D7.5 Final synthesis of the project findings for the Industry

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EXECUTIVE SUMMARY

This deliverable summarizes the different results found throughout the HyTransfer project. They have been turned into recommendations for the Industry: vehicle OEMs, tank manufacturers and HRS manufacturers.

Results can be divided into three main recommendations:

- ✓ Avoidance of non-homogeneous temperatures
- ✓ Investigation into accepting a transient peak liner surface temperature of 95°C in Type 4 tanks, considering the positive effect on CAPEX and OPEX for Hydrogen Refueling Stations
- ✓ Pilot implementation of the HyTransfer protocol

For each of them, a rationale is given, as well as the specific points (practical / scientific) that need to be addressed to be fully applicable.

Note:

The proposed HyTransfer refuelling protocol (as described in D5.1) has been documented to be a new cost-effective fuelling method. However, savings have been demonstrated on the Hydrogen Refuelling Station only, in terms of OPEX and CAPEX. Possible additional costs on the on-board receiving storage, due to a higher temperature limit requirement, have not been considered in the study and might have a significant impact on the global cost analysis of the whole hydrogen chain.

1 INTRODUCTION

Throughout the HyTransfer project, several findings coming from experimental testing or scientific modelling were identified. These findings have been used to propose a new filling protocol for Hydrogen Fuel Cell Electrical Vehicle (FCEV).

This new protocol brings about significant reduction of hydrogen refuelling station (HRS) construction and operating costs in relation to temperature control (see D6.1 technico-economic analysis), but also significant improvements in terms of vehicle tank temperature control (no stratification).

These findings have been turned into Recommendations for Industry. This deliverable summarizes the different recommendations, along with their underlying rationale.

The set of recommendations reflects an ambition to realise the potential improvements in terms of safety, user experience, reliability and resource efficiency that can be achieved before HRS deployment reaches a stage beyond which any change to current practice will be very difficult to implement.

Next steps, including specific points to be addressed for protocol implementation and take up by standardisation are identified in the last part of the document.

2 RECOMMENDATIONS FOR INDUSTRY

<u>**Who are these recommendations intended for?**</u>

These recommendations are intended to different type of industries. They can be divided into three main categories:

- Vehicle OEMs and/or tank system integrators,

- Tank manufacturers (Type IV tanks mainly),

- HRS manufacturers.

2.1 Recommendations for Vehicle OEMs / tank integrators

2.1.1 Recommendation #1

Ensure homogeneous temperature conditions during filling to prevent hot spots / stratification

How? By making sure that the in-tank valve flow section at point of injection is small enough for ensuring a sufficient gas velocity throughout the fill.

<u>Note</u>: Horizontal installation of the tanks is assumed.

Due to gas compression inside the tank during filling, a temperature elevation occurs. One of the main objectives of a fuelling protocol is to keep the gas temperature everywhere below the specified maximum limit. Since the thermodynamic models applied for developing protocols only predict the *average* gas temperature, the expectation that a fuelling protocol allows to control the temperature at any point in the tank is based on the implicit assumption that the gas temperature field is close to homogeneous.

This assumption is however not correct if gas mixing is not sufficient, since this results in heterogeneous temperatures.

The cause of insufficient gas mixing that is both the most likely and which can produce the greatest heterogeneities, through stratification which is defined as the appearance of a vertical temperature gradient, is insufficient injection velocity.

For tanks having a length to diameter ratio greater than 3 lack of mixing can also result (if injection is in the axial direction) from excessive injection velocity preventing recirculation at the scale of the whole tank, and resulting in a horizontal temperature gradient.

This leads to gas temperatures significantly exceeding the targeted maximum temperature in certain parts of the tank.

In order to be sure that the gas temperature is everywhere within the specified limit, **homogeneous temperature conditions** need to be ensured during filling. This can be achieved by the following means:

- To prevent stratification (*vertical temperature gradient)*, a gas velocity at point of injection exceeding **5 m/s** must be maintained in each vessel throughout the fill.
- For long vessels with a L/D ratio greater than 3, to prevent formation of a *horizontal temperature gradient*, the gas velocity at point of injection should not exceed **100 m/s for a long period of time (e.g. the first third of the filling)**; an alternative solution for ensuring proper mixing could be to perform injection in a non-axial direction, providing recirculation over the length of the whole tank, however this has not been validated in the course of the HyTransfer project.

Note: In homogeneous conditions, the maximum difference between the mean temperature and the maximum temperature is less than 3.5°C.

These criteria can be ensured by **adapting a gas injector on the in-tank valve** of each vessel constituting the storage system with a flow section sized to keep the gas velocity in the desired range. The above criteria can then be expressed by using the $\mathbf{Q/d_{inj}^2}$ ratio.

With: - $\mathbf{d_{inj}}$: injector internal diameter, expressed in m

- **Q**: the mass flow rate into the considered vessel, assumed to be constant, expressed in kg/s and estimated by dividing the considered vessel's capacity by the nominal fuelling duration (i.e. 3 min for the HyTransfer approach)..

Note: These criteria are applicable to each vessel constituting the vehicle's storage system.

The injector diameter must be selected according to the following criteria:

Table 1: Gas velocity criteria to ensure homogenous conditions

	Short tank: $L - L_{inj} < 3*D$	Long tank: $L - L_{inj} > 3*D$
Velocity criteria to prevent from **vertical gradient**	**U > 5 m/s**	
Velocity criteria to prevent from **horizontal gradient**	**No criterion**	**U < 100 m/s** *for two third of fill from 20 to 875 bar (pressure ramp rate)*

Note: L and D (resp. Length and Diameter) are based on inner tank dimensions. L_{inj} injector length inside tank.

- Note 2: The speed indicators can be combined in the following criteria on the ratio $\frac{Q}{{d_{inj}}^2}$, here for fillings of 700 bar tanks : For short tanks:

$$\frac{Q}{{d_{inj}}^2} > 203 \ \ \mathrm{kg.m^{-2}.s^{-1}}$$

Considering a maximum density at inlet of 51.6 (kg/m^3) equivalent to 875 bar inlet pressure and -30°C inlet temperature

- For long tanks:

$$1806 > \frac{Q}{{d_{inj}}^2} > 203 \ \mathrm{kg.m^{-2}.s^{-1}}$$

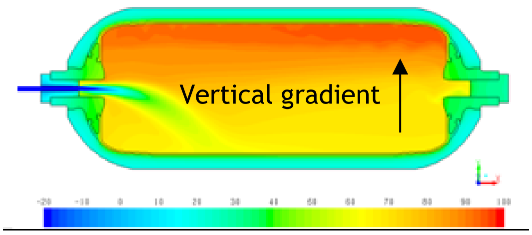
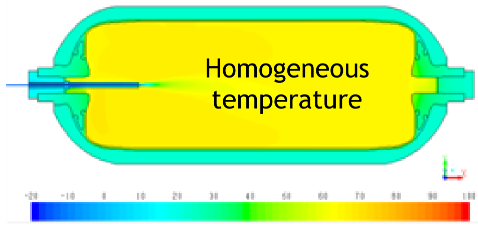
For fillings of lower pressure tanks (e.g. 500 bar), the Q/d^2 relationships have to be adapted. The speed indicators in the table, however, remain the same.

The choice of a proper injector diameter is the responsibility of the tank system integrator for the intended application.

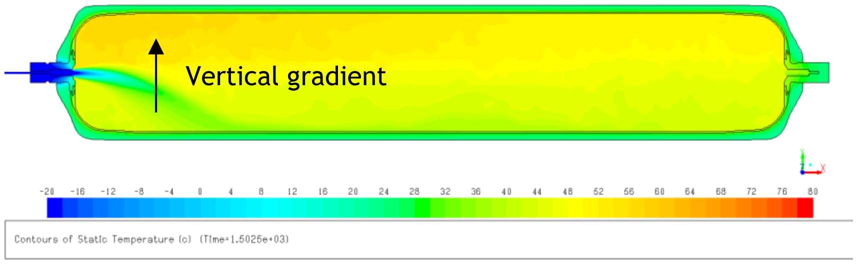
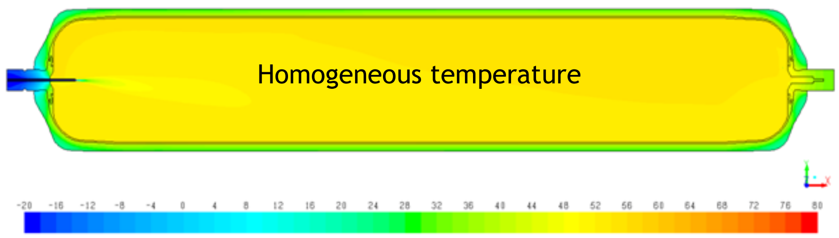
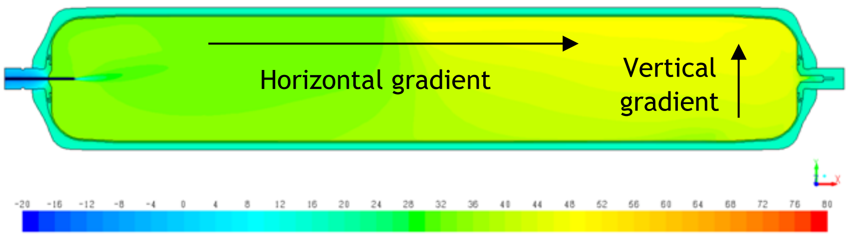
For a given nominal filling duration (i.e. a given pressure ramp rate), the above criterion can be expressed in a simplified way by specifying a minimum and a maximum value for the injection diameter (only a maximum value for short tanks) for a given vessel size range.

<u>Illustrations</u>:

- <u>Short tank</u>: 36l Type IV tank (Hexagon). Ratio L/D = 2.4

U < 5 m/s	U > 5 m/s
	

- <u>Long tank</u>: 531l Type IV tank (Hexagon). Ratio L/D = 5.9

U < 5m/s	
5 < U < 100 m/s	
U > 100 m/s	

Application:

Herebelow, we present an example of selection of the injector diameter depending on type of tank (short vs. long) and the mass flow rate.

Table 2: Example for the choice of injector diameter

	Real cases		Hypothetical case
	Short Tank: 36l Type IV tank (Hexagon)	Long Tank: 531l Type IV tank (Hexagon)	Long tank: 36l Type IV tank
L/D ratio	2.4	5.9	5.75
m_{H2} filled *(5-700 bar, 15°C)*	1.53 kg	22.4 kg	1.53 kg
Flow rate Q *(for a filling in 3 minutes)*	$8.5\ 10^{-3}$ kg/s	$1.24\ 10^{-1}$ kg/s	$8.5\ 10^{-3}$ kg/s
No vertical gradient: **U > 5 m/s ↔ Q/d_{inj}^2 > 203**	d_{inj} < 6,5 mm	d_{inj} < 24.7 mm	d_{inj} < 6.5 mm
No horizontal gradient: **U < 100 m/s ↔ Q/d_{inj}^2 < 1806**	Not applicable	d_{inj} > 8.3 mm	d_{inj} > 2.2 mm

Calculation was done for two real cases: one short tank (36, L/D < 3) and one long tank (531l, L/D > 3) from Hexagon, which were extensively tested during the project (see D4.1 public report). To get comparable results, a hypothetical case was also considered: a 36L tank, with a L/D ratio greater than 3. For both cases, minimal gas velocity is ensured by using an injector with a maximal diameter of 5.2 mm. For the long tank (L/D > 3), an additional criterion on injector diameter is needed to prevent horizontal gradient: diameter must be higher than a minimal value of 2.7 mm.

Remarks:

Remark #1

In contrary to received wisdom, reducing filling pressurization rate (i.e. reducing flow rate / increasing filling duration) ***does not necessarily*** reduce gas temperature.

While the mean gas temperature will be reduced, the gas velocity may fall below the value needed to get proper homogenisation.

Remark #2

Filling of a CHSS[1] like test bench (see Deliverable D5.1) was performed according to the SAE protocol: H70 / T20 / 7-10 kg / Communication (table D30), with an initial pressure of 50 bar and an ambient temperature of 30°C.

Stratification was observed at the end of filling: a difference of around 14°C was recorded between the mean and max temperature. These temperatures were measured on 36l Type IV tanks, which is not the Hot Case situation (as per SAE J2601). For the SAE Hot Case, the mean temperature would have reached 85°C (by protocol construction), and the maximum temperature would have reach up to 99°C (by analogy).

Table 3: SAE requirements vs. measurements

	SAE – Table D30	Measured
P_{init}	50 bar	53 bar
T_{amb}	30°C	32°C
APRR	4,4 MPa/min = 0,73 bar/s	5,2 MPa/min = 0,87 bar/s
P_{target}	871 bar	866 bar
$T_{delivery}$	-26°C < T < -17°C	-17°C

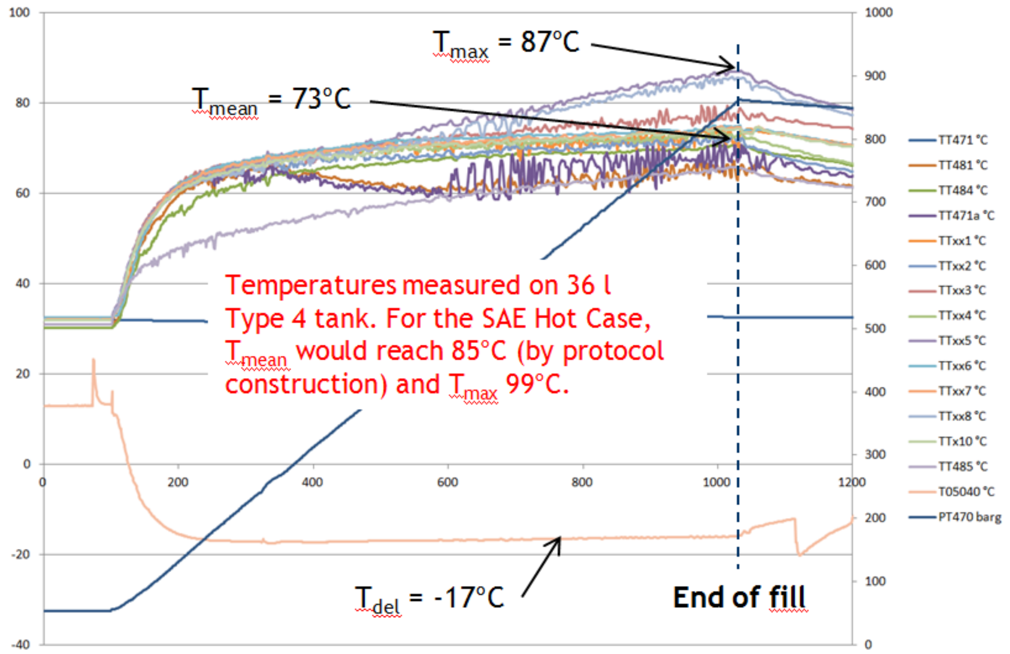


Figure 1: Temperature measurements during filling of the CHSS like test bench according to SAE protocol

[1] vehicle compressed hydrogen storage system

2.2 Recommendations for tank manufacturers

2.2.1 Recommendation #2

Establish the acceptability of transient peak liner surface temperatures of 95°C in Type 4 tanks in the rare event of Hot Case Situation without significant change to the tank design and testing requirements that are applicable today.

This recommendation is motivated by the following considerations:

- The Hot Case defines the worst-case situation in terms of vehicle tank system design, hydrogen refuelling station design, as well as tank initial conditions at time of fill in relation to the ambient temperature. For instance, the initial tank temperature is assumed to be up to 20°C higher than the ambient temperature and the initial pressure is assumed to be only 0.5 MPa[2].
- While this worst-case situation combining all the worst case conditions will seldom occur, it is the one systematically taken into account for defining the measures to be applied to all fills.
- When the ambient temperature exceeds approximately 15°C, the filling to 100% SoC of a depleted tank assuming a Hot Case situation is not possible in 3 min while keeping the delivery temperature above the minimum limit of -40°C.
- Since actually experiencing a Hot Case situation is rare, the new fuelling approach targets slightly derated end-of-fill conditions for the Hot Case: 97% SoC at the maximum delivery pressure of 87.5 MPa, instead of 100% SoC.

  These derated conditions for the Hot Case are defined in such a way that the maximum liner surface does not exceed 95°C. In these conditions, a thin layer of liner material (of maximum 2.5 mm thickness) temporarily exceeds 85°C (for a few minutes, depending on the size of the tank and the delivery temperature profile) without exceeding the maximum liner surface temperature of 95°C.
- Even if a Hot Case situation prevailed at every fill, the cumulated duration of this liner over-temperature in the lifetime of the tank (15 years) would only be a few tens of hours (depending on the size of the vessels constituting the tank). This is expected to be acceptable because the tank is qualified for long duration exposure to 85°C and 87.5 MPa, which generates more creep than the much shorter cumulated duration exposure to an over-temperature of 95°C reached in Hot Case situations. This behaviour is expected to be ensured when the liner material's Vicat Softening Temperature (VST) specification exceeds

[2] Without regards to the measured initial tank pressure, in order to take into account the possibility that the refuelling immediately follows an aborted attempt starting from the lowest possible initial pressure of 0.5 MPa. This conservative hypothesis could be further adjusted in the future, taking into account the fact that the total duration of the consecutive refuelling events will last longer than a single fuelling event.

the 95°C peak temperature by at least 15°C, which is the case for commonly used liner materials such as HDPE and PA based thermoplastic, with VST values of approximately 130°C[3] and 200°C[4] respectively. Creep of the liner is the only identified potentially detrimental phenomenon that could result from increasing the maximum peak liner surface temperature from 85°C to 95°C[5].

The objective is to establish that Type IV tanks can safely be filled in conditions that may in the worst case lead to a maximum liner surface peak temperature of 95°C without changing the minimum (-40°C) and maximum temperature (+85°C) at which the tanks are currently hydraulically tested, adjusting only requirements relating to the behavior of the plastic liner material.

Two possibilities are proposed by the consortium:

- EU regulation 406/2010 currently requires the Vicat softening temperature (VST) specification of the liner material to exceed 100°C, i.e. 15°C above the 85°C maximum gas temperature that can currently be encountered. In order to allow the maximum temperature encountered by the liner surface in contact with the gas to reach 95°C in the rare event of a Hot Case situation, the liner material VST specification should exceed 110°C.
- Modify the currently applied gas cycling test (as required by GTR 13, EU 406/2010 and ISO/CD 19881), in order to include a peak liner surface temperature of at least 95°C on a fraction of lifetime cycles (instead of keeping the gas temperature below 85°C as currently required) is another way of demonstrating suitability for service with the new Hot Case filling criterion.

Type IV pressure vessels as currently constructed are expected to be suitable for service with the new Hot Case end-of-fill criterion[6]. The appropriate way to ensure this for existing and future Type IV tanks designs needs to be established amongst the concerned vehicle OEM's and tank suppliers. Specific points to be addressed are covered in part 3.

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[3] http://www.ineos.com/globalassets/ineos-group/businesses/ineos-olefins-and-polymers-usa/products/technical-information--patents/ineos-typical-engineering-properties-of-hdpe.pdf

[4] C. Dallner et al, Thermische Einsatzgrensen von Kunststoffen Teil II Dynamisch-mechanische Analyse unter Last, Journal of Plastics Technology

[5] See analysis in section 3.

[6] The maximum temperature limit for short term exposure of polymers such as HDPE and PA exceeds 100 °C – see for example C. Dallner et al, Thermische Einsatzgrensen von Kunststoffen Teil II Dynamisch-mechanische Analyse unter Last, Journal of Plastics Technology

2.3 Recommendations for HRS manufacturers

2.3.1 Recommendation #3

Prepare the pilot implementation of the HyTransfer protocol.

Following the investigation and validation of fuelling protocol optimization opportunities, the HyTransfer project has resulted in the proposal of a new protocol exploiting these opportunities with significant quantifiable benefits in terms of fuelling duration, HRS construction and operating costs.

The HyTransfer protocol implements the following four optimization opportunities:

- control of the end-of fill temperature through control of the mass-averaged delivery temperature, in order to avoid strict limits on the instantaneous delivery temperature, which can in practice be difficult to observe.
- adjustment of the required delivery temperature to the ambient temperature
- acceptance of sub-nominal (“derated”) end-of-fill conditions in Hot Case situations (see recommendation #2)
- minimizing station piping heat capacity and pressure drop (see recommendation 4 below)

It should be noted that each of four opportunities are independent of each other and need not be applied all at once, although benefits are maximized by applying them together (see WP6 Techno-economic analysis). An initial step could consist in applying the first two opportunities.

The most effective way to pursue development is to prepare a pilot implementation and evaluation program together with interested vehicle OEMs. This includes performing a risk analysis (see section 3)

2.3.2 Recommendation #4

Minimize piping heat capacity (mass) and pressure drop downstream of cooling

Piping heat capacity and pressure losses increase the level of cooling that needs to be applied. Therefore, to reduce as much as possible the level of cooling, piping heat capacity and pressure drop must be minimized.

This is particularly important in the station downstream of the point where the fuel delivery temperature is specified (just upstream of fuelling assembly break-away) and in the vehicle, since the worst case configuration will define the Hot Case situation impacting the fuelling requirements applied in all fuelling stations and for all vehicles. Piping heat capacity and pressure drop in the piping both contribute to lowering the required delivery temperature for avoiding overheating inside the tank. Piping heat capacity is particularly detrimental for high ambient temperatures (large amount of heat communicated to the gas before it reaches the tank), whereas pressure drop will impact to a lesser extent the required delivery temperature (assuming it is adjusted to needs) similarly for all ambient temperatures.

The actual pressure drop in the fuelling station can be taken into account if the fuelling tables are calculated accordingly.

Calculations performed in HyTransfer made the following assumptions:

1/ For the pressure drop:

Dispenser temperature	-20°C
Initial pressure in the vehicle	100 bar
Mass flow rate	1,5 times the average mass flow rate where the average mass flow rate is such that the filling of the vehicle is made from the initial density to the nominal density in three minutes
Initial density	@ 20 bar, 15°C
Nominal density	@ 700 bar, 15°C
Pressure loss in the vehicle	200 bar
Pressure loss in the station	**50 bar** (*)

(*)Pressure drop is estimated to 150 bar by SAE. In the course of the HyTransfer project, we have assumed that it can be diminished to 50 bar, which is a realistic assumption.

2/ For the piping heat capacity: The assumptions taken for the Hot Case for our recommendations are:

- Maximum station thermal mass of 2300 J/K

Degraded assumption compared to SAE which suggests a maximum of 5500 J/kg.

- Maximum vehicle thermal mass of 2600 J/kg

Same assumption as SAE.

Another possibility is that tables are designed specifically from one station to the other, depending on the possibility or not to reduce the thermal mass and pressure drop.

3 SPECIFIC POINTS TO BE ADDRESSED IN THE NEXT STEPS

The following next steps are foreseen in light of the expressed recommendations.

3.1 Avoidance of non-homogeneous temperatures

Practical measures need to be defined and introduced in standards for ensuring that vehicle tank systems are and remain equipped with in-tank valves providing an adequate injection velocity (see section 2.1.1).

Another question that should be addressed is the situation of the car already on the road: what is the actual range of injection diameters? To what extent are they exposed to stratified conditions and what is the maximum temperature that is reached? How should the existing vehicles be taken into consideration in the new protocols and their underlying model?

The indicator for horizontal temperature gradients is based on a very limited number of experiments and should be further validated. Horizontal heterogeneities are likely in tanks with an L/D of 4, which is not uncommon, at least at the beginning of the filling. However, this may be acceptable if a mixed regime appears in the course of fill before excessive temperatures are reached at the opposite end.

3.2 Modelling assumptions analysis

On the modelling part, some additional points need to be studied:

- Heat transfer correlations:
    - The hot / cold case tank designs assumptions considered for protocol definition are rather different from the tanks tested in the course of the project. In order to use our model we have made assumptions on what the heat exchanges can be for these hot or cold case tanks. These assumptions would need to be validated. If not possible, an estimation of the impact of mis-estimation of the heat exchange coefficient should be done.
    - We have suggested that the tank integrators choose the injection (diameter, shape) in their tank so that the tank stays in homogeneous regime. Some very peculiar injection types have been envisioned (e.g. radial injection with multiple holes). These peculiar types of injection are not taken into consideration by the model as it is, especially: what is the impact of that choice of injection on the heat exchanges?

- Heat exchange in the piping upstream of tank (see 2.3.2) :
    - In its current version, the model performs only a global energy balance on the piping. For this reason, in some cases of high ambient temperature (e.g. > 30°C) and low pressure (e.g. 20 bar) the model does not correctly predict the evolution of delivery temperature throughout the filling. Only the final gas temperature is correctly predicted. In order to validate that the

temperature limitations in the tank are not exceeded throughout the filling, a more complex modelling of the piping is needed. With this, a dispenser temperature "corridor" will be provided along the protocol. This "corridor" should be followed by the station.

- Pressure loss in the piping :
    - The pressure loss is modelled with an equivalent valve parameter. The fact that this simple modelling is sufficient to account for pressure losses between the dispenser and different tanks has not been verified.

- Additional mathematical modeling validation (see conclusion of D3.4).

- Choice of hot and cold case:
    - Are we confident in the hot and cold case chosen by the SAE? Are these really the hottest and coldest case possible? Or are these on the contrary over-conservative, considering the tank designs actually in use?
    - Some elements are not included in the definition of these hot and cold cases and should be determined :
        - Should we add bosses for the hot case, as has been currently done for the building of the new protocol tables?
        - What injection diameter should we consider for the hot/cold case?
        - Heat exchanges around the tank: validate these have a null impact for a 3 minute fill.

- Material exceeding 85°C :
    - With a type III tank: applying the filling conditions defined based on reaching 95°C liner surface temperature for the Hot Case (Type IV tank), can 85°C be exceeded in the composite with a type III tank?
    - In the dome part, the liner thickness can be slightly lower: is this a concern regarding 85°C reaching the composite? In principle, the answer to this being that specifying the liner thickness in the dome part over 2,5 mm will ensure that 85°C is not reached in the composite.

The definition of the Hot Case is currently based on a deterministic combination of conservative assumptions. A probabilistic approach, considering probabilities of occurrence, probabilities of tank failure in function of the deviation magnitude, and a tank reliability target (as already applied in certain fields of structural design) could also be investigated.

3.3 Acceptance of transient peak liner surface temperature of 95°C in Type 4 tanks

3.3.1 Review of the potential impacts of the proposed new Hot Case end-of-fill criterion

The proposed new Hot Case end-of-fill criterion results in the general increase of end-of-fill temperatures by 10 to 15°C. In real cases (by opposition to hot cases), these will nonetheless likely not exceed 85°C, allowing a 100% SoC to be reached (for communication fills).

In the event a Hot Case situation occurs, the liner surface temperature can momentarily reach 95°C. Material temperatures exceeding 85°C will only be found within 2.5 mm of the liner surface, for a duration not exceeding a few minutes, depending the size of the vessel constituting the tank.

The table below provides the analysis of the potential impacts of this change of end-of-fill conditions.

Table 4: Potential impacts due to new end-of-fill conditions

Impact	Analysis
Effect on other on-tank components?	- Valve, PRD and seals are qualified for operation at up to 85°C. - These components are all part of the metallic valve-boss assembly in thermal contact with the cold delivered gas; the maximum temperature they reach during fuelling is therefore much lower than 85°C (typically 30°C lower than the gas temperature) and not significantly impacted by the gas temperature inside the tank. - The main effect of the new criterion is that these components will not be exposed to the low delivery temperatures (<-33°C) currently applied and will be operated at temperatures closer to ambient, which is expected to be beneficial for sealing reliability.
Impact on the liner-boss junction?	- Due to their thermal capacity, the maximum temperature reached by the bosses is typically 30°C lower than the maximum gas temperature. The temperature at the liner-boss junction at both ends therefore does not exceed the qualification test temperature of 85°C.
Impact on liner aging?	- The maximum amount of time that the liner could be exposed to temperatures between 85°C and 95°C is about 30 hours over tank lifetime. - Semi-crystalline thermoplastics such as HDPE and PA are chemically stable and not susceptible to degradation from exposure to temperatures up to

	melt temperature (exceeding 130°C and 200°C respectively).
Effect on H2 permeation?	- The steady state permeation rate approximately doubles with a temperature increase of 10-15°C. - However, an additional temperature elevation of 10-15°C lasting only a few minutes will not significantly impact the amount of H2 permeated, since the response time of the permeation phenomena (reflected by the time required to reach a stationary regime) is much greater (hours to days).
Impact on the high temperature detection in the vehicles?	- In Hot Case refuelling conditions, the bulk gas temperature may reach up to 95°C at end of fill. - The set point of the high temperature detection in the vehicles will need to be increased (e.g. to 95°C), otherwise the fuelling process will be aborted before the target SoC is reached in situations close to the Hot Case. - Sensor accuracy requirements would remain unchanged.
Impact in case of non-homogenous gas temperature?	- Non-homogeneous temperatures need to be prevented already today through requirements on injection conditions or on-tank valve qualification. - Shorter filling durations resulting from the new criteria, reduce the likelihood of stratification (due to increased injection velocity). However higher max temperatures (by 10-15°C) can be expected in the event stratification still occurs (e.g. due to a still too large injection diameter). - This increases the importance of ensuring, by design of the in-tank valve, that stratification is avoided during 3 minutes fills.
Impact on the risk of overheating?	- The application of the new criterion leads to a general increase of end-of-fill temperatures of 10-15 °C. - However this does not change the potential severity of a failure to apply cooling (worst case event). - The use of a single indicator - the mass averaged temperature which must be kept below a certain value set in function of the ambient temperature – and application of a fixed pressure ramp rate are expected to be beneficial for process control reliability.

3.3.2 Points to be further addressed

The following questions need to be addressed through further analysis:

- Further define liner material tests and design qualification tests allowing to establish that the liner remains unaffected by the exposure to a transient peak surface temperatures of 95°C, with minimal change to existing RCS requirements.
  - ➢ It is proposed above to investigate the use of the Vicat Softening Temperature (VST) for demonstrating this, considering also the effect of elevated pressure on the viscoelastic behaviour of the material[7].
  - ➢ Therefore more research work is needed to: 1/ better understand how short duration exposures to over temperature affect liner characteristics; and 2/ define a representative qualification test for liner material.
- Verify that the tank designs currently in use meet these requirements with sufficient margins so that the probability for a failure of the cylinder remains on the same level as for max 85°C.

3.4 Pilot implementation of the HyTransfer protocol

3.4.1 Risk analysis

The main remaining step prior to pilot implementation is to perform an FMEA[8] of the new protocol proposal in order to specify the measures required for achieving the required level of process control safety, considering each potential deviation (such as a sensor failure, a flow control valve failure, etc.) along with the severity of its consequences.

This will provide the requirements for ensuring safe and reliable implementation of the new protocol.

3.4.2 Impact of the new protocol on end-of-fill conditions of vehicles in real life conditions

A key statement associated to the new protocol proposal is that although end of fill temperatures will generally be increased by 10 to 15°C, these will likely remain below 85°C (in actual situations as opposed to the theoretical Hot Case situation), allowing the tank to be filled to 100% SoC.

Examination of recorded data on end-of-fill conditions will help establish consensus on this point.

[7] known to have the same effect as a decrease of temperature

[8] Failure modes and effects analysis

4 CONCLUSIONS

Recommendations are addressed to Industry for applying the findings of the HyTransfer project, with regards to prevention of temperature stratification, implementation of the HyTransfer protocol proposal, and establishing the acceptability of a peak liner surface temperature of 95°C in tanks as currently designed.

The definition of the Hot Case, as well as the peak liner surface temperature that is acceptable in that situation critically defines the level of cooling required for all fills. This point is therefore central with regards to realizing the significant potential HRS cost savings that have been identified.

As an overall conclusion, the HyTransfer filling protocol proposal shows a strong interest from an economic point of view in allowing the liner surface to be exposed for a total of a few hours in their lifetime to temperatures slightly higher than the currently applied limit (95°C instead of 85°C). There are two possible paths forward:

- Either, we can demonstrate by testing that tanks as currently designed can withstand without noticeable impact on the level of safety higher gas temperatures over a short period (without changing the design and testing requirements), also taking into considerations malfunctions in the control system of the fill process. To that end, risks and consequences of an overheating must be quantified in a risk analysis. For that, more work is needed on the tank to better understand the impact of exposing the tank to higher peak gas temperatures.
- Or we demonstrate that risks and consequences are not acceptable. In that case, design and/or testing requirements would need to be changed in RCS, with a potentially significant impact on the tank cost. In this case, an overall techno-economic analysis needs to be performed, taking into account a higher cost for the tank (to be quantified), for demonstrating that it is still interesting from an economic point of view to accept higher peak gas temperatures.

RCS for refuelling protocol will need to be improved eventually when taking into account new improvements in HRS and vehicle tank designs, new liner materials, wider operating temperature range and other requirements.