1.25</td>
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<td>1.1.26</td>
<td>Continuous release from break in pipe</td>
<td>2,41 0,50 0 13 9 22 0 59 41</td>
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<tr>
<td>1.1.27</td>
<td>Continuous release from break in pipe</td>
<td>2,70 0,47 0 7 18 23 0 30 79</td>
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<tr>
<td>1.1.28</td>
<td>Continuous release from break in pipe</td>
<td>2,82 0,52 0 3 4 7 0 40 57</td>
</tr>
<tr>
<td>1.1.29</td>
<td>Continuous release from break in pipe</td>
<td>1,50 0,59 13 10 1 24 54 42 4</td>
</tr>
<tr>
<td>Event Description</td>
<td>Probability</td>
<td>Impact</td>
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<td>----------------------------------------------------------------------------------</td>
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<tr>
<td>Release due to system damage or component failure</td>
<td>0.13</td>
<td>0.02</td>
</tr>
<tr>
<td>Component failure</td>
<td>0.01</td>
<td>0.00</td>
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<tr>
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<td>0.13</td>
<td>0.02</td>
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<td>Component failure</td>
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<td>0.00</td>
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<tr>
<td>Release due to system damage or component failure</td>
<td>0.13</td>
<td>0.02</td>
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<tr>
<td>Component failure</td>
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<tr>
<td>Component failure</td>
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<tr>
<td>Component failure</td>
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<td>Component failure</td>
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<td>0.02</td>
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<tr>
<td>Component failure</td>
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<tr>
<td>Release due to system damage or component failure</td>
<td>0.13</td>
<td>0.02</td>
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<tr>
<td>Component failure</td>
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<td>0.00</td>
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<tr>
<td>Phenomenon</td>
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<tr>
<td><strong>5. H5: OTHER PROPULSION SYSTEMS</strong></td>
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<td></td>
</tr>
<tr>
<td><strong>5.1 ships</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. ship overturn</td>
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<td></td>
</tr>
<tr>
<td>2,15</td>
<td>0,69</td>
<td>2</td>
</tr>
<tr>
<td>b. ship rolling</td>
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<td></td>
</tr>
<tr>
<td>1,95</td>
<td>0,70</td>
<td>4</td>
</tr>
<tr>
<td>c. ship rolling</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2,05</td>
<td>0,64</td>
<td>2</td>
</tr>
<tr>
<td><strong>5.2 portable applications</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>6.6.1 fuel cells</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. leakings from core, piping, etc.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1,81</td>
<td>0,83</td>
<td>7</td>
</tr>
<tr>
<td>b. release from cell purging downstream valve failure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1,71</td>
<td>0,77</td>
<td>8</td>
</tr>
<tr>
<td>c. formation of explosive mixture outside the stack stack gasket rupture, stack disassembly</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2,07</td>
<td>0,70</td>
<td>3</td>
</tr>
<tr>
<td>d. formation of explosive mixture inside the stack due to membrane rupture</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1,88</td>
<td>0,50</td>
<td>3</td>
</tr>
<tr>
<td>e. feeding line rupture (from indoor gas storage)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2,14</td>
<td>0,66</td>
<td>2</td>
</tr>
<tr>
<td>f. explosive atmosphere in room</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2,50</td>
<td>0,63</td>
<td>1</td>
</tr>
<tr>
<td>g. release from cell purging downstream valve failure</td>
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<td></td>
</tr>
<tr>
<td>1,43</td>
<td>0,51</td>
<td>9</td>
</tr>
<tr>
<td>h. leakings from core, piping, etc.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1,36</td>
<td>0,50</td>
<td>9</td>
</tr>
<tr>
<td>i. formation of explosive atmosphere outside the stack</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1,79</td>
<td>0,70</td>
<td>5</td>
</tr>
<tr>
<td>j. production of unconsumed H2 when FC is stopped. Processes to &quot;neutralize&quot; the residual H2 (evacuate, inert)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1,58</td>
<td>0,67</td>
<td>6</td>
</tr>
</tbody>
</table>