PRHYDE

Protocol for heavy-duty Hydrogen refuelling

Deliverable 2.3

Gap analysis of existing gaseous fuelling protocols

Report Status: FINAL

Report Date: 16. October 2020

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Confidentiality Level: PU – Public

Acknowledgement:

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under grant agreement No 874997. This Joint Undertaking receives support from the European Union's Horizon 2020 research and innovation programme, Hydrogen Europe and Hydrogen Europe research.

R E P O R T

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CONTENTS

Tables

Figures

Acronyms and Abbreviations

CAPEX	Capital Expenditures
CHSS	Compressed Hydrogen Storage System
FCEV	Fuel Cell Electric Vehicle
HDV	Heavy Duty Vehicle
HRS	Hydrogen Refuelling Station
LDV	Light Duty Vehicle
NWP	Nominal Working Pressure
OPEX	Operation Expenditures
SoC	State-of-Charge

Note: Vehicle classification (e.g. M1, M2, M3, N1, N2, N3) where applied based on Annex II of Directive 2007/46/EC - DIRECTIVE 2007/46/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 5 September 2007 establishing a framework for the approval of motor vehicles and their trailers, and of systems, components and separate technical units intended for such vehicles (Framework Directive) – see http://data.europa.eu/eli/dir/2007/46/oj

Executive Summary

During the process of refuelling a hydrogen powered vehicle at a hydrogen refuelling point, the automated procedure of controlling the refuelling process is referred to as the fuelling or refuelling protocol.

This deliverable analyses and assesses the existing refuelling protocols in use. Both light duty and heavy duty protocols are assessed, views from wider industry are included in the analysis through the use of surveys and the input from the webinars.

Current refuelling protocols are insufficient for use in heavy duty applications, as they do not support:

- fills to the required amount of hydrogen – most refueling protocols are limited to 10 kg or 30 kg (technically it is possible to fill larger CHSS, but above 30kg operating issues cannot be excluded);
- fills in the required speed / at high transfer rates of hydrogen adequate to the respective applications (max. 120 g/s) – the required flow rates for HD applications are just not supported by current protocols;
- meeting the cost targets for hydrogen – current refueling protocols do not support the required cost decrease path to diesel parity by forcing the station operators to over-design refueling systems.
- Clear but flexible criteria on how to fill an application with hydrogen – either the protocols are too prescriptive or non-informative, such as with SAE J2601-2
- Interoperability between all heavy duty vehicle types on the roads – many stations have been programmed to only service e.g. buses with type 3 CHSSs only – now posing a possible safety threat, as in many cases it cannot be controlled which exact vehicles come to refuel at a certain station. This is especially true for publicly accessible stations.

Since in most cases a conservative scenario is considered (due to the absence of advanced communication between the station and a vehicle), the precooling temperature can be relaxed and the State-of-Charge (SoC) should be improved in the upcoming heavy duty protocols.

1 INTRODUCTION, MOTIVATION AND METHODOLOGY

1.1 General (What is a refuelling protocol?)

During the process of refuelling a hydrogen powered vehicle at a hydrogen refuelling point, the automated procedure of controlling the refuelling process is referred to as the fuelling or refuelling protocol.

The general purpose of the refuelling protocol is to control the refuelling process in a way that prevents damage to the vessel(s) on the vehicle that is being fuelled. This includes the situations of over-pressurisation, over-heating, over-filling (which could lead to over-pressurisation should the ambient conditions change) or other aspects.

Another purpose of the refuelling protocol, relevant for customer convenience and satisfaction, is to achieve good performance by staying within acceptable refuelling times (see also PRHYDE Deliverable D2.1 for benchmark) and to achieve a high State-of-Charge (SoC) of as close to 100% as possible.

Currently, a large variety of refuelling protocols for hydrogen vehicles exist: besides protocols that are designed for the fuelling of specific vehicles, or vehicles with specific characteristics, there are also refuelling protocols appropriate for any vehicle that could come to a refuelling station (given a set of underlying assumptions on the side of the vehicle). Furthermore, some of these refuelling protocols are standardised (whether through a Standards Development Organisation, such as SAE, ISO or CEN), or have been developed and applied at a national or project level. Others remain the intellectual property of those providing the refuelling point, as often the case with e.g. material handling vehicle refuelling.

The requirements for refuelling protocols can be found in a number of places, either within a refuelling protocol standard itself (to give an understanding to the reader of the assumptions taken) or in higher level documents containing requirements for hydrogen refuelling stations. The refuelling protocol standards can also be a mixture of prescriptive measures to take when implementing the refuelling protocol, or in some cases, more general high-level requirements for the designer of a refuelling protocol to keep in mind.

Another important aspect with regard to refuelling protocols is the transfer of information between the vehicle and the refuelling point, also referred to as “communications”. Today, these communication interactions are typically one-directional – from the vehicle to the refuelling point. Depending on the refuelling protocol used, and the particularly refuelling point manufacturer’s decisions in implementing a refuelling protocol, the communicated information can serve different purposes:

- simply to provide information that can be logged by the refuelling station for further analysis if required;
- it can have an impact on the refuelling process, for instance indicating characteristics of the vehicle compressed hydrogen storage system (CHSS) which could lead to the refuelling finishing when the CHSS reaches a certain SoC, or halting the refuelling in the case of an adverse situation.

- The information can also be used to define the refuelling protocol to be used, for instance, by indicating the capacity of the hydrogen storage system on board the vehicle.

1.2 Existing gaseous refuelling protocols

Examples of refuelling protocols, relevant to the fuelling of vehicles of any size, include the following:

- SAE J2601 – Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles[1]

  Note: Whilst SAE J2601: 2016 is limited to a CHSS capacity between 50 and 250 litres, a revision was published in May of 2020 which includes an approach for refuelling vehicles with a larger CHSS capacity to a nominal working pressure (NWP) 700 bar – however all the methodologies for refuelling vehicles in this standard are limited to a maximum flow rate of 60 g/s.

- SAE J2601-2 – Fueling Protocol for Gaseous Hydrogen Powered Heavy Duty Vehicles[2]

  This document includes “the boundary conditions for safe heavy duty hydrogen surface vehicle fuelling, such as safety limits and performance requirements for gaseous hydrogen fuel dispensers used to fuel hydrogen transit buses”, introducing fuelling at flow rates up to 120 g/s. It has a focus on vehicles with an NWP of 350 bar, but principles that can be applied to vehicles operating at any NWP.

- JPEC-S 0003[3]
  This Japanese national standard is a fuelling protocol that is closely related to SAE J2601, as major principles are shared. Some additional specifics are implemented to reflect the Japanese regulatory framework, for example the Japanese high pressure gas safety act, that limits the maximum dispensed pressure. The main difference to earlier version of the SAE J 2601 is that JPEC-S0003, as the first protocol, adapted fuelling of larger CHSS than initially anticipated in SAE-J2601, by allowing to modify the APRR boundaries (specifically the lower boundary) and a small number of other parameter. This approach was later also implemented into SAE-J2601

- Additionally, a protocol was developed for the Clean Urban Transport for Europe (Cute) project, running between 2007 and 2009. Although the protocol isn’t publicly available, it is still used at bus refuelling stations today.

Examples of other relevant documents containing the requirements for refuelling protocols include:

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1 SAE J2601 - Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles: at the time of writing, the latest version is that published in 2016, see https://www.sae.org/standards/content/j2601_201612/

2 SAE J2601-2 - Fueling Protocol for Gaseous Hydrogen Powered Heavy Duty Vehicles: (at the time of writing, the latest version is that published in 2014, https://www.sae.org/standards/content/j2601/2_201409/

3 Japan Petroleum Energy Center (JPEC) S0003

- ISO 19880-1 – Gaseous hydrogen - Fuelling stations – Part 1 – General requirements[4]

  Note: ISO 19880-1 replaces the earlier ISO/TS 19880-1: 2016 of the same name, which contained recommendations for hydrogen refuelling stations – which in turn replaces the much earlier document ISO/TS 20100: 2008[5].

- EN 17127 – Outdoor hydrogen refuelling points dispensing gaseous hydrogen and incorporating filling protocols[6]

  EN 17127 is a document published by CEN which essentially contains the relevant sections extracted from an early draft ISO 19880-1. The EN 17127 is under revision to bring it into line with the final text of ISO 19880-1, for instance removing the current limitation of 120 g/s for high flow applications where mechanical interlocks are provided in the form of ISO 17268 high flow nozzles (please see PRHYDE Deliverable 2.4 for further information).

  To enable interoperability of hydrogen refuelling points across Europe with hydrogen vehicles, the Directive 2014/94/EU[7] on the deployment of alternative fuels infrastructure became a legal requirement across Europe from the 18th November 2017. Amongst other requirements, this introduced a legal requirement for the refuelling protocols used for refuelling points installed onto publicly accessible hydrogen refuelling points, including a normative reference to ISO/TS 20100. The Commission Delegated Regulation (EU) 2019/1745 of 13 August 2019 supplementing Directive 2014/94/EU[8] has updated this normative reference to now point to EN 17127, with a requirement for all new or renewed public refuelling points to comply with EN 17127 from the 12th November 2021.

An example of a standardised communications protocol for the refuelling of hydrogen vehicles is:

- SAE J2799 – Hydrogen Surface Vehicle to Station Communications Hardware and Software[9]

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4 ISO 19880-1 – Gaseous hydrogen - Fuelling stations – Part 1 – General requirements: at the time of writing, the latest version is that published in 2020, see https://www.iso.org/standard/71940.html

5 see https://www.iso.org/standard/39206.html, which was withdrawn upon the publication of ISO/TS 19880-1

6 EN 17127 - Outdoor hydrogen refuelling points dispensing gaseous hydrogen and incorporating filling protocols: at the time of writing, the latest version is that published in 2018 - available, for example, through BSI, see https://shop.bsigroup.com/ProductDetail?pid=000000000030358353

7 DIRECTIVE 2014/94/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 22 October 2014 on the deployment of alternative fuels infrastructure - see http://data.europa.eu/eli/dir/2014/94/oj

8 COMMISSION DELEGATED REGULATION (EU) 2019/1745 of 13 August 2019 supplementing and amending Directive 2014/94/EU - see http://data.europa.eu/eli/reg_del/2019/1745/oj

9 SAE J2799 – Hydrogen Surface Vehicle to Station Communications Hardware and Software: at the time of writing, the latest version is that published in 2019 – see https://www.sae.org/standards/content/j2799_201912/

1.3 Refuelling protocols for heavy duty vehicles

Refuelling protocols for heavy duty vehicles (HDVs) can comprise specifications for the refuelling of an extensive range of vehicles (see also PRHYDE Deliverable D2.1 for definition), with a complicated range of needs when it comes to the method by which hydrogen is transferred to the vehicle.

The refuelling protocol can be defined in a number of ways, based on characteristics of the vehicle being filled and/or the refuelling point itself:

- **Pressure level** – typically equivalent to the NWP of the vehicle being fuelled, although depending on the refuelling point, it may be appropriate for a vehicle rated to a higher pressure than that of the refuelling point to be partially fuelled. For instance, a 700 bar NWP car can be filled at an H35 refuelling point if the refuelling protocol on the H35 refuelling point has a standardised protocol, such as that of SAE J2601.
- **Mass flow rate** – typically up to 60 g/s is appropriate for the refuelling of light duty vehicles (LDVs). However, depending on the hydrogen system deployed on a heavy duty vehicle, this could have the same limit of 60 g/s, or be capable of accepting hydrogen at a high mass flow rate, for instance, up to 120 g/s, or even greater mass flow rates.
- **CHSS capacity** – for light duty vehicles, this is typically between 50 litres and 250 litres for M1 and M2 vehicles [10]but that does not necessarily have to be the case. It can be expected that HDVs would generally have larger capacity for stored hydrogen on board.

Another aspect is that the refuelling protocol is rather determined by the size of the CHSS than the actual weight of the vehicle. Therefore, to prevent misunderstandings, it may be more appropriate to refer to the protocol as a "protocol for filling large CHSS (>250 litres)", rather than "heavy duty refuelling protocol".

With the above mentioned three characteristics in mind, the current status of standardised refuelling protocols is as follows:

[10] For classification see Annex II of Directive 2007/46/EC - DIRECTIVE 2007/46/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 5 September 2007 establishing a framework for the approval of motor vehicles and their trailers, and of systems, components and separate technical units intended for such vehicles (Framework Directive) – see http://data.europa.eu/eli/dir/2007/46/oj

Table 1: Overview of current protocol characteristics for different use cases

Description	H35	H50	H70
0-50 Litres	0-60 g/s: No Protocol 0-120 g/s: SAE J 2601/2 (no details given on how to perform fill)	No Protocol	No Protocol
50-250 Litres	0-60 g/s: SAE J 2601 0-120 g/s: SAE J 2601/2 (no details given on how to perform fill)	No Protocol	0-60 g/s: SAE J 2601, JPEC s 0003
>250 Litres	0-120 g/s: SAE J 2601/2 (no details given on how to perform fill)	No Protocol	0-60 g/s: JPEC s 0003, SAE J2601: 2020

Note: Nozzle/receptacles are standardized in ISO17268/SAE J 2600 for H35, H50 (legacy versions of standard) and H70 for 0-60 g/s; for 0-120 g/s the only existing standard is for H35HF.

Note: SAE J2601:2020 gives no formal upper limit in Category D, however, a practical limit would be reached where the size of the CHSS would require a flow of >60g/s to achieve the lower pressure ramp rate.

Note: JPEC s0003 enables fueling above 250l (10kg at H70) and assumes a maximum size of 30kg (at H70). Larger CHSS can be filled with no safety issues, only operational issues (such as aborted fuelings) might be expected.

2 ANALYSIS OF CURRENT REFUELLING PROTOCOLS

The refuelling protocol landscape is mainly dominated by light duty refuelling protocols, mostly SAE J2601 (in various versions of publication, or by protocols based on or related to SAE J2601, such as JPEC-s-0003), due to the higher number of passenger cars on the road and their larger hydrogen station network.

For LDVs, the current standard refuelling protocol SAE J2601 is a prescriptive approach that limits the fuelling performance because the worst-case tanks must be taken into account. In addition, a limited amount of vehicle data can be used by the station. The prescriptive approach also requires accurate station controls and minor excursions result in termination of the fuelling process. Contrary to SAE J2601, the SAE J2601-2 protocol is non-prescriptive – it primarily specifies what situations or parameters to avoid during fuelling in order to avoid an impact on safety. It does, however, not specify how this is achieved, in particular with regards to safe communication and collection of data from the vehicle side.

A later addition to the SAE J2601 protocol is the inclusion of the *MC-Formula* or *MC-Method*, as developed and proposed by Honda. Here, the real temperature of the hydrogen gas dispensed to the vehicle is measured and a ramp rate adjustment is introduced. This is a clear improvement over the very prescriptive table-based protocol option, especially as it allows for a correction and adaptation of the refuelling rate during the fill, thereby eliminating one of the very frequent reasons for fuelling terminations: the leaving of a temperature range. In the table-based SAE J2601 version, only very minor deviations from a temperature were considered, typically +/-3°C from a reference value. This results in very expensive station designs and the requirement to very tightly control both, the pressure ramp rate and the temperature of the hydrogen. In practice, as a consequence, often oversized coolers with controlled bypasses have to be installed. The *MC-Method*, on the contrary, allows the station to adjust the ramp rate based on the measured pre-cooling temperature without any discrete steps that would require the fuelling to be terminated. One of the drawbacks of the *MC-Method* is that it still works towards the same boundary conditions and assumptions as the table-based method, therefore it does not solve the issue of stacking tolerances and conservative assumptions, and therefore still doesn't prevent an overdesign on the station side. While this already increases costs on a light duty station, it would likely have a much higher effect on a heavy-duty station costs, due to the much wider variety of CHSS to be filled and therefore likely a much worse (much more conservative) case tank model. Therefore, this is not an acceptable or feasible approach.

For HDVs in service today (mainly buses), the landscape is more diverse, as the corresponding refuelling protocol standard, SAE J2601-2, only gives very little guidance on how to actually fill and focusses on the boundary conditions and process limits for a refuelling protocol, instead.

This has led to individual station manufacturers developing their own refuelling protocols, such as: NEL (based on the mass flow control), Linde (based on pressure ramp), Air Liquide (based on pressure ramp) or ITM Power (based on pressure ramp).

3 LIMITATIONS AND BOUNDARY CONDITIONS

Structurally, because of both, the inherent margins used in SAE J2601 and the very strict control and precooling requirements, it is virtually impossible to meet the cost targets for N3 tractor-trailer vehicles, if the same approach was to be extrapolated to a new heavy-duty protocol. Mostly the precooling system and the required control over ramp rates would make the station prohibitively expensive.

HDVs have much larger tank system sizes storing quantities up to as much as 100 kg – trains, ships and transport systems even more – which is substantially higher compared to LDVs currently having tank capacities of 1 to 10 kg. Foremost expansion to such larger tank system sizes requires a substantial increase in average flow (kg/min) during fuelling to achieve sufficiently fast fuelling speed for the long driving ranges in typical HDV applications, should a refuelling time comparable to conventional fuels be required. This is discussed in PRHYDE deliverable 2.1 in detail.

One tempting approach would be to just expand the tank size range of the SAE J2601 to cover the sizes needed for HDVs (as is the case with the JPEC-S 0003 and the recently published 2020 revision to SAE J2601, see Section 1.2) or to use the SAE J2601-2. However, both have great constraints that may impact the ability to meet end-user requirements both regarding refuelling time and fossil fuel price parity. These constraints are based on the fundamentals surrounding fast fuelling of hydrogen into a vehicle tank.

The key message is that knowing 1) tank type, 2) tank size, 3) tank pressure, and 4) tank temperature can greatly help to optimize fuelling speed and SoC, and most importantly enable the station equipment to achieve this with the most cost optimal equipment setup. Knowing even more about the system to be filled, such as design parameters, geometry parameters, etc. can be useful for even further optimization. The parameter values, however, must be communicated between the vehicle and the infrastructure via a method, which is safe according to relevant standards to enable adequate station equipment certification. The non-availability of such a method is one of the main limitations of the way hydrogen vehicle refuelling is performed, today.

The current overarching boundary conditions that must be adhered to with a refuelling protocol are documented in the standards ISO 19880-1 (specifically in Chapter 8), and EN 17127 (see Section 1.2 above).

4 COST DRIVERS ON INFRASTRUCTURE SIDE

Cost drivers are elements that increase the cost of a station without either adding additional functionality or increasing throughput. Therefore, it is important to analyse and understand the effect that some requirements from existing refuelling protocols have on the station design and how these requirements (often unintentionally) drive cost.

4.1 Precooling

Precooling consumes large amounts of energy at the point of dispensing. This reduces the overall efficiency of the supply chain and typically takes place where the energy is most expensive (in €/kWh). The problem gets aggravated by station designs that buffer large amounts of hydrogen at high pressures and use a control valve to throttle the hydrogen. Throttling the pressure over large gradients results in a temperature increase of several °C, caused by the Joule-Thomson-effect, and translates into additional cooling power that is needed

According to a techno-economic impact study by LBST in the HyTransfer-project, the application of the HyTransfer approach results in a cost-saving of up to 0.8 €/kg hydrogen for LDVs.[11] This effect is likely much stronger for HDVs, as the cost pressure is much higher (i.e. the cost parity as described in PRHYDE Deliverable D2.1 occurs at much lower hydrogen costs for HD applications compared to LD applications).

NREL presented to PRHYDE that an increase of the gas temperature inside the tank by 1°C allows the precooling temperature to be relaxed by 1.5°C, i.e. if there is inbuilt margin of 10°C, the precooling would not need to be done to at least -33°C, but only to -18°C, lowering both the CAPEX and OPEX of the station.

4.2 High pressure applications

In general, the costs of high-pressure equipment increase with higher pressure levels. This is not only true for storage vessels, but also for compressors, piping, heat exchangers, etc. Accordingly, an increase in power costs can be expected for higher pressure levels, also associated with the efficiency and more work needed to compress the hydrogen.

4.3 Close boundaries on temperature control

The temperature classes on SAE J2601 are very narrow and pose a significant control problem. There are several designs on the market that try to meet the very strict temperature requirements, which all involve a rather large effort in process control and a bulky, high complexity installation that typically needs to be mounted underground, close to the dispenser. Almost all known systems require the use of additional valves, such as bypasses, and control logic driving the installation costs. Additionally, leaving the very tight temperature window causes many refuelling aborts, especially in non-com mode (refuelling without communications signal, see SAE J2601), or significantly slows down the fill. Improvements can be achieved using the

[11] For details on the HyTransfer project, please see https://www.hytransfer.eu/

MC-Formula protocol, showing a possible direction for the development of a new refuelling protocol.

4.4 Close boundaries on pressure control

Similar to the very close boundaries on the temperature control, there are pressure boundaries, which need to be considered. It has been argued that the pressure corridor with its boundaries is safety relevant, though at the same time, JPEC-s-0003 has essentially removed the lower pressure boundary without any replacement; a development that has since been adapted by SAE J2601, which relaxes the requirements for staying above the lower pressure corridor boundary (allowing excursions of up to 15 secs), but it does not eliminate it. It is necessary to review the importance of these boundaries and find a less restrictive and more flexible but at the same time appropriately reliability-rated approach for the future refuelling protocol, that has no negative effect on the safety of the refuelling operation. This becomes especially important, as the range of tank sizes for HD applications is going to increase widely, which poses a situation that makes it very difficult for a station to guarantee a certain pressure ramp rate. Also, with a possible move to stations which operate on a direct compression scheme – possibly even from a source that decreases in pressure as it is being emptied – a lot more flexibility in both the flowrates and pressure ramp rates are going to be required. Ideally, a protocol would allow for all possible deviations from an ideal fill and only check on not exceeding the design envelope of the CHSS to be filled.

4.5 Use of worst case tank models and conservative assumptions on heat capacities

The use of the worst case tank scenario means that there is significant overdesign required on the station side to meet the requested performance in refuelling. In case, the details of a tank system are known in advance, the refuelling time required could be reduced or the design requirements for a station significantly lowered. Data collected from stations fuelling primarily Honda and Toyota vehicles and displayed in Figure 1 and Figure 2 suggests that the precooling temperature could be relaxed by 15-20°C (compared to -33°C) in 90% of the cases without any adverse effect. Hence, simplification of the precooling system along with reliable communication could help to save a lot of valuable CAPEX and OPEX and increase the SoC. A future refuelling protocol must be able to take that into account.

Same applies for the use of conservative assumptions on heat capacities of station components, such as breakaways and nozzles. By assuming higher heat capacities, the overall precooling power is overestimated, leading to undershooting the end-of-fill temperature in the tank significantly.

4.6 Stacking up tolerances and margins leads to overdesign on stations

All effects and additional assumptions on parameters that are not directly measured or parametrized lead to a significant overdesign of the station, thus driving up costs. A future protocol will need to take the most significant contributors into account and find a way to use these as parameters in the control of the station.

The MC Formula protocol, see example end temperatures in Figure 1, can be seen to more consistently achieve higher temperatures than the table-based approach in SAE J2601, see example end temperatures in Figure 2.

It can also be seen in Figure 1 however that even the MC method is typically conservative in the temperatures reached during fuelling, as there is still significant margin remaining to the vehicle tank design temperature of 85 ºC.

This could potentially be taken advantage of to further optimise the refuelling protocol (e.g. enabling less pre-cooling or allowing faster fuelling).

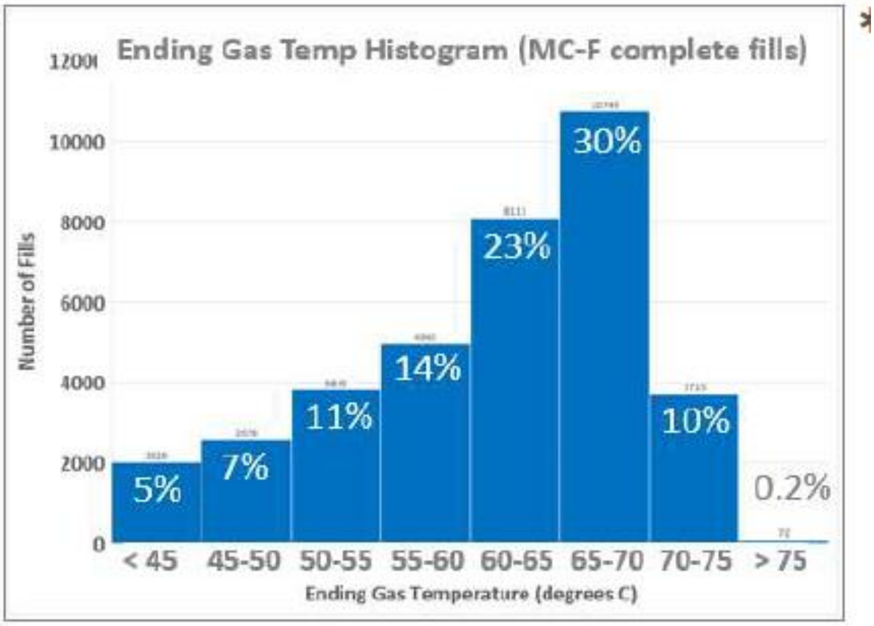

Figure 1: **End of fill temperatures for MC-Formula fills**

Source: S. Mathison presentation at the ISO TC 197 Strategic Planning Meeting in Vancouver, BC, in December 2018 - published as ISO TC 197 document N1077 – with thanks to Joe Cohen and Air Products for providing the data

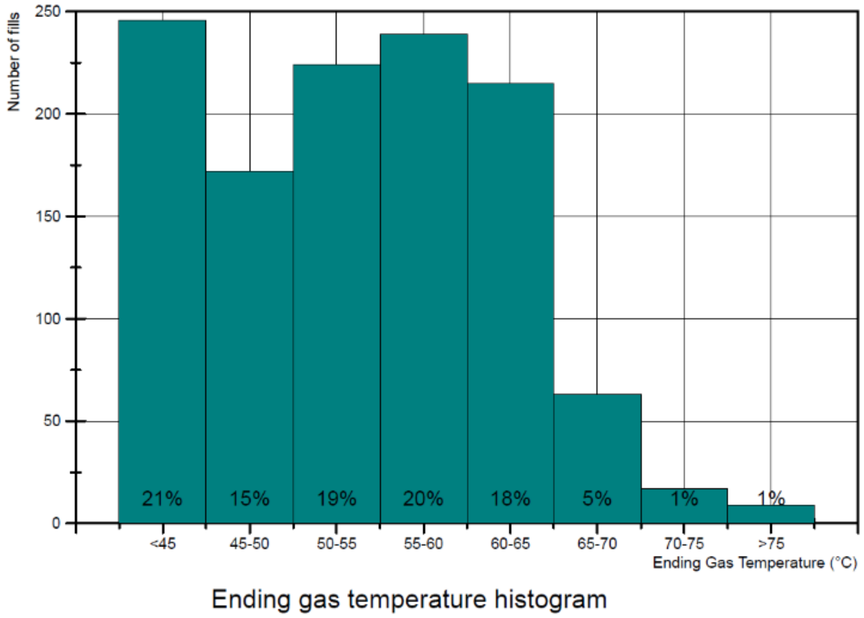

Figure 2: **Ending gas temperature in the tank vs. number of fills**

Source: Toyota Motor Europe measurements

Note: Refuelling times are typically faster for MC formula fills, therefore the end temperatures are naturally higher. Some additional deviation between Figure 1 and Figure 2 could also be due to different SOCs at the end of fill, ambient conditions and start pressures. Not enough data is available to compare like for like, though a major contribution is likely to come from faster fuelling.

5 SUMMARY

Current refuelling protocols are insufficient for use in heavy duty applications, as they do not support:

- fills to the required amount of hydrogen – most refuelling protocols are limited to 10 kg or 40 kg;
- fills in the required speed / at high transfer rates of hydrogen adequate to the respective applications (max 120 g/s) – the required flow rates for HD applications are just not supported by current protocols;
- meeting the cost targets for hydrogen – current refuelling protocols do not support the required cost decrease path to diesel parity by forcing the station operators to over-design fuelling systems.
- Clear but flexible criteria on how to fill an application with hydrogen – either the protocols are too prescriptive or non-informative, such as with SAE J2601-2
- Interoperability between all heavy duty vehicle types on the roads – many stations have been programmed to only service e.g. buses with type 3 CHSSs only – now posing a possible safety threat, as in many cases it cannot be controlled which exact vehicles come to refuel at a certain station. This is especially true for publicly accessible stations.

Activities on new refuelling protocols outside of PRHYDE

It has been brought to the attention of the PRHYDE consortium that there are a number of activities around the globe that also have the understanding of the refuelling process in mind and are working on advanced or improved refuelling protocols. The PRHYDE consortium is in exchange with the following present and past project groups and aims to exchange frequently with these groups and with the aim of mutual benefit:

- **Korean real time refuelling protocol[12]:** The group investigates a protocol that relies on real-time feedback between the vehicle and the station via advanced communications. Simulations have been performed and show promising results, field tests are planned. PRHYDE is certainly interested to understand the effect and implications of direct feedback.
- **HySpeed** is a small consortium in the Netherlands operating a HRS that is to fill commercial vehicles. Due to the lack of an available refuelling protocol, the group develops their own approach to refuelling. The PRHYDE consortium is in exchange through the workshops (see PRHYDE Deliverable D6.3) and personal contact with the consortium members.

[12] Real-time responding communication protocol (RTR), "Development of a new real time responding hydrogen fueling protocol", Chung Keun Chae, et al, international journal of hydrogen energy, 2020

- **Clean Energy Partnership (CEP)[13]:** The CEP was approached by bus fleet operators with the problem that most HRS for buses were programmed to work with buses using type 3 CHSSs. Since type 4 CHSSs show a much more challenging thermal behaviour, the activities of the CEP focus on enabling the use of buses with type 4 CHSSs with existing stations, i.e. a kind of bootstrap refuelling protocol. The PRHYDE consortium is in frequent exchange with the CEP, as some of its members are participating in both groups. It is likely that the simulations performed in either of the groups will be used as datapoints for later verification.

13 See https://cleanenergypartnership.de/en/home/.

ANNEX

A1 INPUT FROM EXTERNAL STAKEHOLDERS

In order to gather information from stakeholders external to the project, the PRHYDE consortium developed a set of surveys which interested parties were invited to complete and return to the project. Additionally, webinars were held on the 24th March and 23rd April 2020, to disseminate information about the project, but also, and equally importantly, to gather relevant information from those involved in the refuelling of heavy duty vehicles, or development of the vehicles themselves. Further information on the webinars and the surveys is available in PRHYDE Deliverable 6.3 or on the PRHYDE website[14].

Feedback on stakeholders' desires for a future refuelling protocol and the limitations of existing fuelling protocols for both light and heavy duty vehicles was gathered from the surveys and webinars. The section below includes summarised feedback that is relevant to this document and is to be taken into consideration in the development of the PRHYDE project refuelling approach.

Feedback received from participants of the workshops and survey responders on existing refuelling protocols was as follows:

- Achieving higher SoC (compared to that seen in the field for light duty vehicle fuelling protocols, where 95 – 100 % would be desirable but, depending on the station, often is not achieved – further information will be available from upcoming H2ME deliverable 2.6);
- Faster fuelling (due to conservative assumptions in the fuelling protocol used);
- Reduce energy consumption due to precooling, by enabling fuelling with less precooling;
- Decrease cost of HRS (compared to fossil parity requirements);
- A protocol without precooling for <120 g/s for type 3 and type 4 CHSS (CEP is working on this – see Deliverable 6.3);
- Reliable communication and measurements - Accurately knowing pressure and temperature of the vehicle high pressure hydrogen storage – data of pressure, temperature and any other type often need to be rated to an appropriate SIL (or ASIL) level to be useful for control and safeguarding purposes. Therefore, an appropriately rated data interface needs to be developed for future use.
- The ability for the station to know the CHSS volume on vehicle;
- Less complexity in protocols;
- Less prescriptive protocols, and more flexible in their working. More performance based than, for example, the current SAE J2601;

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14 See www.PRHYDE.eu.

- Taking into account design temperatures /values of the CHSS and using that to control the fill to a tank specific target value;
- Make better use of existing temperature and design margins of the CHSSs;
- Future proofing the protocol by allowing for technical improvements in tank design, e.g. by using actual tank design values to control the fill;
- If possible, taking into account the real thermodynamic properties of tanks and components to have less conservative margins.
- For the protocol to be developed together with its validation document, so it is clear how to test and what success criteria look like.
- A standard for protocol development would be helpful – something that allows for common criteria for protocol development;
- Be careful when naming the standard this work is going into – to avoid issues currently seen at SAE, where a protocol gets expanded beyond its original intent and the title cannot be changed to reflect this.
- Protocols for different pressure levels are important, not just H70;
- Be clear to which CHSS capacity a protocol and/or a station is applicable to avoid confusion;
- How to introduce a safeguard for subsequent refuelling at different pressures, especially in a case where there is no communication available between the vehicle and the station?
- Different service pressure ranges need to be intercompatible with each other in the safe direction.
- For H35HF there is a short term need for a universal refuelling protocol, also covering type 4 tanks ---> check similarities and differences to CEP and HySpeed work and align to fill gaps but prevent duplicate work;
- A reliability rated way to prevent overtemperature (and undertemperature) situations is required (both with abnormal refuelling situations and with subsequent refuelling) -> advanced communications or inherently safe fuelling approach;
- Have fallback option (see SAE J2601: 2014 onwards) available to enable fuelling without precooling;
- Consider vehicle controlling the fill – if this is not a feasible solution, document why;
- What is the criticality of inaccurate data being received from the vehicle, how can situations be handled, where, e.g. part of the CHSS remains closed or is reported incorrectly, or inaccurate temperature due to location of the sensor -> Protocol should take into account possible inaccuracy of information communicated;
- If an approach for the protocol is chosen that relies on accurate flow metering, an appropriate flow meter needs to be available;

- A reliability rated way to prevent over pressurization situations (due to Malfunctioning of the communication system or of the control system) is required. -> advanced communications or inherently safe fuelling approach;
- Need for new communications protocol to guarantee secured data exchange from vehicle to station;
- Need of protocol for large CHSS capacity (current limit affect HD operation) for H35, H35 HF, H70 and H70 HF;
- New protocol should differentiate type III and type IV CHSS;
- New protocol should allow for using different precooling temperatures, depending on ambient conditions, e.g. less precooling in winter, possibly steered by a target refuelling time;
- Current implementations that include the use of a manual or key switch to select for a different tank type or CHSS category are used, but uniformly seen as inadequate for the future;
- Strong preference for an automatic, safe handling of different tank types, with using the benefit of faster fill/lower precooling for type 3;
- Lack of uniformity for larger CHSS capacities seen as legal hinderance to roll out infrastructure; even with several different vehicles operating at the same station, as each station/protocol/vehicle combination needs to be individually approved.
- The combination of precooling and the existing hardware is seen as troublesome by some responders, two issues are named, a) the vulnerability and breaking of the IrDa unit on the nozzle, and b) the freeze-on of nozzles and blockage of control- and on-off valves at temperatures below –20 or -25°C.

A compilation of the types of refuelling approaches currently used to fill large CHSS on MD and HD vehicles is as follows:

- Custom average pressure ramp rate and pressure target (fixed or table base), often dedicated to one specific vehicle model (defined CHSS capacity, type, dimension etc...) and validated with test on the vehicle – both at 35 MPa and 70 MPa;
- Protocols for filling transport tube trailers with hydrogen up to 45-50 MPa;
- LH2 transfill operations from LH2 trailer to GH2 trailers or mobile GH2 refuellers;
- APRR based protocols;
- Mass flow control-based protocols;
- Fixed orifice-based protocols;
- Simple approach of opening a valve between the storage and the vehicle being fuelled for applications where over heating is not an issue (e.g. Type 1 tanks) JPEC-S 0003;
- SAE J2601-2;

- SAE J2601-1:2020, which is making provisions to fill up to 30 kg CHSS at 70 MPa and CHSS up to 10 kg from the same dispenser, using max 60 g/s flow;
- Protocol from CUTE project (2000) which is also table based.
- NEL Optifill concept;
- Slow fill overnight;
- Custom protocol to fill 8 kg at 350 bar in a sportscar (6 kg being the upper limit for H35 refuelling according to SAE J2601).

A range of comments received reflected important considerations, but do not fit into the project scope:

- Some stations in the market do not allow for the filling of CHSS larger than XYZ kg (this is a station design and implementation issue – but the question remains how to match station design performance to the protocol range);
- Inaccuracy of hydrogen dispensed quantity (a priority due to station design and operation and not to protocol itself).

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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