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Minutes of the FCH 2 JU Workshop on Safe Storage of Compressed Gas Hydrogen in road transport applications and related infrastructure held on 18 November 2021

On 18 November 2021 from 9:00 to 13:00 (CET) an online workshop on "Safe Storage of Compressed Gas Hydrogen in road transport applications and related infrastructure" was organized by the FCH 2 JU with the support of the European Safety Panel (EHSP). The workshop is part of the support, the EHSP is providing to the FCH 2 JU at both, the project and the program level. The agenda of the project is provided in Annex 1.

The workshop focused on the safety aspects of hydrogen storage in road transport applications and related infrastructure and had three main objectives:

1. Summarize the state-of-the-art, progress in pre-normative research (PNR) and standardization with regards to safe storage of compressed gas hydrogen in road applications and related infrastructure;
2. Review the available experience with regard to safe design, operations, and the lessons learnt from incidents; and
3. Exchange experiences and best practices related to hydrogen safety beyond project boundaries.

About 60 participants attended the workshop, most of them representing 15 FCH 2 JU related projects. Eight projects presented their results and experience related to storage of hydrogen in road transport applications.

After a welcome by the Chairperson Alberto Garcia, responsible project officer at FCH 2 JU, Mirela Atanasiu, Head of Unit Operations and Communities FCH 2 JU, provided the keynote address in behalf of Bart Biebuyck, who was able to join the workshop later only due to other commitments. Mrs. Atanasiu stressed the relevance of the topic and the importance of safety and the EHSP, which will receive even more attention in the new framework program starting in 2022. The introduction was concluded with Inaki Azkarate, EHSP Chairperson, presenting the EHSP, its function, activities and services at the project and program level of the FCH 2 JU.

SESSION 1. Safety-related issues on hydrogen storage

The first session consisted of two presentations. In the first presentation Pietro Moretto, JRC, provided an overview on the specific regulations, codes and standards (RCS). He referred to the HyLAW database, which informs about national legal and administrative processes and identifies legal barriers EU Members States. The HyLaw database dedicate considerable attention to the case of hydrogen refueling stations and selected public transport infrastructures. He also illustrated the current situation for vehicle storage tanks which is addressed in GTR13. Although there is progress with regard to interoperability (e.g. connectors for refueling), a consolidated sharing of experience and insights gained from incidents and near misses is still needed in this early phase of hydrogen fueled road transport, to maximize processes safety.

The second presentation, given by Daniele Melideo, University of Pisa, EHSP member and former staff member of JRC, presented lessons learnt from safety-related events involving hydrogen storage. For preventing often observed escalations he recommended to follow the safety principles listed in the EHSP document Safety Planning for Hydrogen and Fuel Cell Projects[1]. Since the presentation was based on a preliminary data analysis, after the workshop, a more thorough analysis was performed (Annex 2). Its outcome is summarised here:

1. In all road collisions recorded, also with total vehicle loss, the on-board hydrogen system was not affected and the related safety measure preventing releases functioned as designed.
2. The majority of the hydrogen releases at hydrogen refueling stations (HRS) occurs nowadays at the dispenser (hoses, breakaway, the connectors, flow-control valves, the chiller). The mass of hydrogen released is relatively small and comes rarely to ignition.
3. Hoses and detachable parts are causes reported during hydrogen delivery to the HRS.
4. Stationary storage at HRS experiences regularly loss of containment due to failure of malfunctioning of the pressure management system (fittings, pressure relief devices, bolts).
5. Similar conclusion can be drawn also for the HRS compressors, which however experience a much higher number of malfunctioning due to moving parts.
6. Maintenance operations in garages, hydrogen on-board detection and hazards related to on-board conventional systems are probably areas deserving still attention.

SESSION 2. Compressed gas hydrogen storage (CGH2) – On–board storage

The second session was opened with a presentation of Georg Mair, BAM / EHSP, on the safety considerations for onboard CGH2 storage. He gave an overview on the test requirements, operational conditions and accidental loads.

Then a series of project related presentations started highlighting the experience made in the H2ME/H2ME2, H2HAUL, REVIVE, and THOR projects.

The session was concluded with a summary of the outcomes of the pre-normative project HyTunnel-CS, including the presentation of the breakthrough safety technology of explosion free in a fire self-venting (TPRD-less) tank allowing hydrogen-powered vehicles to enter tunnels and underground parking at risk below of current fossil fuel vehicles and allows fire brigades act in the usual manner (extinguish the fire as soon as possible). The need to modify the fire test protocol of GTR#13 was demonstrated. This presentation was given by Vladimir Molkov, University of Ulster/ EHSP.

The discussion chaired by Thomas Jordan, KIT/EHSP, addressed the following topics.

- How do designers and first responders interact in the initial phase when a refueling station or a new tunnel is planned? It was supposed to be fruitful to include the experience of the first responders.
- How do first and second responders know the status of the pressure vessels if a hydrogen car/truck is involved in an accident? So far no standardized solution is available to address this issue.

[1]https://www.fch.europa.eu/sites/default/files/Safety_Planning_for_Hydrogen_and_Fuel_Cell_Projects_Release1p31_20190705.pdf

- Especially the H2ME representatives complained about a scattered situation with regard to permissions to enter large public garages. In Austria, Netherlands and France there is legislation on the way prohibiting access of hydrogen vehicles. There was the strong wish that this might be relaxed on a sound scientific basis in a European coordinated approach. However, RCS for stationary traffic infrastructure, like garages and tunnels, tend to have a strong national and sometimes even regional influence.

SESSION 3. Hydrogen storage – Safety-related aspect in supply infrastructure

The third and last session was dealing with the safety-related aspect of hydrogen in the supply infrastructure. Elena Vyazmina, Air Liquide / EHSP, presented a short overview on the safety considerations for hydrogen refueling stations, storage and compression.
Nick Hart, ITM Power, reported on the experience with hydrogen refueling stations in the H2ME/ H2ME2 projects. He listed relevant RCS, identified safety vulnerabilities, risk assessment methodology applied, prevention and mitigation concepts and technologies. The safety issues observed so far were mainly associated with leaks from fitting connections. Remaining challenges are

- lacking consistent separation distances and hazardous areas classification for high pressure hydrogen;
- unclear overall effect of fire walls on safety, with their positive contribution in terms of fire protection on one side, and promotion of stronger combustion effects by increased confinement on the other;
- discrimination point, when minor leaks become unacceptable and necessitate significant maintenance activity;
- determination of maximum quantity of hydrogen to be stored inside enclosures; and
- standardized methodology for regular monitoring of potential leak points.

Then, the COSMHYC and MULTHYFUEL projects' experience was presented by a representative of EIFER and Elena Vyazmina, Air Liquide / EHSP.
Finally, an outlook on safety issues related to liquid and cryo-compressed hydrogen storage was presented by Thomas Jordan, KIT / EHSP. He summarized the results of the pre-normative FCH JU project PRESLHY and concluded with highly prioritized open issues in this field.

A broader discussion was not possible because of the lack of time.

Closing Remarks

Safe gaseous hydrogen storage is key for the successful introduction of hydrogen as a fuel for road transport applications and associated infrastructure. Although the technology proves high maturity and only few incidents have happened, there is still potential for improvement. In particular for the harsh operational conditions defined by road transport and the corresponding refueling processes in public space standards for safe design, protocols for regular checks and safe access strategies for first and second responders are needed. Unified rules for using traffic infrastructure will help achieving acceptance and generating trust in this new technology.

ANNEX 1 – Agenda of the Workshop on Safe Storage of Compressed Gas Hydrogen in road transport applications and related infrastructure

FCH 2 JU Workshop on Safe Storage of Compressed Gas Hydrogen in road transport applications and related infrastructure

AGENDA

8:45-9:00	Login, registration	
9:00-9:05	Opening and organizational remarks	FCH 2 JU
9:05-9:10	Keynote address	FCH 2 JU
9:10-9:20	European Hydrogen Safety Panel (EHSP)	EHSP
Session 1: Safety-related issues on hydrogen storage		
9:20-9:30	Safety in Regulations, Codes and Standards relevant to hydrogen storage - Overview	JRC
9:30-9:40	Lessons learnt from safety-related events involving hydrogen storage	EHSP
9:40-9:55	Q&A/ Panel discussion	EHSP
9:55-10:00	Break/ contingency time	
Session 2: Compressed gas hydrogen storage (CGH2) - On-board storage		
10:00-10:10	On-board CGH2 storage - Safety considerations	EHSP
10:10-10:20	H2ME/ H2ME2 project - Light-duty vehicles	BMW
10:20-10:30	H2ME/ H2ME2 project - Light-duty vehicles	CLEAN ENERGY PARTNERSHIP
10:30-10:40	H2HAUL project - Heavy-duty vehicles	VDL
10:40-10:50	REVIVE project - Heavy-duty vehicles	ALL ENGINEERING
10:50-11:00	THOR project - CGH2 Tanks	FAURECIA
11:00-11:10	HYTUNNEL-CS project - Safe design of TPRD/ TPRD-free tanks	UNIVERSITY OF ULSTER
11:10-11:40	Q&A/ Panel discussion	EHSP
11:40-11:45	Break/ contingency time	

Session 3: Hydrogen storage - Safety-related aspect in supply infrastructure		
11:45-11:55	Hydrogen refuelling stations, storage and compression - Safety considerations	EHSP
11:55-12:05	H2ME/ H2ME2 project - Hydrogen refuelling stations	ITM POWER
12:05-12:15	COSMHYC DEMO project - H2 Compression	EIFER
12:15-12:25	MULTHYFUEL project - Multi-fuel refuelling stations	AIR LIQUIDE
12:25-12:35	PRESLHY project - LH2/ Cryo-compressed H2 Storage	KARLSRUHE INSTITUTE OF TECHNOLOGY
12:35-12:55	Q&A/ Panel discussion	EHSP
12:55-13:00	Closing Remarks	FCH 2 JU/ EHSP

ANNEX 2 – Analysis of incidents and near-misses related to hydrogen storage

Scope & Methodology

The scope of this analysis covers fuel cells and hydrogen vehicles and the related infrastructure. Excluded are all the non-road transport modes. The conclusion provided in this work has been based on the analysis of:

- The incidents contained in the European databases HIAD 2.0 and HELLEN, jointly managed by JRC and the FCH JU. The former is a public database based on publicly available incidents descriptions; the latter is a controlled access database for incidents and near misses produced during the execution of FCH 2 JU projects.
- The incidents descriptions contained in the US public database H2TOOLS. Its search function does not seems to be based on a coherent set of key words, so that it is probable that not all the related events could be found.
- The statistics on HRS performance provided by the NREL *National Fuel Cells Technology Evaluation Center*.

A rather limited number of events in scope was found in the databases:

- 17 traffic events (collisions) involving **fuel cells buses** and 14 traffic events (collisions) involving **fuel cells private cars**
- Inside the HRS, 11 events related to **stationary components** (storage tanks, compressors, electrolyser), 12 related to **dispensers** and their components and 4 to **delivery** of hydrogen to stationary storage.

The reason for this relatively low number of events is because malfunctions are often not considered safety-related events and are classified as more generic failures affecting systems reliability. It is therefore difficult to obtain the required level of details which could allow a thorough safety analysis, a return of experience and possible safety-based failure statistics. Another contributing reason is the different definition of the term incidents, accidents and near misses adopted for the individual reporting systems.
Therefore, the events available in the mentioned databases have to be considered only a fraction of the real life events. This is why also the data provided by the NREL Evaluation Center has been used. NREL data system has a different approach and contains much more data on HRS failures, however the publicly available reports provide strongly aggregated statistics with scarce details. Despite these limitations, these collections systems still allow, in complementary way, for useful conclusions.

Finally, the events reported cover a period of two several years. After each of the reported events, better safety measures have been designed and implemented. It would be therefore important to consider the events timeline and its technology progress when drawing general conclusions. However, due to the scarce number of events, it is very difficult to do so. The conclusion here below have been based without timeline consideration, but very old incidents (approximately before the last two decades), have been disregarded.

Conclusions

Incidents occurred on FC vehicles consist mainly in collisions with other vehicles or road infrastructure. None of these cases caused a release of hydrogen. Also for the few collisions with heavy damages to the vehicles, there have not been escalation of the incident to the on-board

hydrogen systems. Human error is the most obvious and the solely reported cause for road collisions.
A total loss collision reported in H2TOOLS is particularly interesting because it reports details on the response of the on-board safety measures: the crash correctly triggered the isolation of the hydrogen storage from the rest. There was no release. The Fuel cells stack was not damaged and cold be reused on another FC vehicle. Unfortunately, nothing is said on the fate of the storage system. One of the lesson learned from this event is that the emergency response staff rotates very often, what requires a frequent repetition of hydrogen-related intervention trainings.
Few events not related to collisions deserve also to be mentioned:

- Malfunctioning and hydrogen releases during **maintenance** of the storage system of a FC bus. It is very probable that this type of incidents are under-reported: once in HIAD 2.0 and once in H2TOOLS. In both cases, the analysis of the causes suggests that maintenance design and procedures require additional attention.
- Hydrogen **detection** on FC buses can cause considerable disruptions. These alarms, which are normally only recorded in companies books, can be caused by false-positive signals, and classified as near miss or non-incident. Nevertheless, if occurring during functioning, they trigger local evacuation and the freezing of the operation of the whole fleet, until the cases are thoroughly investigated.
- A very recent European (2021) incident was a fire on a fuel cells bus caused probably by a system not related to hydrogen on-board components. It occurred at the depot of the buses, and the investigation is still ongoing.

Releases from HRS **stationary storage** are regularly reported: hydrogen releases are mainly caused by malfunctioning or failures of the tanks pressure management system. This is the cases also for the best known and more recent ones, such as:

i) the release without ignition at a HRS in Hamburg in 2012 due to the leak at a Teflon fitting,
ii) the release and ignition of 300 kg of hydrogen at the HRS in Emeryville due to the breaking of a valve incompatible with hydrogen,
iii) the explosion at Kjølbe near Oslo in 2019, due to loss of tightness of the bolts of the tank flange.

The analysis of these incidents have been important for the improvement of safety measures.
Full tank failure has never been reported at a HRS. The only recent case known of catastrophic failure of a low-pressure tank at the renewable energy park in Gangneung in 2019, caused by the formation of a hydrogen-oxygen ignitable mixture due to the malfunctioning of the electrolysers. However, the components design and operation of this case are not comparable to those in a HRS.

Compressors are HRS components with a high failure statistics. The labelling of these failures as safety-related events has not been commonly agreed. Therefore, it is rare that they are reported as safety incidents, unless they cause hydrogen releases. The few events in the databases report failure of valves and of the moving parts as causes of hydrogen release and ignition.

The **dispenser** is another HRS component which show also relatively high malfunctioning the dispenser. As reported by NREL, the dispensers and its components, such as the hoses, breakaway, the connectors, flow-control valves and the chiller became in recent years the most frequent causes of malfunctioning at HRS’s. Failures at dispenser are very often followed by hydrogen releases. The mass of hydrogen released is however relatively small and comes rarely to ignition.. H2TOOLS reports various and different cases: a breakaway which does not open when it should, to one which opens when it should not, high-pressure opening of the hoses and wrong filling speed.

Events occurred also during delivering hydrogen to the HRS. More in general, it is not surprising to note that there is a high probability that things go wrong **when transferring hydrogen**, either when delivering hydrogen to the HRS or when fuelling vehicles, because:

- Flexible and mobile connections are used, mostly manually operated (human factor).
- Traditionally, the safety design focussed in first instance on stand-alone systems, not interconnected to each-others.
- The need of interoperability requires that connectors, data exchange mechanisms and software must work equally well on both side of the transfer and at different sites.