RISK ASSESSMENT OF HYDROGEN EXPLOSION FOR PRIVATE CAR WITH HYDROGEN-DRIVEN ENGINE

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ABSTRACT

The aim of the study is to identify and quantify the additional risks related to hydrogen explosions during the operation of a hydrogen driven car. In a first attempt the accidents or failures of a simple one-tank hydrogen storage system has been studied as a main source of risk. Three types of initiators are taken into account: crash accidents, fire accidents without crash (no other cars are involved) and hydrogen leakages in normal situation with following ignition. The consequences of hydrogen ignition and/or explosion depend strongly on environmental conditions (geometry, wind, etc.), therefore the different configurations of operational and environmental conditions are specified.
Then Event Tree / Fault Tree methods are applied for the risk assessment.
The results of quantification permit to draw conclusions about the overall added risk of hydrogen technology as well as about the main contributors to the risk. Results of this work will eventually contribute to the on-going pre-normative research in the field of hydrogen safety.

1. TASK SPECIFICATION

The aim of the study is to identify and quantify the additional risks related to hydrogen explosions when the private car operates with a hydrogen-essence hybrid engine.

2. SYSTEM DESCRIPTION

In a first attempt a simple one-tank hydrogen storage-supplying system was considered with three parts divided according to the hydrogen pressure: high pressure part, medium pressure part and low pressure part as shown in Figure 1.
The high pressure part of the system (up to 700 bars) contains piping, supports and fixations, a storage tank equipped with a main shut off valve (MIV) and an excess flow valve (overflow prevention valve - OPV), refueling and storage tank check valves (CV1, CV2), one high pressure safety valve (HPSV) also called TPRD (thermally activated pressure relief device) and a high pressure regulation valve (HPRV). HPSV (or TPRD) is a passive device to protect the system against overpressure and it is actuated by a high environmental temperature.
The medium pressure part of the system includes piping, supports and fixations, as well as a medium pressure safety valve (MPSV) and a medium pressure regulation valve (MPRV).
The low pressure part includes piping, supports and fixations, fuel cell stack and fuel cell discharger.
Total storage capacity is assumed being about 4 kg of hydrogen, which corresponds to approximately 400 km of vehicle range (traveling autonomy).

3. INITIATING EVENTS AND ENVIRONMENTAL CONDITIONS

Three types of initiators were considered:
- crash accidents,
- fire accidents without crash (no other cars are involved),
- hydrogen leakages followed by ignition.

As the consequences of hydrogen ignition or explosion strongly depend on environmental conditions (geometry, wind, etc.) the following situations were taken into account in this study:

- normal circulation (highway, country road, suburban roads, streets),
- circulation in a semi-confined environment (city, tunnels, gas station, covered collective parking etc.)
- circulation and parking in a confined environment (private garage).

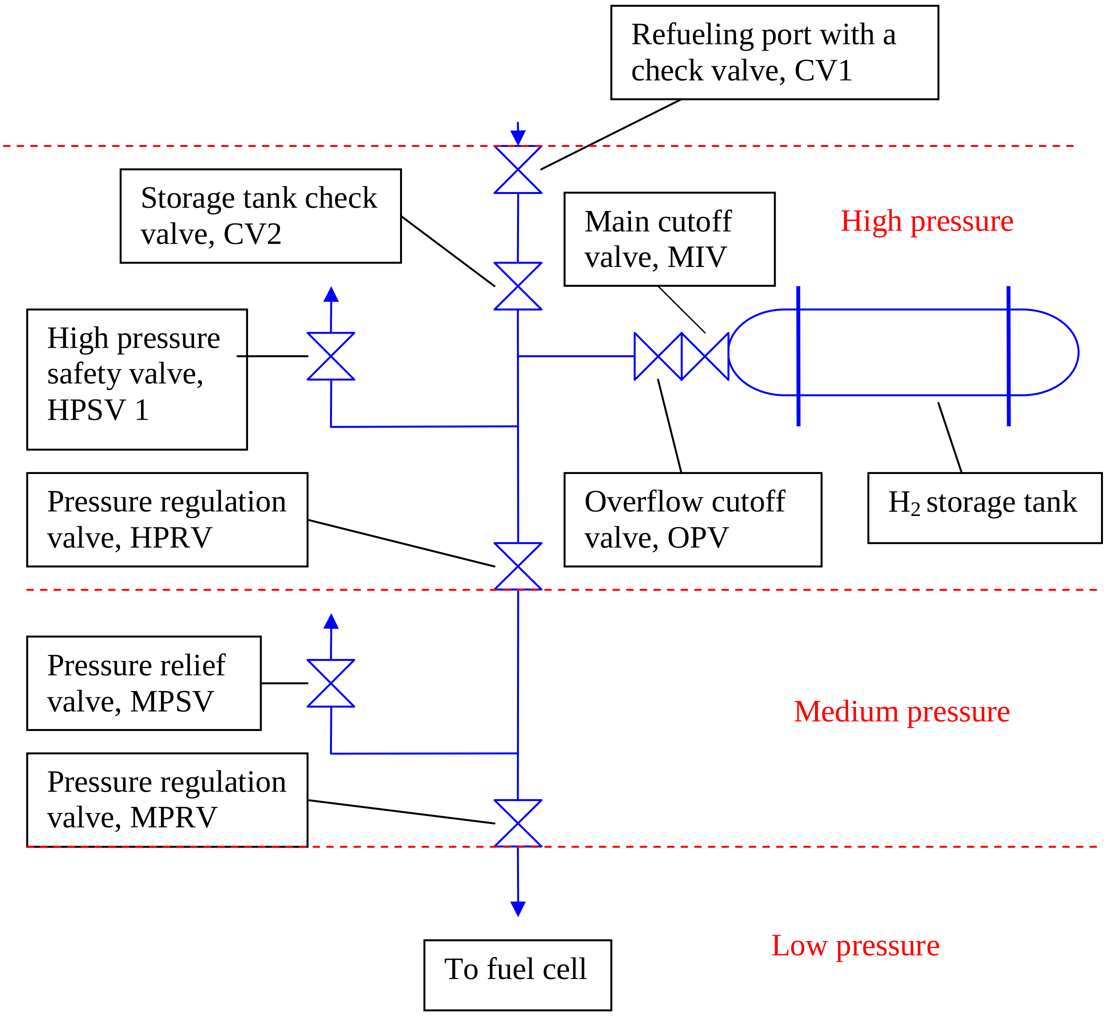

Figure 1. Simplified on-board one-tank hydrogen fuel system.

4. EVENT TREES

The Event Tree (ET) method is applied for the analysis.
For each initiating event the correspondent ET is developed using the RiskSpectrum PSA Professional [RS]computer code. The figures 2-4 present the ET's for each specified case of initiating events.

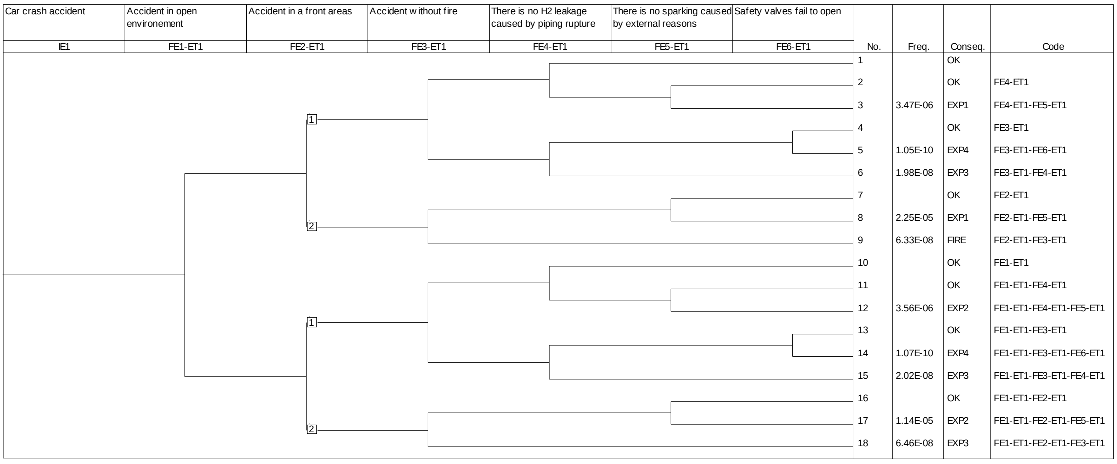

Figure 2. ET1 for car crash accidents.

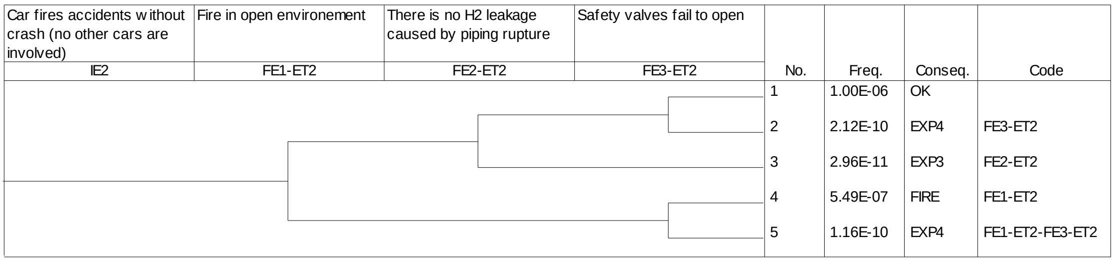

Figure 3. ET2 for fire accident without crash.

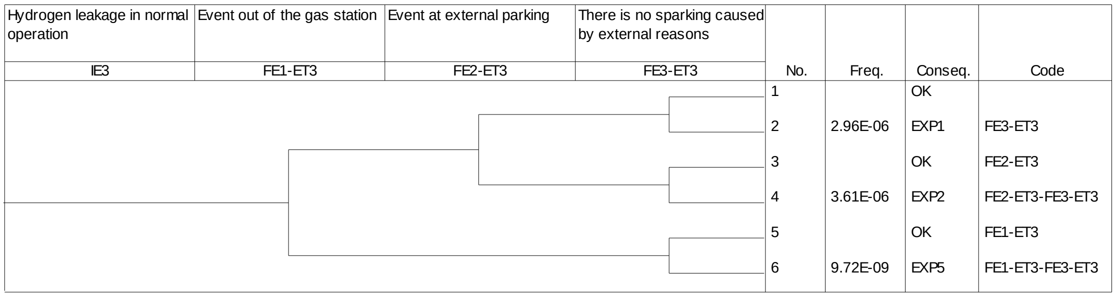

Figure 4. ET3 for hydrogen leakage during normal operation (without an accident).

5. CONSEQUENCES SPECIFICATION

There are three types of consequences specified in the ETs:

- OK – no consequences related to hydrogen explosion or ignition,
- FIRE - consequences related to hydrogen fire,
- EXPi - consequences related to hydrogen explosion.

Consequences related to hydrogen fire and explosion (EXPi) were classified as followed:
FIRE: initial fire in open environment extended to the hydrogen fire by release of hydrogen.
EXP1: release of hydrogen with consequent explosion of hydrogen in the atmosphere in an open environment – possible damage of car and injuries of individuals in the area of the accident due to hydrogen fire.

EXP2: release of hydrogen with consequent explosion of hydrogen in the atmosphere in a semi-confined environment – possible damage of car and damage of surrounding property in the accidental zone of 10 m, injuries of the individuals in the area of incident due to hydrogen fire and overpressure.
EXP3: initial fire caused by crash accident or by any external reasons in combination with hydrogen releases (due to the failure of equipment) into the passenger compartment leads to a hydrogen explosion - destruction of the car, damage of surrounding property in the accidental zone and possible severe injuries of all individuals in the passenger compartment of the car.
EXP4: explosion of hydrogen storage tank by high pressure raise – destruction of the car, damage of surrounding property in the accidental zone of 80 m (projectiles) and all individuals killed within 10 m due to overpressure and 80 m due to projectiles around the accidental zone.
EXP5: explosion of hydrogen in atmosphere in open environment with consecutive fire/explosion of other stored H2 **-** destruction of the car, damage of other property in the accidental zone of ~100 m and kill the persons in the accidental zone.

The consequences have been estimated based rather on literature research than on a detailed technical analysis. Nevertheless this is common practice in expert judgment. In particularly, Venetsanos et. al. [2008] has been used to predict the consequences of a fast release of hydrogen into a semi-confined or confined environment while Pasman et. al. [1974] has been at the basis of the prediction of the consequences of a release into vented spaces such as the passenger compartment or a semi-detached garage. The characteristics of consequences considered in these studies are presented below.
Semiconfined urban situation:

- maximum mass in flammable range 1.327 kg
- maximum mass in flammable range at 5.5 s after the start of the release
- maximum fireball (diameter) size 8.5 m (possible skin burn or secondary fire)
- 2.0 kPa overpressure 10 m (diameter) (window damage, no direct injury due to overpressure, e.g. eardrum rupture at overpressure larger ~20 kPa)

Confined tunnel situation:

- maximum mass in flammable range 3.73 kg
- maximum mass in flammable range at 20 s after the start of the release
- maximum fireball (along the tunnel) size ca. 50 m (possible skin burn or secondary fire)
- 2.3 kPa overpressure 60 m (along the tunnel) (window damage, no direct injury due to overpressure, e.g. eardrum rupture at overpressure larger ~20 kPa)

Vented situation:
The vented situation is much more difficult to predict, because it depends very much on the ratio between the venting area and the combustion volume. It is assumed that for the situation of a car park venting areas exist and therefore the pressure build will be limited.

6. ACCIDENT SEQUENCES

In this section the accident sequences (AS) will be briefly described.
ET1-AS3 and AS8, ET3-AS6 (EXP1): after the release of hydrogen due to an accident (IE1) or due to equipment failure (IE3), the entire volume of the storage tank is released into the atmosphere. During the discharge a spark might occur and will cause a hydrogen explosion.
Similar events: HIAD ref. 131-1-2005 from 16/04/2005 San Jose California.
Total release volume $V_{H2} = V_{\text{storage tank}} = 4$ kg ;
Time of discharge $t = V_{\text{storage tank}} / F_{\text{leak}} = 30$ sec ;

Note: to justify the accident sequences assumptions, 144 events recorded in the Hydrogen Incidents & Accidents Database (HIAD) on January 2009 [HIAD] have been checked out. Only very few events occurred on vehicles equipped with a hydrogen-driven engine. Under "similar event" denomination it's understood events sharing the same nature, accident development, phenomena or root causes. The purpose of the above examples is not to provide the statistical or physical illustration, but to show similar phenomenological circumstances leading to the explosion of hydrogen in other industries or applications.

ET1-AS5 and AS14, ET2-AS2 and AS5 (EXP4): The car is catching fire due to an accident (ET1) or due to internal or external reasons (ET2) without crash. If the system is leak-tight prior to the fire ignition it remains leak-tight during fire extension. Due to the fire, the temperature and consequently the pressure increase in the storage tank. The moment at which the pressure in the storage tank reaches the safety valves opening threshold, the safety valves will open and release hydrogen into the atmosphere.
If safety valves fail to open the tank will explode due to internal pressure.
Similar events: HIAD ref. 21-1-2006 from 12/02/2006 Yangquan, China, HIAD ref. 20-1-2004 from 23/05/2004 Haifa, Israel, HIAD ref. 116-1-2005 from 18/04/2005 Ludwigshafen, Germany
ET1-AS9, ET2-AS4 (FIRE): The car is catching fire due to an accident (ET1) or due to internal/external reasons without crash (ET2). This provokes H2 ignition and followed by a hydrogen fire in addition to the initial fire.
Similar events: HIAD ref. 17-1-1983 from 03/03/1983 Stocholm, Sweden (leakage+failure of cut-off valves), HIAD ref. 16-1-1980 from 31/10/1980 Alabama, USA (leakage+failure of cut-off valves)
ET1-AS12 and AS17 and ET3-AS4 (EXP2): after a leak of hydrogen due to an accident (ET1) or due to an equipment failure (ET3), the entire volume of storage tank is released into a closed environment. During the discharge a spark occurs and will provokes a hydrogen explosion.
Similar events: HIAD ref. 309-1-1999 from 27/05/1999 (leakage + spark from static electricity).
Total release volume $V_{H2} = V_{storage\ tank} = \quad = 4$ kg ;
Time of discharging $t = V_{storage\ tank} / F_{leak} = 30$ sec;
ET1-AS6, AS15 and AS18, ET2-AS3 (EXP3): The car is catching fire due to an accident (ET1) or due to internal/external reasons (ET2) without a crash. The system has a leak or rupture prior to or during the accident with H2 releases into the passenger compartment. This leads to a hydrogen explosion.
ET3-AS6 (EXP5): Hydrogen leakage appears during the refueling of the car at the gas station. The entire volume of storage tank is released. During the discharge a spark occurs and will provokes the explosion of the hydrogen with subsequent ignition and explosion of other stored hydrogen within the refueling station.

7. INPUT DATA CONCERNING THE CAR ACCIDENTS AND ROAD TRAFFIC

For the present project the examples of data concerning German road traffic and car accidents came from two sources: Federal Highway Research Institute (BASt) Traffic Data (Annexe 1) and Car Accident Data Base (GIADS) Medical School of Hannover [Otte et. al. 2009]
Analysis of these data sources allows the evaluation of the following parameters:

- frequency of a car crash per car and per year is estimated by 3.69E-03/car*year,
- conditional probability of accident in urban environments is 0.757,
- conditional probability of accident in urban confined environments (city) is 0.505,
- conditional probability of accident near the bus, tram station is 0.113,
- conditional probability of fire during the accident was estimated as 4.54E-03,

The provided information permits to build up the distributions for maximal deformation of the car involved in the accident in accordance with damage location. Fig.5 presents the different zones of the car considered in the study.
The following conditional probabilities are used in the study:

- the conditional probability to have a crash in the front area (zones 0 x F1-F4 in Fig. 5) is 0.68,
- the conditional probability of crash in front side with equivalent crash energy corresponding to a car speed higher than 30 km/h is $6.23\ 10^{-2}$,
- the conditional probability to have a crash in the rear area (zones 4 x H1-H4 in Fig. 5) is 0.177,
- the conditional probability of damage deeper than 40 cm in rear side of the car is $7.63\ 10^{-3}$.

For data related to the internal failures (valves actuations, pipe ruptures, etc.) generic reliability data sources were used.

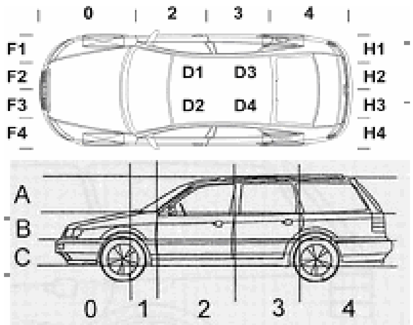

Figure 5. Accidental crash damage location and propagation mapping.

8. COMPONENT RELIABILITY DATA

Table 1 presents the reliability data selected from different data sources, which are used in the study.
No reliability data presented in the table are specific of hydrogen-technologies. The data reflect the situation in the chemical, nuclear or aviation industry. In the scope of the present study these data were selected for the following reasons:

- The equipment used in these industries operate under more severe conditions than in ordinary automobile applications, furthermore the requirements for design, commissioning and operation are stricter.
- For the detailed design risk assessment specific data from hydrogen-technology automobile applications will be needed.

9. MODELING ASSUMPTIONS

<u>IE1 Car crash accidents</u>

Operating states

It has been assumed that the car is in driving operating state. The available statistics considers accidents with several cars involved and casualties. Certainly some car accidents may occur during parking or refueling. However the number of car accidents in those states is negligible in comparison with the number of car accidents in driving operating state.

Crash / Damage location and probability of hydrogen release

It has been assumed that the probability of hydrogen releases caused by a crash strongly depends on the location, the degree of deformation and the energy of the crash (i.e. the speed of the car(s) during the accident).
As an integrated characteristic of these parameters the damage propagation distribution was applied, as shown in Fig. 6, 7.
It has been assumed that all accidents with damages in the front area (zones 0 x F1-F4 in Fig. 5) with equivalent crash energy corresponding to a car speed higher than 30 km/h lead to the rupture of piping in low and medium pressure parts of the system. In this case the closure of the HPRV valve is implemented to avoid hydrogen leakage.
By a front area crash, it has been considered the possibility of a leakage coming from the high pressure part of the system in case of a latent (hidden) failure of supports or fixations of the tank and piping. It has also been considered that such failures may occur during the inter-maintenance period of 1 year.

Table 1. Generic component reliability data set

Component	FM	Failure description	Type of equipment / environment	Reliability parameters : Failure rates, per hour (/h) and Failure probability, per demand (/d)	Confident limits	Source of data
Storage tank, (under pressure)	Leak		Mobile at ground (military) (commercial)	$5.5\ 10^{-6}$ /h $1.4\ 10^{-6}$ /h		CNET, p.101 [1]
			Roads / generic Roads/ pressure	$0,15 \times 20\ 10^{-6}$ /h $0.08 \times 20\ 10^{-6}$ /h		AVCO, p.111 [1]
			Accum. / HP tanks	$0.36\ 10^{-6}$ /h $0.24\ 10^{-6}$ /h		IRSN [2]
			Vessels under pressure	$1.09\ 10^{-8}$ /h	$1.42\ 10^{-10}$ / $4.24\ 10^{-4}$	SAIC [3], p.205
	rupture					
Safety valve	Fail to open		Mechanical Spring-loaded	$1.2\ 10^{-4}$ /d $2.12\ 10^{-4}$ /d	 $7.9\ 10^{-6}$ / $7.98\ 10^{-4}$	IRSN [2] SAIC [3], p.212
	Spurious actuation			$4.1\ 10^{-8}$ /h $1.68\ 10^{-6}$ /h	 0.275 / $4.8\ 10^{-6}$	IRSN [2] SAIC [3], p.212
Regulation valve	Rupture			$3\ 10^{-9}$ /h		IRSN [2]
MOV (cut-off)	Fail to open		old data	$3\ 10^{-4}$ /d		IRSN [2]
	Fail to close			$3\ 10^{-4}$ /d $5.58\ 10^{-3}$ /d	 0.5 / $18.6\ 10^{-3}$	IRSN [2] SAIC [3], p.200
	rupture			$3\ 10^{-9}$ /h		IRSN [2]
	Spurious actuation			$1.36\ 10^{-6}$ /h	0.24 / $3.8\ 10^{-6}$	SAIC [3], p.200

Piping	Leak		Weld joint / roads	$0.004 \times 20\ 10^{-6}$		AVCO, p.111 [1]
	catastrophic		Connections Straight sections	$5.7\ 10^{-7}$ /h 4.42 10-7 /h	$9.9\ 10^{-9}$ / $2.2\ 10^{-6}$ $7.43\ 10^{-9}$ / $1.7\ 10^{-6}$	SAIC [3], p.184 SAIC [3], p.185
	rupture		Generic Straight sections	$3\ 10^{-9}$ /h $8.85\ 10^{-7}$ /h	 $1.54\ 10^{-8}$ / $3.42\ 10^{-6}$	IRSN [2] SAIC [3], p.186
Supports	rupture		Support / roads Fixation / roads	$0.5 \times 20\ 10^{-6}$ $0.012 \times 20\ 10^{-6}$		AVCO, p.107 [1]
Flame detector	Fail to function (including spurious actuation)			$4.32\ 10^{-4}$ /h	$5.3\ 10^{-8}$ / $1.76\ 10^{-3}$	SAIC [3], p.173
Fire detector			catastrophic	$1.14\ 10^{-6}$ /h	$1.98\ 10^{-8}$ / $4.41\ 10^{-6}$	SAIC [3], p.206

[1] P. Lyonnet. La maintenance. Mathematique et methods. Thechnique & Documentation, Lavoisier, 1992.
[2] EPS1/REP 900 – CP0/BUGEY. Rapport de synthèse (conduite APE). DSR/SESPRI n°67, Tome 2/2 (internal report). IRSN, 2007.
[3] Guidelines for Process Equipment Reliability Data. CCPS of American Institute of Chemical Engineers, 1989.
[4] NUREG-75/014 (WASH-1400). Reactor Safety Study. An assessment of accident risk in US commercial Nuclear Power Plants. Appendix III. US NRC, 1975.

The failures (i.e. the leakages or ruptures) of piping and tank, as well as the spurious actuation of safety valves before the accident occurred have not been considered in this study.
By a crash in the rear area (zones 4 x H1-H4 in Fig. 5), a failure of piping in medium and high pressure parts of the system has been assumed. In case of a damage propagation deeper than 40 cm (see distribution in Fig. 7), the rupture of the hydrogen storage tank was assumed.
In all of the crashes a value of 0.8 was has been adopted for the probability to generate a spark or an explosion.
Probability of supports and fixations failure is assessed by taking into account a constant failure rate according to a yearly preventive maintenance operation. It has been assumed that between the maintenance operations there is no possibility to detect a failure of supports and fixations. The criterion of the loss of the support function was considered to be the failure of two supports out of four located in non-isolated areas of the system.

IE2 Car fire accident without crash

Fire initiation and releases of hydrogen

It has been assumed that a car-fire is due to internal or external causes and is not related to the hydrogen system itself (for example by the failure or overheating of the brake system). If this occurs when the vehicle is in driving operating state, it has been further assumed that the car stops and the hydrogen fuel system is isolated.
In case of a fire in an open environment, it has been assumed that after increasing the hydrogen tank temperature the hydrogen is released by the actuation of safety valves (HPSV–TPRD or MPSV). These releases will increase the fire intensity but will not lead to an explosion. In case of a fire in a closed environment there is a strong probability that any hydrogen releases due to the leakage form the system or by the emergency actuation of safety valves will provoke the explosion.
The possibility that the fire could be extinguished before the temperature or pressure of the storage tank reach the limit of actuation of safety valve (HPSV–TPRD) has not been taken into account.

IE3 - hydrogen leakage in normal situation.

Operating states

To estimate the initiating event frequency and develop the accident sequences three operating states were considered:

- driving: 2 hours per day, which sum up to 2 x 365 = 730 hours per year,
- refueling: once a week by a refueling time of 0,25 hour, which sum up to 52 x 0,25 = 13 hours per year,
- parking: rest of the time, which corresponds to 8760 – 730 – 13 = 8017 hours per year.

The initiating event frequency was calculated as a probability of leakage due to the equipment failures during the period of one year (Fig.10). The probabilities of functional events related to the particular operating state (Fig.4), were calculated using the conditional probabilities of being in this operating state:

- P(refueling) = 13/8760 = 1,48 10^{-3},
- P(parking) = 8017/8760 = 0,915.

For the parking operating state, it was assumed that 60% of the time is spent in a closed environment (garages or closed car parks for private use after work) and 40% of time in open environment (open car parks used during the day/at the workplace).
This assumption is very subjective and has to be verified with the statistical data (or expert judgments).

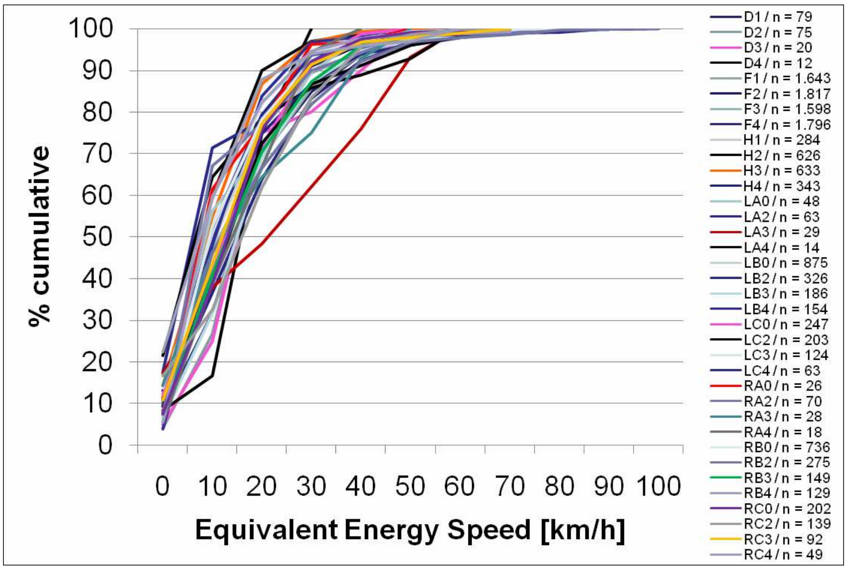

Figure 6. Distribution of the car speed during crash accidents.

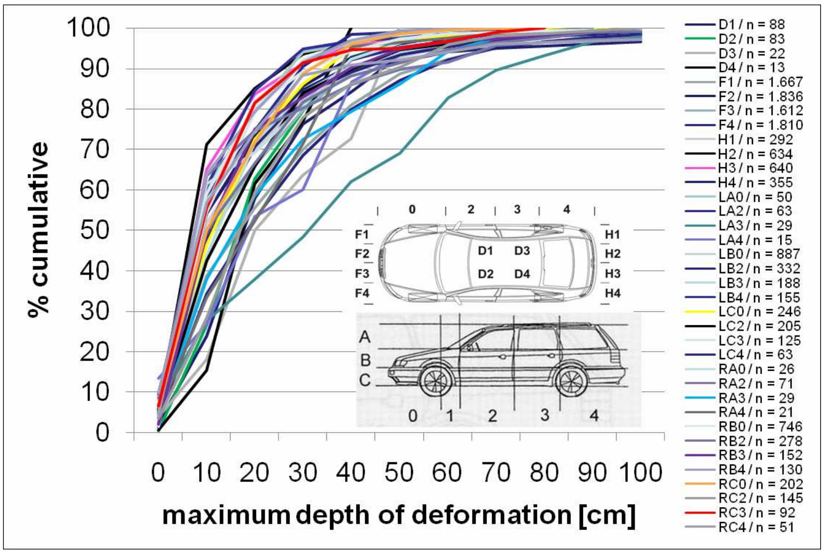

Figure 7. Distribution of maximum depth of car deformation during crash accidents.

Leakage probability

To calculate leakage probability, the failure rates and failure probability per demand for all types of components were considered as constant in time. In fact, this means that the maintenance of components is optimized and permits to avoid the degradation failures of equipment with time. This is a quite important assumption (to be verified) knowing the sensitivity of metallic component to corrosion and hydrogen and embrittlement.

It was considered that a leakage could be detected immediately during the driving and refueling operating states (loss of hydrogen will stop the engine).

It was further assumed that the leakage is not repairable; consequently the whole volume of hydrogen is released if the leakage occurs in the high pressure part of the system.

For the parking state the assumption was as follows: leakage is a latent failure, which could be detected at least once a day, when somebody starts up the engine. This assumption leads to assign

a “tested” reliability model for related basic events in the Fault Tree model with test interval as 24 hours.
Nevertheless the last assumption and the assumption on constant failure rate for passive components have to be verified. A sensitivity study could show the important impact of those assumptions on the final result.

Probability of ignition

Hydrogen air clouds, which are formed after the release of hydrogen into the environment, have a huge potential to cause fire or explosions due the wide flammability range of hydrogen-air mixtures. Such clouds could be ignited by any kind of spark (static electricity, switching on the light, shock of metallic parts, etc.). Nevertheless the probability of a spark is lower than in an accident situation and therefore an ignition probability of 0.1 was assumed in the present study.

10. MODELING OF FUNCTIONAL EVENTS AND FAULT TREES

In order to quantify accident sequences frequencies (probability) two types of modeling approach were applied:

- Assignment the frequency of Initiating Events (IE) or probability of Functional event by Basic Event probability (FE),
- Calculation of IE frequency or FE probability with Fault Tree.

Table 2 provides the list of Basic Events used for IE and FE quantifications. Fig. 8-10 presents the Fault Trees developed for IE3 and several FE’s.

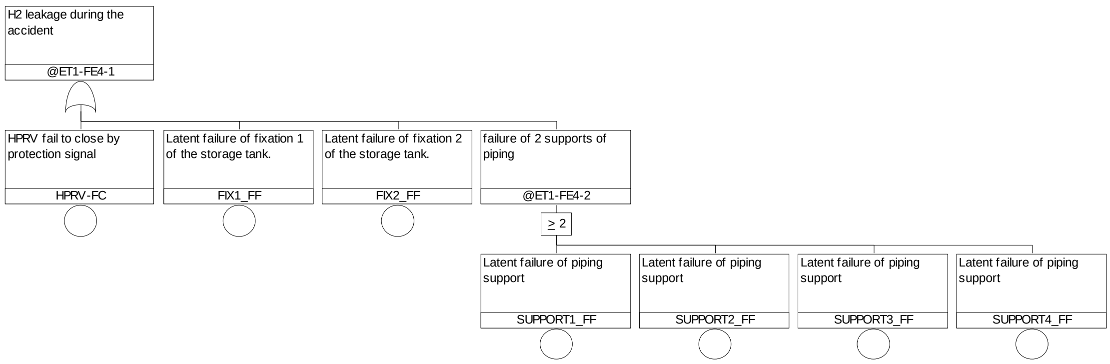

Figure 8. Fault tree for ET1-FE4

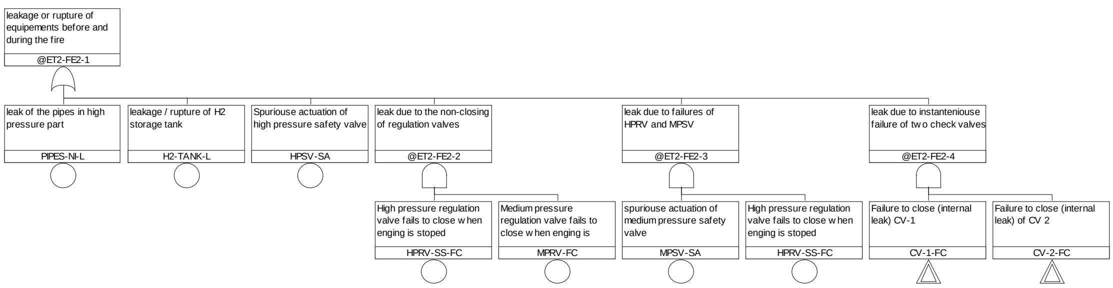

Figure 9. Fault tree for ET2-FE2

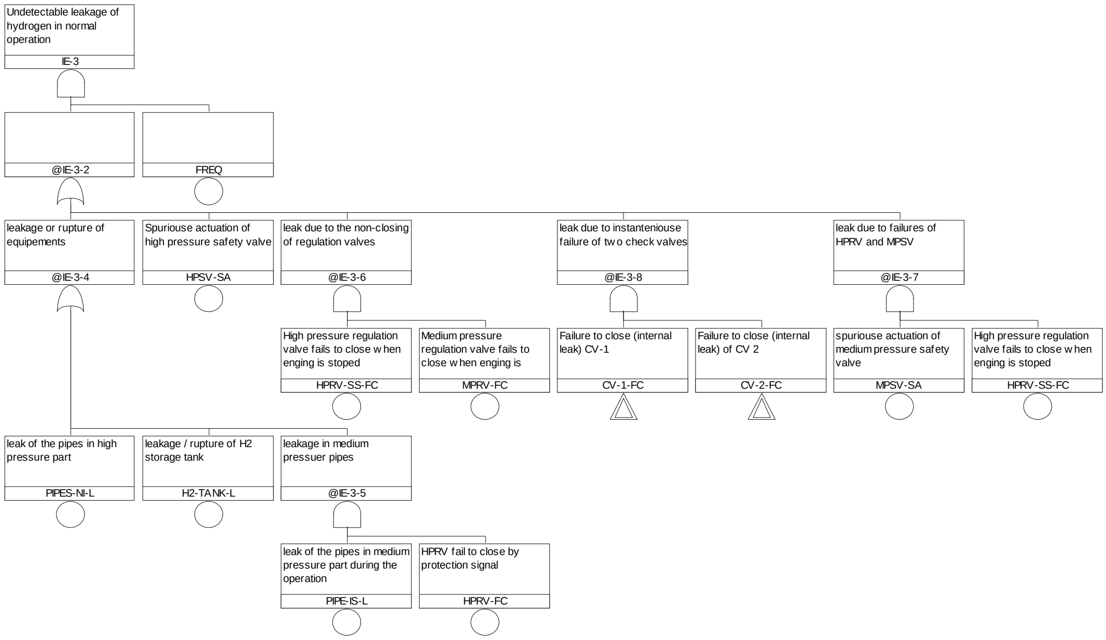

Figure 10. Fault tree for ET3-IE3

10. CALCULATION RESULTS

Explosion frequency

Table 2 presents the results of quantitative analysis by consequence types for all the considered scenarios (for all ETs). Estimated explosion frequency is 5.47E-05 per car per year. The major part of the risk, about 99,8%, relates to the explosions in open and semi-confined environments (EXP1 and EXP2). These types of consequences are comparable with consequences of normal traffic accidents (injuries of individuals, damage of cars and properties in the area of accident). As it was mentioned in section 7, the frequency of a traffic accident is estimated as 3.69E-03 per car per year, which is about two orders of magnitude higher than the calculated risk of hydrogen explosion.

Note: an explosion in a semi-confined environment (EXP2) could lead to small damages of the surrounding property of people not directly involved in the accident (e.g. broken windows), although considered as a minor incident, in the media it might create a negative impact on the public's perception of hydrogen technology.

Table 2. Results of quantitative risk analysis

Consequence type	Explosion frequency	Contribution to the total risk
EXP1	3.61E-05	65.98%
EXP2	1.85E-05	33.81%
EXP3	1.05E-07	0.19%
EXP4	4.33E-10	0.00%
EXP5	9.72E-09	0.02%
Total	5.47E-05	100%

More severe consequences with possible lethal casualties not directly involved in the accident, damage of buildings and other properties in the area of accident, etc. (EXP3 – EXP5) have a residual risk contribution to the total risk.

However, taking into account the total population of cars in circulation and the likely increase of hydrogen-driven vehicles among the whole population in the future, the frequency of severe accidents of 10^{-7} per car per year could be a non-negligible risk for any individual. For example, in case of Germany there are about 45 10^{6} passenger cars in circulation, the risk of hydrogen explosion of the car (EXP3) with lethal casualties would represent (in the worst scenario) five events every year. Such a frequency cannot be neglected.
The frequency of explosion at a gas station (consequence EXP5) could be interpreted as one event every two years, which should also be considered as a hardly acceptable risk level. In addition, for this type of consequence the study considers only the scenarios initiated by internal failures in the car. The risk related to the failures of equipment at the refueling station has to be added to the calculated frequency.
It is recommended to implement more detailed risk analysis for the scenarios related to the severe consequences like EXP3 and EXP5.

Minimal Cut Sets analysis

Analysis of minimal cut sets (MCS) shows the importance of the crash location and, in particular, the damages in the rear part of the car. In the list of MCS's for consequences EXP1, EXP2, EXP3 there are MCS's including the events of a crash in the rear area (zones H1-H4 x 4 in Fig.5) with a damage deeper than 40 cm. Those MCS's are the dominant ones and contribute more than 60% to the risk in each of these cases.
Contrary to the crash in the front area where the design features (system configuration and safety devices) permit to reduce the probability of explosion, the crash in the rear area directly leads to an explosion (without any additional failures of the components). It has to be mentioned that the scenarios with a crash in the rear area are based on the assumption on dependent leakage from the medium and high pressure parts of the system as a result of the crash. The validity of this assumption has to be justified or demonstrated.
It makes the total risk sensitive to the crash in the rear area and misbalances the risk profile.

11. CONCLUSIONS AND RECOMMENDATIONS

The risk assessment of hydrogen-driven vehicles identified and quantified the additional risks related to hydrogen explosions.
1) Five types of hydrogen explosions were identified:
- **explosion in atmosphere** in open environment – possible damage of car and injuries of individuals in the area of incident **(EXP1),**
- **explosion in atmosphere and in semi-confined environment** – possible damage of car and damage of other property in the accidental zone of 10 m, injuries of individuals in the area of the incident **(EXP2)**,
- **explosion of the car** due to initial fire in combination with hydrogen releases in internal compartment of the car – possible destruction of the car, damage of other property in the accidental zone and possible severe injuries **(EXP3)**,
- **explosion of storage tank –** destruction of the car, damage of other property in the accidental zone of ~80 m and lethal casualties in the accidental zone **(EXP4),**
- **explosion of an refueling station -** destruction of the car, damage of other property in the accidental zone of ~100 m and lethal casualties in the accidental zone **(EXP5)**.

2) Estimated hydrogen explosion frequency is 5.47E-05 per car per year.
3) 99,8% of the risk relates to explosions in open and semi-confined environments (EXP1 and EXP2). These types of consequences are comparable with consequences of normal traffic accidents (injuries of persons, damage of cars and properties in the area of accident) and represents less than 2% of traffic accidents (3.69E-03 per car per year).

4) The explosion in semi-confined environment (EXP2) which represents of 33% of additional risk and could lead to small damages of the surrounding property of people not directly involved in the accident (e.g. broken windows), however issued as a minor news item in the media it might create a negative impact on the public's perception on hydrogen technology.
5) Severe consequences with possible lethal casualties, damage of buildings and other properties in the area of accident (EXP3 – EXP5) represents less than 0,2% of additional risk (1.15 10^{-7} per car per year).
6) Taking into account the population of the cars in circulation and the possible increase of hydrogen-driven vehicles among the whole population, the frequency of severe accidents represents a non-negligible risk for a person. For example, in Germany there are about 45 10^{6} passenger cars in circulation, the risk of hydrogen explosion of the car (EXP3) with lethal casualties would represent (in the worst scenario) five events every year.
7) The estimated risk of explosion at a hydrogen refueling station (EXP5) could be interpreted as one event every two years, which should also be considered as a hardly acceptable risk level. For this type of consequence the study considered only the scenarios initiated by internal failures in the car. The risk related to the failures of equipment at the refueling station has to be added to the calculated frequency. Nevertheless due to the limited information currently available the number of incidents and consequences might be overestimated.
8) It could be recommended to implement more detailed risk analysis for the scenarios related to the severe consequences like EXP3 and EXP5.
9) Analysis of Minimal Cut Sets shows the importance of the crash location and, in particular, the damages in the rear part of the car. For the consequence types EXP1, EXP2, EXP3 the MCS's with rear crash location contribute more than 60% to the total risk. It makes the total risk sensitive to the crash in the rear area and misbalances the risk profile.
10) The scenarios with the crash in the rear area are based on the assumption of the dependent leakage from the medium and high pressure parts of the system caused by a crash. In order to improve the risk profile and reduce the risk the validity of this assumption has to be studied in depth.

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