Deliverable D6.8

PRHYDE: Topics for Further Work

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REPORT

Disclaimer

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Revision History

Revision	Revision date	Summary of changes
1	09.12.2022	Final version for publication

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Name	Company	Date
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Name	Company	Date
Nick Hart WP6 leader	ITM Power	09.12.2022
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FIGURES

References

Documents

EN ISO 17268 2020	Gaseous hydrogen land vehicle refuelling connection devices
ISO 19880-1 2020	Gaseous hydrogen — Fuelling stations — Part 1: General requirements
ISO 19885	Gaseous hydrogen – Fuelling protocols for hydrogen-fuelled vehicles *(under development)*
SAE J2601 202005	Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles
PRHYDE D2.3	Gap analysis of existing heavy duty gaseous hydrogen vehicle refuelling protocol
PRHYDE D6.2	Final dissemination and exploitation plan
PRHYDE D6.7	Results as Input for Standardisation

All public deliverables of the PRHYDE project are available here: https://prhyde.eu.

Acronyms and Abbreviations

CEP	Clean Energy Partnership
CFD	Computational Fluid Dynamics
FCEV	Fuel Cell Vehicle
H_2	Hydrogen
HD	Heavy Duty
HF	High Flow
HRS	Hydrogen Refuelling Station
ISO	International Standards Organisation
ITF	Interface Task Force
OEM	Original Equipment Manufacturer
PLC	Programmable Logic Controller
SDOs	Standards Development Organisations
SOC	State of Charge
TC	Technical Committee
WG	Working Group
WP	Work Package

Executive Summary

Following completion of the PRHYDE project, the transfer of the learnings in the project to Standards Development Organisations (SDOs) is critical to progress the work done to the point of being widely accepted, and able to facilitate the safe, and efficient, fuelling of heavy duty hydrogen vehicles.

The PRHYDE **Deliverable D6.7** includes a detailed explanation of the fuelling protocol concepts developed in the PRHYDE project.

This deliverable describes the intentions for transferring these learnings, and highlights where further development work is needed to enable fuelling of heavy duty hydrogen vehicles according to the PRHYDE concepts, or developed from the PRHYDE concepts.

The PRHYDE project recommends following key topics for further work related to the development and improvement of high performance H_2 fuelling of heavy duty (HD) vehicles:

- Development of a reliable and secured (advanced) communication between HRS and vehicle, as the high performance H_2 fuelling will increasingly rely on the data communicated from vehicle to station and requires increased reliability of communication loops.
- Development of the appropriate H_2 fuelling high flow hardware (nozzle, receptacle, hose and breakaway).
- Further test activities are needed to optimize protocol performance for fuelling of different HD vehicles (and tank solutions).
- Optimisation of on-tank valve temperature sensors to ensure accurate representation of the gas temperature in the tank.
- Ongoing development of refuelling tables (as tank systems will be further developed) and ongoing validation of associated vessels (type 3, 4 and 5); Refuelling tables should be also validated vs experimental measurements or modelling results (using another validated model).
- Development of an open-access platform for model validation for the creation of refuelling tables.
- The PRHYDE protocol can be further developed and integrated by Standards Development Organisations.
- The PRHYDE protocol approach can be extended in the future for other HD applications such as rail, maritime, aviation etc. Specific stakeholder requirements should be considered in the development process.
- Ongoing process to update the risk assessment work on new H_2 fuelling concept developments.

1 INTRODUCTION

The PRHYDE project has enabled the development of concepts that can form the basis of fuelling protocols for heavy duty hydrogen vehicle fuelling in the future. The results of the project are summarised in PRHYDE **Deliverable D6.7**. In order for these to reach their potential, two things need to happen:

1) The generation of standards that define the requirements for fuelling protocols for heavy duty hydrogen vehicle.
2) The development of the enabling technologies, such as vehicle-station communications and consensus about how to deploy them, plus hardware developments necessary to allow fuelling up to 300 g/s.

This deliverable explains the further work needed in order to progress the PRHYDE concepts from concepts to standardised fuelling protocols that can be deployed in the field.

Further information on developments within the Standards Development Organisations most relevant to PRHYDE [1], also other developments since the publication of PRHYDE **Deliverable D2.3**, are included in Appendix A.

[1] Interactions between the PRHYDE consortium and such SDOs are detailed in the PRHYDE **Deliverable D6.2** (Final Dissemination and Exploitation Plan).

2 ROADMAP TO INDUSTRY ADOPTION

2.1 Introducing the world to PRHYDE Protocols

Previous protocols such as SAE J2601 are based on the assumption that an HRS has no, or extremely limited, information on the vehicle that can be used to define the fuelling protocol: for instance, the CHSS properties (total volume, unitary volume, tank types, thermodynamic properties of the tank material, tank shapes etc), or the gas thermodynamic gas conditions (temperature and pressure).Due to this lack of information, such fuelling protocols are required to take conservative approaches, which leads to unoptimized fuelling. The absence of communicated information about the CHSS also leads to the overdesign of the station for the required precooling, which affects both OPEX and CAPEX. The figure below demonstrates the excess margin on the temperature. There is a clear opportunity to decrease the "T40" precooling.

• The ending gas temperature margin is at least 15°C for 90% of the fills

• The ending gas temperature margin is at least 25°C for 60% of the fills

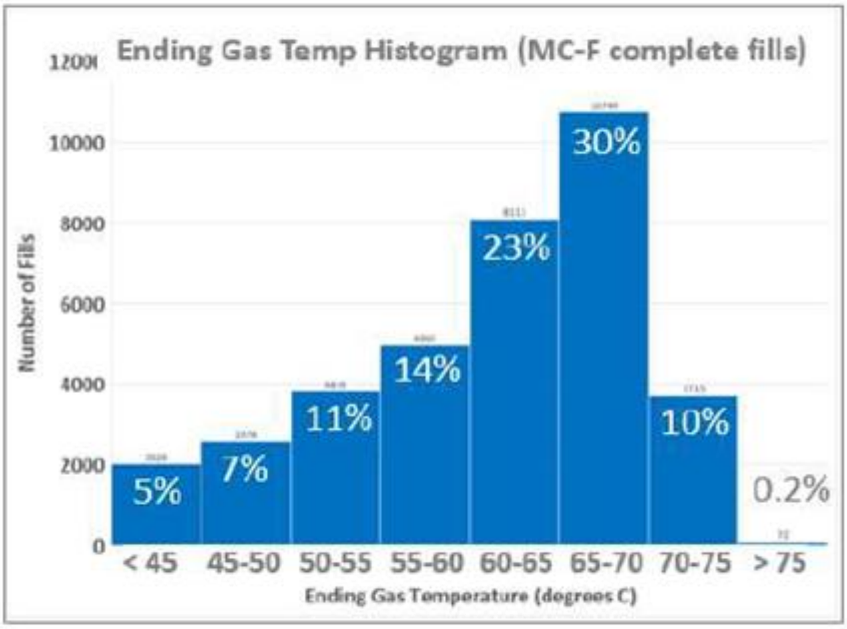

Figure 1: End of fill temperatures for MC-Formula fills

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.

Modelling performed in the PRYDE project, as described in Deliverable D6.7, have demonstrated the capability of the PRHYDE fuelling protocol concepts to achieve equivalent performance whilst allowing higher fuel temperatures in the T20 temperature category.

Changing from T40 to T20 can substantially reduce the CAPEX and also OPEX (up to 50% cooling power may be saved) and hence lower the hydrogen price to the end user.

Finally, preventing overshooting the temperature limit is of great importance. The ability to achieve fast fuelling times without exceeding the CHSS maximum temperature and maintaining high SOC can be further optimized in the future iterations of the PRHYDE approaches. The fuelling protocol approaches offer a solution to situations where a vehicle starts with a higher tank temperature than accounted for in the standard use of a current fuelling protocol, for instance due to prior fuelling events.

Additionally, the PRHYDE protocol concepts offer a solution for situations where reduced station performance can still enable a fuelling event to take place, for instance using a lower SOC than normally targeted, or extending the fuelling time to prevent overheating the tank.

All these examples demonstrate that the development of a protocol able to take into account the static information (vehicle tank characteristics, , initial gas conditions (P, T)) and T and/or P tuning during fuelling, is a high priority for large-scale deployment of FCEV for HD road applications and not only.

PRHYDE protocol concepts change paradigms used by previous protocols. PRHYDE uses bi-directional or advanced communications to overcome the issues listed before. All the previously mentioned data will be stored (static) and measured (dynamic) on the vehicle side and communicated to the HRS. This makes the PRHYDE protocol concepts essential for safe, responsible and sustainable deployment of HD hydrogen vehicles. The PRHYDE protocol concepts can also be adjusted for other applications with lower and higher flow rates, different types of tanks, sizes and other performance parameters such as, maritime, rail, aviation and other applications.

2.2 Hardware

Fuelling connectors for road heavy-duty applications are addressed by in ISO 17268 and SAE J2600. The specifications for light duty vehicle fuelling connectors (intended for implementation on dispensers with protocols with flow rates up to 60 g/s) and high flow (HF) connectors, for 350 bar only currently, intended for implementation on dispensers with protocols with a maximum mass flow rate of 120 g/s, are included in these standards.

ISO/TC 197 WG5 is working on expanding their work to include specifications for fuelling connectors that enable the dispensing of hydrogen at flow rates up to 300 g/s. It is important to develop standardised flow and thermodynamic properties in order to define t_{final} tables, including a standardised approach to defining these (there are multiple methods to derive flow coefficients currently), see Chapter 4.1 of Deliverable D6.7.

Additionally, a standardised methodology for enabling qualification of CHSS to temperatures higher than 85 ºC needs to be defined through appropriate standardisation organisations or regulatory platforms as appropriate.

2.3 Need for developing industry-accepted model for generating t_{final} values

The concepts of the PRHYDE protocol were developed by PRHYDE Work Packages (WP) 3, WP4 and WP5 and tested using modelling tools (H2Fills, SOFIL and HyFill), via experimental data (see D6.7). However, at the current stage only the concept of the protocol based on SOFIL and H2Fills simulations is available. For further larger development and integration on the PLC of HRS or vehicle in the EU and worldwide an open source modelling tool for the generation of the t_{final} values is needed. This can be based on a simplified version of the already existing reference tools or other validated tools.

For the deviation of t_{final} values, the first step is to input each component of the CHSS into the fuelling model. The fuelling model should accurately represent the detailed design of the CHSS, including the piping, junctions and valves from the receptacle to each of the individual tanks in the CHSS. In addition to the CHSS, the station side fuel delivery components must be input to the fuelling model. These include the breakaway, hose, and nozzle. These components are not unique to the vehicle CHSS. These components are common to the derivation of the t_{final} tables by all vehicle OEMs. The modelling tool should correctly take into account the fluid dynamic and thermodynamic properties of the vehicle and station side components The properties for these components should be conservative since there are a number of manufacturers of these components in the marketplace. The fuelling protocol standard should specify the values to use for the thermodynamic properties of these components.

The development of the dedicated tool for the derivation of t_{final} values is outside the scope of PRHYDE and needs to be done shortly in the frame of another industrial project.

Figure 1 below shows the concept of PRHYDE protocol:

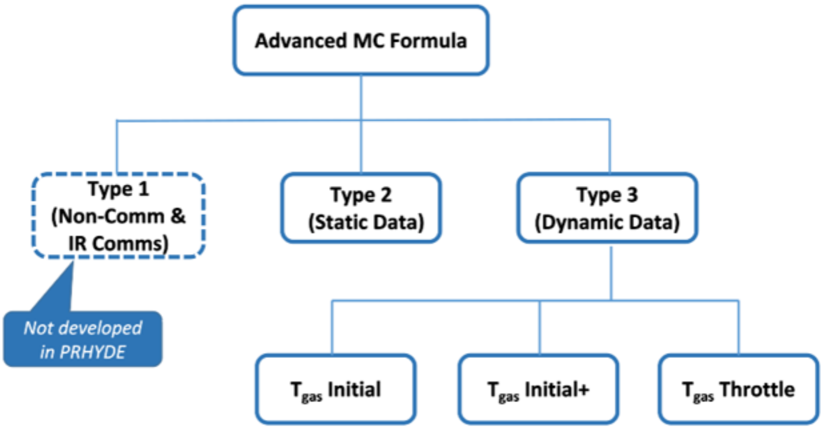

Figure 2: Diagram showing the relationship of different PRHYDE protocols as defined in Deliverable D6.7

Type 2 protocol is only based on the static data, type 3 is based on the measurement (T,P) inside the tank, see PRHYDE **Deliverable D6.7** (Section 3.2). In both cases, the availability of communication between the vehicle and the station is assumed.

The PRHYDE protocol type 3 is based on real-time monitoring of the temperature measurements inside the tanks. Hence, the temperature sensors and vehicle and station safety controls related to this system need to have a high reliability rating. Another approach is to include measurement errors of on-board temperature to the static data to be used by the protocol.

Future protocols which require higher level of reliability, their communication may need to meet the following requirements:

- Safety critical
- Establishing trust-identity management
- Protected in terms of cybersecurity
- Establishing a station/vehicle stable pairing
- Able to communicate the protocol requirements and other necessary/critical information

An added advantage associated with increased reliability in communications between the vehicle and station is that this facilitates taking further measures to address possible situations where a dispenser could be used to refuel, whether unintentionally, or intentionally, an inappropriate vehicle / other pressure receptacle.

However, there are already a number of vehicles on the road without any advanced communication and communications may not work. In order to avoid stranding the vehicles, a protocol also should be able to refuel even if the communication is lost, possibly in a reduced performance mode which would involving adjusting the final performance targets (SOC and fuelling time) and the fuelling parameters.

2.4 Interim adoption of PRHYDE Protocol Concepts

Fuelling performance should be excellent with the PRHYDE fuelling concepts even under warm fuel delivery temperatures, however, these concepts necessarily require reliable, trustworthy, secure communications, which do not exist today and are not likely to for several years. To bridge this gap, there is a need for a Type 1 "general purpose" fuelling protocol, which facilitates high flow fuelling without needing advanced communications. The SAE ITF is working on general-purpose MC Formula high-flow fuelling protocol (MCF-HF-G) which can serve this purpose. It will be published as a new TIR (J2601-5) in SAE.

Key differences of the MCF-HF-G from PRHYDE concepts are detailed in PRHYDE Deliverable D6.7, Chapter 5.1.1

Fuelling speed of MCF-HF-G will not be as optimized as with the PRHYDE fuelling concepts but acceptable with sufficiently cold pre-cooling as the intermediate solution. According to the preliminary timeline the target publication of TIR J2601-5 is by the end of 2023.

2.5 Future adoption of PRHYDE Protocol Concepts

Nowadays, the most important development of the fuelling protocol for the heavy-duty application is addressed by ISO/TC197/WG24 which is working on three separate documents:

- Document 1 focuses on the process for designing and developing hydrogen fuelling protocols for a wide range of automotive applications (ISO 19885-1).
- Document 2 is dedicated to the advanced communication (ISO 19885-2).
- Document 3 covers the fuelling protocol dedicated to heavy duty road vehicles (ISO 19885-3).

Document ISO 19885-1 is under review and provides guidance for all fuelling protocols.

The concept of PRHYDE protocols is planned to be included into the document ISO 19885-3, whereas requirements for advanced communications systems and examples of hardware will be addressed in ISO 19885-2. The target publication date of these documents is 2024. Please see below the complementary approaches for standardization of MCF-HF-G and the PRHYDE protocols.

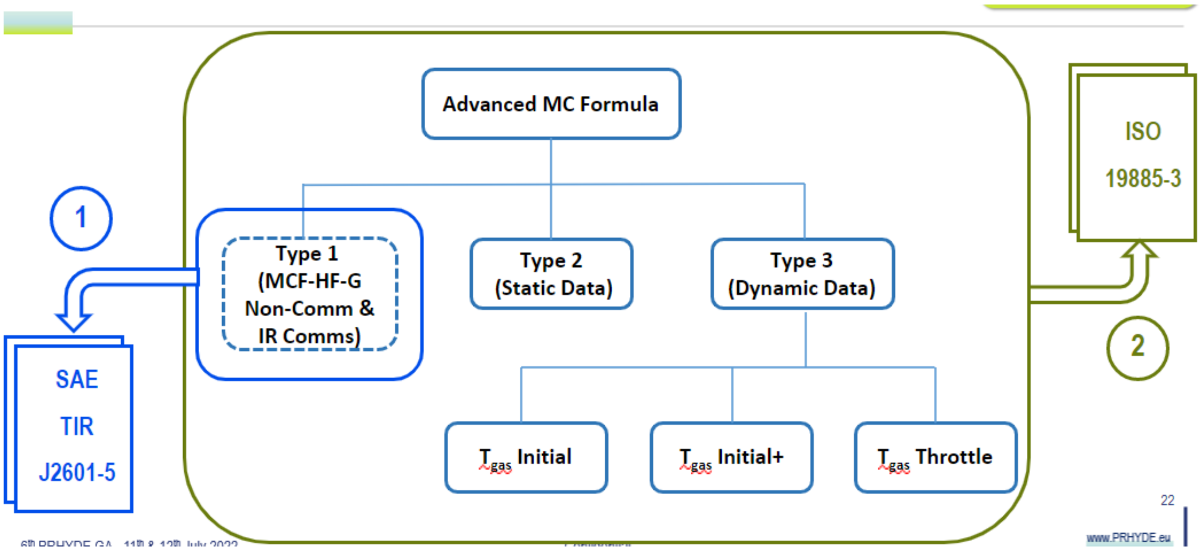

Figure 3: **Anticipated future work activity of the two most relevant Standards Development Organisations; SAE FCEV ITF and ISO/TC 197**

Estimated Standardization Schedule is presented on the figure below:

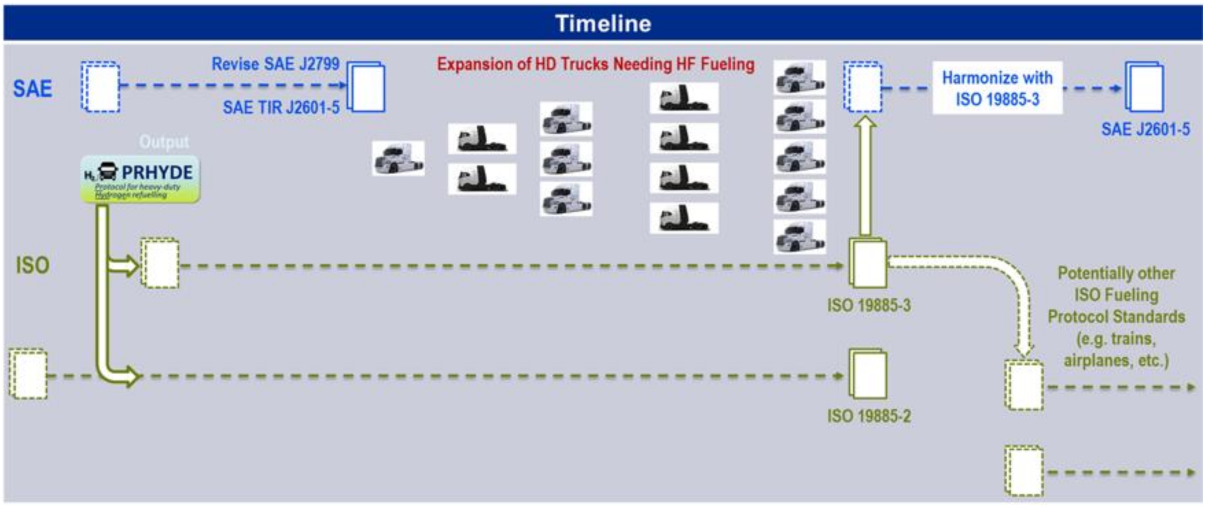

Figure 4: **Anticipated timeframes for upcoming future work activity of the two most relevant Standards Development Organisations**

2.6 Areas for further development following on from PRHYDE Protocol

Certain elements in the context of the PRHYDE fuelling protocol concepts would benefit from further development activity:

- Prerequisites for applying the protocol concepts:
    - Development of **advanced communications** requirements and hardware.
    - For further details on the dispensing system and **hardware** see Section 2.2.
- Further improvement of PRHYDE protocol concepts:
    - A **standardized approach for the development of t_{final} tables** taking account of information such as range and interval of the ambient and precooling temperature and initial pressures:
        - model used for the derivation of t_{final} values also should be validated for associated vessels (type 3, 4 and 5).
        - an open-access platform for model validation for the creation of t_{final} values and the development of t_{final} values can be done within another collaborative project.
        - t_{final} values should be also validated vs. experimental measurements or modelling results (using another validated model).
    - Further **optimisation of user specified parameters** such as $t_{lookback}$ (see 3.2.5 of D6.7) or T_{gas} throttle constants (see 3.2.4 of D6.7)
    - **“Hot and cold soak” temperature assumptions** should be reviewed in the HD fuelling protocol standardization process for applicability to HD vehicles.
    - **Safety modules** (‘safety watchdog’) could be also **integrated on the PLC** of the HRS as an independent module from the main protocol to monitor and ensure the safe fuelling. This module should be able to stop the fuelling or/and reduce the pressure rate and the final SOC if appropriate to perform the fuelling in safe conditions
- Modelling and simulation:
    - Development of a **better understanding of temperature stratification** within a tank(s) during fuelling, including effect of injector design / orientation / angle[2], and the tank characteristics, and how this affects the liner temperature throughout the tank.

[2] The geometry of the injector seems to impact greatly the mixing of the gas. For the 165 L Type IV tank, the injector was directed upwards, and for the 240 L Type IV tank, the injector was directed upwards and sideways. In both of these cases, in contrary to the 350 L Type IV tank, no or very small temperature heterogeneities were observed.

It should be noted that the simulation software (other than CFD, which is expensive to set up and to run) cannot accurately predict these thermal gradients. **Further development of CFD models** could help to better understand the thermal effects within the tank during fuelling, see D6.7 chapter 9.3.

- **Further improvements and validation of thermodynamic and CFD models** as described in D6.7 chapter 10.2

- Experimental testing
  - **Further testing (incl. full system testing)**, such as the upcoming work planned at the HF NREL facility or other facilities, is needed to evaluate PRHYDE protocol performance for fuelling of a CHSS (see also recommendation in as described in Deliverable D6.7 chapter 10.3).
  - Further investigation including **experimental testing regarding data fluctuations** (see Section 3.2.6 of Deliverable D6.7)
- Further improvements
  - Development of tanks with higher temperature ratings than the current limit of 85 °C.
- Outlook
  - The PRHYDE protocol approach can be extended in the future **for other HD applications** such as rail, maritime, aviation etc.

3 ISSUES ENCOUNTERED WITH INADEQUATE DESIGN OF TEMPERATURE SENSOR IN THE ON-TANK VALVE

3.1 Observation of effect of OTV temperature sensor design

In some of the tests conducted at ZBT, the gas temperature as measured by the OTV was impacted by the incoming pre-cooled gas and rendered inaccurate. The cause of this can be due to several reasons and is likely specific to the OTV and tank combination.

As most CHSS utilize only one temperature sensor inside of the tank, which is typically located on the OTV, this is key finding that should be considered by the industry. The gas measurement that is used and communicated needs to be accurate, representative, and reliable for the protocol concepts requested. This is especially important for the Tgas Throttle protocol concept which required dynamic measurement and control using the gas temperature measurement. The following Figure 5 shows a bad and a good example of temperature measurement via OTV sensor during a T40 fuelling.

Due to the large number of thermocouples in the tanks, we assume that the average tree temperature corresponds approximately to the average bulk gas temperature. During all tests, even for the good OTV tank combinations, the measured OTV temperature was always below the assumed average bulk gas temperature.

Recommendation: The potential for this issue arising should be highlighted to standard organizations and other industry stakeholders, such as SAE FCEV safety task force, and ISO/TC 197/JWG30 for consideration in the documents generated by these groupings, as well as, the protocol development work in SAE ITF and ISO/TC 197/WG 24.

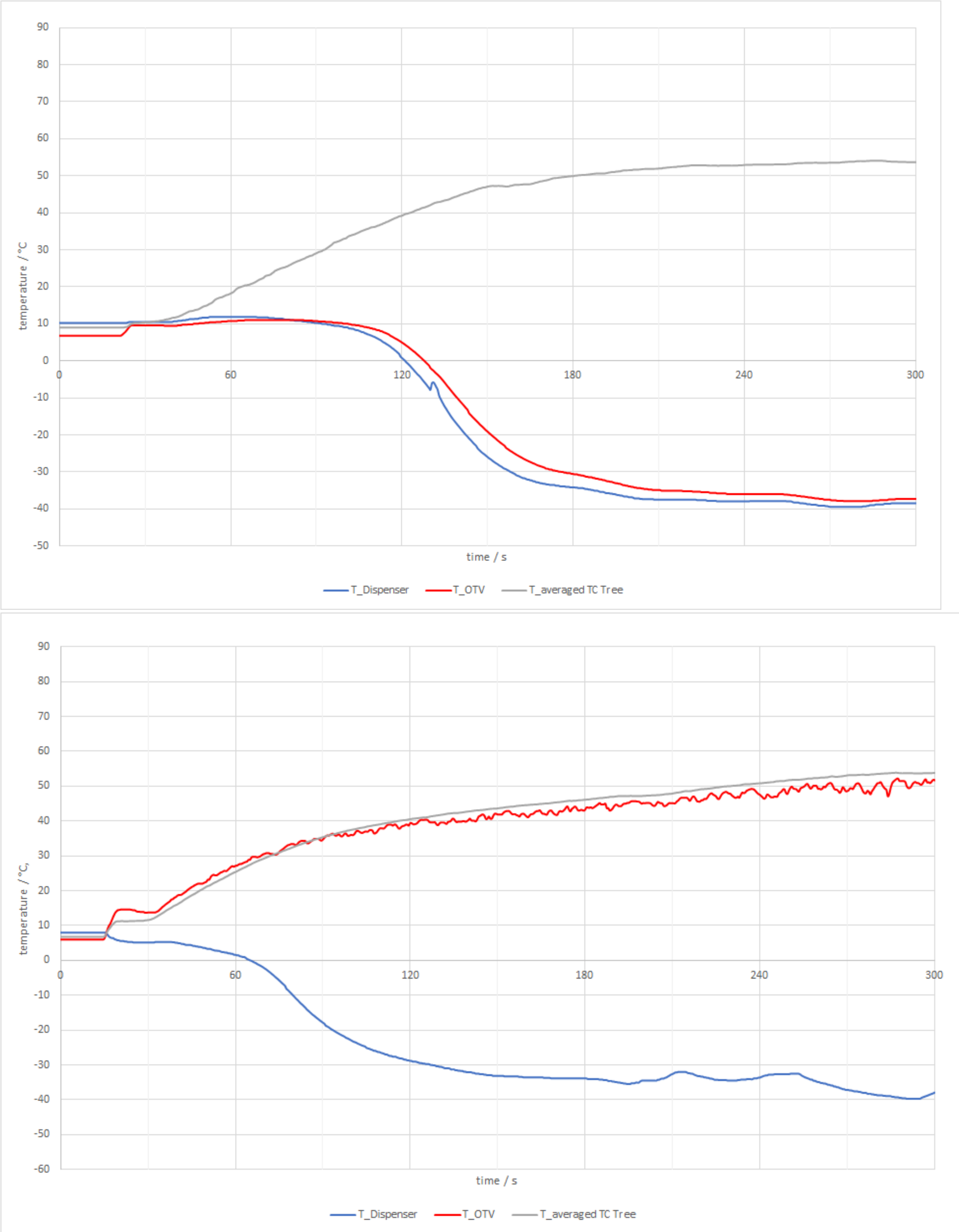

Figure 5: Figures showing the difference between temperature reading with different OTV tank combinations

APPENDIX A: REFUELLING PROTOCOL STANDARDISATION DEVELOPMENTS SINCE THE PUBLICATION OF PRHYDE DELIVERABLE D2.3

A.1 ISO/TC 197

ISO/TC 197 is the International Standards Organisation (ISO) Technical Committee (TC) which develops in the field of systems and devices for the production, storage, transport, measurement and use of hydrogen.[3] Amongst the standards developed is the ISO 19880-1 "Gaseous hydrogen — Fuelling stations — Part 1: General requirements", published in 2020, which includes top level requirements for fuelling protocols for filling hydrogen gaseous vehicles.

ISO/TC 197 Working Group (WG) 24 is, at the time of writing, developing a new series of standards under the number ISO 19885 "Gaseous hydrogen – Fuelling protocols for hydrogen-fuelled vehicles". These standards will provide significantly more detail about the requirements for gaseous hydrogen vehicle fuelling protocols than those in ISO 19880-1, in areas such as fuelling protocol verification and validation, communications protocols (for the transfer of information about the vehicle to the fuelling point, and vice versa, and finally, for the fuelling of heavy duty vehicles. For the latter, it is expected that the work progressed within the PRHYDE project will be a key input into the development of this standard, and members of the PRHYDE consortium will transfer all the necessary information (as far as any intellectual property allows) into WG24.

A.2 SAE FCEV Interface Task Force (ITF)

The SAE FCEV ITF is the standards development committee that prepared the suite of standards which are used for the majority of vehicle fuelling around the world – particularly SAE J2601: "Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles", along with starting work on SAE J2601/5 which "establishes prescriptive general-purpose high-flow fuelling protocols and process limits for hydrogen fuelling of vehicles with compressed hydrogen storage system (CHSS) volume capacities between 750 and 2500 liters".

Further detail can be found in PRYDE Deliverable D2.3. SAE J2601 is the publication including the MC Formula on which the PRHYDE work for heavy duty vehicle fuelling is based.

[3] For further details see: https://www.iso.org/committee/54560.html

A.3 Clean Energy Partnership (CEP)

It should also be noted that, since the publication of Deliverable 2.3, the CEP has developed a fuelling protocol similar to that of the existing table based SAE J2601 fuelling protocol.[4]

Similarly to SAE J2601: 2019 with the CHSS category D tables, this protocol has been developed for the interim until advanced communications between the vehicle and fuelling point become available that would enable a more effective protocol to be deployed.

4 Clean Energy Partnership (CEP): Technical Report: Minimum Ambient Precooling (MAP) Hydrogen Refueling Protocol for 35MPa Heavy Duty Vehicles (20-42.5 kg), version 1.4, 9.11.2022. https://cleanenergypartnership.de/wp-content/uploads/2022/11/2022-11-09_MGR_MAP-Fueling-Protocol-for-35-MPa-Heavy-Duty-Vehicles-20-42.5kg_Wenger-Engineering_Rev1.41-min.pdf

What is PRHYDE?

With funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (FCH 2 JU, now CHJU) under Grant Agreement No 874997, the PRHYDE project aimed 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 concepts were 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 was captured via an intense stakeholder participation process throughout the project.

The work enables the widespread deployment of hydrogen for heavy duty applications in road, train, and maritime transport. The results are 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 on the project website (https://prhyde.eu). For feedback on the PRHYDE project or the published deliverables, please contact info@prhyde.eu.

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Members of the PRHYDE Consortium:

Further linked third partner to the project are MAN and Toyota North America.

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