WENGER
Engineering GmbH

Technical Report

Title: Minimum Ambient Precooling (MAP) Hydrogen Refueling Protocol for 35MPa Heavy Duty Vehicles (20-42.5 kg)

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Contents

1 General

1.1 Scope

This document describes a look-up table based fueling protocol approach for 35 MPa compressed hydrogen gas (CHG) heavy duty vehicles with a hydrogen tank system size of 20 to 42.5 kg, e.g. busses and trucks.

The protocol should be used for vehicles and stations accomplishing the following criterias:

- Buses, trucks and vehicles with a 350bar receptacle designed for up to 120 g/s according to SAE J2600 [1]
- Type III and Type IV tanks
- Tank system sizes from 20 to 42.5kg H2 (single tank size from 4 to 8.5kg H2)
- Non-Comm and Comm (using IrDA)
- Look-up table fueling (same methodology as in SAE J2601 [2]) with ramp rates and target pressures for different precooling levels

Unless described different, all process-describing definitions (e.g. pressure corridor, termination criteria, etc.) of SAE J2601-2020 [2] apply.

1.2 Background

Before the publication of this document there was no common heavy duty fueling protocol defining ramp rates and target pressures available, which could be used by industry to establish a consistent fueling experience for their customers. SAE J2601/2 [3] describes safety limits and performance requirements for gaseous hydrogen fuel dispensers used to fuel hydrogen tank systems larger than 10 kg, but is non-prescriptive in how to achieve a full fill.

As the demand for uniform CGH_2 fuelings for heavy duty vehicles has been increasing, this project was established by H2 Mobility, the Clean Energy Partnership and Wenger Engineering („the group“) to develop such a fueling protocol. By applying established fueling methods well-known from light duty vehicle fueling protocol SAE J2601 [2] a complete fueling simulation model with all relevant parameters was available to generate fueling pressure ramp rates and target pressures.

Tank system geometry data from bus manufactures was used to derive parameter sets for a best and worst case tank system (in terms of thermodynamics). These worst case tank systems have been investigated within a parameter sensitivity study to understand the influence of each parameter for the heavy duty tank systems. With this knowledge the group defined the boundary conditions for the look-up table creation.

1.3 Glossary

Unless otherwise described terminology is concurring with [2].

Table 1 - Glossary

Term	Description
APRR	Average Pressure Ramp Rate [MPa/min]
CGH_2	Compressed Gaseous Hydrogen
CHSS	Compressed Hydrogen Storage System
Comm	Communication (Fueling) according to [2]
H35 / H70	Tank Systems with NWP at 35 / 70 MPa
HD	Heavy Duty
HPRR	Hot Pressure Ramp Rate
HRS	Hydrogen Refueling Station
LD	Light Duty
MAP	Minimum Ambient Precooling
MOP	Maximum Operating Pressure
Non-Comm	Refueling without communication according to [2]
RR	(Average Pressure) Ramp Rate
SAE	Society of Automotive Engineers
SOC	State of Charge, 100% defined at 24.0 kg/m³
Tcf	Temperature Cold Fill (= H2 fuel delivery temperature)

2 Fueling Protocol Development

2.1 Overview

For the fueling of H2 tank systems, a distinction must be made between safety-related and performance objectives.

Safety objectives:

- Vessel and tank system remain within their specified approval limits
  - Operating pressure lower than the maximum operating pressure (MOP=1.25*NWP=43.75 MPa)
  - Gas temperature in the tank lower than the maximum allowable limit of 85°C, see SAE J2601 [2] , GTR 13 [4] etc.)
- Maximum mass flow on the refueling path is less or equal than 120 g/s (the upper operating limit of the fuel line components)

Performance targets:

- Fast refueling: 10 to 15min
- Full tank after refueling: 100% SOC, i.e. 24.0 kg/m³ (maximum density in the tank defines the maximum fill level, State of Charge of 100%)

As long as the safety targets are met in all conceivable operating scenarios, refueling can be considered safe, as the tank system has been tested for operation within the operating limits in its approval process.

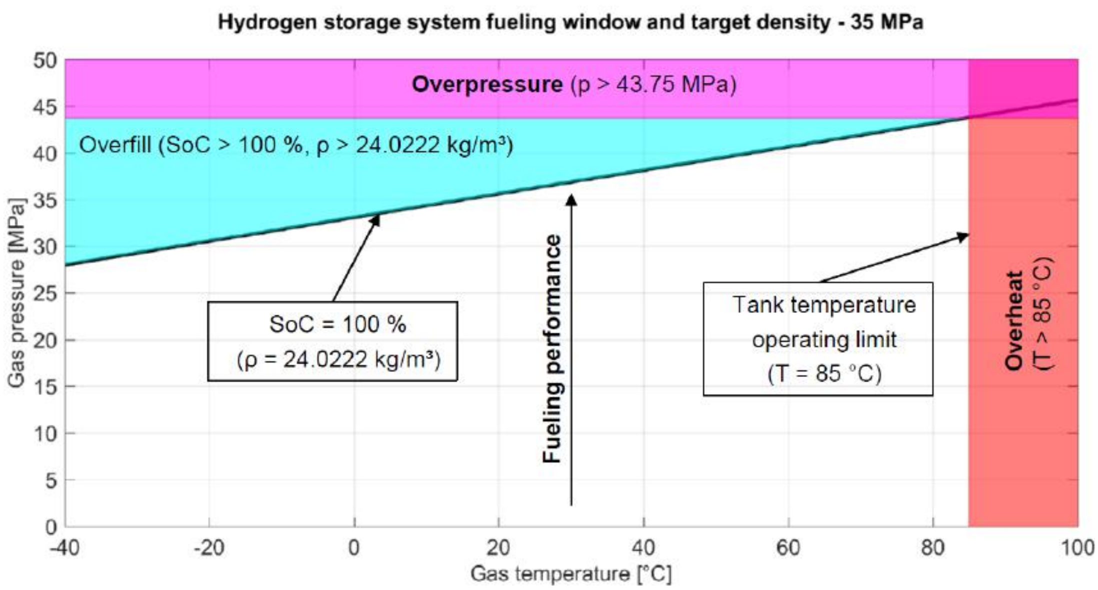

Figure 1 - Operation boundaries for 35 MPa HD tank systems

The performance goals can compete with the safety goals, e.g. at high ambient temperatures a fast refuelling in 10 min can lead to overheating in the gas (average gas temperature in vehicle vessel > 85°C). The evolution of the gas temperature depends on many parameters: the tank geometry, material data, temperature of the hydrogen supplied, etc. Due to the many parameter combinations and operating points, which cannot all be represented with a finite number of tests, it has proven useful to use a simulation model for the thermodynamic evaluation of the operating points. The simulation model represents the physics during refuelling and can - provided it has been validated with tests - be used to evaluate all operating conditions in the approved operating range.

In addition to the physical equations, the geometry (thermal mass, flow diameter, heat transfer surfaces, wall thicknesses, container configuration, etc.) of the refueling path from the HRS (last p/T measuring point) to the tank vessel inlet and the geometry of the tank vessel (wall surfaces, diameter, length, etc.) are also represented in the model.

In this way, the simulation model can be used to calculate the temporal development of the gas temperature and the pressure in the tank during refuelling.

The validated simulation model is used to determine fuelling tables that define a pressure ramp and target pressure for the fuelling station depending on ambient temperature and starting pressure.

The simulation model is of great advantage for the determination of the table values, as it allows extreme cases to be included in the creation of the table, which would be very difficult to represent in tests, or only in small numbers. By including all conceivable extreme cases, the resulting table thus becomes even more meaningful with the help of the simulation and the resulting refuelings even more reliable.

2.2 Derivation of MAP look-up tables

With the help of the generic refueling rules developed in SAE J2601 [2], a refueling protocol was developed for larger HD tank systems. This is possible because HD vehicle tank systems follow the structure of light duty vehicle tank systems and differ only in tank size and supply line dimensions. With the parameterised simulation model, however, these differences can be taken into account and the safety objectives of the protocol can also be confirmed with appropriate tests after the protocol development.

The tables were developed using the steps:

- Collection of tank system data from industry for heavy duty vehicles (20-42.5kg tank system size)
- Derivation of representative parameters from these data (cf. Table 2)
- Adoption of existing refueling simulation tool (Figure 2) described in [2] and validated in real-world tests (Figure 3, cf. [5]) by using the heavy duty tank system parameters. The rationale to use the same parameterized simulation model as for

LD vehicle is that HD tank system consist of the same components than LD tank system, e.g. composite vessels, nozzle, receptecle, breakaway coupling, piping, but with partially bigger dimensions. The difference in dimensions is covered by the parameter set adopted to HD tank systems.

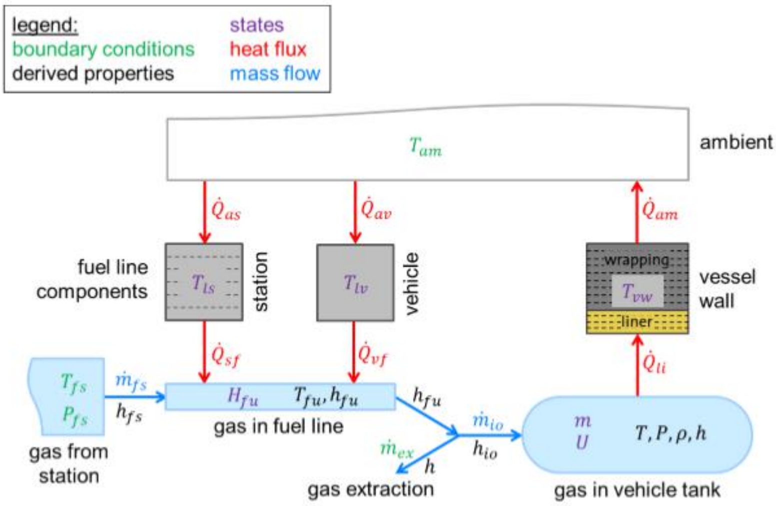

Figure 2 - Generic fueling simulation model [2]

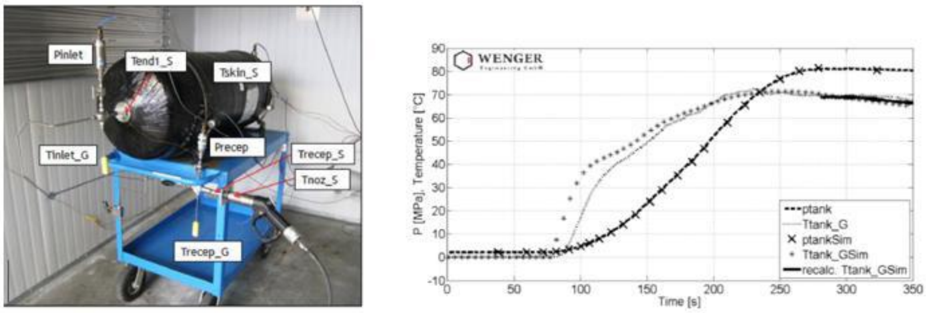

Figure 3 - Model validation [5] for protocol development for light duty vehicles in [2]

- Conduction of parameter sensitivity study to see the influence of parameters on average gas temperature in tank system vessel
- Derivation of worst case parameters for Hot and Cold Case (cf. [2]) considerations (see Table 2)
- Simulation of look-up tables using these Hot and Cold case parameter sets (cf. Figure 8 and Figure 9) to make sure that all refuelings stay within the operation limits and do not end as „overfilled“ or „overheated“ as shown in Figure 4
  - ➢ Overheating avoided by deriving appropriate pressure ramp rates considering Hot Case conditions

➢ Overfilling (and therefore overpressure) avoided by deriving appropriate target pressures considering Cold Case conditions

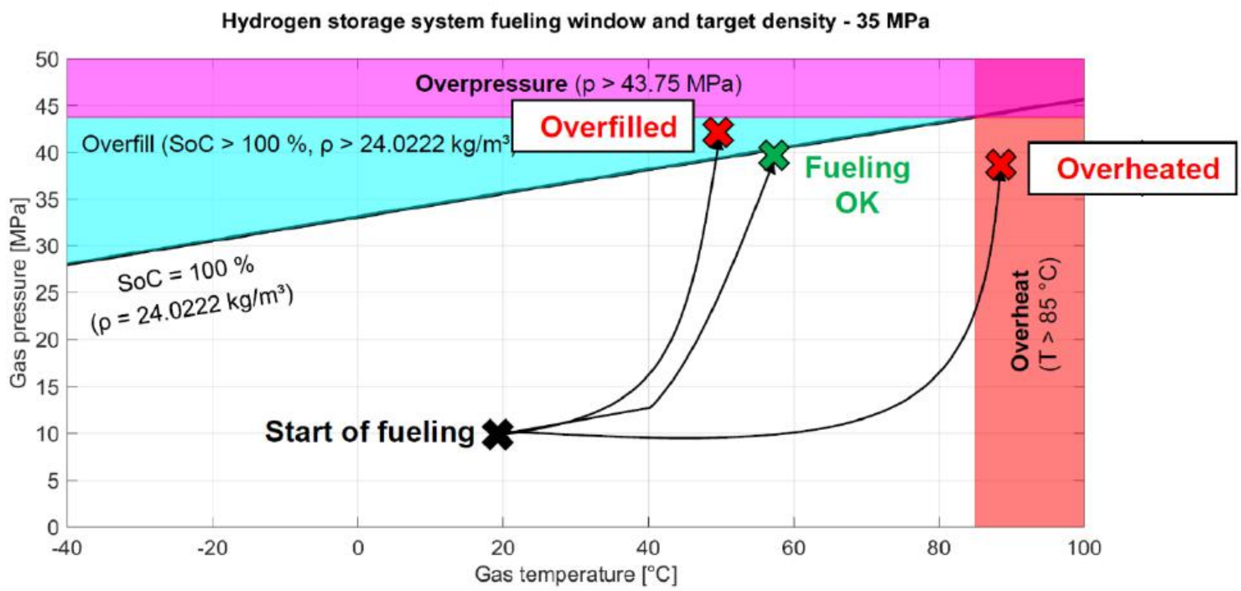

Figure 4 - Refuelings inside and outside operation boundary conditions

The group agreed on the following limits and definitions for the protocol development:

- Non-Comm and Comm tables use the same average pressure ramp rate
  → to avoid miss-use case, e.g. when a customer re-starts a fill with a higher initial pressure then the same ramp rate will be choosen by the HRS
- Initial fueling pressures range from 1 to 35 MPa (see MAP tables)
- Use Non-Comm tables as fallback for Comm refuelings if communication fails during refueling (according to [2])
- If precooling level fails for an A-MAP table refueling, the B-MAP table can be used as fallback refueling for Comm refuelings according to figure 8 in [2]; abort the refueling in Non-Comm refueling cases
- The station pressure corridor limits are the same as in [2] (Δp_up= 7 MPa; Δp_low=2.5 MPa)
- Maximum Highest Pressure Ramp Rate considered for look-up table creation: 4,275 MPa/min (= 10min fill from 1 MPa to 43.75 MPa)
- The ramp rate will be limited in the protocol development such that the overall mass flow of the tank system is not higher than 120 g/s
- To avoid vehicles check valves chattering, any refueling with an average ramp rate lower than 1 MPa/min must be done with a pause and flow strategy, maintaining a target ramp rate of 1 MPa/min during flow periods and not exceeding 10 pauses.
- Maximum allowed massflow: 120 g/s

- Limit for target pressure calculation in Non-Comm tables: SOC_end = 100 % (at 43,75 MPa and 85 °C)
- Limit for target pressure calculation in Comm tables: SOC_end = 108.8 % (at 43.75 MPa and 50 °C)

  The rationale for raising the fueling target pressure for communication fuelings is similiar to chapter A3.13 in [2], but even more narrowly defined. If communication fails and a fill ends at a table defined end pressure with an SOC up to 108.8%, it may stay at the fueling station without consuming hydrogen and two cases are considered:

  Case a) If the tank gas temperature at the end of the fill is higher than ambient temperature, it will converge to ambient temperature over time and pressure decreases. Therefore, the tank system stays within its pressure certifcation limit.

  Case b) If the tank gas temperature at the end of the fill is lower than ambient temperature, it will also converge over time to ambient temperature, but pressure increases. Eventually, the tank system may be hot soaked at temperatures up to 50 °C ambient temperature. The corresponding maximum hot soak temperature is 50 °C; see Table A4 in [2]. With 50°C gas temperature and a SOC at 108.8% the pressure can reach at maximum 43.75 MPa in the tank, which is still within its pressure certification limit.

- Maximum station pressure: 43.75 MPa (for some cases pressure will be held at this level but not exceeded)
- Station is allowed to hold its pressure at p_target until mass flow gets below a measurement limit e.g. < 5 g/s
  → This allows to continue refueling and reach high SOC also for high pressure drop tank systems

2.3 MAP-Tables

The protocol consists of four different minimum ambient precooling (MAP) table sets, each with a Non-Comm and Comm table. The MAP approach has the goal to avoid precooling wherever it is possible without leaving the tank system specification.

Therefore, MAP tables define the allowed precooling corridor [T_min; T_max] at each ambient temperature with two extra table columns. At low ambient temperatures (or in the D-MAP) no active precooling is necessary indicated by the enlarged precooling corridor in the table.

The spectrum of the MAPs is designed such that many existing stations are covered and are able to use this refueling protocol. Every MAP is characterized by its precooling level and the ramp rate level, which both have influence on the refueling speed.

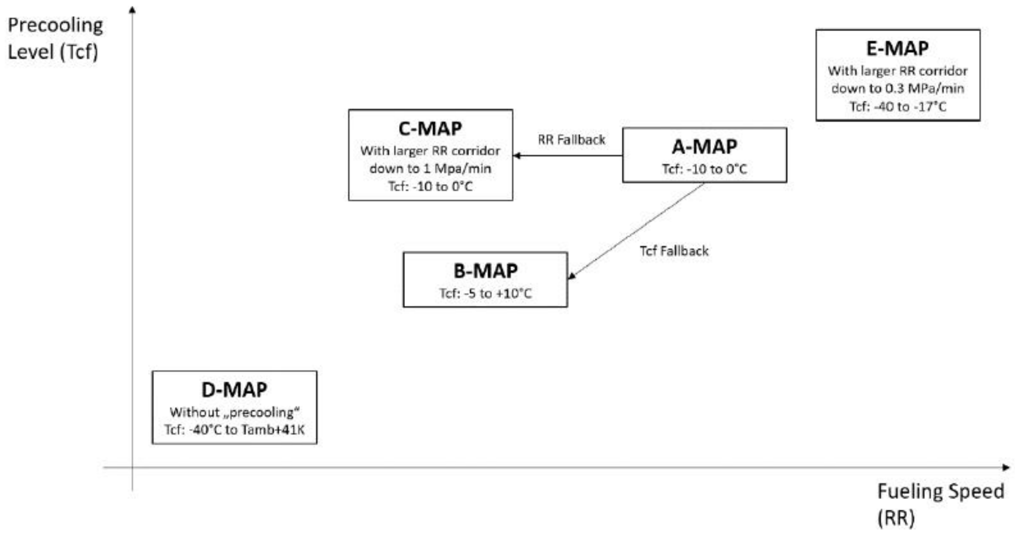

Figure 5 - Overview Refueling MAPs

Each MAP can be implemenented independently or parallel at a station. The option to use a MAP-table as a fallback for another MAP-table is only allowed for Comm refuelings and for the two indicated paths in Figure 5.

A-MAP:

- Highest refueling speed due to precooling of -10 to 0°C at most ambient temperatures
- Performance target: enable refueling < 10 min
- See detailed values in Table 4 (Non-Comm) and in Table 5 (Comm)

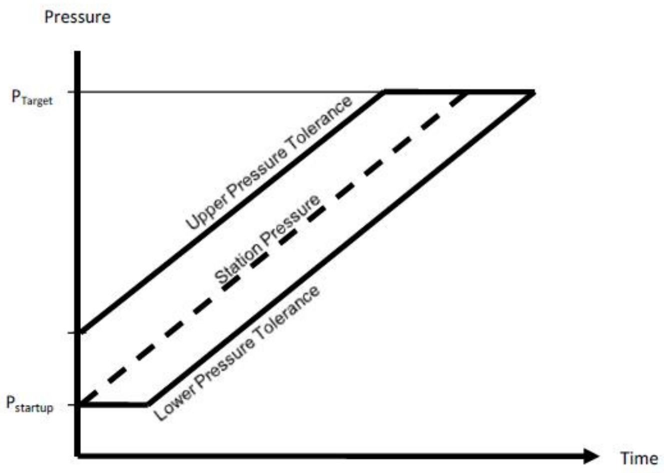

Figure 6 - Regular pressure corridor for A-, B- and D-MAP (as for Non-D-Categories in [2])

B-MAP:

- Precooling from -5 to 10°C H2 fuel delivery temperature
- Can be used as precooling fallback MAP for the A-MAP for Comm (cf. methodoly described in [2] section 8.10) refueling
- Perfomance target: enable refueling <20 min at initial pressures >5MPa and at an ambient temperature of 25°C
- See detailed values in Table 6 (Non-Comm) and in Table 7 (Comm)

C-MAP

- Precooling from -10 to 0°C H2 fuel delivery temperature
- Can be used as ramp rate fallback MAP for the A-MAP Comm fill for reduced ramp rates down to 1 MPa/min . If used as fallback the pressure target is simply changed to the C-MAP value instead of the prior used A-MAP target pressure value. At the same time a lower pressure corridor limit of 1 MPa/min is allowed.
- See detailed values in Table 8 (Non-Comm) and in Table 9 (Comm)
- Rationale:
  - ➢ Existing stations have a certain buffer size and compressor capacity that were designed to meet the back to back filing requirements.
  - ➢ Most existing LD HRS will not be capable of maintaining A-MAP APRR of 3.325MPa/min at 20°C ambient temperature. The lower station pressure corridor limit might be reached before the target pressure is reached.
  - ➢ For all end users, a good SOC is by far more important than a fast filling time that does not deliver a full tank.
  - ➢ The protocol should allow the use of a lower APRR as defined in [2] for CHSS Capacity Category D tanks.

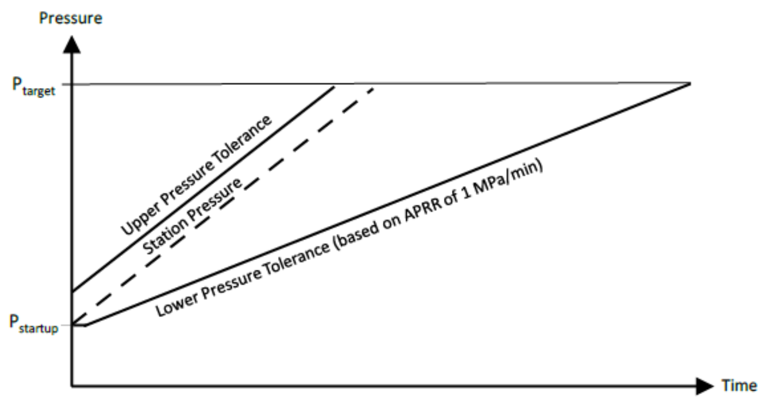

Figure 7 - Enlarged pressure corridor for C-MAP analogue to category D in [2]

D-MAP

- The D-MAP allows refueling without any precooling with reduced refueling speed
- See detailed values in Table 10 (Non-Comm) and in Table 11 (Comm)

E-MAP

- Precooling from -40 to -17°C H2 fuel delivery temperature
- Enlarged pressure ramp rate corridor with minimum ramp rate of 0.3 MPa/min (cf. Figure 7)
- Allows stations to use current precooling levels from light duty vehicle filling
- See detailed values in Table 12 (Non-Comm) and in Table 13 (Comm)

Further MAPs could be included in future to reflect the different HRS operation concepts and their specific precooling capacity.

2.4 Interaction with other tank system sizes and pressure classes

The protocol is defined for tank system sizes from 20 to 42.5 kg at a NWP of 35 MPa. It is not designed for smaller or larger tank system sizes, respectively smaller or larger single tank sizes as indicated in Table 2, with 35 MPa NWP because of the risk for overheating or overfilling.

Rationale for potential overheating if leaving the defined total tank system boundaries (20kg to 42.5kg) and single vessel size boundaries (4kg to 8.5kg):

The tank system size has influence the total mass flow, which is an important parameter for gas temperature development:

- the larger the tank system size the higher the total mass flow
    - exceeding the total tank system size of 42.5kg could lead to exceeding the maximum mass flow of 120 g/s
    - exceeding the total tank system size of 42.5kg could lead to an increased Joule Thomson effect and warmer gas temperature in the tank
- the smaller the tank system size the smaller the total mass flow
    - falling below 20kg in total tank system size could lead to an increased sensitivity on heat flow from thermal masses station and vehicle components and as a result in an increased gas temperature

Additionally the single tank vessel size also influence the gas temperature development:

- the larger the single vessel size the lower its volume-to-surface-ratio. Therefore single tank sizes bigger than 8.5kg can result in increasing the gas temperature development.
- the smaller the single vessel size the smaller its initial gaseous heat capacity at the start of the fueling. Therefore, single tank sizes smaller than 4kg could lead to overshooting the maximum gas temperature during the first seconds of the fill.

Combined with each other or with other parameters considered in the protocol development these effects will not always lead to overheating, but could do so.
Vehicle OEMs have to make sure that they stay within the defined worst case boundaries for refueling with this protocol:

- tank system size from 20 to 42.5kg H2
- single tank size from 4 to 8.5kg H2

Combinations are allowed as long as the single tank sizes and the total tank system sizes are respected.

If tank systems are outside these defined boundaries they can be qualified for refueling with this protocol conducting additional hot and cold case evaluation with the individual material and geometry data.

Due to the geometric compatibility of H35 nozzles with H70 receptacles it might occur that a H70 vehicle gets refueled with this protocol. There is no risk for overfilling these H70 vehicle with this protocol as the maximum density of hydrogen at MOP 43,75 MPa and -40°C (worst case pressure and temperature combination) is at 33,8 kg/m³, which equals 84% SOC for a H70 vehicle. Overheating might still be possible. Therefore, it shall be avoided to fuel H70 vehicles with this protocol.

3 Appendix

Table 2 - Cold and Hot Case parameter assumptions

Parameter	Description	Cold Case	Hot Case
Tank system	Various aspects of the tank system are significant during refueling: tank type (i.e. liner material), wall thickness, configuration of different vessels in a vehicle tank system, ratio of inner liner surface to gas volume for each vessel, and pressure drop in the refueling line.	5x4kg (=20kg) Type III $\lambda_{Liner} = 164 \frac{W}{mK}$ $c_p = 1106 \frac{J}{kgK}$ $s_{liner} = 5\ mm$	5x8.5kg (=42.5kg) Type IV $\lambda_{Liner} = 0.4 \frac{W}{mK}$ $c_p = 2100\ \frac{J}{kgK}$ $s_{liner} = 5\ mm$
HRS Piping Components:	summarized surface to ambience for heat transfer between station component (pipe, break-away, hose, nozzle) and ambience	0,380 m²	0,380 m²
	summarized surface to hydrogen for heat transfer between station components ((pipe, break-away, hose, nozzle) and hydrogen	0,139 m²	0,139 m²
	summarized mass of the station components (pipe, break-away, hose, nozzle)	12,5 kg	12,5 kg
	combined heat capacity of station components (pipe, break-away, hose, nozzle)	6712 J/K	6712 J/K
Vehicle Piping Components:	summarized surface to ambience for heat transfer between car components (receptacle, piping, OTV) and ambience	0,450 m²	0,536 m²
	summarized surface to hydrogen for heat transfer between car components ((receptacle, piping, OTV) and hydrogen	0,300 m²	0,321 m²
	summarized mass of the vehicle components (receptacle, piping, OTV)	5,6 kg	9,9 kg
	combined heat capacity of vehicle components (receptacle, piping, OTV)	2600 J/K	6256 J/K

pressure drop in refueling line [MPa]	pressure drop in refueling line from dispenser outlet (upstream the break-away, at the location of the dispenser pressure and temperature measurements) to tank at reference condition; definition of reference condition: for a given tank pressure PTANK=10MPa and a given fuel temperature TFUEL=-15°C at the dispenser outlet with an infinite diameter at outlet; the pressure at the interface is then PTANK + PDROP	smallest reference pressure drop conceivable for station and vehicle equipment: PDROP = 9 MPa (at 106 g/s) (cf. Table 3)	Largest reference pressure drop allowed for station and vehicle equipment: PDROP = 30 MPa (at 106 g/s) (cf. Table 3)
nozzle diameter [mm]	The condition of the dispensed hydrogen gas is defined by pressure and temperature at the fuel delivery location inside the dispenser. If the inner diameter there is sufficiently small, the fuel gas has a significant flow velocity yielding a kinetic energy. This additional kinetic energy will lead to higher gas temperatures in the vehicle tank.	use the largest specified diameter (=infinite)	use the smallest specified diameter (=6,35 mm)
ambient temperature [°C]	Ambient temperature is measured by the HRS. It is assumed that there is no sensor error. Considered range in tables: -40°C to +50°C	No variation	No variation
initial tank pressure [MPa]	Initial vehicle tank pressure is measured by HRS by initial pressure pulse. It is assumed that this pulse does not alter the initial tank pressure. It is also assumed that there is no sensor error.	1, 2, 5, 10, 15, 20, 25, 30, 35 MPa	2 MPa for RR determination
rated cold fill temperature [°C]	The rated cold fill temperature defines the fuel delivery temperature at the station and has to stay between T_min [°C] and T_max [°C] defined in each row of the MAPs. Necessary precooling levels will be derived based on refueling time	use lowest cold fill temperature, i.e. lower tolerance	use warmest cold fill temperature, i.e. upper tolerance inkl. 30s cooldown (cf. [2])
pressure ramp rate (at dispenser inlet upstream break-away-	Pressure ramp rate is assumed to represent an ideal linear pressure increase right upstream the break-away nozzle. It is assumed that there is no error on the ramp rate. The nozzle pressure is limited to an upper value of	APRR calculated from HPRR APRR=HPRR*(1-(Δp_up+Δp_low)/(43.75 Mpa- PINI	HPRR

coupling) [MPa/min]	43.75 MPa in all simulations. Tolerances of Δp_up= 7 MPa and Δp_low= 2.5 MPa are defining the pressure corridor the Ramprate is limited to.		
soak condition [°C]	The soak condition defines the initial homogeneous temperature of wall and gas in the vehicle tank system. It may deviate from the ambient temperature for various reasons. For each ambient temperature the maximum and minimum soak temperature is defined. The soak of the refueling line components is also considered, as the station components have thermal impact on H2-Temperature (Tcf)	Vessel cold soak profile according to the driving history derived from Step 0 defueling results. Step 0 started with cold soak conditions Station and vehicle piping components are soaked at ambient temperature	Vessel hot soak according to hot soak conditions following [2] Station and vehicle piping components are soaked at ambient temperature
history after soak [°C]	After soaking and before refueling, the vehicle tank may be operated by extracting or refueling hydrogen. This operating history changes the homogeneous temperature profile in the tanks that were obtained during the previous soaking.	Driving history (= vehicle driving): * tank is soaked at maximum density and then depleted until ist minimum pressure is reached * reduce extraction rate if gas temperature reaches lower operation limit * Defueling rate (per tank system): 1,9 g/s	No additional hystory after soak condition

Table 3 - Reference pressure drop calculation

Property	Cold-Case	Hot-Case
Reference mass flow [g/s]	106 (10min fill of 42.5 kg)	106 (10min fill of 42.5 kg)
Station refueling path:		
Di pipe measuring location to break away [mm]	8,89	8,89
Kv-Break-Away [m³/h]	2	1
fueling-hose inner diameter [mm]	6,35	6,35
Kv-Nozzle [m³/h]	2,5	0,25
Reference pressure drop HRS [MPa]	4,2	13
Vehicle refueling path:		
Kv-Receptacle [m³/h]	0,7	0,3
Length refueling line vehicle [m] Refueling line vehicle inner diameter [mm]	12,5 8	12,5 8
Kv-Check-Valve [m³/h]	2	2
Kv-On-tank-valve [m³/h]	0,4	0,17
Reference mass flow [g/s]	50	106
Reference pressure drop vehicle [MPa]	4,8	17
Complete Refueling path:		
Reference pressure drop [MPa]	9	30

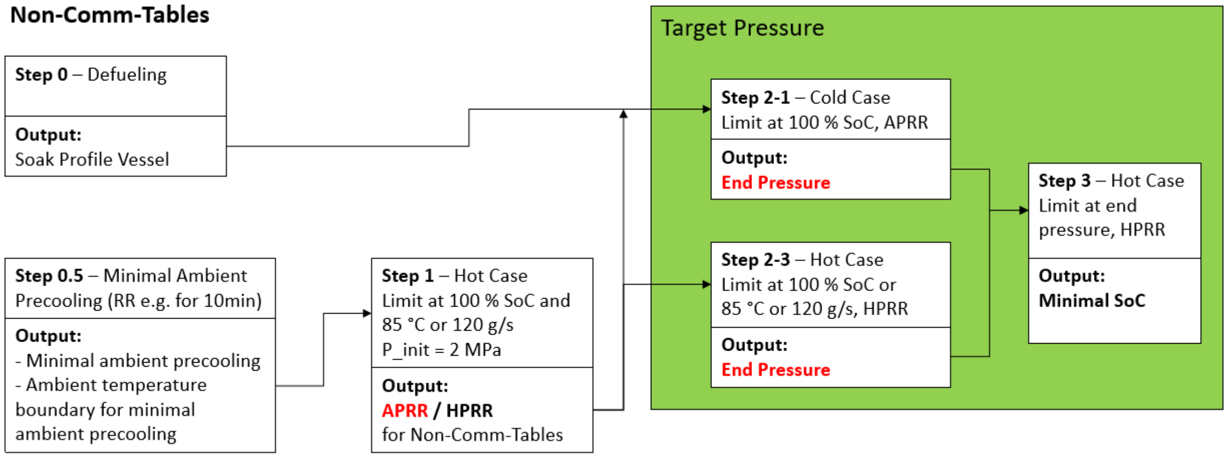

Figure 8 - Non-Comm table simulation steps

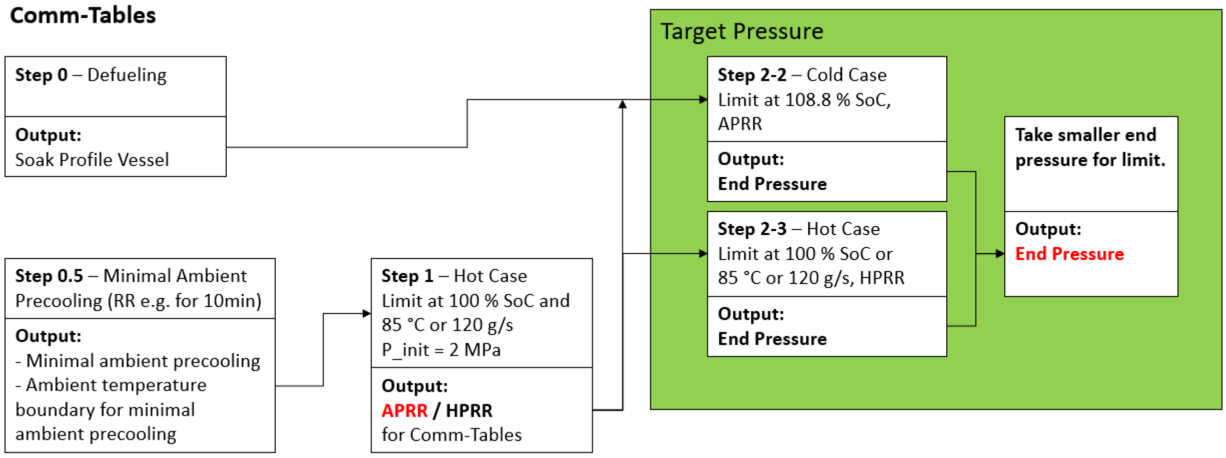

Figure 9 - Comm table simulation steps

Table 4 - A-MAP Non-Comm

A-MAP 35MPa Non-Comm (20-42.5kg)	T_fuel H2 [°C] precooling corridor		Average Pressure Ramp Rate [MPa/min]	Target pressure [MPa] / Initial Pressure [MPa]								
Ambient temperature [°C]	T_min [°C]	T_max [°C]		1	2	5	10	15	20	30	35	> 35
>50	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling
50	-10	0	1,019	39,8	39,6	39,2	38,6	38,1	37,6	36,9	36,4	no fueling
45	-10	0	1,507	39,4	39,2	38,8	38,2	37,7	37,3	36,8	36,4	no fueling
40	-10	0	2,084	37,6	38,9	38,5	38,0	37,5	37,2	36,7	36,4	no fueling
35	-10	0	2,153	37,4	38,6	38,2	37,7	37,3	37,0	36,7	36,4	no fueling
30	-10	0	2,776	35,3	38,3	37,9	37,3	36,9	36,5	36,1	35,7	no fueling
25	-10	0	3,301	36,4	38,0	37,6	36,9	36,5	36,1	35,5	no fueling	no fueling
20	-10	0	3,325	37,8	37,6	37,3	36,6	36,0	35,6	34,9	no fueling	no fueling
10	-10	0	3,325	37,1	36,9	36,7	35,9	35,2	34,6	33,6	no fueling	no fueling
0	-10	0	3,325	36,3	36,1	36,0	35,1	34,3	33,6	32,2	no fueling	no fueling
-10	-10	14,0	3,325	35,9	35,6	34,8	33,7	32,9	32,2	30,6	no fueling	no fueling
-20	-20	14,6	3,325	35,1	34,8	34,1	33,0	31,9	30,9	no fueling	no fueling	no fueling
-30	-30	15,3	3,325	34,1	33,9	33,3	32,4	31,4	30,4	no fueling	no fueling	no fueling
-40	-40	16,0	3,325	33,4	33,2	32,7	31,9	31,0	30,1	no fueling	no fueling	no fueling
< -40	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling

Table 5 - A-MAP Comm

A-MAP 35MPa Comm (20-42.5kg)	T_fuel H2 [°C] precooling corri-dor		Average Pressure Ramp Rate [MPa/min]	Target pressure [MPa] / Initial Pressure [MPa]								
Ambient temperature [°C]	T_min [°C]	T_max [°C]		1	2	5	10	15	20	30	35	> 35
>50	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling
50	-10	0	1,019	40,9	43,4	43,2	42,8	42,4	41,9	41,0	40,3	no fueling
45	-10	0	1,507	39,5	43,3	43,0	42,6	42,1	41,6	40,5	39,7	no fueling
40	-10	0	2,084	37,6	43,2	42,9	42,4	41,8	41,3	39,9	39,0	no fueling
35	-10	0	2,153	37,4	41,6	42,8	42,2	41,8	41,3	39,9	39,0	no fueling
30	-10	0	2,776	35,3	42,9	42,5	41,8	41,3	41,0	39,5	38,5	no fueling
25	-10	0	3,301	36,4	42,6	42,1	41,4	40,9	40,5	39,1	no fueling	no fueling
20	-10	0	3,325	42,3	42,1	41,8	41,1	40,5	40,0	38,7	no fueling	no fueling
10	-10	0	3,325	41,5	41,3	41,2	40,3	39,5	39,0	38,0	no fueling	no fueling
0	-10	0	3,325	40,7	40,5	40,5	39,4	38,5	37,9	36,5	no fueling	no fueling
-10	-10	14,0	3,325	36,2	40,0	39,1	37,9	37,0	36,3	35,2	no fueling	no fueling
-20	-20	14,6	3,325	36,1	39,0	38,3	37,1	35,9	34,8	no fueling	no fueling	no fueling
-30	-30	15,3	3,325	35,9	38,0	37,4	36,3	35,3	34,2	no fueling	no fueling	no fueling
-40	-40	16,0	3,325	35,7	37,2	36,7	35,7	34,8	33,9	no fueling	no fueling	no fueling
< -40	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling

Table 6 - B-MAP Non-Comm

B-MAP 35MPa Non-Comm (20-42.5kg)		T_fuel H2 [°C] precooling corridor		Average Pressure Ramp Rate [MPa/min]	Target pressure [MPa]								
					Initial Pressure [MPa]								
		T_min [°C]	T_max [°C]		1	2	5	10	15	20	30	35	> 35
Ambient temperature [°C]	>50	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling
	50	-5	10	0,419	40,4	40,3	39,9	39,2	38,6	38,0	36,9	36,5	no fueling
	45	-5	10	0,700	39,8	39,6	39,2	38,6	38,0	37,5	36,8	36,4	no fueling
	40	-5	10	1,064	39,3	39,2	38,8	38,1	37,6	37,2	36,7	36,4	no fueling
	35	-5	10	1,132	39,0	38,8	38,4	37,8	37,3	37,0	36,6	36,4	no fueling
	30	-5	10	1,390	38,6	38,4	38,0	37,3	36,8	36,4	36,0	35,7	no fueling
	25	-5	10	1,661	38,2	38,1	37,6	36,9	36,4	35,9	35,5	no fueling	no fueling
	20	-5	10	1,982	37,3	37,7	37,2	36,5	35,9	35,4	34,9	no fueling	no fueling
	10	-5	10	2,724	34,7	37,1	36,5	35,7	35,0	34,5	33,6	no fueling	no fueling
	0	-5	10	3,325	36,6	36,4	35,8	34,9	34,1	33,5	32,2	no fueling	no fueling
	-10	-10	14,0	3,325	35,9	35,6	34,8	33,7	32,9	32,2	30,6	no fueling	no fueling
	-20	-20	14,6	3,325	35,1	34,8	34,1	33,0	31,9	30,9	no fueling	no fueling	no fueling
	-30	-30	15,3	3,325	34,1	33,9	33,3	32,4	31,4	30,4	no fueling	no fueling	no fueling
	-40	-40	16,0	3,325	33,4	33,2	32,7	31,9	31,0	30,1	no fueling	no fueling	no fueling
	< -40	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling

Table 7 - B-MAP Comm

B-MAP 35MPa Comm (20-42.5kg)		T_fuel H2 [°C] precooling corri-dor		Average Pressure Ramp Rate [MPa/min]	Target pressure [MPa]								
					Initial Pressure [MPa]								
		T_min [°C]	T_max [°C]		1	2	5	10	15	20	30	35	> 35
Ambient temperature [°C]	>50	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling
	50	-5	10	0,419	41,5	43,5	43,3	42,9	42,4	41,9	40,9	40,3	no fueling
	45	-5	10	0,700	41,2	43,4	43,1	42,6	42,1	41,5	40,4	39,7	no fueling
	40	-5	10	1,064	40,3	43,3	42,9	42,4	41,8	41,2	39,9	39,0	no fueling
	35	-5	10	1,132	40,1	43,2	42,9	42,3	41,8	41,2	39,9	39,0	no fueling
	30	-5	10	1,390	39,2	42,9	42,6	41,9	41,4	40,9	39,5	38,5	no fueling
	25	-5	10	1,661	38,3	42,7	42,2	41,4	40,8	40,4	39,1	no fueling	no fueling
	20	-5	10	1,982	37,3	42,3	41,7	41,0	40,3	39,9	38,7	no fueling	no fueling
	10	-5	10	2,724	34,7	41,6	40,9	40,1	39,3	38,8	38,1	no fueling	no fueling
	0	-5	10	3,325	41,1	40,8	40,2	39,2	38,3	37,7	36,6	no fueling	no fueling
	-10	-10	14,0	3,325	36,2	40,0	39,1	37,9	37,0	36,3	35,2	no fueling	no fueling
	-20	-20	14,6	3,325	36,1	39,0	38,3	37,1	35,9	34,8	no fueling	no fueling	no fueling
	-30	-30	15,3	3,325	35,9	38,0	37,4	36,3	35,3	34,2	no fueling	no fueling	no fueling
	-40	-40	16,0	3,325	35,7	37,2	36,7	35,7	34,8	33,9	no fueling	no fueling	no fueling
	< -40	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling

Table 8 - C-MAP Non-Comm

C-MAP 35MPa Non-Comm (20-42.5kg)		T_fuel H2 [°C] precooling corri-dor		Average Pressure Ramp Rate [MPa/min] (reduction down to 1 MPa/min possible for C-MAP)	Target pressure [MPa]								
					Initial Pressure [MPa]								
		T_min [°C]	T_max [°C]		1	2	5	10	15	20	30	35	> 35
Ambient temperature [°C]	>50	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling
	50	-10	0	1,019	39,8	39,6	39,2	38,6	38,1	37,6	36,9	36,4	no fueling
	45	-10	0	1,507	39,4	39,3	38,9	38,3	37,8	37,3	36,7	36,4	no fueling
	40	-10	0	2,084	37,6	38,9	38,5	38,0	37,5	37,1	36,6	36,4	no fueling
	35	-10	0	2,153	37,4	38,6	38,2	37,6	37,2	36,8	36,5	36,4	no fueling
	30	-10	0	2,776	35,3	38,2	37,7	37,1	36,7	36,3	35,9	35,7	no fueling
	25	-10	0	3,301	36,4	37,7	37,3	36,7	36,1	35,7	35,3	no fueling	no fueling
	20	-10	0	3,325	37,5	37,3	36,9	36,2	35,6	35,2	34,7	no fueling	no fueling
	10	-10	0	3,325	36,7	36,5	36,0	35,2	34,5	34,1	33,4	no fueling	no fueling
	0	-10	0	3,325	35,8	35,6	35,1	34,2	33,5	32,9	32,1	no fueling	no fueling
	-10	-10	14,0	3,325	35,3	35,0	34,3	33,2	32,4	31,7	30,6	no fueling	no fueling
	-20	-20	14,6	3,325	34,4	34,2	33,5	32,5	31,4	30,4	no fueling	no fueling	no fueling
	-30	-30	15,3	3,325	33,4	33,2	32,7	31,8	30,8	29,9	no fueling	no fueling	no fueling
	-40	-40	16,0	3,325	32,6	32,5	32,0	31,3	30,5	29,7	no fueling	no fueling	no fueling
	< -40	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling

Table 9 - C-MAP Comm

C-MAP 35MPa Comm (20-42.5kg)		T_fuel H2 [°C] precooling corri-dor		Average Pressure Ramp Rate [MPa/min] (reduction down to 1 MPa/min possible for C-MAP)	Target pressure [MPa]								
					Initial Pressure [MPa]								
		T_min [°C]	T_max [°C]		1	2	5	10	15	20	30	35	> 35
Ambient temperature [°C]	>50	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling
	50	-10	0	1,019	40,9	43,3	43,2	42,8	42,4	41,9	41,0	40,3	no fueling
	45	-10	0	1,507	39,5	43,3	43,0	42,6	42,1	41,6	40,5	39,7	no fueling
	40	-10	0	2,084	37,6	43,2	42,9	42,4	41,8	41,3	39,9	39,0	no fueling
	35	-10	0	2,153	37,4	41,6	42,8	42,2	41,7	41,3	39,9	39,0	no fueling
	30	-10	0	2,776	35,3	42,8	42,3	41,7	41,2	40,8	39,5	38,5	no fueling
	25	-10	0	3,301	36,4	42,3	41,8	41,2	40,6	40,2	39,1	no fueling	no fueling
	20	-10	0	3,325	42,0	41,8	41,4	40,6	40,0	39,6	38,7	no fueling	no fueling
	10	-10	0	3,325	41,1	40,9	40,4	39,5	38,9	38,3	37,8	no fueling	no fueling
	0	-10	0	3,325	40,2	40,0	39,4	38,5	37,7	37,1	36,4	no fueling	no fueling
	-10	-10	14,0	3,325	36,2	39,3	38,6	37,4	36,5	35,8	35,0	no fueling	no fueling
	-20	-20	14,6	3,325	36,1	38,3	37,7	36,5	35,4	34,3	no fueling	no fueling	no fueling
	-30	-30	15,3	3,325	35,9	37,2	36,7	35,7	34,7	33,7	no fueling	no fueling	no fueling
	-40	-40	16,0	3,325	35,7	36,4	35,9	35,1	34,2	33,4	no fueling	no fueling	no fueling
	< -40	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling

Table 10 - D-MAP Non-Comm

D-MAP 35MPa Non-Comm (20-42.5kg)		T_fuel H2 [°C] precooling corri-dor		Average Pressure Ramp Rate [MPa/min]	Target pressure [MPa]								
					Initial Pressure [MPa]								
		T_min [°C]	T_max [°C]		1	2	5	10	15	20	30	35	> 35
Ambient temperature [°C]	>50	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling
	50	-40	85	0,084	33,5	40,3	40,2	39,8	39,4	38,9	37,5	36,6	no fueling
	45	-40	85	0,103	36,7	39,6	39,4	39,1	38,6	38,2	37,0	36,5	no fueling
	40	-40	81	0,129	38,7	39,0	38,7	38,3	37,9	37,5	36,7	36,4	no fueling
	35	-40	76	0,159	38,4	38,3	38,1	37,7	37,2	36,9	36,4	36,3	no fueling
	30	-40	71	0,199	37,8	37,7	37,4	37,0	36,5	36,2	35,7	35,7	no fueling
	25	-40	66	0,252	37,2	37,1	36,8	36,3	35,9	35,5	35,1	no fueling	no fueling
	20	-40	61	0,321	36,4	36,3	36,0	35,5	35,1	34,8	34,5	no fueling	no fueling
	10	-40	51	0,529	35,5	35,4	35,1	34,5	34,0	33,6	33,3	no fueling	no fueling
	0	-40	41	1,044	34,2	34,1	33,6	33,1	32,6	32,3	32,0	no fueling	no fueling
	-10	-40	31,0	1,555	33,9	33,7	33,2	32,5	31,9	31,4	30,6	no fueling	no fueling
	-20	-40	21,0	2,550	33,7	33,5	33,0	32,1	31,2	30,4	no fueling	no fueling	no fueling
	-30	-40	15,3	3,325	33,5	33,3	32,8	31,9	31,1	30,2	no fueling	no fueling	no fueling
	-40	-40	16,0	3,325	33,4	33,2	32,7	31,9	31,0	30,1	no fueling	no fueling	no fueling
	< -40	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling

Table 11 - D-MAP Comm

D-MAP 35MPa Comm (20-42.5kg)		T_fuel H2 [°C] precooling corri-dor		Average Pressure Ramp Rate [MPa/min]	Target pressure [MPa]								
					Initial Pressure [MPa]								
		T_min [°C]	T_max [°C]		1	2	5	10	15	20	30	35	> 35
Ambient temperature [°C]	>50	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling
	50	-40	85	0,084	33,5	42,8	42,9	42,7	42,5	42,2	41,1	40,3	no fueling
	45	-40	85	0,103	36,7	42,8	42,8	42,5	42,2	41,8	40,5	39,6	no fueling
	40	-40	81	0,129	38,7	42,8	42,6	42,4	41,9	41,4	39,9	38,9	no fueling
	35	-40	76	0,159	39,2	42,7	42,6	42,2	41,7	41,3	39,8	38,9	no fueling
	30	-40	71	0,199	39,7	42,1	41,8	41,4	41,0	40,6	39,4	38,4	no fueling
	25	-40	66	0,252	40,0	41,5	41,2	40,7	40,2	39,8	38,9	no fueling	no fueling
	20	-40	61	0,321	40,1	40,6	40,3	39,8	39,4	39,1	38,5	no fueling	no fueling
	10	-40	51	0,529	39,8	39,6	39,3	38,7	38,2	37,8	37,4	no fueling	no fueling
	0	-40	41	1,044	38,3	38,2	37,7	37,1	36,6	36,3	36,1	no fueling	no fueling
	-10	-40	31,0	1,555	37,5	37,7	37,2	36,4	35,8	35,3	34,8	no fueling	no fueling
	-20	-40	21,0	2,550	34,6	37,5	36,9	36,0	35,0	34,2	no fueling	no fueling	no fueling
	-30	-40	15,3	3,325	35,9	37,3	36,7	35,8	34,9	34,0	no fueling	no fueling	no fueling
	-40	-40	16,0	3,325	35,8	37,2	36,7	35,7	34,8	33,9	no fueling	no fueling	no fueling
	< -40	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling

Table 12 - E-MAP Non-Comm

E-MAP 35MPa Non-Comm (20-42.5kg)		T_fuel H2 [°C] precooling corridor		Average Pressure Ramp Rate [MPa/min] (reduction down to 0.3 MPa/min possible for E-MAP)	Target pressure [MPa] / Initial Pressure [MPa]								
		T_min [°C]	T_max [°C]		1	2	5	10	15	20	30	35	> 35
Ambient temperature [°C]	>50	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling
	50	-40	-17	4,0	39,3	39,2	38,9	38,5	38,0	37,6	36,8	36,4	no fueling
	45	-40	-17	4,0	38,8	38,7	38,5	38,0	37,6	37,2	36,6	36,4	no fueling
	40	-40	-17	4,0	38,3	38,2	38,0	37,6	37,2	36,9	36,4	36,3	no fueling
	35	-40	-17	4,0	37,9	37,8	37,5	37,2	36,8	36,5	36,3	36,3	no fueling
	30	-40	-17	4,0	37,4	37,3	37,0	36,6	36,2	36,0	35,7	35,7	no fueling
	25	-40	-17	4,0	36,9	36,8	36,5	36,1	35,7	35,4	35,1	no fueling	no fueling
	20	-40	-17	4,0	36,4	36,3	36,0	35,5	35,1	34,8	34,5	no fueling	no fueling
	10	-40	-17	4,0	35,4	35,3	35,0	34,4	34,0	33,6	33,2	no fueling	no fueling
	0	-40	-17	4,0	34,5	34,3	34,0	33,4	32,8	32,4	32,0	no fueling	no fueling
	-10	-40	-17	4,0	33,7	33,5	33,0	32,3	31,7	31,2	30,6	no fueling	no fueling
	-20	-40	-17	4,0	33,0	32,9	32,5	31,7	30,9	30,0	no fueling	no fueling	no fueling
	-30	-40	-17	4,0	32,3	32,2	31,8	31,2	30,4	29,6	no fueling	no fueling	no fueling
	-40	-40	-17	4,0	31,6	31,6	31,3	30,7	30,1	29,4	no fueling	no fueling	no fueling
	< -40	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling

Table 13 - E-MAP Comm

E-MAP 35MPa Comm (20-42.5kg)		T_fuel H2 [°C] precooling corridor		Average Pressure Ramp Rate [MPa/min] (reduction down to 0.3 MPa/min possible for E-MAP)	Target pressure [MPa] / Initial Pressure [MPa]								
		T_min [°C]	T_max [°C]		1	2	5	10	15	20	30	35	> 35
Ambient temperature [°C]	>50	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling
	50	-40	-17	4,0	43,2	43,2	43,0	42,7	42,4	41,9	40,9	40,3	no fueling
	45	-40	-17	4,0	42,9	42,8	42,7	42,3	41,9	41,5	40,3	39,6	no fueling
	40	-40	-17	4,0	42,6	42,5	42,3	41,9	41,5	41,0	39,7	38,9	no fueling
	35	-40	-17	4,0	42,4	42,3	42,0	41,6	41,3	41,0	39,7	38,9	no fueling
	30	-40	-17	4,0	41,8	41,7	41,4	41,0	40,7	40,4	39,2	38,4	no fueling
	25	-40	-17	4,0	41,3	41,2	40,9	40,4	40,0	39,7	38,8	no fueling	no fueling
	20	-40	-17	4,0	40,7	40,6	40,3	39,8	39,4	39,1	38,4	no fueling	no fueling
	10	-40	-17	4,0	39,6	39,5	39,2	38,6	38,2	37,8	37,4	no fueling	no fueling
	0	-40	-17	4,0	38,6	38,4	38,1	37,4	36,9	36,5	36,0	no fueling	no fueling
	-10	-40	-17	4,0	37,7	37,5	37,0	36,3	35,6	35,2	34,6	no fueling	no fueling
	-20	-40	-17	4,0	36,9	36,8	36,3	35,6	34,7	33,9	no fueling	no fueling	no fueling
	-30	-40	-17	4,0	36,0	35,9	35,6	34,9	34,2	33,3	no fueling	no fueling	no fueling
	-40	-40	-17	4,0	35,3	35,2	34,9	34,4	33,8	33,1	no fueling	no fueling	no fueling
	< -40	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling

References

[1] S. I. W. Group, "SAE J2600 - Compressed Hydrogen Surface Vehicle Fueling Connection Devices," SAE International, Detroit, 2015.

[2] S. I. W. Group, "SAE J2601-2020 Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles," SAE International, Detroit, 2020.

[3] S. I. W. Group, "SAE J2601/2 - Fueling Protocol for Gaseous Hydrogen Powered Heavy Duty Vehicles," SAE International, Detroit, 2014.

[4] UNECE, *UN GTR No. 13 - Global Technical Regulation concerning the hydrogen and fuel cell vehicles,* Geneva: United Nations, 2013.

[5] J. M. G. M. S. V. M. e. a. Schneider, "Validation and Sensitivity Studies for SAE J2601, the Light Duty Vehicle Hydrogen Fueling Standard," SAE International, Detroit, 2014.