2nd Workshop | Webcon | 23 APRIL 2020

PRHYDE-Protocol for heavy-duty hydrogen refuelling

Call Identifier FCH-04-2-2019:
Refuelling Protocols for Medium and Heavy-Duty Vehicles

H_2 PRHYDE
Protocol for heavy-duty Hydrogen refuelling

Horizon 2020
European Union Funding
for Research & Innovation

FCH
FUEL CELLS AND HYDROGEN JOINT UNDERTAKING

AGENDA, 2nd Workshop (1/2)

Time (CET)	Subject
14:45	*Join webinar*
15:00	Introduction to project
15:10	Summary of first webinar
15:20	PRHYDE deliverable D2.1: Performance targets for refuelling protocols for heavy duty hydrogen vehicles
15:35	PRHYDE deliverable D2.2: Requirements for safe heavy duty gaseous hydrogen vehicle refuelling
15:50	PRHYDE deliverable D2.3: Gap analysis of existing heavy duty gaseous hydrogen vehicle refuelling protocols

AGENDA, 2nd Workshop (2/2)

PRHYDE
Protocol for heavy-duty Hydrogen refuelling

Time (CET)	Subject
16:15	PRHYDE deliverable D2.4: Gap analysis of existing hardware used for heavy duty gaseous hydrogen vehicle refuelling
16:30	PRHYDE deliverable D2.5: Analysis of existing non-gaseous hydrogen refuelling protocols or applications
16:35	PRHYDE deliverable D3.1: Report on the characteristics of the cases to be simulated in the preliminary simulations
16:50	Next steps / Plans for smaller web meetings (anticipated in May)
17:00	*End*

Introduction

- *PRHYDE-Protocol for heavy-duty hydrogen refuelling*
  Refuelling Protocols for Medium and Heavy-Duty Vehicles
- 01 JAN 2020 - 31 DEC 2021
- The PRHYDE project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under grant agreement No 874997.
  This Joint Undertaking receives support from the European Union's Horizon 2020 research and innovation programme.

Objectives of PRHYDE (1/3)

- Identify relevant requirements for HDV fuelling - in particular with regards:
  – to driving range,
  – fuelling time,
  – tank sizes,
  – average kg/fill,
  – SoC, and
  – customer impact, particularly taking the commercial boundary conditions of typical HDV operators into account

Objectives of PRHYDE (2/3)

- Identify limitations and gaps of current fuelling hardware capability (for HDV):
  - Capability of state-of-the-art nozzle and receptacle to achieve the flow required for HDV and potential gaps
  - Capability of state-of-the-art vehicle data collection and communication hardware to achieve sufficiently reliable data collection and communication of vehicle data to station and potential gaps
  - Consider how a potential HDV fuelling protocol is to navigate and transition from current state-of-the-art component capability to a future required capability/norm

Objectives of PRHYDE (3/3)

- Develop concept(s) for HDV fuelling protocol(s)
- Validate the impact of HDV fuelling protocol(s) concept(s) on achieving key metrics (temperature and pressure) on the vehicle side
  - through tank refuelling simulation with simplified model and CFD approaches
  - through experimental validations on fuelling of tank(s) at station(s).
- Formulate recommendations (outcome of project) for HDV fuelling protocol(s) for use in relevant standardization forums – with the aim of eventually achieving standardization.

PRHYDE project partners

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No.	Participant organisation name	Short name	Country
1	Ludwig-Bölkow-Systemtechnik GmbH (Coordinator)	LBST	DE
2	Zentrum für BrennstoffzellenTechnik GmbH	ZBT	DE
3	Air Liquide SA	AL	FR
4	Engie Lab CRIGEN	ENGIE	FR
5	Toyota Motor Europe NV	TME	BE
6	ITM Power (Trading) Limited	ITM	UK
7	NEL Hydrogen AS	NEL	DK
8	Shell Deutschland Oil GmbH	SHELL	DE
9	Commissariat à l'énergie atomique et aux énergies alternatives	CEA	FR
10	Nikola Motor Company	Nikola	USA

Third linked partners: MAN and Toyota North America

Work plan

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WP2 – State-of-the-art & specification

Iterative process

WP3 – Protocol development | **35MPa**

WP4 – Simulations | **50MPa**

WP5 – Experimental validations | **70MPa**

WP6 – Recommendations and dissemination

WP7 – Project coordination

WP2: Defining state-of-the-art on protocols, vehicles and component capabilities, gap analysis of current protocols, Specifying (new) tank categories, boundary conditions (flow temperature, connections etc.) target fueling times and quantities for the three pressure levels

Outcome: A detailed specification guiding the following protocol development and test efforts

WP3: Develop protocol approaches for the three pressure levels

Outcome: Protocol approaches for simulations (WP3) and test (WP4)

WP4: Modeling and Simulations of tank systems/categories to determine flow/temperature/pressure aspects

Outcome: Simulation results in order to assess impact of different protocol approaches

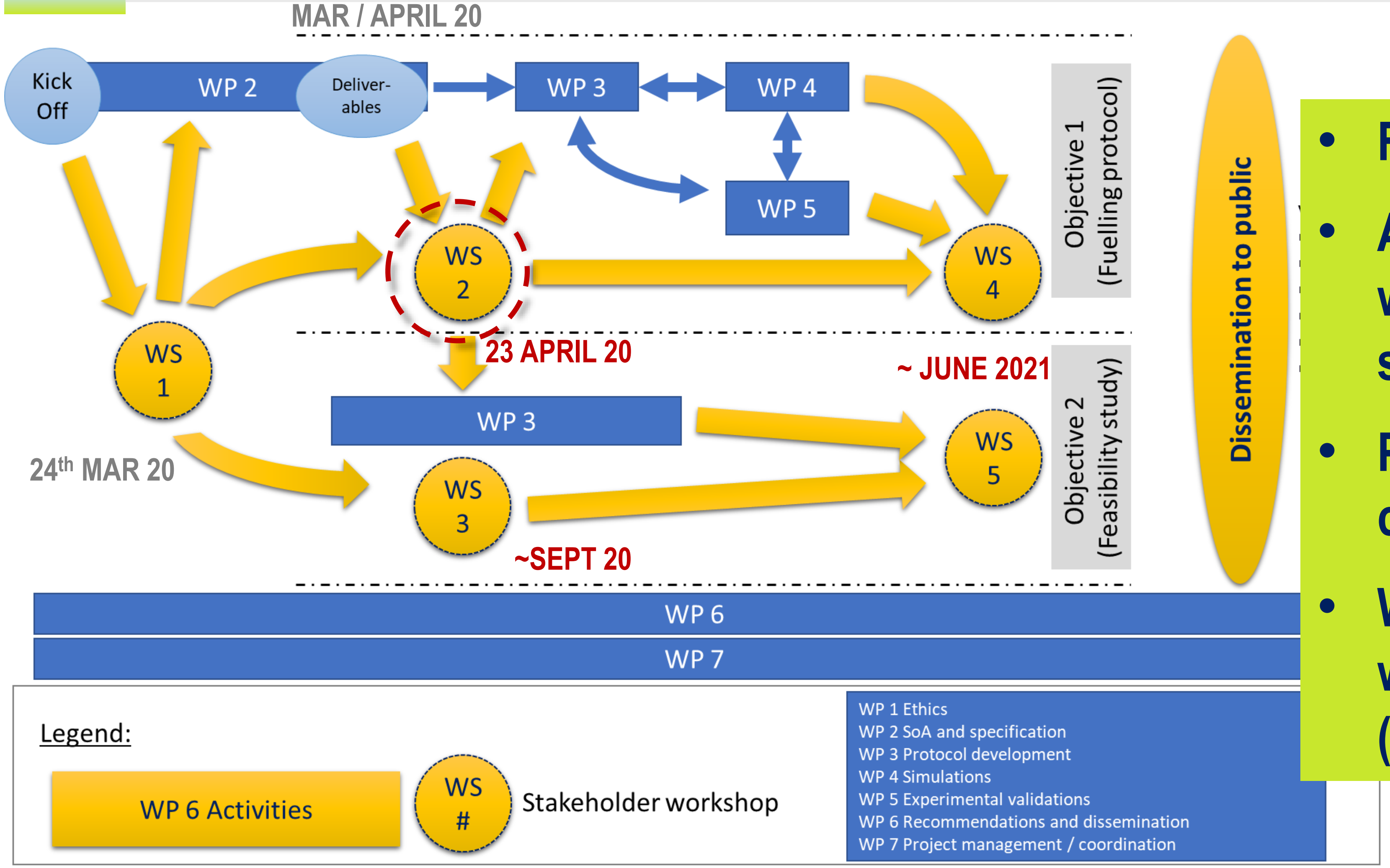
WP5: Experimental validation of protocol approaches at HRS(s)

Outcome: Validation of technical feasibility of protocol approaches

WP6: Formulate recommendations for standardization forums and dissemination

Outcome: Specific recommendations that can help create international standards on HDV hydrogen fueling

Work plan – workshops (in-person meetings)



- **Five Workshops in 24 months**
- **After first two WS (→only webinars) additional inputs from stakeholders are requested**
- **Please provide written feedback / comments to PRHYDE**
- **We plan to organise additional webinars with small number of (invited) participants**

First workshop (webinar) summary

- Held on 24th March 2020, ~130 people in attendance
- Summary of anticipated activities in PRHYDE project
- Additional presentations from consortium members and invited guests to help gather information on State of the Art

- Faun (Bluepower): Georg Sandkühler
- Air Products (communications): Joe Cohen
- CEP (protocol): Benjamin Coiffier, Air Liquide
- HySpeed (protocol project): Roel de Natris, TNO

- SAE status update:
  - Nico Bouwkamp (SAE J2600 & J2601-2 document sponsor)
  - Steve Mathison (SAE J2601 document sponsor)

First workshop (webinar) – what remains?

- Presented some of the summarised survey responses – remainder to come today
- Received and answered some questions – difficult to really discuss in webinar forum ⇨ once PRHYDE deliverables are available, distribute & request feedback for discussion in small web based workshops (May)
- (Where possible, presentations to be uploaded to PRHYDE website)

Overview: WP2 State of the Art (SoA) and specifications

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- WP2 Leader: Paul Karzel, Shell
- Objectives

WP2 has as an aim to review the current state of art, set targets for future protocols and to perform a gap analysis between the status quo and the requirements of future protocols.

- Split into 6 deliverables:
  - 5 on State of the Art,
  - 1 developing the framework to be used for fuelling protocol development activities in PRHYDE
- First 5 deliverables to be presented today – with a view to receiving feedback from external stakeholders ⇨ to guide final deliverable ⇨ hand over to WP3

Introduction to deliverables being prepared for publication

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- Running order:

Subsection	Presenter	Slides
PRHYDE deliverable D2.1: Performance targets for refuelling protocols for heavy duty hydrogen vehicles	*Quentin Nouvelot*	*Included*
PRHYDE deliverable D2.2: Requirements for safe heavy duty gaseous hydrogen vehicle refuelling	*Lena Glatz, Nick Hart*	*Included*
Related topic: Safety Watchdog concept	*Elena Vyazmina*	*Included*
PRHYDE deliverable D2.3: Gap analysis of existing heavy duty gaseous hydrogen vehicle refuelling protocols	*Nick Hart*	*Included*
Related topic: Presentation by FillnDrive (~16:00)	*Adrien Zanoto*	*Separate slide pack*

Introduction to deliverables being prepared for publication

- Running order:

Subsection	Presenter	Slides
PRHYDE deliverable D2.4: *Gap analysis of existing hardware used for heavy duty gaseous hydrogen vehicle refuelling*	*Nick Hart,* *Quentin Nouvelot*	*Included*
PRHYDE deliverable D2.5: *Analysis of existing non-gaseous hydrogen refuelling protocols or applications*	*Nick Hart*	*Included*
WP3 summary *PRHYDE deliverable D3.1:* *Report on the characteristics of the cases to be studied in the preliminary simulations*	*Claus Sinding*	*Included*

D2.1: Contents

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Performance targets for refuelling protocols for heavy duty hydrogen vehicles

- Intro
- Fossil parity requirements
- Selected use cases and associated technical target
  - Heavy duty road vehicles
  - Non-Road vehicles
  - Possible performance targets for different applications
- Economical aspects

D2.1: Fossil parity requirement

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- Four main refueling performance criteria that determine the fossil parity are
  - cost
  - range (amount of H_2 stored)
  - time to refuel.
  - state of charge (SoC)
- Achieving refueling performance fossil parity will create market pull
- Performance criteria can be adjusted to usage if relevant

D2.1: Many potential applications

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D2.1: Heavy duty road vehicles – Definition and categories

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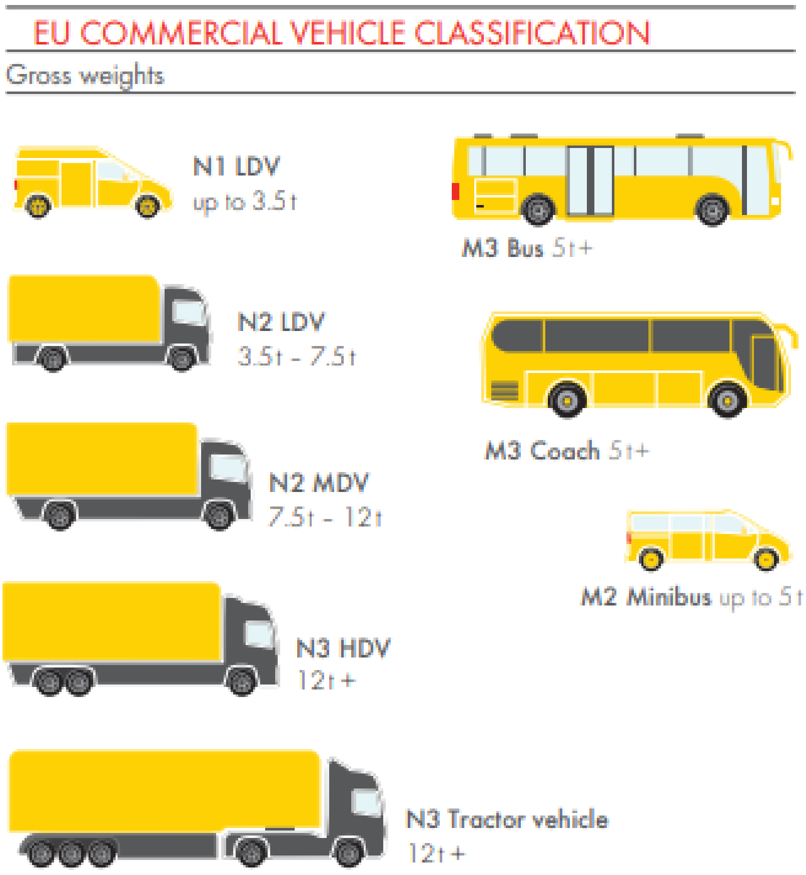
- Different definition of HDV and MDV around the world
- Vehicle categories in Europe
  - Category M: carriage of passengers
  - Category N: carriage of goods.



D2.1: Heavy duty road vehicles - performances

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- N3 tractor trailer vehicles in long haul use and M3 coaches seems the more challenging use case :
  - 1000 km range => ~ 80 kg H2
  - 10 min refueling
- M2 and N2 vehicles and smaller N3 vehicles with less range requirements, the performance can be lower :
  - 10-40kg H2
  - 5-8min refueling

D2.1: Heavy duty - Non-Road vehicles

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Train

- SoA and business case report
- Different business case study :
  - regional passenger trains
  - Mainline locomotive
  - Shunter etc…
- storage capacity range : 150 – 500 kg
- Expected refueling time : 15-30 min

Inland ships

- Study from NOW in Germany

	Leistung (kW$_{mech}$)	Tankgröße CGH_2 (kg H_2)
Gütermotor-schiff (Europaschiff)	706	4.569
Schubverband	400	874
Tagesausflugs-schiff	132	282
Kabinenschiff	2.100	20.576

STROMBASIERTE KRAFTSTOFFE FÜR BRENNSTOFFZELLEN IN DER BINNENSCHIFFFAHRT
Studie im Auftrag des BMVI
NOW-GMBH.DE

- storage capacity range : 300 – 20 000 kg
- Expected refueling time : 20-40 min

D2.1: Heavy duty – possible performance target

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	CHSS capacity [kg]	Ideal target fill time [min]	Corresponding maximum anticipated average H2 flow [kg/min]
N1 commercial vehicle (included for comparative purposes)	2-10	3-5	2
N2 commercial vehicle	10-40	10	4
N3 commercial vehicle	40-80	10	8
M2 passenger carrier	10-40	8	5
M3 passenger carrier	30-100	12	8
Train, low case	150	10	15
Train, high case	500	15	33*
Inland ship, bulk carrier	4.500	60	75**
Inland ship, push barge	900	60	15
Inland ship, day cruise	300	60	5

State of charge ⇨ approaching 100% SoC is challenging form safety point of view

⇨ 90-95% estimated as reasonable value, acceptable by the final user and achievable under safe conditions

D2.1: Economical aspects

- Refueling protocols impact HRS Capex and Opex and then H2 fuel cost
- Trade-off between cost and technical performances
- Refueling protocol should match the performance targets while not exceeding the necessary flow rate and cooling needed to do so

D2.2: Contents

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Requirements for safe heavy duty gaseous hydrogen vehicle refuelling

- Intro
- Risk Assessment – Methodology
- Scenarios & Challenges
- Summary and Forecast

⇨ Related topic: "Safety watchdog"

Intro

- First initiative for a risk assessment of the refueling process in 2015 for ISO TC197 WG24
- Risk assessment continues to be evolved by EIGA (European Industrial Gas Association)
- Methodology of risk assessment corresponds with technical safety engineering approach of process industry and is a solid and verified globally applied process
- There are overall recommendations based on a risk assessment workshop for LD refueling based on SAE J 2601, held in 2019 by EIGA which are the basis for a specific risk assessment for the HD hydrogen refueling process, to be carried out in this project
- The results and updates of the EIGA risk assessment are continuously presented to ISO TC197, SAE Interface task force and UN-GTR13

Risk Assessment Methodology – SIS/SIL/SIF

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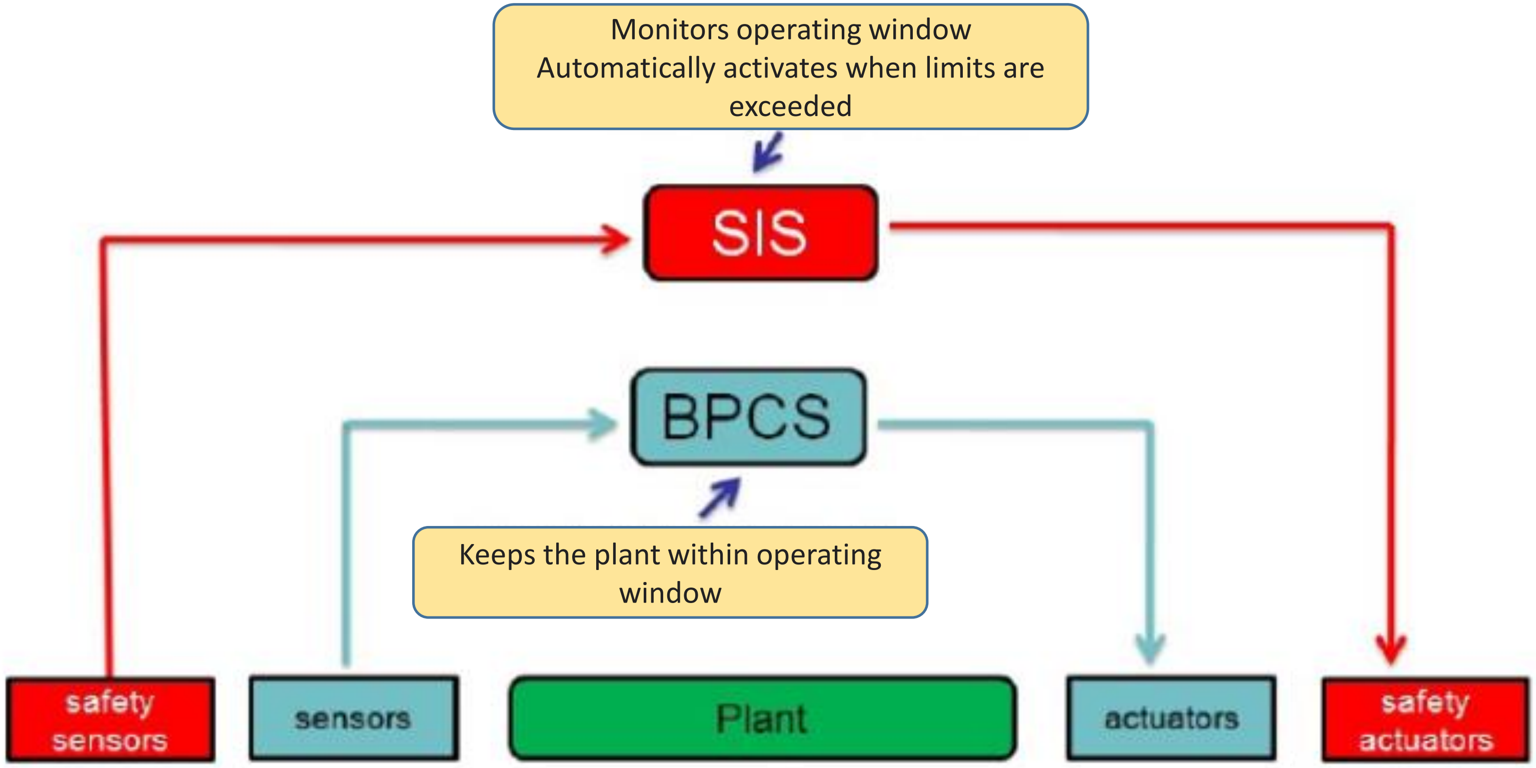
- Safety Instrumented System (SIS): performing Safety Instrumented Functions (SIF)
- Safety Sensors
- Logic Solver (PLC)
- Safety Actuator

- Safety Integrity Level (SIL):
  Determining the Probability of Failure on Demand of a SIF to a given risk:

SIL	Required PFD as per IEC61511
1	$10^{-2} \leq PFD < 10^{-1}$
2	$10^{-3} \leq PFD < 10^{-2}$
3	$10^{-4} \leq PFD < 10^{-3}$
4 *	$10^{-5} \leq PFD < 10^{-4}$



Risk Assessment Methodology – HRS Bow Tie LOPA : Ramp Rate Control Failure

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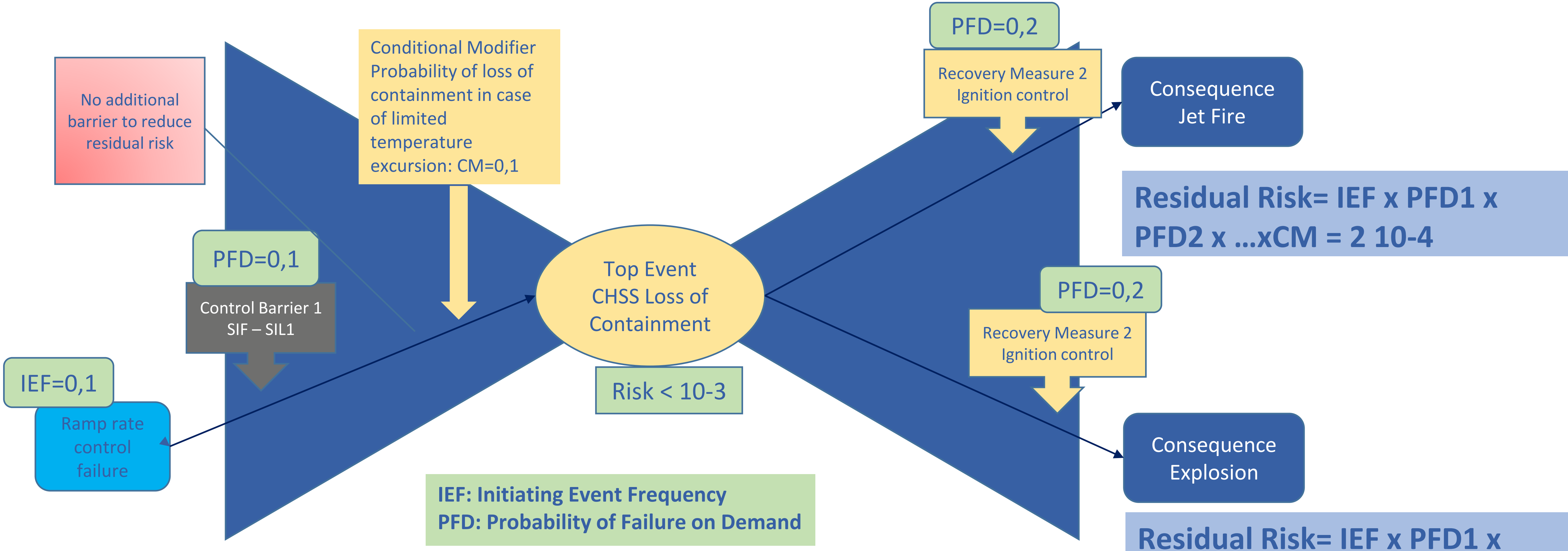
IEF=0,1 ✖ PFD=0,1 ✖ CM=0.1 = Risk < 10-3 ✖ PFD=0,2 = Residual Risk < 2 x 10-4



Residual Risk= IEF x PFD1 x PFD2 x … = 2 10-4

Scenarios and Challenges - HRS Bow Tie LOPA : Synthesis

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Scenario	Initiating Event	Effect	Top Event	Top Event probability	Consequence/ Residual Risk
Pressure control failure	Control Loop failure	Overpressure	CHSS burst	< 10 -7	Pressure wave: 10-7
Loss of cooling	Control Loop failure	Overtemp: T up to 140°C	Loss of containment	<10-5	Fire 2 x 10-6 Explosion 2 x 10-6
Wrong Ambient temperature measured	Control Loop failure	Too high APRR Overtemp: T <120°C	Loss of containment	<10-4	Fire 2 x 10-5 Explosion 2 x 10-5
Incorrect tank size selection	Control loop failure/Incorrect communication	Overtemp<100°C (hot soak)	Loss of containment	None assumed	None assumed
Failure Pressure Ramp rate control	Control Loop failure	Overtemp ~120°C	Loss of containment	<10-4	Fire 2 x 10-5 Explosion 2 x 10-5
Wrong dispenser temperature class used for ramp selection	Control Loop failure	Overtemp < 105°C	Loss of containment	None assumed	None assumed
Failure of Low Temp Control (LH2 storage)				TBD	TBD

Assuming a SIL 2 level on PRR control

2 Higher residual risk scenarios.
Both resulting in uncontrolled APRR

Risk mitigation

	Solution	Pro	Cons	Solves the pb?	Burden on HRS	Burden on Car	Liability in case of damage due to Loss of control
Adding Barriers	1) Increase SIL Level on HRS	No change on car	Cost + on station Adding a Lot of instrument. Feasibility not granted Is it realistic to obtain it from all HRS suppliers?	Residual risk reduced by 1 order of magnitude Residual Risk < 3.5/y	+++	0	HRS
	2) Temp signal to HRS	Allows other protocol optimization And enhanced refueling + other concerns (successive refueling…)	ASIL temp Secure com Still needs an additional valve on HRS side to count as fully independant Prohibiting non com refueling	Residual risk reduced by 1 order of magnitude (up to 2 depending on SIL level on temp signal) Residual Risk once every 3y (with SIL2)	+	++	HRS or Car. Depending on the cause
	3) Abort signal to HRS	Does not involve HRS BPCS or PLC	Similar to #2	Residual risk reduced by 1 order of magnitude (up to 2 depending on SIL level on temp signal) Residual Risk once every 3y (with SIL2)	+	++	HRS or Car. Depending on Cause
	4) On board valve	Car in control of its safety	Cost + on car Need to keep energy on during fueling Pressure drop Mass Would it make sense to complexify the vehicle.	Residual risk reduced by 2 order of magnitude (depending on SIL level) Residual Risk once every 3y (with SIL2)	0	+++	Car

Risk mitigation

	Solution	Pro	Cons	Solves the pb?	Burden on HRS	Burden on Car	Liability in case of damage due to Loss of control
Adding Barriers	5) Modify Protocol	Allows other protocol optimization	ASIL temp Secure com Still needs an additional valve on HRS side to count as fully independant Prohibiting non com refueling	No reduction of residual risk (BPCS dependant)	+	++	
Limit the effects	6) Make CHSS tolerant to PRR control failure	No change on HRS Positive effects on CHSS resislience to improper refueling	Need to change the qualification requirement on CHSS	Yes Risk eliminated	0	+	No damage due to loss of control

Summary and Forecast – Identified approaches for further risk reduction

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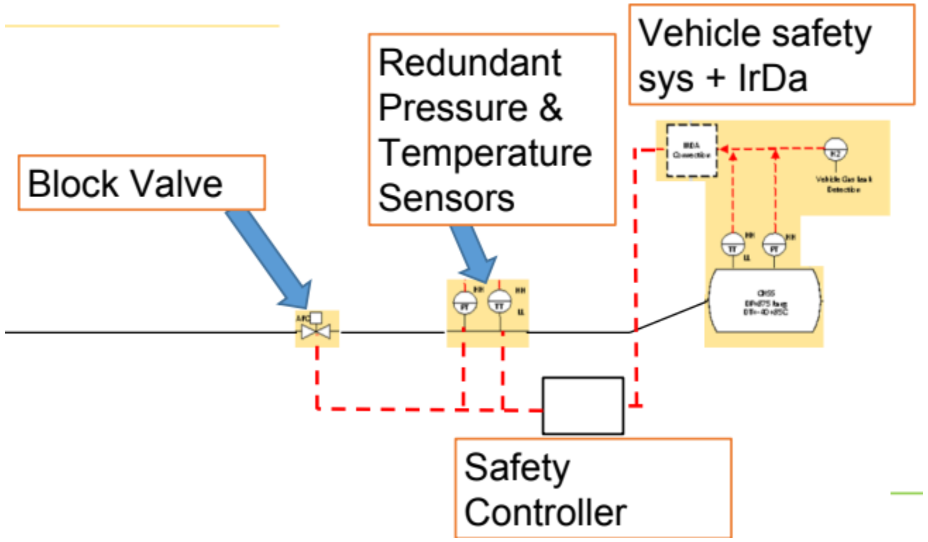
- Adding barriers
- Limiting the effects

→ See table (previous slides)

- Conduct a specific risk assessment for HD refueling process and take overall recommendations into account
  - Assess necessary SIL Levels
  - Translation to bigger CHSS
  - Analysis of max. temperatures
  - Impact of advanced communications/interfaces

Related topic: Safety Watchdog Logic

- Curent situation:
  - the safety of refueling protocols (Table Method or MC Method) are made by requiring strict control of the pressure in a corridor and temperature in a given range;
  - this restricts performance, reliability and flexibility of HRS designs.
- Concept of the ***Safety Watchdog***:
  - total flexibility is given to the HRS for refueling control (i.e. pressure and temperature evolutions during refueling are not restricted)
  - the ***Safety Watchdog*** logic is implemented to stop the refueling in case actual refueling control brings the FCEV tank close to acceptable limits
  - the ***Safety Watchdog*** logic main principle is to make a **real time calculation of a conservative estimate of temperature in the FCEV tank** using dispenser actual outlet pressure/temperature and possibly other parameters (tank type, flow rate…)



- **Proposal: the next refueling standards include the *Safety Watchdog Logic***

D2.3: Contents

Gap analysis of existing heavy duty gaseous hydrogen vehicle refuelling protocols

- Summary
- Survey responses + question

⇨ Related topic: Presentation from FillnDrive

D2.3: Summary of standardised refuelling protocols

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Currently used standardised refuelling protocols identified:

- SAE J2601: Light duty H35 & H70 (2-10kg) + medium / heavy duty H70 (>10kg) ⇨ 60 g/s max (2020 edition)
- JPEC-S-0003 (up to 30kg)
- CUTE project – 2007-2009, not publically available? But still used in some cases?

Boundary limits for heavy duty vehicle fuelling, or general fuelling:

- SAE J2601-2
- ISO 19880-1
- EN 17127 (based on ISO 19880-1) – referenced in Directive 2014/94/EC (AFID) – see last webinar presentation

Communications protocol: SAE J2799 (same as for LD)

Flexibility of protocol that is not prescriptive can be beneficial, however, not having a full protocol with individual ramp rates and configurations of the HRS ⇨ application specific issues when applications change

State of the Art analysis: Survey (v1.1): Part 1.1

- Directed at:
  - hydrogen refuelling infrastructure providers, operators and users
  - also other stakeholders
- Responses:

Providers	Operators	Users	Other
8	9	7	7

European	Outside Europe
23	5

State of the Art analysis: Survey (v1.1): Part 1.1

- Q.1: What experience do you have of refuelling protocols for hydrogen vehicles? (e.g. a manufacturer, operator, user, other)
- Responses:
  - Wide range of responders, covering manufacturers and operators of light & heavy duty road vehicle stations, also, to a lesser extent, maritime and, in the future, rail.
  - Also captured input from users – vehicle manufacturers or other (e.g. CaFCP)
  - Input from organisations involved in HyTransfer project
  - Additional stakeholders – tank manufacturer, station co-funding body, national measurement service

State of the Art analysis: Survey (v1.1): Part 1.1

- Q.2: What gaps/issues do you consider there to be with the existing protocols in use today, whether for light, medium or heavy duty road vehicles?
- Responses:
  - Clear protocol for medium and heavy duty – for Type 3 and Type 4 (+ testing to enable approvals)
  - Flexible protocol for medium and heavy duty (current LD protocols generally felt as too limiting)
  - Lack of standardised way forward for HD → many different solutions and none are universal
  - Cost / energy consumption of precooling, and related reliability issues
  - Reliable communication, to establish storage volume, also tank pressure / temperature

State of the Art analysis: Survey (v1.1): Part 1.1

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- Q.2: What gaps/issues do you consider there to be with the existing protocols in use today, whether for light, medium or heavy duty road vehicles?
- Responses:
  - Limitations from liner temperature requirements / capabilities
  - Name! SAE J2601 (light duty) is unrelated to vehicle weight / size
  - Absence of fuelling approach in SAE J2601: 2020 (or at stations) for H35 vehicles:<60 g/s; >6 kg
  - Metrology (variance in dispensed quantity vs the relevant regulations, i.e. OIML R-139)

State of the Art analysis: Survey (v1.1): Part 1.1

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- Q.3: What types of fuelling protocols do you offer (manufacturer)/ have knowledge of (operator/user) for compressed (gaseous) hydrogen vehicles with a high pressure hydrogen storage capacity greater than ~250 litres? (i.e. greater than 6 kg @ 35 MPa NWP or 10 kg @ 70 MPa NWP – the SAE J2601 definition of "light duty")
- Responses:
  - Multiple individual approaches mentioned (thanks!) – references to SAE J2601-2 boundary conditions (or equivalent), plus CUTE protocol, SAE J2601-2 and JPEC-S 0003 where appropriate
  - Generally pressure control /fixed APRR and Ptarget, often with qualification of vehicles needed, others with fixed orifices / mass flow control (+ due to range of vehicles – one "size" doesn't fit all)

State of the Art analysis: Survey (v1.1): Part 1.1

- Q.4: Do you make an assumption that a particular vessel type will be used in the vehicle, or is the fuelling protocol considered suitable for all types of tanks? If you have different protocols for different types of tanks, how does the station differentiate between them?
- Responses:
  - Mixed – some responses for “controlled” stations (or parts of the world) advised of protocols adjusted / defined depending on expected vehicles (presumably meaning Type 3 only protocol)
  - For other stations, stated that protocols assume worst case, or are designed for Type 4 vehicles
  - Additionally, noted some have manual switch to enable heavy duty protocol over light duty

State of the Art analysis: Survey (v1.1): Part 1.1

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- Q.5: Have you ever carried out any modelling on the protocol and the thermal effect on the vessel(s) receiving the hydrogen?
- Responses:
  - Large proportion of respondents carry out modelling on their refuelling protocols

State of the Art analysis: Survey (v1.1): Part 1.1

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- Q.6: Do you use (or anticipate using) hydrogen pre-cooling for fuelling of vehicles with a storage capacity >250 litres?
- Responses:
  - Mixed: some “yes” depending on the specific case (especially for Type 4 suitable protocols / where fuelling time necessitates this), some “no”
  - Example of refuelling larger marine projects - type 2 steel cylinders used, so temperature limitations are not a concern

State of the Art analysis: Survey (v1.1): Part 1.1

- Q.7: Do you have options for refuelling liquid / cryo-compressed hydrogen? If so, what limitations are there in the protocol regarding the vehicle storage system capacity?
- Responses:
  - No responses from organisations involved with non-gaseous hydrogen refuelling
- Difficult to develop Deliverable D2.5 to include input from external stakeholders on this basis

State of the Art analysis: Survey (v1.1): Part 1.1

- Q.8: What dispensing specific components (e.g. nozzle, hose, breakaway, flow meter, pre-cooling if applicable) do you use for gaseous hydrogen high flow dispensing (defined in this case as >60g/s) and do you find any issues with these components?

Come back to this in next section of agenda

State of the Art analysis: Survey (v1.1): Part 1.1

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- Q.9: SAE J2601 (to be published 2020) now includes an example "standard" fuelling protocol for 700 bar NWP vehicles with storage capacity above 250 litres (10kg):
- a) if a refuelling station (or refuelling point) manufacturer, would you anticipate providing this to a customer?
- Responses:
  - Mixed – some "yes" depending on customer requirements (some already providing it), some "no", some wanting to look into it further first / not considering it at all
  - Also some doubt that vehicles needing these conditions would become commercially available

State of the Art analysis: Survey (v1.1): Part 1.1

- Q.9: SAE J2601 (to be published 2020) now includes an example “standard” fuelling protocol for 700 bar NWP vehicles with storage capacity above 250 litres (10kg):
- b) if a refuelling station operator, would you find this useful to be able to buy a refuelling point with this capability?
- Responses:
  - Mixed – some “yes” depending on customer requirements (some already providing it) others not considering it (e.g. due to flow limitations)
  - Also some doubt that vehicles needing these conditions would become commercially available (as per part a)

State of the Art analysis: Survey (v1.1): Part 1.1

- Q.9: SAE J2601 (to be published 2020) now includes an example "standard" fuelling protocol for 700 bar NWP vehicles with storage capacity above 250 litres (10kg):
- c) would you prefer to see this fuelling protocol integrated into a "light duty" vehicle refuelling point, or as a stand-alone refuelling point?
- Responses:
  - Extremely mixed! – some "yes", others expressed concern about heavy duty vehicles using the same refuelling points (safety and performance wise), some would prefer all "light duty" refuelling points to be designed in a way that heavy duty vehicles can also access them
  - Also, operational concerns for large tank systems depleting storage for light duty applications

State of the Art analysis: Survey (v1.1): Part 1.1

- Q.9: SAE J2601 (to be published 2020) now includes an example “standard” fuelling protocol for 700 bar NWP vehicles with storage capacity above 250 litres (10kg):
- d) would you like to see an equivalent for 350 bar NWP vehicle fuelling?
- Responses:
  - Largely “yes”, although some also suggest it would not have as much benefit for heavy duty applications at H35 due to existing options for high flow refuelling at this pressure
  - For smaller CHSS (e.g. on “medium duty” vehicles) that are >250 litres, but not big enough to merit “high flow” this could have the most benefit

State of the Art analysis: Survey (v1.1): Part 1.1

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- Q.10: Have you considered fuelling of medium or heavy duty vehicles to a NWP of 500 bar? (or other pressures)
  - If so, what do you see as being the benefits of refuelling at this pressure?
  - Also, what constraints have you found with the components on the market currently?
- Responses:
  - Some “yes” but not many – benefits listed included increased range for same space but without the additional cost of 700 bar (including reduced precooling requirements) and with improved reliability, conversely, some don’t see much cost gap between 500 and 700 bar
  - Opinion that it might be more suited to regions where distances travelled are shorter

State of the Art analysis: Survey (v1.1): Part 1.1

- Q.11: Do you have any further comments / issues to raise regarding fuelling of medium or heavy duty vehicles?
- Responses:
  - Very wide range: to be summarised as a deliverable from the project

Question received

"The SAE J2601-2 HDV protocol doesn't prescribe any precooling currently. In general, several solutions are applied for refuelling Heavy duty Vehicles; mostly H35 T20 or H35 Tambient. Can anything be said regarding a certain obligated precooling protocol to come?"

- Response (individual) from Nick Hart:
  - For public stations, the use of precooling is not obligated (by law, see AFID, and EN 17127) in Europe for any type of fuelling - method of refuelling must be appropriate, which can be a standardised protocol, or another approach
  - Regarding standardised protocols:
    - To use the latest SAE J2601 standardised refuelling protocol for light duty vehicles, then this currently requires precooling.
    - Other options can be used if the fill time can be extended, and are being explored in SAE J2601-4 for light duty vehicles
    - For public heavy duty vehicle refuelling stations, in the absence of a standardised heavy duty vehicle fuelling protocol, the protocol used needs to be acceptable to the manufacturers of vehicles using the station.

Question received

"The SAE J2601-2 HDV protocol doesn't prescribe any precooling currently. In general, several solutions are applied for refuelling Heavy duty Vehicles; mostly H35 T20 or H35 Tambient. Can anything be said regarding a certain obligated precooling protocol to come?"

- Response (individual) from Nick Hart (cont.):
  - PRHYDE is a project looking into the effect of precooling in certain scenarios – it will not create any requirements for anyone in the future, just give an idea where precooling would be necessary to achieve certain targets under certain conditions
  - For standards, these would happen in a standardisation forum, such as ISO TC 197, or the SAE FCEV ITF – but, again, alternatives can always be accepted as long as they meet the minimum safety requirements of EN 17127 (or ISO/TS 20100)
  - For private stations, people can do whatever they want – any requirements would come from the operators of the station, and the vehicle suppliers.

Current status regarding fuelling protocols & components

FillnDrive

Presenter: Adrien Zanoto

Slides: Not available to public

D2.4: Contents

Gap analysis of existing hardware used for heavy duty gaseous hydrogen vehicle refuelling

- Connectors
- Survey responses (summary) + question
- Tanks
- On-tank valve
- Fuelling line

D2.4: Existing connectors

H2 PRHYDE
Protocol for heavy-duty Hydrogen refuelling

- Nozzles and receptacles:
  - The most common hardware is H70 (LD) with up to 60g/s flow

    Note: H70 receptacle compatibile with H35 (and H25) nozzle
  - Buses and trains mostly use H35HF with up to 120 g/s
- Neither of these give enough flowrate to refuel the applications as needed
- It is necessary to develop appropriate hardware (nozzles, receptacles, breakaways, hoses, control valves, flow meters, etc.) for applications in the required ranges

NOZZLE - pressure range/coding \ RECEPTACLE - pressure range/coding	25 MPa	35 MPa	35 MPa HF*	70 MPa
25 MPa	✓	✓	✓	✓
35 MPa		✓	✓	✓
35 MPa HF*			✓	
70 MPa				✓

* HF = High-Flow

D2.4: Existing connectors

- Communication devices:
  - The most common hardware for LD is InfraRed (IrDA) – typically using SAE J2799 communications protocol
    - Vulnerable to damage
  - Heavy duty applications often use “wired“ approach, for instance options presented by Joe Cohen, Air Products, in 1st webinar:
    - Deutch connector (standardised at CaFCP) – many pins
    - Samtech connector (standardised for material handling vehicles) – small pins
    - Stereo ¼“ cable
  - Other wireless options (earlier presentation)

D2.4: Existing connectors

Example of products on market for heavy duty applications: WEH

"High flow nozzle"

- TK16 H2

"nozzle for fast filling"

- TK25 H2

corresponding receptacle:

- TN1 H2

(ISO 17268 geometry)

corresponding receptacle:

- TN5 H2

All provide mechanical interlocks to prevent light duty vehicles filling at inappropriate HRS

D2.4: Hardware Development

H₂ PRHYDE
Protocol for heavy-duty Hydrogen refuelling

- H70HF Industry Group
  - Vehicle OEMs
  - Infrastructure providers
- Objectives
  1. Develop license-free, high-flow (>120 g/s), heavy duty fueling receptacle
  2. Validate receptacle design with prototype hardware: Nozzle, hose and breakaway coupling
  3. Anticipate promotion of design for global standard, for instance ISO 17268 / SAE J2600

D2.4: Hardware Development

- Outstanding question(s) to resolve (?)
  - Should a H70 HD vehicle be able to access hydrogen from an H35 (or H50) HD station?
    - H35 nozzles can supply hydrogen to H35HF receptacles – typically however protocol (and often quantity of hydrogen available) makes this impractical
    - H35 nozzles can supply hydrogen to H70 receptacles (partial fuelling) – beneficial if refuelling protocol is appropriate (i.e. suitable for Type 4 tanks, no issues with consequecutive fuelling)
    - Current proposition for a “high flow“ H70 receptacle is not compatibile with existing H35HF nozzles design
    - Would this restriction for H70 HD vehicles affect access to existing infrastructure?
    - Many H35HF systems are designed for specific vehicles – would a series of receptacles that don‘t pair with the existing H35HF be more appropriate for vehicles with Type 4 tanks, to prevent potential overheating?

State of the Art analysis: Survey (v1.1): Part 1.1

- Q.8: What dispensing specific components (e.g. nozzle, hose, breakaway, flow meter, pre-cooling if applicable) do you use for gaseous hydrogen high flow dispensing (defined in this case as >60g/s) and do you find any issues with these components?
- Responses:
  - Whilst only manufacturer mentioned is WEH, mixture of WEH TK25 or TK16HF nozzles – suggesting vehicles will not always be compatible with stations
  - Issues raised: heavy and awkward to use TK25, and concerns about lack of diversity of supply

State of the Art analysis: Survey (v1.1): Part 1.2

- Q.9: What refuelling related components (e.g. receptacle, communications equipment, etc.) do you use for gaseous hydrogen high flow dispensing (defined in this case as >60g/s) and do you find any issues with these components?
- Responses:
  - Again only manufacturer mentioned for receptacles is WEH, and only IrDA mentioned
- However, other options for (non standard) communications understood to be used, so further investigation needed *(e.g. presentations from Air Products, FillnDrive)*

State of the Art analysis: Survey (v1.1): Part 1.2

- Q.10: What gaps have you encountered in the capabilities of existing refuelling related components on the market, including those required for interoperability?
- Responses:
  - No standardisation of components specifically for H50 refuelling
  - No existing H2 components certified for use on railways

Question received

"Shall we consider Type A nozzle only or also Type C ?" (from a nozzle manufacturer)

- Background:
- ISO FDIS 17268: 2019 – clause 5.2: Nozzles shall be one of the following three types: A, B & C:
  - TYPE A — Nozzle for use with dispensing hoses that may remain fully pressurized at dispenser shutdown.
  - Equipped with integral valve(s) which first stops the supply of gas and safely vents the trapped gas before allowing the disconnection of the nozzle from the receptacle.
  - TYPE B — A nozzle for use with dispensing hoses that may remain fully pressurized at dispenser shutdown.
  - A separate three-way valve connected directly, or indirectly, to the inlet of the nozzle shall be used to safely vent trapped gas prior to nozzle disconnection.

Question received

"Shall we consider Type A nozzle only or also Type C ?" (from a nozzle manufacturer)

- Background (cont.):
- ISO FDIS 17268: 2019 – clause 5.2: Nozzles shall be one of the following three types: A, B & C:
  - TYPE C — Nozzle for use with dispensing hoses which are depressurized (0,5 MPa and below) at dispenser shutdown.
- In each case (A, B & C):

The nozzle shall not allow gas to flow until a positive connection has been achieved

Question received

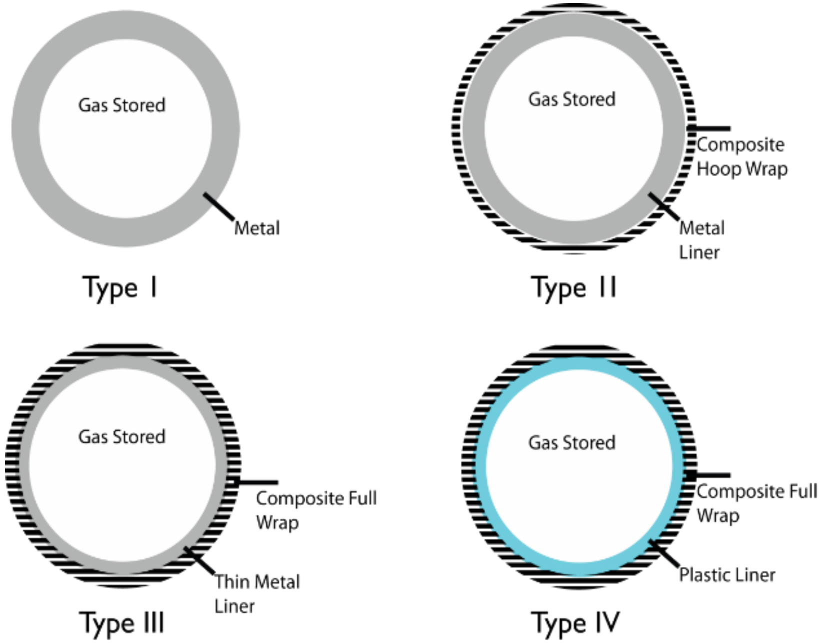
"Shall we consider Type A nozzle only or also Type C ?" (from a nozzle manufacturer)

- Response (individual) from Nick Hart:
  - In France - maintaining the nozzle and hose at pressure after fuelling, the intention of ISO 17268 Type A or Type B nozzles is not permitted.
  - **Is this the case anywhere else in the world?**
  - Result ⇨ may be the case that typical dispenser design ⇨ one where everything in the fuelling assembly is vented after the fill, therefore there would be no benefit in Type A or B nozzles in the future?
  - It seems that Type A/B can still be / are used (as the only things on the market for high flow applications)
  - **However, there may be no further need for them in the future?**

D2.4: Existing tanks

- Currently 4 different type of tanks:

Type 1	Metal container
Type 2	Container which contains a metal liner reinforced with a resin impregnated continuous filament(hoop-wrapped)
Type 3	Container which contains a metal liner reinforced with a resin impregnated continuous filament(fully-wrapped)
Type 4	Container which contains a resin impregnated continuous filament with a nonmetallic liner (all composite)



- Mostly Type 3 and Type 4 are used for H_2 vehicles
- Different pressure class: 35MPa, 70 MPa, (50 MPa sometime considered)
- Tank volume range on the market (EC 79 certified): 36L to 350L

D2.4: Existing tanks

PRHYDE
Protocol for heavy-duty Hydrogen refuelling

- Design/certification temperature (GTR13 / R134 / EC79): -40/+85 °C
- Any plan to extend? HyTransfer recommendation -> Investigation into accepting a transient peak liner surface temperature of 95°C in Type 4 tanks
- Type of tanks + material thermal properties impact the thermodynamic of the refuelling
- Example of range of thermal properties of tanks in the literature:

	λ range (W.m-1.K-1)	**c_p range (J.kg-1.K-1)**	**Thickness (mm)**
Type 3 liner	164 - 180	896 - 1106	~3mm
Type 4 liner	0.39 - 3.04	1600 -2100	~5 mm
Type 3 and 4 outer wall	0.66 – 1.14	1375 - 1500	15-35 mm

- Is this range representative of the market? Feedback from manufacturer welcome...

D2.4: On-tank valve

- Key component gathering different function (TPRD, filter, excess flow valve, temperature and pressure sensor, check valves …)
- Parameters impacting the refueling :
  – Kv range -> ~0,1 ? Feedback from valve and tank manufacturers are welcome.
  – Injection orifice orientation and diameter -> range mm ?

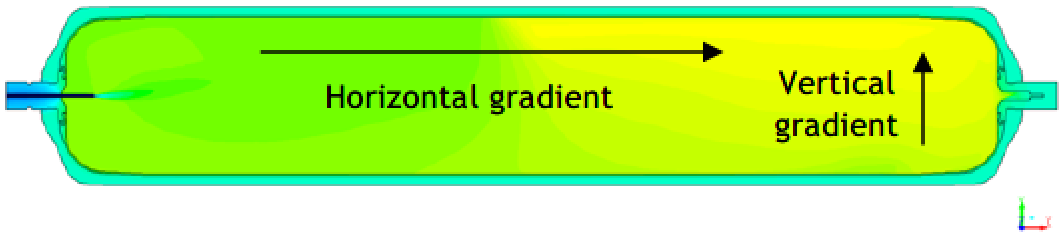


Table 1: Gas velocity criteria to ensure homogenous conditions

	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)*

D2.4: Fueling line

- Kv of the whole line :
  - Length of the pipe + elbow
  - Specific component : receptacle (Kv~ 0,3-0,7), nozzle (Kv~_0.5-2.5), filter, break-away etc…
- Thermal mass of the line:
  - Maximum station thermal mass : 5500 J/K (SAE hypothesis) ; 2300 J/K (HyTransfer hypothesis)
  - Maximum vehicle thermal mass : 2600 J/K (SAE and HyTransfer hypothesis)
  - Still valid for HDV? Feedback from vehicle manufacturers is welcome…

D2.5: Summary

PRHYDE
Protocol for heavy-duty Hydrogen refuelling

Analysis of existing non-gaseous hydrogen refuelling protocols or applications

- Aims to compare different existing approaches of non-gaseous storage on-board vehicular applications, such as:
  - liquid (cryogenic) hydrogen (LH2),
  - liquefied naturel gas (LNG),
  - cryo-compressed storage
  - ammonia,
  - liquid organic hydrogen carriers (LOHC),
  - hydrides and chemical storage

The target is to benchmark them by listing their advantages and disadvantages and current technology readiness level (TRL).

Work Package 3 (WP3)

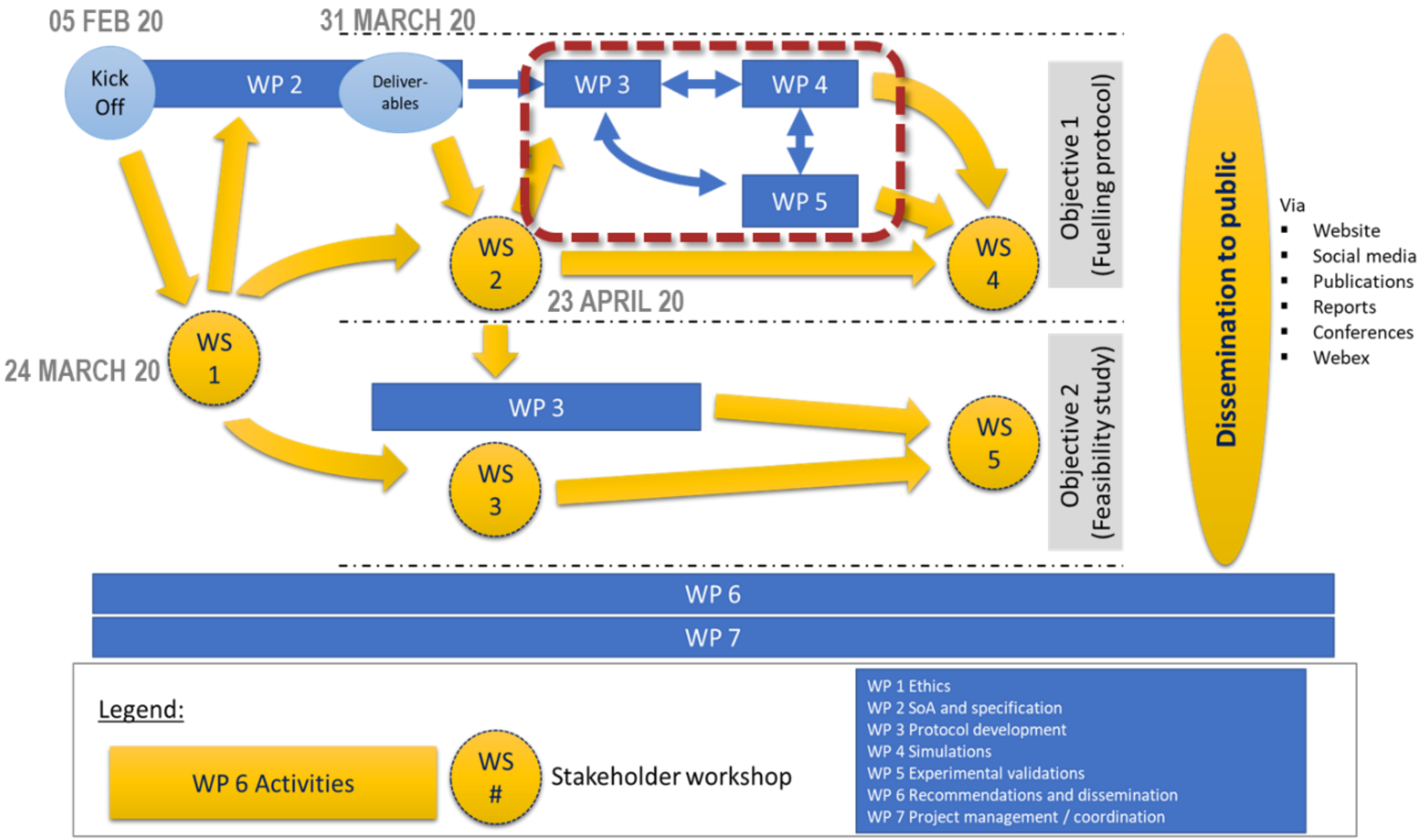
- Purpose
  - To develop technical approaches for fuelling protocol(s) that meets WP2 spec
  - Specify fueling protocol(s) for use in validation tests (WP4, WP5)
  - Safety and risk assessment of fuelling protocol(s)
  - Optimization of fueling protocol(s) based on validation test results
- Deliverable D3.1: Report on the characteristics of the cases to be studied in the preliminary simulations

Work Package 3 (WP3)

- First steps
  - Output shall not provide prescriptive protocols
  - Output shall provide process limits and guidelines on how to refueling HD vehicles.

Work Package 3 (WP3)

- Overview



Work Package 3 (WP3)

- Phases
  - Phase 1 – Preliminary Study
  - Phase 2 – Development of initial protocol
  - Phase 3 – Support field testing
  - Phase 4 – Iterate and optimize control protocol
  - Phase 5 – Final Protocol

Work Package 3 (WP3)

- Phase 1 – Preliminary Study
  - Upcoming public document:
  - ***D3.1: Report on the characteristics of the cases to be studied in the preliminary simulations***
  - Objective:
    - ***Define characteristics for WP4 efforts***
    - ***Evaluate capabilities for fueling within 10/15 minutes with existing methods***
  - Constraints:
    - **Average Pressure Ramp Rate Approach, fill to 100% within 10/15 minutes**
    - **Disregard thermal effect on inlet piping**
    - **Single vessel CHSS**

D3.1: Inputs

PRHYDE
Protocol for heavy-duty Hydrogen refuelling

- CHSS limits
  - Successful cases in preliminary study will not exceed limits

a) **Gas Pressure limit:** **125% NWP**

b) **Gas Temperature Limit:** **85° C**

c) **Gas Density Limit:** $\rho_{nominal}(NWP, 15°C)$

D3.1: Inputs

Fueling conditions for preliminary study

- CHSS Tank Type
- Vessel Volume + Configuration
- Ambient Temperature
- Initial Pressure
- Ref. Pressure Drop
- Fuel Delivery Temperature
- APRR

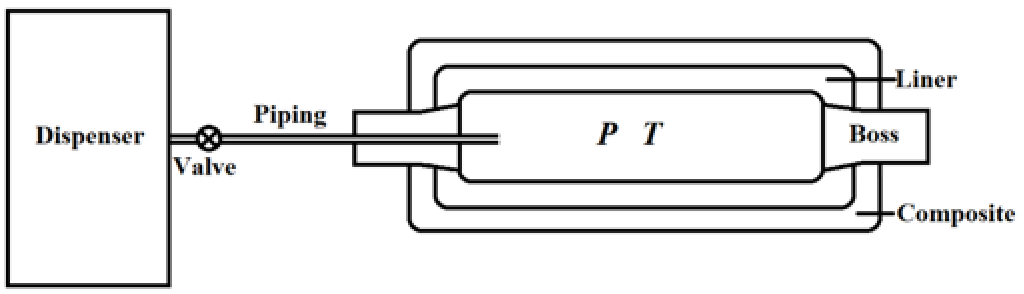


Figure 2: Sketch of simulation model (Source: Air Liquide)

D3.1: Inputs

PRHYDE Protocol for heavy-duty Hydrogen refuelling

- Assumptions on Hydrogen Single Vessel geometry and material properties

Type III - Small

Table 2 Single Vessel Characteristics – Type III Single Vessel (Small)

Description	H35	H50	H70	Unit
Internal volume	0.050	0.050	0.050	[m^3]
Internal length	0.710	0.710	0.710	[m]
Internal radius	0.150	0.150	0.150	[m]
Liner thickness	0.005	0.005	0.005	[m]
Composite layer thickness	0.010	0.017	0.027	[m]
Liner material density	2700	2700	2700	[$kg\ m^{-3}$]
Liner material specific heat capacity	1106	1106	1106	[$J\ kg^{-1}\ K^{-1}$]
Liner material thermal conductivity	164	164	164	[$W\ m^{-1}\ K^{-1}$]
Composite wrapping material density	1494	1494	1494	[$kg\ m^{-3}$]
Composite wrapping material specific heat capacity	1120	1120	1120	[$J\ kg^{-1}\ K^{-1}$]
Composite wrapping material conductivity	0.740	0.740	0.740	[$W\ m^{-1}\ K^{-1}$]
Boss material density	-	-	-	[$kg\ m^{-3}$]
Boss material specific heat capacity	-	-	-	[$J\ kg^{-1}\ K^{-1}$]
Boss volume	-	-	-	[m^3]
Boss contact surface with hydrogen	-	-	-	[m^2]
Boss contact surface with ambient air	-	-	-	[m^2]

Type III - Large

Table 3 Single Vessel Characteristics – Type III Single Vessel (Large)

Description	H35	H50	H70	Unit
Internal volume	0.350	0.350	0.350	[m^3]
Internal length	1.240	1.240	1.240	[m]
Internal radius	0.300	0.300	0.300	[m]
Liner thickness	0.005	0.005	0.005	[m]
Composite layer thickness	0.010	0.017	0.027	[m]
Liner material density	2700	2700	2700	[$kg\ m^{-3}$]
Liner material specific heat capacity	1106	1106	1106	[$J\ kg^{-1}\ K^{-1}$]
Liner material thermal conductivity	164	164	164	[$W\ m^{-1}\ K^{-1}$]
Composite wrapping material density	1494	1494	1494	[$kg\ m^{-3}$]
Composite wrapping material specific heat capacity	1120	1120	1120	[$J\ kg^{-1}\ K^{-1}$]
Composite wrapping material conductivity	0.740	0.740	0.740	[$W\ m^{-1}\ K^{-1}$]
Boss material density	-	-	-	[$kg\ m^{-3}$]
Boss material specific heat capacity	-	-	-	[$J\ kg^{-1}\ K^{-1}$]
Boss volume	-	-	-	[m^3]
Boss contact surface with hydrogen	-	-	-	[m^2]
Boss contact surface with ambient air	-	-	-	[m^2]

D3.1: Inputs

- Assumptions on Hydrogen Single Vessel geometry and material properties

Type IV - Small

Table 4 **Single Vessel Characteristics – Type IV Single Vessel (Small)**

Description	H35	H50	H70	Unit
Internal volume	0.050	0.050	0.050	[m^3]
Internal length	0.710	0.710	0.710	[m]
Internal radius	0.150	0.150	0.150	[m]
Liner thickness	0.005	0.005	0.005	[m]
Composite layer thickness	0.015	0.022	0.032	[m]
Liner material density	945	945	945	[$kg\ m^{-3}$]
Liner material specific heat capacity	2100	2100	2100	[$J\ kg^{-1}\ K^{-1}$]
Liner material thermal conductivity	0.500	0.500	0.500	[$W\ m^{-1}\ K^{-1}$]
Composite wrapping material density	1494	1494	1494	[$kg\ m^{-3}$]
Composite wrapping material specific heat capacity	1120	1120	1120	[$J\ kg^{-1}\ K^{-1}$]
Composite wrapping material conductivity	0.740	0.740	0.740	[$W\ m^{-1}\ K^{-1}$]
Boss material density	7900	7900	7900	[$kg\ m^{-3}$]
Boss material specific heat capacity	500	500	500	[$J\ kg^{-1}\ K^{-1}$]
Boss volume	0.002	0.002	0.002	[m^3]
Boss contact surface with hydrogen	0.045	0.045	0.045	[m^2]
Boss contact surface with ambient air	0.047	0.047	0.047	[m^2]

Type IV - Large

Table 5 **Single Vessel Characteristics - Type IV Single Vessel (Large)**

Description	H35	H50	H70	Unit
Internal volume	0.350	0.350	0.350	[m^3]
Internal length	1.240	1.240	1.240	[m]
Internal radius	0.300	0.300	0.300	[m]
Liner thickness	0.005	0.005	0.005	[m]
Composite layer thickness	0.015	0.022	0.032	[m]
Liner material density	945	945	945	[$kg\ m^{-3}$]
Liner material specific heat capacity	2100	2100	2100	[$J\ kg^{-1}\ K^{-1}$]
Liner material thermal conductivity	0.500	0.500	0.500	[$W\ m^{-1}\ K^{-1}$]
Composite wrapping material density	1494	1494	1494	[$kg\ m^{-3}$]
Composite wrapping material specific heat capacity	1120	1120	1120	[$J\ kg^{-1}\ K^{-1}$]
Composite wrapping material conductivity	0.740	0.740	0.740	[$W\ m^{-1}\ K^{-1}$]
Boss material density	7900	7900	7900	[$kg\ m^{-3}$]
Boss material specific heat capacity	500	500	500	[$J\ kg^{-1}\ K^{-1}$]
Boss volume	0.002	0.002	0.002	[m^3]
Boss contact surface with hydrogen	0.045	0.045	0.045	[m^2]
Boss contact surface with ambient air	0.047	0.047	0.047	[m^2]

D3.1: Inputs

PRHYDE
Protocol for heavy-duty Hydrogen refuelling

- Cases

Table 6 Selected characteristic cases for preliminary simulations

Description		H35	H50	H70	Unit
CHSS Tank Type		III IV	III IV	III IV	
CHSS Volume		1400.0	1400.0	1400.0	[L]
Single Vessel Unit	(28 vessels) (4 vessels)	50.0 350.0	50.0 350.0	50.0 350.0	[L]
Ambient Temperature		15.0	15.0	15.0	[°C]
Initial Pressure		6.0	8.0	10.0	[MPa]
Ref. Pressure Drop		20.0	20.0	20.0	[MPa]
Fuel Delivery Temperature		+15.0 - 20.0	+15.0 - 20.0	+15.0 - 20.0	[°C]
APRR	(10 min. fuelling time) (15 min. fuelling time)	3.78 2.52	5.45 3.63	7.75 5.17	[MPa min^{-1}]
Stop criteria		100.0	100.0	100.0	[%]

- Total: 48 cases

Work Package 3 (WP3)

- Outlook
  - Hand over characteristic cases to WP4 (April 2020)
  - Commence Phase 2 (April-May 2020)
  - Develop initial fueling protocol approach (September 2020)
  - Conduct risk assessment on approach (December 2020)
  - Final fueling protocol specification (September 2021)

Next steps (1/2)

- Further feedback and inputs requested from stakeholders:
  - E-mail list for PRHYDE stakeholders
    (→ please send e-mail to info@prhyde.eu if you want to receive or not to receive info / news)
  - PRHYDE deliverables & presentation will be made available for your comments and feedback
    (sent to you by e-mail / or to be downloaded from the PRHYDE website)

→ Please provide your comments / inputs any time to info@prhyde.eu

Next steps (2/2)

- Additional engagement with the project:
  - Due to travel restrictions and missing in-person meetings / workshops, we plan a series of additional webcons with limited number of participants,
    → **Only small discussion groups enable discussion during webcons**
  - The organization and planning of these webcons (time, contents, participants) will depend on the received feedback and topics to be addressed
    → **Plan: Start in May 2020**
  - **Next originally planned workshop: SEP 2020**

THANK YOU!

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