White Paper Requirements Specification

Subcooled Liquid Hydrogen Fuelling Process for Ground Vehicles

Status: Novmber 2021

Release 1.8

Document Change Management/ open items

This document has undergone 7 revision levels before this release Version “1.8”.

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1. Content

2. List of Abbreviations

CEP	Clean Energy Partnership Germany
ECU	Electronic Control Unit
FS	Fuelling Station (as Prefix/Suffix: Component belongs to fuelling station)
H2	Hydrogen gas
MAWP	Maximum Allowable Working Pressure (125 % NWP)
NIST	National Institute of Standards and Technology
NWP	Nominal Working Pressure
OEM	Original Equipment Manufacturers of vehicles
PRV	Pressure Relief Valve (mechanical valve in fuelling station for overpressure protection)
SAE	Society of Automotive Engineers
sLH2	Subcooled Liquid Hydrogen
SoC	State of Charge (in %). Ratio of actual to target hydrogen density
Tbc	To be confirmed
Tbd	To be determined
TCU	Tank Control Unit (of vehicle)

3. Referenced Documents 14687 14687

3.1 CEP Documents

This document shall be used in conjunction with the following document:

* White Paper Subcooled Liquid Hydrogen Fuelling Interface (September 21, Release 1.9)

3.2 ISO Documents

* ISO 19880-1: 2020 – Gaseous hydrogen – Fuelling Stations – Part 1: General requirements

* ISO 19880-8: 2019 – Gaseous hydrogen – Fuelling Stations – Part 8: Fuel Quality Control

* ISO 14687: 2019 – Hydrogen Fuel Quality: Product Specification

* ISO 17268: 2020 – Gaseous hydrogen land vehicle refuelling connection devices

3.3 CEN Documents

* EN 17124: 2018 – Hydrogen fuel – Product specification and quality assurance – Proton exchange membrane (PEM) fuel cell applications for road vehicles

* EN 17127: 2018 – Outdoor hydrogen refuelling points dispensing gaseous hydrogen and incorporating filling protocols

3.4 UNECE Documents

* GTR 13: Global technical regulation on hydrogen and fuel cell vehicles

* R 134: Uniform provision concerning the approval of motor vehicles and their components with regard to the safety-related performance of hydrogen-fuelled vehicles (HFCV)

3.5 SAE Documents

* SAE J2579 Standard for Fuel Systems in Fuel Cell and Other Hydrogen Vehicles

* SAE J2578 Recommended Practice for General Fuel Cell Vehicle Safety

* SAE J2574 Fuel Cell Vehicle Terminology

* SAE J2719 Hydrogen Quality Standard for Fuel Cell Vehicles

* SAE J2799 Hydrogen Surface Vehicle to Station Communications Hardware and Software

* SAE J2760 Pressure Terminology Used in Fuel Cells and Other Hydrogen Vehicle Applications

3.6 IEC Documents

* IEC 61508 Functional safety of electrical/electronic/programmable electronic safety-related systems

* IEC 61511 Functional safety – Safety instrumented systems for the process industry sector

* IEC 62061 Safety of machinery - Functional safety of safety related electrical, electronic and programmable electronic control systems.

3. Terminology

* sLH2 tank: Storage tank for sLH2 in the vehicle. Designed according to implementing act 2021/535. (Note: implementing act 2021/535 may be superseded in the future by UN ECE regulation.)

* sLH2 Storage System: Storage tank for sLH2 in the vehicle including primary closure devices, and other components, designed according to implementing act 2021/535. (Note: implementing act 2021/535 may be superseded in the future by UN ECE regulation.)

* sLH2 Fuel System: Complete sLH2 tank system in the vehicle consisting of one or more sLH2 tank(s), receptacle, inlet and outlet valves, interconnecting lines, control system, boil-off gas management and safety devices. Designed according to implementing act 2021/535. (Note: implementing act 2021/535 may be superseded in the future by UN ECE regulation.)

* Target Pressure (PTARGET): The station pressure at which the hydrogen fuelling protocol targets for the end of fuelling or dispenser fuel pressure that the hydrogen fuelling protocol targets for the end of fuelling Pressure at which the ECU of the FS stops the fuelling. The fuelling pressure in the dispenser behind the fuelling valve (Rem.: latest point where we can measure).

* Fuelling Protocol: Industry specification of minimum critical characteristics and performance requirements of the fuelling process that is achieved by all fuelling stations and is accounted for in the design of all vehicle storage systems.

* Fuelling Process: Procedure to implement vehicle fuelling according to parameters established under the industry-wide fuelling protocol to which vehicles are designed for receiving fuel. The FS fuelling process includes design, hardware, and procedures for the control and operation of hardware, at a FS to dispense fuel in accordance with the common industry fuelling protocol.

* Valve(s): Electronically controlled shut-off valve(s) in the vehicle's fuel storage system capable of opening and completely shutting off the flow out of the storage cylinder(s).

* Check-valve(s): Valves that limit the gas flow through them to one direction. Check Valves are typically spring-loaded to open when the pressure difference between the input and the output of the valve creates enough force to overcome the spring force.

* FS valve(s): Main flow controlling valve(s) within the FS. Operated and electronically controlled by the ECU of the FS. The valve enables and disables the hydrogen flow from the FS to the vehicle. The valve is intended to control the flow rate by automatic adjustment of the valve position to allow a continuous pressure increase rate independently of the volume of the vehicle's sLH2 fuel system.

* FS PRV: Pressure relief valve within the FS that opens and re-closes to prevent the outlet pressure of the dispenser from exceeding the MAWP of the vehicle sLH2 storage system.

* Pressure unit: All the pressure data are given in absolute values.

* Fuelling: Transfer of hydrogen fuel from the fuelling station to the fuel storage system of a vehicle.

* Operator: Person or persons owning, maintaining, and ensuring the proper functionality of the fuelling station.

* Ambient temperature: The environmental temperature in the vicinity of the dispenser.

* Tolerance: The allowable deviation from a standard; especially the range of variation permitted in maintaining a specified measurement or performance accuracy.

* Demonstration phase: The pre-commercial period during which vehicles and fuelling stations demonstrate capability to meet performance requirements reliably and cost efficiently. During this time, standards developing organizations are expected to finalize the first set of standards. This period is expected to be 2022 - 2024.

5. Introduction

Increasing environmental pollution, the limited amount of fossil fuels and the reduction in the emission of climate affecting gases lead to a great effort in finding an alternative to traditional combustion engines in trucks fueled with diesel. Therefore, manufacturers all over the world develop alternative engine concepts, which do not use fossil fuels.

One of the most promising concepts based on hydrogen is fuel cells combined with an electric engine. Fuel cells are miniature electrochemical power plants that release energy from the chemical reaction between hydrogen and oxygen. Offering a high efficiency factor and producing mainly pure water vapor.

There are various technical options for storing hydrogen on board of a vehicle and feeding it into the propulsion system. This project is based on the option of liquid hydrogen storage at temperatures as low as minus 253°C, calling for technical challenges.

Having the vehicle storage system, connected to the propulsion unit, on one hand and the fuelling unit on the other, a component joining both units for hydrogen transfer is required. Therefore, the goal of this project is the development of a liquid hydrogen fuelling interface applied in trucks. This coupling component shall be easily reproducible in a series production process.

The initiators of this project are truck manufacturers, which carry out research and development (R&D) around liquid hydrogen applications as energy source for automotive propulsion units. Fuelling possibilities of trucks with liquid hydrogen are analyzed within this focus as well. The partners aim to develop a standardized fuel system with regard of an essentially uniform infrastructure for liquid hydrogen fuelling. The components of this fuel system shall be easily reproducible in a series production process.

Furthermore, the system shall be suitable for international standardization since it is intended to propose a successful result of standardization for recommended industrial practice.

LH2 fuelling from station into the truck is well known from former projects, but has some disadvantages as e.g., gas return from tank to the fuelling station and fuelling stops only based on the signal from the truck. Therefore, in this project, sLH2 (subcooled liquified hydrogen) fuelling is proposed to avoid gas return from vehicle tank and definite fuelling stop without data communication by stopping the fuelling process when a certain fuelling pressure is reached. sLH2 fuelling is a process in which the liquefied hydrogen is subcooled and can be filled in this state to a pressure exceeding the critical pressure of hydrogen at approx. 1.3 MPa. Once this threshold is exceeded the hydrogen is in a single-phase state with no liquid-to-gas interface.

6. Project Scope and Organization

6.1 Scope

This document defines common requirements between vehicle manufacturers (OEMs) for fuelling of sLH2 vehicle storage systems as guidance during the demonstration phase. The purpose of this document is to share safety requirements and performance expectations of vehicle manufacturers to aid station providers in designing FS in the period before a complete set of standards are adopted. The first aim is thus to ensure that vehicles can be designed to be fuelled at common FS. The second aim is to indicate performance targets for fuelling seen by drivers as competitive with conventional fuelling. The third aim is to guide future station performance. Most of the features identified herein are achievable today. Capacity and reliability targets are set forth to support expected growth in numbers of vehicles in cluster regions over the 2023 - 2025 period.

This document also describes generic elements of an sLH2 fuelling protocol. The specific elements of the protocol are targeted to be completed in 2023. Station designers will develop hardware, control and operating systems and procedures to achieve fuelling within the parameters of the fuelling protocol under which vehicles will have been designed to accept fuel. FS providers, component manufacturers and other OEMs are invited to participate in the development of a common fuelling protocol.

The contents of this document will be made available to Standards Development Organizations such as ISO, SAE, and CSA for consideration, as appropriate, in the development of FS, vehicle and dispenser standards, respectively.

This document will serve as interim guidance. It applies to the design, safety, operation, and verification of subcooled liquefied hydrogen fuelling stations (sLH2 FS) that fuel vehicles with sLH2 storage systems with a set pressure of PRV1 (PPRV1) of 2.2 MPa (see diagram Figure 3-1). Target pressure (PTARGET) of the fuelling is 1.6 MPa.

This document is focused on FS for heavy duty ground vehicles with nominal capacity of the fuel storage between 40 kg and 120 kg sLH2. However, these requirements might also be applied to fuelling of other vehicles – such as buses or distribution trucks – with lower fuel capacities. The sLH2 storage system may consist of several sLH2 tanks connected.

This document is intended to be submitted to the Clean Energy Partnership (CEP) Working Group. It assumes the fuelling interface hardware is specified in White Paper "Subcooled Liquid Hydrogen Fuelling Interface for Ground Vehicles" and that the fuel quality is being addressed through ISO 14687:2019.

The document is intended to provide minimal elements of expected commonality, not to restrict implementation of additional features in individual fuelling stations.

An experimental program is under way to evaluate the response (internal temperature & pressure) of currently representative sLH2 tanks and sLH2 storage systems to variations in initial conditions, nozzle fuel temperature and fuelling rate. It is expected that this information will be used to define an sLH2 fuelling protocol that will specify common industry-wide characteristics and limits that all fuelling processes implemented at sLH2 fuelling stations (all variations of hardware, controls, and control algorithms) shall satisfy.

It would then be the responsibility of the station operators to periodically verify that fuelling processes performed at the FS provide fuelling within the boundaries of the fuelling protocol and according to applicable standards. It would be the responsibility of the vehicle manufacturers to ensure that vehicle storage systems are designed and verified to be capable of being fuelled FS that provide fuelling in accordance with the sLH2 fuelling protocol. Verification means a documentation proving the compliance of the fuelling of the sLH2 tank systems with multiple storage sLH2 tanks that may differ in size and construction, and that may not fuel simultaneously, and that may not have the same initial temperature or pressure. Therefore, both vehicle manufacturers and FS providers have an interest in developing a clear, well-validated sLH2 fuelling protocol specification and ensuring it is sufficiently robust.

This document is expected to be revised in 2023 to include specification of a robust sLH2 fuelling protocol based on experimental findings and modelling assessments.

Key elements of this protocol will be the specification of parameters and limits on fuelling processes, and station verification testing to ensure adequate performance under extreme conditions.

6.2 Project implementation and participating parties

The participating parties aim to establish sLH2 fuelling according to this specification. In addition, the participating parties expect, that the described sLH2 fuelling will be a future main path in the fuelling technology of LH2 for heavy duty trucks. Therefore, this working group has been established, coordinated by CEP (Clean Energy Partnership Germany) with the goal to develop an international standard for sLH2 fuelling. The standardization process for the fuelling process has been started by CEP on 12th of May 2021.

6.3 Time Schedule

The White Paper process will be started on 12th of May 2021 and should be finished by the end of 2021 (refer to Figure 2-1).

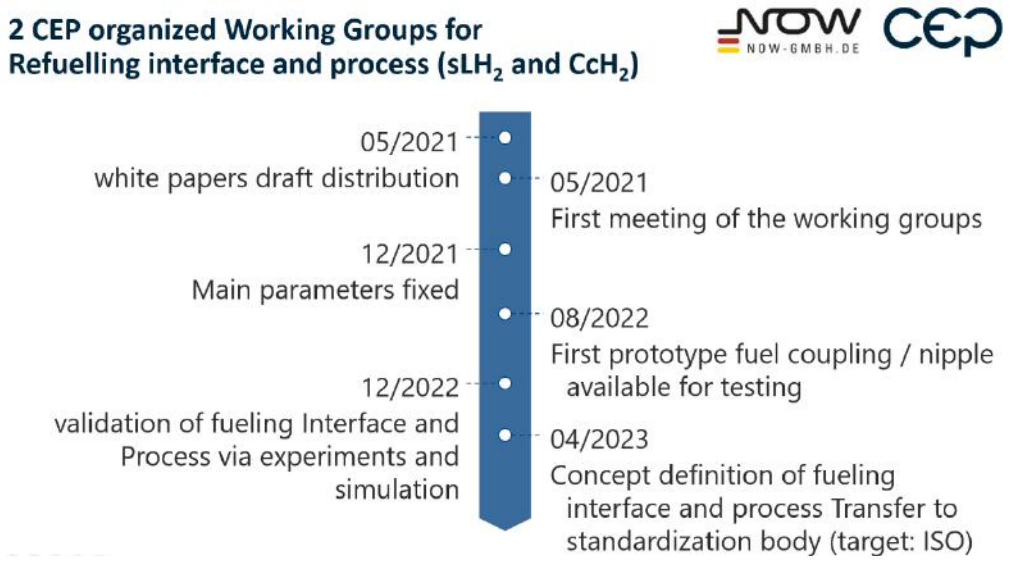

Figure 2-1: Time Schedule for the White Paper process and further Standardization

7. sLH2 Fuelling Station Specification

The following is a summary guideline of the technical specification for an sLH2 FS. The details of the fuelling process are described in Section 8 of this document.

7.1 sLH2 Fuelling Limits

- Target fuelling pressure in sLH2 Storage System (measured in the dispenser located < 0.5 m upstream of fuelling hose connection at dispenser) ………………1.6 MPa ± 0.05 MPa
- Required temperature levels, pressure levels and fuelling rates at the dispensing nozzle (the point of delivery to the sLH2 storage system) are described in section 8. During the demonstration phase, the Hydrogen temperature in the dispenser should be continuously monitored, recorded, and controlled to meet the requirements.
- Minimum sLH2SS fuelling pressure at start up……………………………………….0.2 MPa
- Maximum sLH2SS fuelling pressure at start up...1.0 MPa
- Remark: If sLH2 Tank has more than 1.0 MPa, sLH2 Tank will be depressurized automatically by FS ECU via the dispenser to 1.0 MPa. The depressurization is performed according to White Paper sLH2 Fuelling Interface for Ground Vehicles in its valid version.
- Target fuelling rate (fuelling time ~ 12 min for 80 kg sLH2 storage capacity)……….400 kg/h
- Max. fuelling rate……………………………………………………………………………………500 kg/h
- Station-side feed PRV (FPRV) activation pressure…………………………………1.8 MPa
- Station-side dispenser PRV (DPRV) activation pressure……..………………………2.5 MPa
- Vehicle-side boil off pressure releave (Overflow)……………………………………2.0 MPa
- Vehicle-side primary PRV activation pressure (PPRV1)…………………………………2.2 MPa
- Vehicle-side secondary PRV activation pressure (PPRV2)…………………..…………..2.5 MPa
- Remark: The vehicle side PRV should be capable of venting 400 kg/h sLH2 continuously without damage to the sLH2 fuel system.
- Vehicle-side maximum total pressure drop from receptacle to onboard vehicle storage of less than approx. 0.07 MPa, under the following conditions: sLH2 fuelling rate of 400 kg/h at 26.5 K, i. e. one-phase subcooled liquid hydrogen flow.
- Criteria for fuelling stop and full fuelling (measured in the dispenser located < 0.5 m upstream of fuelling hose connection at dispenser): …………………..1.6 MPa ± 0.05 MPa (this corresponds to a maximum SoC of 100 % (under ideal conditions the sLH2 density in the sLH2 container can be 62 g/L))
- Ambient temperature range of FS to which these requirements apply:
- Minimum ambient temperature: - 40 °C
- Maximum ambient temperature: + 50 °C
- Fuelling outside of the specified temperature range is dependent on OEM/FS operator requirements and should be treated on a case-by-case basis.

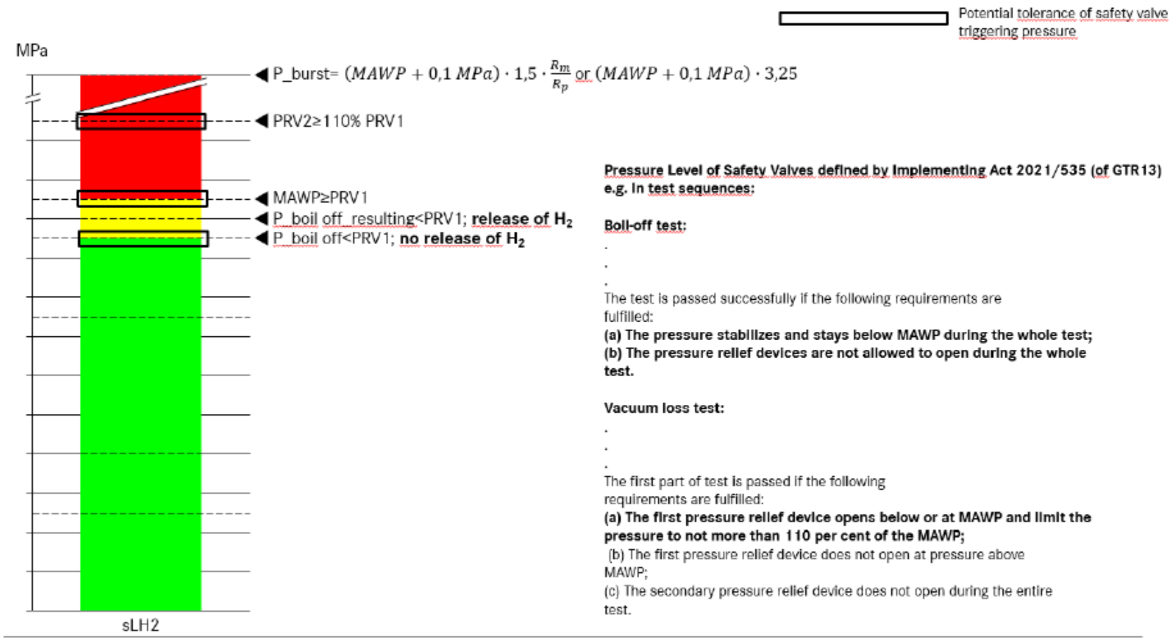

Figure 3-1.: Description of pressure levels in Implementing Act 2021/535

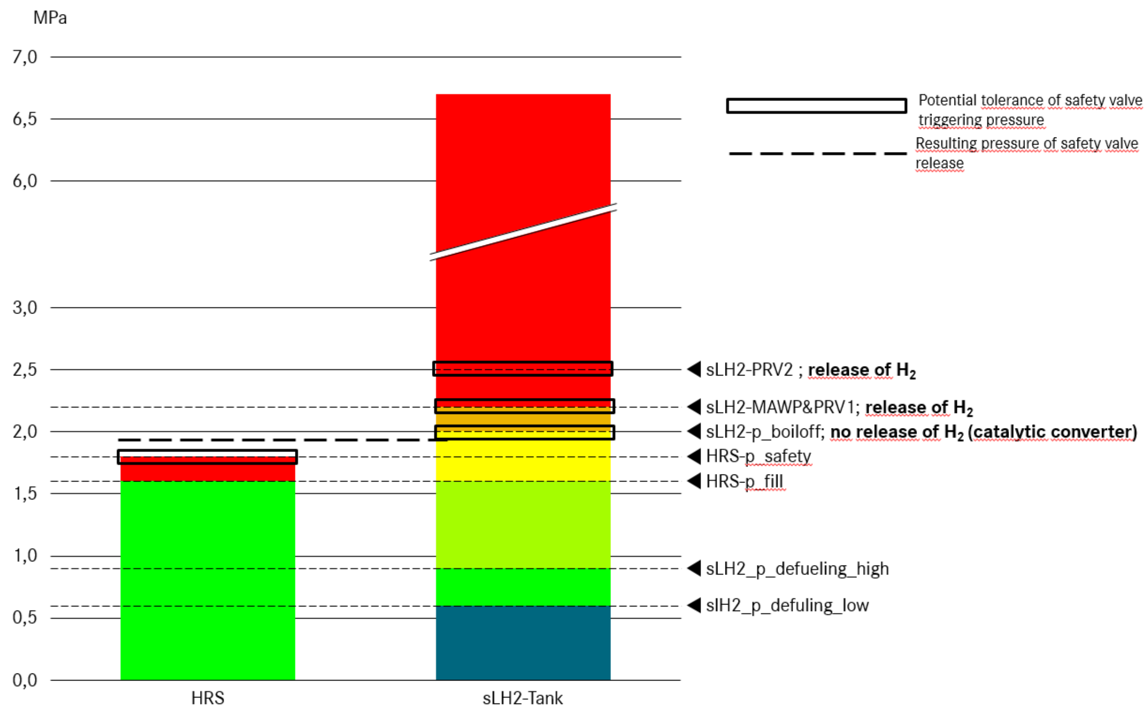

Figure 3-2: Pressure levels at HRS and impact on pressure levels at sLH2 Tank

7.2 sLH2 Dispenser Fuelling Capability

- Typical sLH2 storage system capacity:
- Commercial vehicles: 40 - 120 kg sLH2.
- The target fuelling time for transferring 80 kg sLH2 (= total fuelling time from push of start button until the nozzle is ready for decoupling)…………………………………………< 15 min
- Average pressure drop downstream of last pressure sensor (downstream of main filling valve) to outlet of nozzle at flow of 400 kg/h...0.03 MPa

- FS should have data record capability to confirm that from the station side the pressure and fuelling rate requirement are met (pressures and temperatures at different locations within the FS and flow rate to dispenser).
- Pressure fuelling target………………………..…………………………1.6 MPa ± 0.05 MPa
- (this corresponds to a Maximum SoC 100 % (65 g/L))
- Communication between station and vehicle: the fuelling process does not need any data communication between station and vehicle.
- A typical FS with one dispenser should have at least the capability to fuel four 80 kg sLH2 storage systems within a time span of 60 minutes and 40 vehicles per day. Daily capacity may be larger based on-site specific operation hours.

7.3 Hydrogen Quality

LH2 quality guidance is given by the ISO 14687:2019 and EN 17124.

Regarding filtering particulates in the sLH2 mass flow a wire mesh filter (10 µm mesh size or smaller) shall be installed upstream of the fuelling nozzle.

The FS shall include a means of minimizing foreign gases or liquids, to the H2 stream and stay within ISO 14687:2019 specification for PEMFC vehicles.

FS owner / provider shall demonstrate that the H2 composition is reliably controlled to the requirements of ISO 14687:2019 and ISO 19880-8, when applicable to LH2. Statistical capability should also be demonstrated.

7.4 Dispenser / Fuelling nozzle / Leakage

Fuelling nozzle, basic dispenser requirements and regulations are defined in the White Paper Subcooled Liquid Hydrogen Fuelling Interface for Ground Vehicles. Refer also to chapter 7.2 and figure 9-1 of this document.

The main basic dispenser requirements are:

- Calibratable flow measurement system
- Holder to position sLH2 interface nozzle, when not in use
- Shall be capable of controlling and performing sLH2 interface functions, e.g. pressure swing purging etc.
- Crashsensor or equivalent measures for crash detection or crash protection
- Main fuelling valve (for disruption of sLH2 flow from dispensers towards vehicle) and controlled discharge valve (for depressurization of sLH2 fuel systems with high pressures and cool down procedure for warm sLH2 fuel systems)
- Capable of depressurizing an sLH2 tank which has a high starting pressure (1.0-2.0 MPa) to < 1.0 MPa at the beginning of the fuelling (procedure tbd, input from experimental program required)
- Capable of performing a special cool down procedure for warm sLH2 tanks (procedure tbd, input from experimental program needed)

7.5 Electrostatic Discharge

Electrical requirements including requirements on the electrostatic discharge are specified in the White Paper Subcooled Liquid Hydrogen Fuelling Interface for Ground Vehicles.

7.6 Material Compatibility

All materials used in a hydrogen fuelling station that are in direct contact with hydrogen should be hydrogen compatible according to applicable standards.

7.7 Station Failure Protocol

Fuelling station should meet applicable codes, standards and regulations that govern hydrogen fuelling stations.

Alarms and critical failures detected by the ECU should be incorporated into a notification system of the station owner/operator.

An emergency switch should be easily accessible in the case of failure. Its integration shall comply to local regulations.

The station owner / provider should provide a 24-hour, 7-day per week toll-free number for servicing the station or have a contract person on-site to assist with station recovery.

Station recovery to normal operation should be completed as soon as possible. Fuelling station provider / owner should have a plan for backup fuelling of vehicles in the event the station is out of service for more than 24 continuous hours.

Minimum target station availability is 95 %.

Via the sLH2 nozzle exclusively sLH2 vehicles with the corresponding sLH2 receptacle (according the White Paper sLH2 Fuelling Interface for Ground Vehicles) shall be fuelled.

7.8 Remote Monitoring

The station should incorporate remote monitoring to:

- Alert station operator/entity in charge of maintenance of system failures.
- Optional: alert station operator/entity in charge of maintenance of the need to service critical process equipment.
- Provide capability to remotely collect fuelling and related data.
- Capability for real-time reporting of station operation status to owner / provider and end customer.

7.9 Other Requirements

- Park position for vehicle shall be classified with an ASIL (Automotive SIL Level to be defined). This requirement should be transferred to a future entire vehicle homologation on a mid to long term time perspective.
- No special clothing or other personal protective equipment should be required during fuelling.
- FS operator/entity in charge of maintenance should develop an Emergency Response Procedure for operators and users of the station.

- FS operator/entity in charge of maintenance should be responsible for training operators and users of the station.
- FS operator/entity in charge of maintenance should provide an overall fire protection concept.
- FS should have a means of detecting and alerting operators of major station leaks where required.
- FS operator/entity in charge of maintenance is responsible for compliance with all applicable ordinances, regulations and laws, and for acquiring and maintaining all required permits for construction and operation. This will include meeting requirements for periodic inspection and maintenance.
- FS location and dispenser access should be convenient to the customer.
- FS should be well lit, clean, and clearly labelled.
- FS hours of operation should be agreed upon between station operator / customer.
- FS should provide fuelling convenient to customer or by attendant.
- FS should post or otherwise provide convenient reminder of fuelling process steps.

8. Fuelling Process

FS that expect to fuel vehicles with sLH2 storage systems should be capable of the performance described herein in order to fulfil the vehicle manufacture’s requirements for safe operation and customer expectations.

The fuelling procedure is subdivided into the three steps

- pre-fuelling,
- main fuelling, and
- post-fuelling,

which are described in more detail hereafter.

Apart from the standard fuelling procedure other special procedures must be defined to account for e. g., first fuelling after vehicle assembly, cool down of a warm tank, fuelling and defueling during service, and mobile refuelling. These special procedures will be established later, once first experiments are accomplished.

8.1 Pre-fuelling steps

As shown in figure 8-1 pre-fuelling starts with accessing the FS and preparing the vehicle for fuelling. For this purpose, the user stops the driving systems and indicates his intent to fuel the vehicle by e.g., opening the flapper door. Afterwards the user removes the nozzle from its parking position within the FS dispenser and connects it to the receptacle of the vehicle. A switch located in the dispenser signalizes the removal of the nozzle and thus the intend to fuel a vehicle. Once a correct connection between nozzle and receptacle is established (signalized by a sensor on the vehicle side) the user presses the start fuelling button on the dispenser. The FS activates the automatic fixation between nozzle and receptacle to block the connection. This ensures that an unlocking of the connection is not possible during the following steps. Afterwards purging and leakage testing is performed.

Before starting the fuelling, the pressure of the sLH2 storage system is determined. Fuelling can start if the pressure of the sLH2 storage system is in the range of 0.4 MPa to 1 MPa. For pressures greater than 1 MPa the FS must depressurize the sLH2 storage system. This ensures that the pressure and temperature level requirements stated in chapter 8.4 and 8.5 are meet throughout the entire fuelling process. To avoid a contamination of the sLH2 by returning gas to the sLH2 storage system of the FS, vent gas is discharged via the FS vent stack – refer to figure 9-1. Procedures for handling sLH2 storage systems with pressures below 0.4 MPa are not yet defined and will be established later.

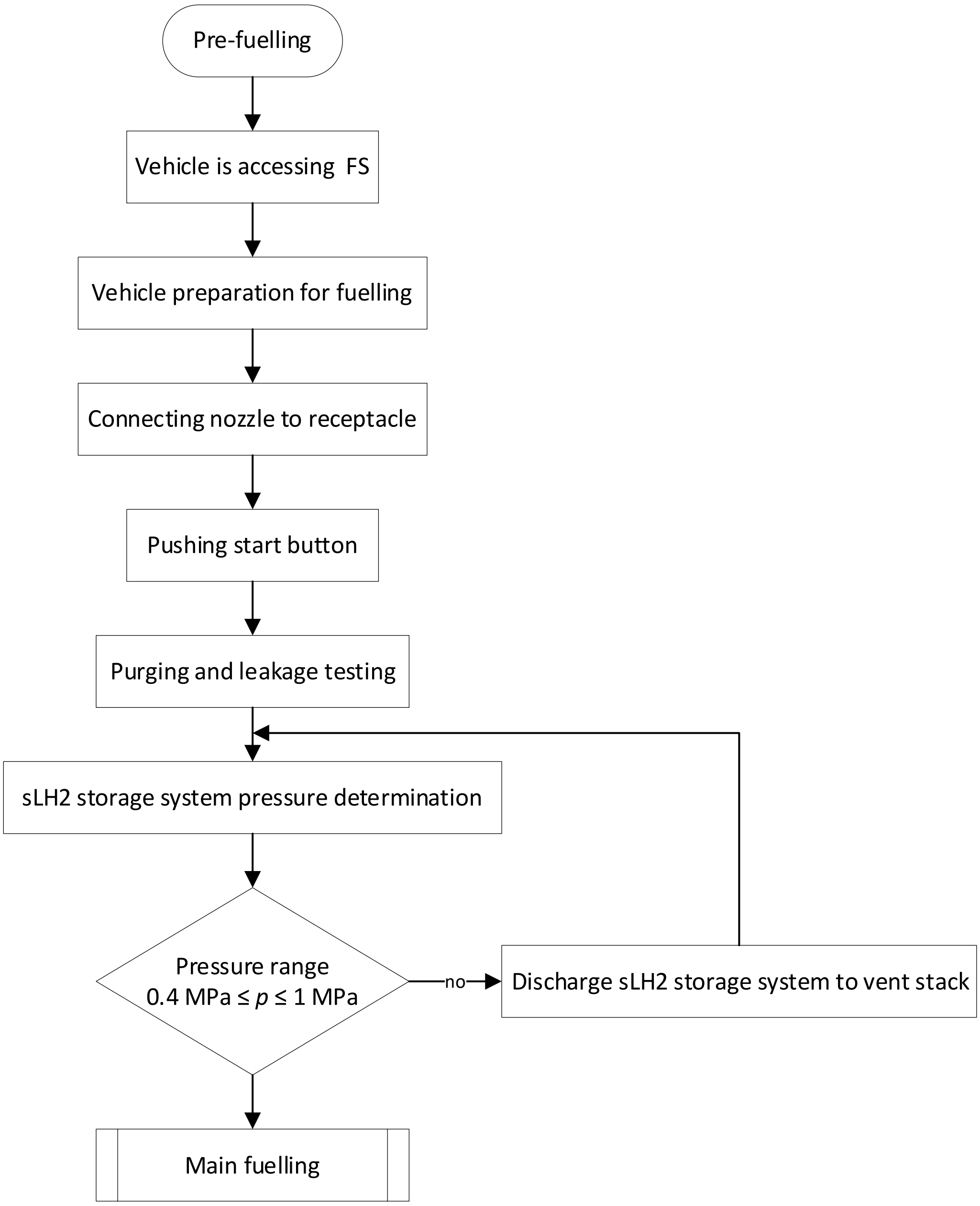

Figure 8-1: Pre-fuelling steps

8.2 Main fuelling steps

Once all pre-fuelling steps are accomplished fuelling is initiated. Main fuelling is subdivided into three steps as shown in figure 8.2. Figure 8.3 shows exemplary flow, pressure, and temperature profiles for all main fuelling steps. Additionally, associated limits given in chapter 8.4 through 8.6 are highlighted. Those must be maintained throughout the entire fuelling process.

During the first main fuelling step, the so-called start fuelling step, the sLH2 fuelling rate is ramped up and maintained at 10 % to 20 % of the max. fuelling rate. This corresponds to 50 kg/h to 100 kg/h. The low fuelling rate is maintained until the entire piping and the sLH2 storage system are cooled down – refer to figure 8.3. For evaluation purposes, the pressure of the sLH2 storage system is used as the evaluation parameter.

After cooling down the fuelling rate is ramped up to 400 kg/h. Upon reaching the average fuelling rate, the main fuelling step 2 starts (steady state fuelling step). During this step the sLH2 storage system pressure changes slowly. Here, the temperature of the sLH2 coming from the FS determines whether the pressure rises or falls slightly. Once the sLH2 storage system is approaching the target fill level the pressure starts to rise at a higher rate (slope change in figure 8.3).

To avoid reaching a fuelling end pressure higher than the target pressure (PTARGET) the fuelling rate is reduced to 10 % to 20 % of the max. fuelling rate as soon as the pressure reaches PTARGET – 0.2 MPa. The fuelling rate reduction introduces the main fuelling step 3 (end of fuelling step). The fuelling continues until the sLH2 storage system is filled. This state correlates with a target pressure of 1.6 MPa (PTARGET). Once PTARGET is reached the fuelling stops. In addition, there is also the option of stopping fuelling prematurely by pressing a stop button located at the dispenser of the FS.

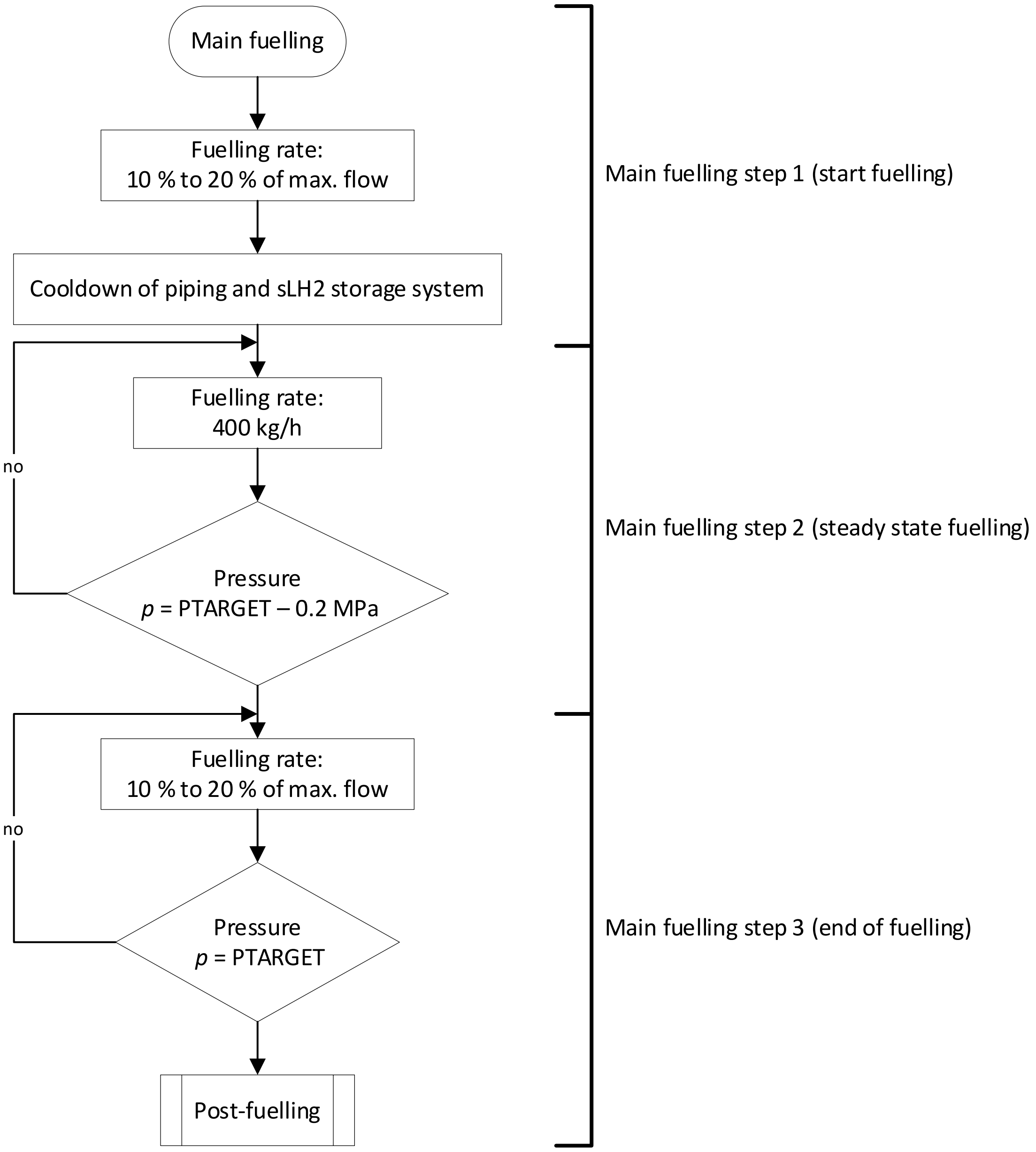

Figure 8-2: Main fuelling steps

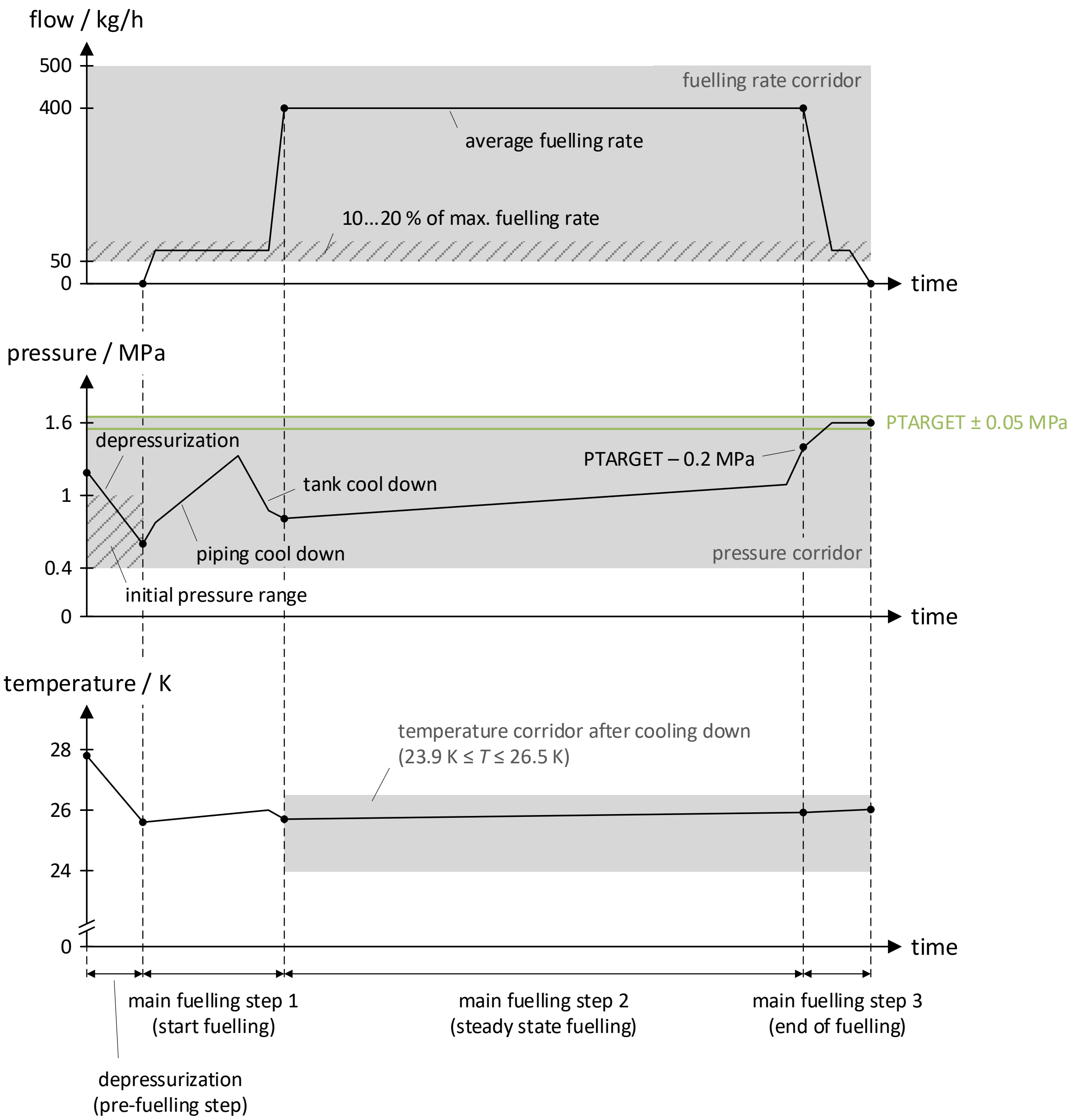

Figure 8-3: Exemplarily flow, pressure, and temperature profiles

8.3 Post-fuelling steps

The last steps of the standard fuelling procedure start again with purging and leakage testing – refer to figure 8.4. The FS then releases the nozzle blocking mechanism and indicates to the user via a display message that fuelling is complete. With the appearance of this message, the user can disconnect the nozzle, remove it, and place it in the parking position at the dispenser. The switch in the dispenser signalizes a correct nozzle parking. After closing the flapper door, the driving systems can be started, and the user can drive the vehicle away.

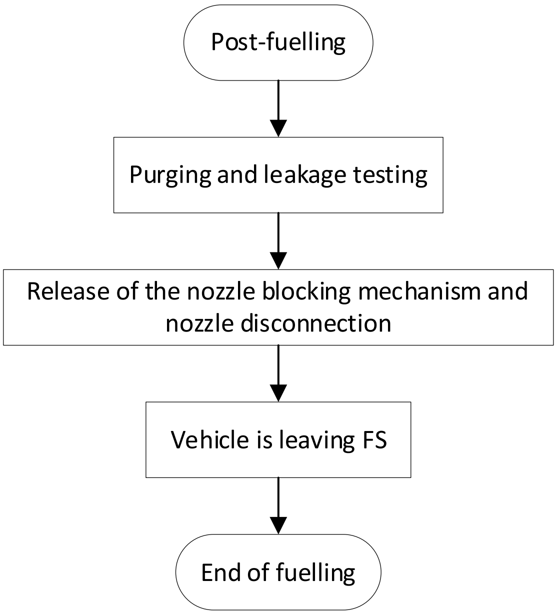

Figure 8-4: Post-fuelling steps

8.4 Pressure levels

The fuelling station should be capable of fuelling sLH2 fuel systems to 100 % of targeted pressure in a reproducible manner without exceeding the limits described in Section 7.1.

Pressure corridor limits for each fuelling stage shall be within 0.4 MPa to 1.6 MPa. These limits might be adjusted according to results of the experimental program.

8.5 Temperature levels

Temperature corridor limits for fuelling stages after cooling down of piping and hoses shall be within 23.9 K and 26.5 K (e. g. for filling a cold sLH2 tank starting at 0.6 MPa and 28.1 K). Allowable cool down time and corridor limits will be adapted according to results of the experimental program.

8.6 Fuelling rates

The FS should ensure that the fuelling rate does not exceed the maximum allowable flow rate.

The FS should control the fuelling rate to provide the targeted average fuelling rate.

A reduced fuelling rate may be acceptable for fuelling outside of the specified ambient temperature range.

Fuelling rate corridor limits for each fuelling shall be within 50 kg/h (e. g. for start of fill and end of fill) to 500 kg/h (max. flow rate) and will be adapted according to results of the experimental program. Target fuel time shall be reached.

8.7 Termination of Fuelling and Fault Management

The fuelling station should protect the sLH2 storage system from pressurization over MAWP by following an industry standard safety evaluation method (e. g. HAZOP or equivalent).

For information:

A typical example for using multiple protection levels against pressurization over MAWP might consist of:

1st Level (normal control process):

Termination of the fuelling process when the pressure in the fuel system reaches the target pressure (PTARGET). The fuelling rate should be reduced to 10 % to 20 % of max. fuelling rate when the pressure in the sLH2 storage system reaches PTARGET minus 2 bar.

2nd Level (redundant electronic protection level):

Termination of the fuelling process when the pressure at the dispenser reaches 1.65 MPa. A dedicated, highly reliable, and calibrated station-side pressure sensor and processing of its signal should be used. A separated safety loop will be necessary

3rd Level (final, fully mechanical protection level):

Prevention of any further pressure increase in the sLH2 storage system by activation of a station-side (FS) PRV set pressure at 1.8 MPa. At set pressure, the fuelling stations should release the fuelling line pressure via a vent line.

Remark: A fully opened FS PRV at set pressure can have up to 10 % (= 0.18 MPa) additional pressure and might start to open at 10 % below the set pressure.

9. Hardware

9. 1 Vehicle Fuel System Hardware

The vehicle fuel system hardware is described in the White Paper Subcooled Liquid Hydrogen Fuelling Interface for Ground Vehicles. Specific OEM systems are likely to differ in several respects such as the number of sLH2 tanks, number of internal components (i.e., valves and sensors), and placement/design of internal components. Some fuel systems may include a stop-fuelling-valve in the fuelling line that allows for an active mechanical interruption of the fuelling process by the vehicle.

Each sLH2 storage system will be equipped with a fuelling receptacle. When designing the sLH2 storage system the sLH2 fuelling limits incl. set pressures of overflow and safety valves for the sLH2 storage system must be considered to allow a safe and reliable fuelling.

9.2 Fuelling Station Hardware

Figure 9-1 shows a simplified generic schematic of an sLH2 FS that illustrates basic functional elements. As with OEM fuel systems, each hydrogen station will likely differ in its design and implementation. The equipment must be designed to provide fuelling according the fuelling stages specified (see chapter 8.1 to 8.3 using a variety of methods.

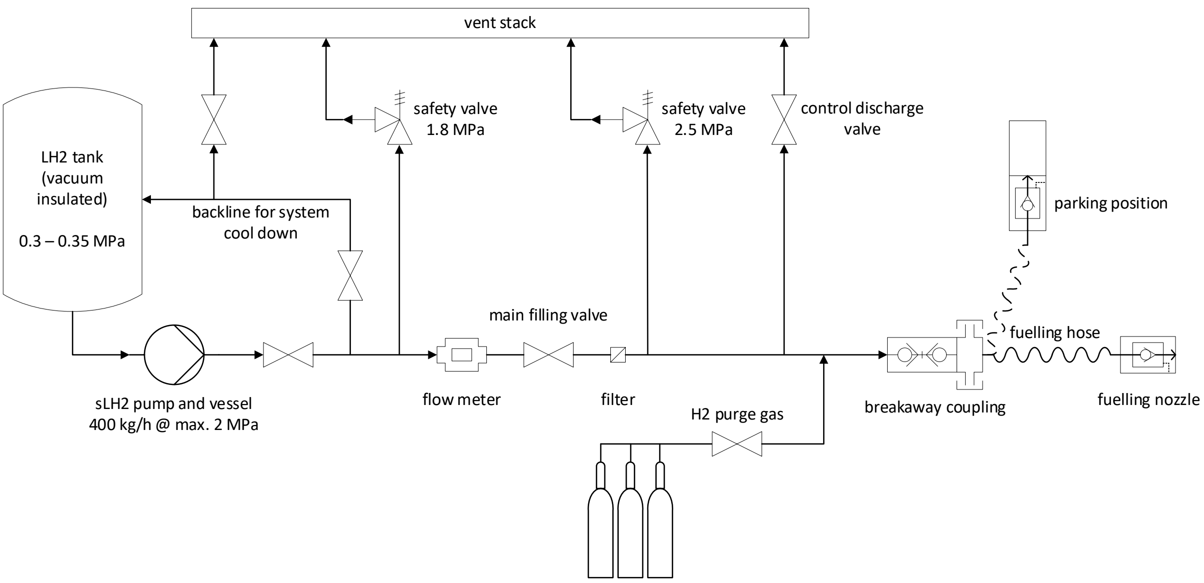

Figure 9-1: schematic example of a simplified sLH2 FS

10. Tests to Verify Compliance of Fueling Process

The capability of a fuelling station to fulfil the requirements of the sLH2 fuelling protocol should be assured to perform reliable and efficient fuelling. That capability is provided using reliable equipment operated under the control of robust fuelling algorithms that execute the fuelling process according the sLH2 fuelling protocol. This capability can be verified by performance tests described in this section. These performance tests are designed to demonstrate required performance under extreme conditions. Specifically, they are designed to prove that neither overfilling nor overheating of the vehicle sLH2 storage system will occur during fuelling, and that the fuel meets quality expectations at the point of delivery to the vehicle. Station performance verification tests will be revised subject to their evaluation as extreme fuelling conditions in fuelling experiments that are underway and are expected to be referenced in the new standard.

10.1 Test to Verify "Reaching target specification for a typical large fill"

For large sLH2 storage systems with H2 capacities ≥ 80 kg. Test requirements will be determined considering the results of the experimental program.

10.2 Test to Verify "Reaching target specification for a typical filling ()"

For small sLH2 storage systems with H2 capacities > 40 kg and <80 kg. Test requirements will be determined considering the results of the experimental program.

10.3 Test to Verify "Filling a warm sLH2 storage system"

For determining consequences of filling a warm sLH2 storage system and establishing a cool down procedure. Test requirements will be determined considering the results of the experimental program.

10.4 Test to Verify "Prevent over-pressurization of a sLH2 storage system"

Will be determined considering the results of the experimental program.

10.5 Test to Verify "Purging process and quality of fuel delivered to vehicle (at nozzle)"

Provide chemical analysis of H2 sampled at point of delivery to a vehicle (nozzle outlet) to confirm ISO 14687:2019 / EN 17124 threshold values.