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State of the Art on Refuelling Risk Assessment

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R E P O R T

Disclaimer

CONTENTS

FIGURES

Acronyms and Abbreviations

ALARP	As Low as Reasonably Practicable
APRR	Average Pressure Ramp Rate
BPCS	Basic Process Control System
CHSS	Compressed Hydrogen Storage System
FC	Fuel Cell
FCEV	Fuel Cell Electric Vehicle
GTR	Global Technical Regulation
HAZOP	Hazard and Operability Study
H_2	Hydrogen
H70	Indication for 70 MPa NWP hydrogen fuelling as defined in ISO 17268
HP	High Pressure
HRS	Hydrogen Refuelling Station
HSSE	Health, Safety, Security and Environmental
IEF	Initiating Event Frequency
IrDA	Infrared Data Association
ISO	International Organization for Standardization
LHS	Left Hand Side
LOPA	Layer of Protection Analysis
LP	Low Pressure
MAWP	Maximum Allowable Working Pressure
MVC	Measurement Validation and Comparison
NWP	Nominal Working Pressure
OEM	Original Equipment Manufacturer
PAER	Incident consequences for People, Assets, Environment, and/or Reputation
PFD	Probability of Failure on Demand
PLC	Programmable Logic Controller
PRR	Pressure Ramp Rate
PRV	Pressure Relief Valve
QRA	Quantitative Risk Assessment
RA	Risk Assessment
RASS	Risk Assessment Summary Sheet
RHS	Right Hand Side
RO	Restriction Orifice
SIF	Safety Instrumented Function
SIL	Safety Integrity Level
SIS	Safety Instrumented System
SOC	State of Charge
TBC	To Be Confirmed
TPRD	Thermally-activated Pressure Relief Device
UNECE	United Nations Economic Commission for Europe
VCE	Vapour Cloud Explosion
WG	Working Group

EXECUTIVE SUMMARY

This document summarizes previous risk assessments, showing the results of previously performed Risk Assessments (RA). It also provides a basis for a specific risk assessment for any new proposed refueling protocol which will be covered by PRHYDE work package 3.

Previous RA efforts covering the refuelling process were conducted at ISO, EIGA, workshops with the automotive industry and have been presented to GTR. It was pointed out that the risk of not being able to control the refuelling ramp rate cannot be reduced far enough to go to very high deployment numbers without making sure the consequences on the onboard tank are under control. These are gaps that could be closed with a new protocol and better definition of the vehicle-to-station interface, especially with an improved communications interface. Another recommendation was to better take failure modes of the station into account when qualifying on-vehicle equipment, suggestions have been made to GTR to this effect.

Also, there were considerations in the industry to assess the open points around non-type approved vehicles fuelling at public refuelling stations.

This report details recommendations for safe hydrogen refuelling of Fuel Cell Electric Vehicles (FCEVs) based on the findings of previous refuelling risk assessment activities. They are the basis for a specific risk assessment for hydrogen refuelling of Heavy-Duty Fuel (HD) FCEVs, which will be covered by PRHYDE WP3.

1 INTRODUCTION

This document will look at risk assessments for the refuelling of hydrogen vehicles, predominantly focused on light duty vehicles, carried out in the industry and summarize their findings. Their aim was to assess the risks of fuelling hydrogen vehicles based on data and schemes according to a General Fuelling Protocol Description based on SAE – J2601 -Surface Vehicle Standard version 2014[1].

One risk assessment was carried out to analyse the refuelling of non-type approved fuel cell electric vehicles (FCEVs) at public stations.

Another risk assessment was started at ISO TC197, WG24 and was carried on at EIGA WG11 and eventually its outcome was presented at IWG GTR13 and discussed in a workshop format with delegates from the infrastructure/equipment manufacturer and automotive industry.

This report details recommendations for safe hydrogen refuelling of Fuel Cell Electric Vehicles (FCEVs) based on the findings and recommendations of the refuelling risk assessment workshop held in June 2019 with a follow up in October 2019.

Those recommendations are the basis for a specific risk assessment for hydrogen refuelling of Heavy-Duty (HD) FCEVs, which will be covered by WP3.

1 SAE J2601: Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles. July 15th, 2020. Available at https://www.sae.org/standards/content/j2601_201407/

2 REVIEW OF EXISTING RISK ASSESSMENTS

In the following, existing risk assessments for refuelling of FCEVs are reviewed to derive specific recommendations as basis for a specific risk assessment for hydrogen refuelling of HD FCEVs, which will be covered by PRHYDE WP3.

2.1 ISO/EIGA risk assessment

2.1.1 Introduction, methodology and scope

The scope of the review was limited to risk assessment of the hydrogen fuelling process for passenger vehicles, specifically the potential impact of the H_2 station conditions on the vehicle Compressed Hydrogen Storage System (CHSS). The risk assessment was limited to H70 type dispensers and focussed very much on the control philosophy intended in SAE J2601. The work on the RA was started at ISO TC197 WG24 and has been transferred to EIGA WG11 for better fit with scope. Since then, it was further developed in several workshops and its outcome and recommendations presented to GTR No. 13[2] for the inclusion of over-temperature related faults in the tank certification.

Methodology

The risk assessment followed a bow tie and Layer of Protection Analysis (LOPA) methodology, which is a standard way of carrying out risk assessments in the process industry for process equipment.

On a basic level, risk is defined as the product of probability and severity of the unwanted effect (see Figure 1).

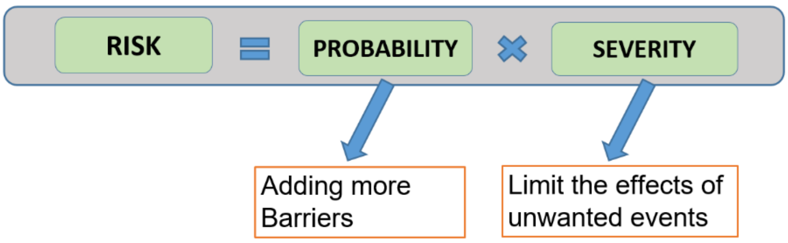

Figure 1: Basis model for calculating risk and how to mitigate it (Source: own illustration).

Both the probability of the event and the severity can be influenced by technical means. This can also be illustrated and formalized in a bow tie. The bow tie methodology allows evaluation of the risk that the different threats in a system result in hazardous consequences. A typical illustration is shown in Figure 2 below.

[2] Global Technical Regulation (GTR) No.13 (Hydrogen and fuel cell vehicles). Available at https://www.unece.org/fileadmin/DAM/trans/main/wp29/wp29wgs/wp29gen/wp29registry/ECE-TRANS-180a13e.pdf

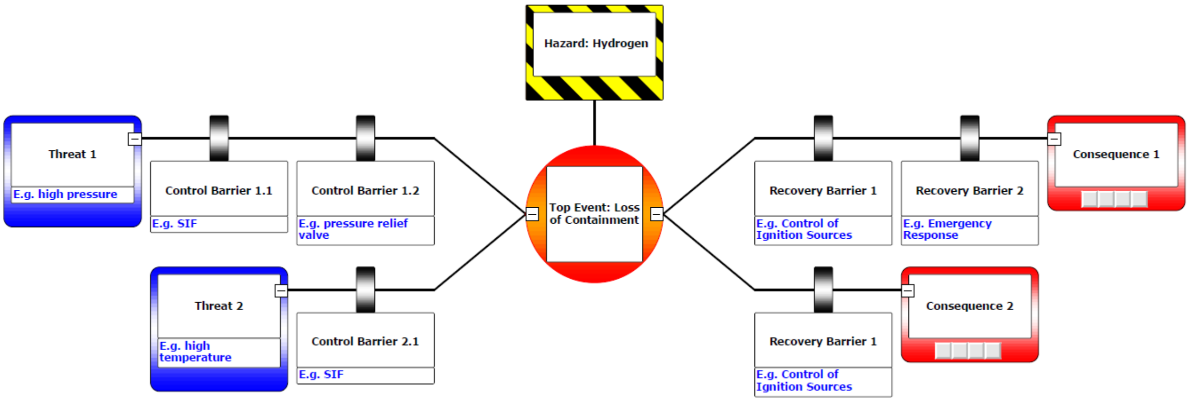

Figure 2: Typical illustration of bow tie model (Source: own illustration).

The bow tie shows the following elements:

- **Hazard, in this case hydrogen:** an agent with the potential to cause harm to people, damage to assets, or an impact on the environment or reputation
- **Top Event**: incident that occurs when a Hazard is released, or the release of the Hazard, typically some type of loss of control or release of energy. If this event can be prevented there can be no effect or Consequence from the Hazard.
- **Threat:** occurrence that causes a Top Event and releases the Hazard.
- **Consequence:** the potential hazardous outcomes arising from the Top Event.
- **Barrier:** risk control or a recovery measure. Barriers provide the means of preventing an event or incident, or of mitigating the Consequences. A Barrier can be an item of equipment or a human intervention. Barriers on the left-hand side (LHS) of the Bowtie prevent Threats from releasing a Hazard. Barriers on the right-hand side (RHS) of the bow tie prevent, limit the extent of, or provide immediate recovery from the Consequences.

Layer of Protection Analysis (LOPA) was used to evaluate the effectiveness of barriers in the bow tie analysis and to provide a conservative estimate of residual risk. This means that if the calculated risk is found to be acceptable, it can be used to demonstrate that adequate controls are in place.

LOPA is a semi-quantitative risk assessment method and fits well onto the bow tie analysis since the risk reduction along the path from each threat to each consequence and the residual risk can be readily estimated. With this, it provides assurance that the scenario analysed within the bow tie is adequately controlled.

LOPA involves a combination of factors assigned to an initiating event and the defined valid barriers to establish a residual risk. Situational factors (enabling factors) may also be considered when an initiating event can only occur a portion of the time.

Conditional modifiers can be used to express the probability that a certain (unmitigated) initiating event leads to the consequence under consideration.

The residual risk is calculated with:

$$Residual\ Risk = IEF \cdot P_e \cdot (PDF_1 \cdot PDF_2 \cdot \ldots \cdot PFD_n) \cdot P_c$$

where:

IEF is the initiating event frequency, i.e. how often would the initiating event occur,

P_e is enabling probability,

PFD is probability of failure on demand of a barrier, i.e. the probability that a barrier will not work when needed,

P_c is conditional probability.

Residual risk can be reduced in two general ways:

a) adding more barriers to prevent unwanted event, or
b) reducing their severity/consequences.

LOPA methodology is a widely accepted process for risk assessment across industry and is used by some regulators as a means of evaluating design.

The process followed in this study was:

1) to identify individual threat lines initiated by threats that could potentially lead to a loss of containment of hydrogen during the fuelling process, and the worst credible consequences of the threats,
2) evaluate the initial risk in the absence of barriers, and
3) propose practicable barriers to limit the risk.

Scope

The risk assessment assumed a typical station design and control system that would follow the assumptions and philosophy of SAE J2601:

- design for station occupancy similar to current fuel stations.
- all hydrogen refuelling station components are rated according to Pressure Equipment Directive (PED) or equivalent.

A typical setup for the dispenser is shown in Figure 3 below.

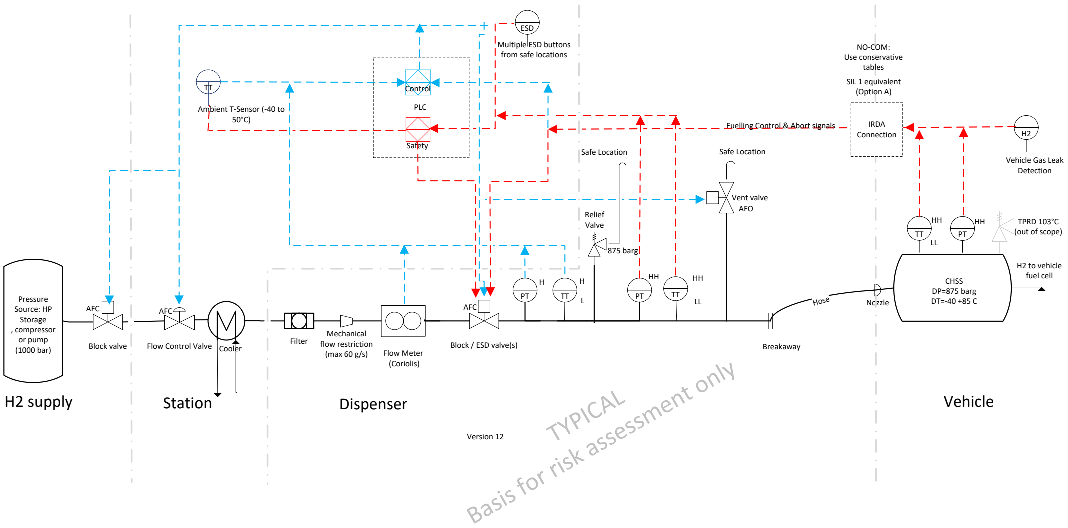

Figure 3: Example for typical Dispenser set up (Source: own illustration).

Consequently, not included in the scope of this review are:

- risk assessment for safe refueling for HD FCEV,
- conventional station risks (e.g. vehicle drive away, hose rupture, dispenser leaks),
- hydrogen production, supply, and quality (assurance),
- impact and issues with the vehicle Compressed Hydrogen Storage System (CHSS) after the fuelling has been completed unless directly related to the refuelling process, and finally
- use of unsuitable components in CHSS, e.g. components designed for less than the Maximum Allowable Working Pressure (MAWP), tanks smaller outside of SAEJ2601 specification etc.

Outcome and recommendations

The refuelling station controls have some (limited) impact on residual risk. Improvements, e.g. around vehicle to station communications, will improve the overall situation somewhat.

However, the larger impact is to be gained from improving component and subsystem specification and qualification in order to make them tolerant to a refuelling station fault: e.g. a controller failure cannot be fully eliminated, therefore the equipment to be filled needs to be able to withstand uncontrolled flow rates.

The results of the risk assessment clearly show that a global system approach to the HRS and the vehicle would provide much better risk reduction than just measures isolated to one of the sides by

a) adding more barriers to prevent unwanted event (excess temperature) due to pressure ramp rate control failure, e.g. advanced communications, triggering termination of the fill,

b) reducing severity/consequences by ensuring the CHSS can withstand the overtemperature resulting from a control failure without catastrophic consequences,

as already indicated in Figure 1.

A number of potential solutions were discussed in the risk assessment and rated for effectiveness:

1) adding barriers,
2) increase Safety Integrity Level (SIL) Level on HRS,
3) temperature signal to HRS,
4) abort signal to HRS,
5) onboard valve,
6) modify protocol,
7) limiting the effects, and
8) make CHSS tolerant to PRR control failures.

2.1.2 Discussion of the results

The risk assessment methodology of the ISO/EIGA workstream is very focussed on a “traditional” control scheme like is used on processing plants. The basic method of a control system doing its work and being monitored by an independent “watchdog” may not be easily applicable to more complex and dynamically operating control systems. It may well be possible that the risk assessment methodology for the PRHYDE protocol will need to be adapted to suit the protocol structure. It might be the case that other industries, such as aviation, for example, have more suited risk assessment methods for the type of application that we develop in PRHYDE.

Interestingly, the risk assessment suggests that only some specific conditions or combinations of ambient temperature and initial pressure in the vehicle tank would allow a PRR control failure to result in high temperature of the tank. If the onboard temperature could be used to determine the initial temperature, then the HRS could determine a maximum pressure that would guarantee that the maximum temperature will not be exceeded, independent of the ramp rate. That would require to use onboard temperature measurement and communication.

This approach could further be explored in PRHYDE WP3 to possibly create an additional barrier.

Some detail is spent on the concept of “inherently safe refuelling”, where an appropriate tank qualification procedure is suggested to qualify tanks for one-time overtemperature exposure by hydraulic or pneumatic testing with overtemperature conditions in the qualification tests. This would altogether eliminate any residual risk from overtemperature exposure, as the consequence of such an event occurring would be zero, and therefore the residual risk would also be zero. It could be explored further in WP3 if communicating the design (or better: qualification) temperature of the vehicle CHSS to the station could be used in a clever way to safeguard CHSSs with the new refuelling protocol, besides only adapting fuelling speed to allow for higher end temperatures.

2.2 Risk assessment of fuelling non-type approved vehicles

Considerations for risk assessment of refuelling not covered by the ISO TC 197 WG24 / EIGA risk assessment

The risk assessment process described in Section 2.1 'ISO/EIGA risk assessment' above assumes the vehicle (in that case, a light duty vehicle) being refuelled (in that case, using an SAE J2601 compliant refuelling protocol) is type-approved against the GTR No.13 or UNECE R134[3], and in the "as-built" state when it comes to refuelling.

For refuelling vehicles which are not type approved against the GTR No. 13 or UNECE R134, it may be necessary to carry out further, individual or general, risk assessments prior to refuelling. Some of the points to consider are as follows:

1) Is the vehicle type approved against EC79/2009[4] or UNECE R134? If so, this refuelling can pretty much be treated as equivalent from a risk assessment side of things.[5]
2) If not, it might be worth considering the design characteristics of the vehicle high pressure hydrogen storage system:
    a. The pressure rating of all the components in the vehicle high pressure hydrogen storage system:

       Are they rated to the set point of the Pressure Relief Valve (PRV) protecting the dispenser? (noting that in Europe, it is likely that the PRV set pressure would be limited to only 125% NWP, due to the manufacturer's rated pressure of components such as the nozzle, hose and breakaway coupling, as opposed to in other parts of the world where the PRV can be set to a higher pressure)
    b. The temperature rating of all components in the vehicle high pressure hydrogen storage system:

       The tank may see temperatures between -40 and +85°C, but the capability for the top end of this range is more critical. Equally the components in the refuelling line may also see temperatures between the same range, however, the capability for the bottom end of the range is more critical.

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[3] Regulation No 134 of the Economic Commission for Europe of the United Nations (UN/ECE) — Uniform provisions concerning the approval of motor vehicles and their components with regard to the safety-related performance of hydrogen-fuelled vehicles (HFCV) [2019/795]. Available at: https://op.europa.eu/en/publication-detail/-/publication/8aad3d19-7870-11e9-9f05-01aa75ed71a1/language-en

[4] Regulation (EC) No 79/2009 of the European Parliament and of the Council of 14 January 2009 on type-approval of hydrogen-powered motor vehicles, and amending Directive 2007/46/EC. Available at: http://data.europa.eu/eli/reg/2009/79/oj

[5] There is a slight discrepancy between the GTR No. 13 and the EC79/2009 requirements when it comes to the pressure rating of the vessel, with the requirement for onboard storage tanks to be tested to 138% NWP not being incorporated into EC79/2009.

The use of components individually certified against either UNECE R134 for the tank, or EC79/2009 for the tank or individual components gives an indication of whether or not these things have been addressed.

3) Additionally, it might be worth considering whether the vehicle high pressure hydrogen storage system has already been pressure tested following assembly:

   If not, further control measures may be necessary, such as whether a partial pressure test with an inert gas can be carried out (for instance with the storage tank isolated), refuelling the vehicle in controlled incremental steps in pressure, and leak testing following each step.

When refuelling heavy duty vehicles, a number of other things may also be worth keeping in mind:

- The ability of the components utilised in the vehicle high pressure hydrogen storage system to cope with the maximum flow rate that can be expected from the dispenser:

  Particularly relevant to heavy duty vehicles due to these typically being fuelled at higher flow rates than those of light duty vehicles. For instance, the mechanical interlock of the nozzle and receptacle contributes to the safety case for high flow refuelling as long as the vehicle is only fitted with a "high flow" receptacle if it can deal with the flow rate from the dispenser – however there is no true standardisation on what this flow rate needs to be limited to other than the recommendation of SAE J2601-2 for the dispenser.

- Due to the absence of a prescriptive protocol for filling heavy duty vehicles, the refuelling protocol is likely to be bespoke:

  Therefore, it is important to consider whether the protocol is designed for the tank system that is being filled, or if it has been designed for, for instance vehicles with type 3 tanks, in which case a lock-out approach may be necessary (equally applicable to light duty vehicles, but significantly less likely to be encountered)

2.3 Risk Assessment of fuelling taking into consideration the condition of the vehicle (for both type-approved and non-type approved vehicles)

Additionally, an element of the refuelling risk assessment should consider whether maintenance is carried out on the vehicle to

a) ensure no leaks have developed as a result of on-going use, or

b) following invasive maintenance, or replacement of parts, that these have been correctly installed.

It is worth noting that whilst

a) **recommending a maintenance frequency** is part of the vehicle type approval responsibilities for a vehicle manufacturer (see i below) (although not necessarily the case for non-type approved vehicles),

b) **ensuring that maintenance is carried out** is typically not part of the vehicle manufacturer's responsibility, and falls upon the person responsible for the vehicle. Upkeep of the hydrogen system on board a vehicle may be required legally in some countries, in the same way as are requirements for suitability of brakes, tyres, windscreen wipers, etc., but not other countries. An example of measures to try to address this is the Directive 2014/45/EU[6] (see ii below)

i. The requirements for vehicle manufacturers of type-approved vehicles to provide information for periodic inspection, see Article 4 clause 5 of Regulation (EC) No 79/2009[7] and Annex I, part 3 of Regulation (EU) No 406/2010[8]:

(EC) No. 79/2009: Art. 4(5): Obligation of manufacturers

Manufacturers shall provide information for the purposes of inspection of hydrogen components and systems during the service life of the vehicle.

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6 Directive 2014/45/EU of the European Parliament and of the Council of 3 April 2014 on periodic roadworthiness tests for motor vehicles and their trailers and repealing Directive 2009/40/EC. Available at http://data.europa.eu/eli/dir/2014/45/oj

7 Regulation (EC) No 79/2009 of the European Parliament and of the Council of 14 January 2009 on type-approval of hydrogen-powered motor vehicles, and amending Directive 2007/46/EC. Available at: http://data.europa.eu/eli/reg/2009/79/oj

8 Commission Regulation (EU) No 406/2010 of 26 April 2010 implementing Regulation (EC) No 79/2009 of the European Parliament and of the Council on type-approval of hydrogen-powered motor vehicles. Available at: http://data.europa.eu/eli/reg/2010/406/oj

Annex I of (EU) No 406/2010:

Administrative Documents for EC type-approval of vehicles with regard to hydrogen propulsion

PART 3: Information to be provided for inspection

1. Manufacturers shall provide:

(a) recommendations for inspection or testing of the hydrogen system during its service life;

(b) information on the need for periodic inspection and the necessary frequency in the owners' manual of the vehicle or by means of a label close to the location of the statutory plate according to Council Directive 76/114/EEC.

2. Manufacturers shall make the information specified in section 1 available to approval authorities and the competent authorities in the Member States responsible for the periodic inspection of vehicles in the form of manuals or by means of electronic media (e.g. CD-ROM, on-line services).

ii. Directive 2014/45/EU includes a passing reference to the need for visual inspections of the fuel tank and pipes of hydrogen vehicles over a pit or on a hoist on periodic roadworthiness tests for motor vehicles and their trailers. (see table in ANNEX I: Minimum requirements concerning the contents and recommended methods of testing, 6.1.3: Fuel tank and pipes (including heating fuel tank and pipes)).[9]

[9] The Directive should have been transposed into national legislation and applied by 20 May 2018, but this does not appear to have necessarily been the case across Europe.

3 CONCLUSIONS: REQUIREMENTS FOR A HD RISK ASSESSMENT FOR A NEW PROTOCOL STRUCTURE

Generally, a protocol must aim to not overpressure, not overtemperature and not overfill (too high density or SOC) a vehicle CHSS.

A risk assessment should test credible failure scenarios and quantify possible consequences and make sure these are realistically assessed. Exemplary questions in this regard are:

- Which consequences can we face when the pressure regulator does not work as intended and a tank is subjected to overpressure?
- Is it necessary to distinguish between levels of overpressure?
- Are there step changes?

Past risk assessments struggled to find a good answer for that on the question of over-temperature exposure of the tanks:

- Are there good/new insights?
- How can different design (or certification) temperatures be addressed?
- Is there a way to link overtemperature to possible future tank designs?

Also, the RA can be used to derive acceptable margins on the design that may be used in exceptional cases (e.g. when process control fails, etc.), such that process and safety limits can be defined by the station manufacturer.

It might be helpful to better understand consequences of adverse situations, e.g. test existing tanks on the market to gain further understanding on out of spec situations and the failure rate of tanks exposed to overtemperature events, or to understand the possibilities to capture faults of dynamically calculated control algorithms. As a starting point, the consequence assessment of the ISO/EIGA RA could be used, together with the identified scenarios, and checked for the presence of barriers.

Also, the criticality of inaccurate data being received from the vehicle, needs to be assessed. Credible scenarios need to be developed to handle situations, where e.g. part of the CHSS remains closed or is reported incorrectly. Another example would be that inaccurate temperature is transmitted due to location of the sensor or the sensors are malfunctioning. Therefore, a future refuelling protocol should take possible inaccuracy of information communicated into account.

It would be recommended that the risk assessment for the new protocol should predominantly assume an appropriate station and vehicle design and certification, and focus on faults that would prevent the protocol to correctly control the fill.

In addition to that, also operational aspects could be brought into the RA. Example topics would be to consider barriers against filling of non-approved or unsuitable vessels, e.g. users trying to re-fill gas bottles of different working pressures by using adapters or CHSS that are outside of their validity dates.

What is PRHYDE?

With funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (FCH 2 JU), the PRHYDE project is aiming to develop recommendations for a non-proprietary heavy duty refuelling protocol used for future standardization activities for trucks and other heavy duty transport systems applying hydrogen technologies.

Based on existing fuelling protocols and current state of the art for compressed (gaseous) hydrogen fuelling, different hydrogen fuelling protocols are to be developed for large tank systems with 35, 50, and 70 MPa nominal working pressures using simulations as well as experimental verification. A broad industry perspective is captured via an intense stakeholder participation process throughout the project.

The work will enable the widespread deployment of hydrogen for heavy duty applications in road, train, and maritime transport. The results will be a valuable guidance for station design but also the prerequisite for the deployment of a standardized, cost-effective hydrogen infrastructure.

Further information can be found under https://www.prhyde.eu. For feedback on the PRHYDE project or the published deliverables, please contact info@prhyde.eu.

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