Development of LH2 fuelling procedures and risk assessment within ISO/TC197/WG35

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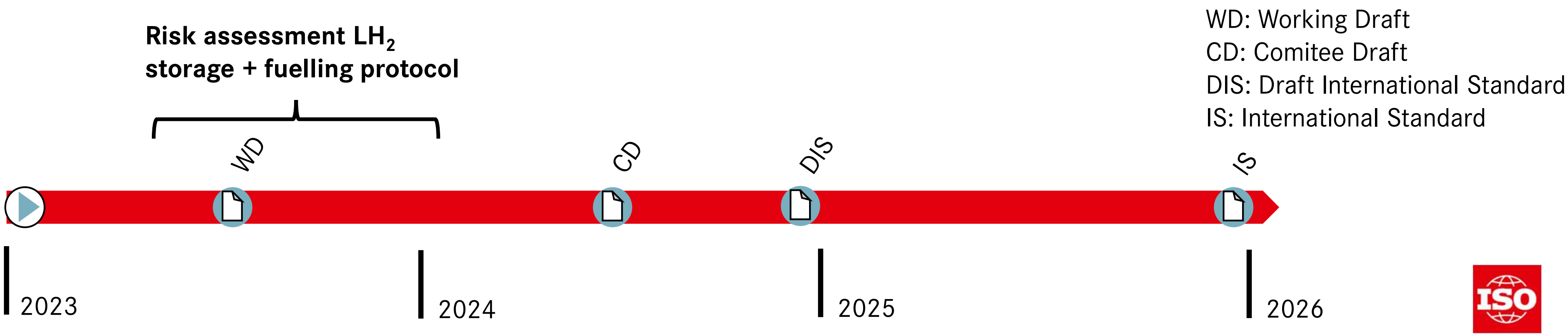
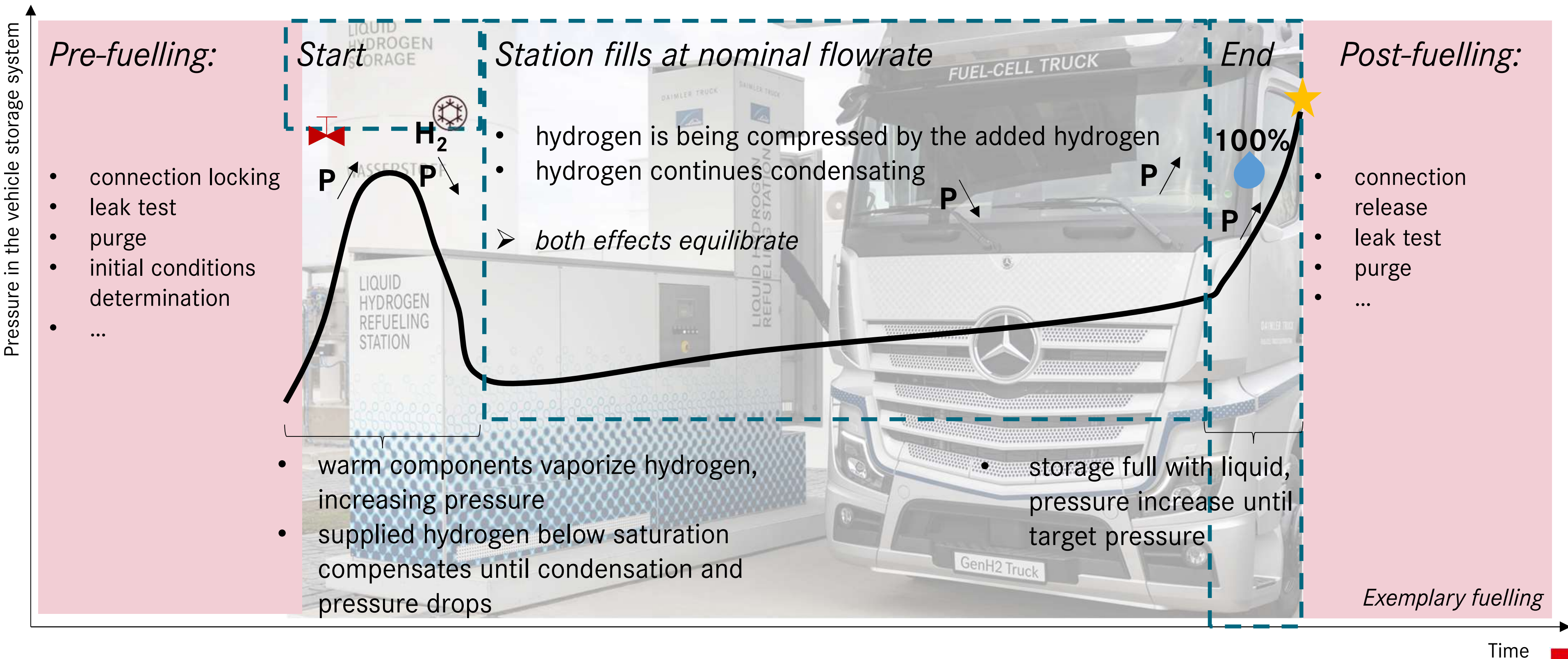
ELVHYS Workshop 3 – June 7th, 2024

Introduction – ISO 13984 revision

- Revision of the original standard from 1999 started last year
- New title: Liquid Hydrogen - Land Vehicle Fuelling Protocol
- Risk assessment performed with the group working on LH_2 storage standard (ISO 13985) between April 2023 and January 2024



Liquid Hydrogen Fueling Protocol Introduction



Risk assessment - introduction

- Risk assessment HAZID like, at the crossroad of automotive ISO 26262 and industrial systems IEC 61508.

First phase

System description & identification → „Nodes definition“ → Deviation parameters and keywords → Causes identification → Consequences determination

Second phase

Severity, probability & controlability assessment → „ASIL“ level calculation → Countermeasures proposal → Qualitative discussion → Summary and recommandations

Risk assessment - introduction

Severity class			Probability class			Controllability class		
						C1	C2	C3
						Simply controllable	Normally controllable	Difficult to control or uncontrollable
S1	Light & moderate injuries	More than 10 % probability of AIS 1-2 (and not S2 or S3)	E1	Very low probability	Operational situation occurs once by year or less often	QM	QM	QM
			E2	Low probability	Operational situation occurs few times by year	QM	QM	QM
			E3	Medium probability	Operational situation occurs every month or more often	QM	QM	A
			E4	High probability	Operational situation occurs every day of use	QM	A	B
S2	Severe and life-threatening injuries (survival probable)	More than 10 % probability of AIS 3-4 (and not S3)	E1	Very low probability	Operational situation occurs once by year or less often	QM	QM	QM
			E2	Low probability	Operational situation occurs few times by year	QM	QM	A
			E3	Medium probability	Operational situation occurs every month or more often	QM	A	B
			E4	High probability	Operational situation occurs every day of use	A	B	C
S3	Life-threatening injuries (survival uncertain), fatal injuries	More than 10 % probability of AIS 5-6	E1	Very low probability	Operational situation occurs once by year or less often	QM	QM	A
			E2	Low probability	Operational situation occurs few times by year	QM	A	B
			E3	Medium probability	Operational situation occurs every month or more often	A	B	C
			E4	High probability	Operational situation occurs every day of use	B	C	D
S0								

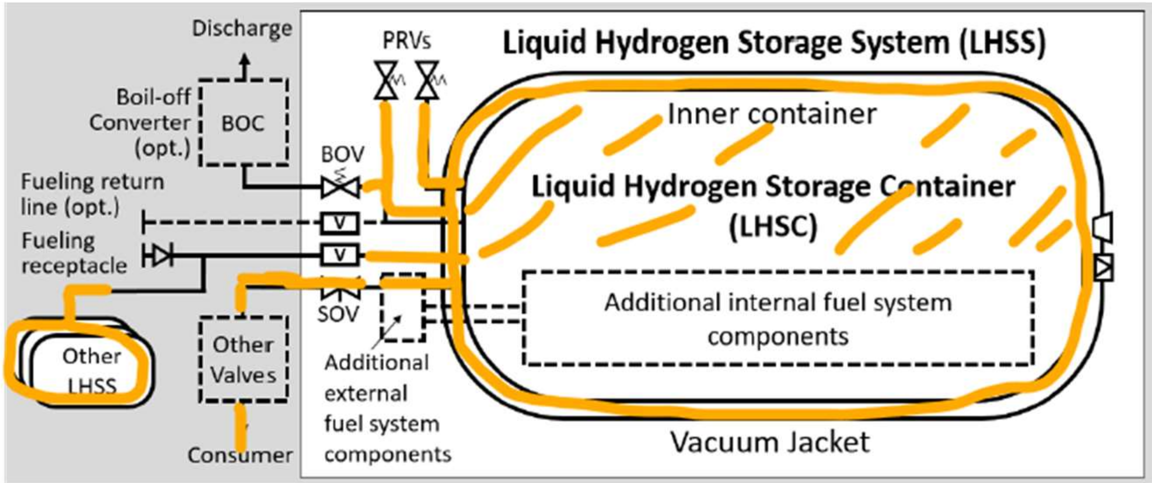
Caption

Abbreviated Injury Scale (AIS)

- AIS 1: light injuries such as skin-deep wounds, muscle pains, whiplash, etc.;
- AIS 2: moderate injuries such as deep flesh wounds, concussion with up to 15 minutes of unconsciousness, uncomplicated long bone fractures, uncomplicated rib fractures, etc.;
- AIS 3: severe but not life-threatening injuries such as skull fractures without brain injury, spinal dislocations below the fourth cervical vertebra without damage to the spinal cord, more than one fractured rib without paradoxical breathing, etc.;
- AIS 4: severe injuries (life-threatening, survival probable) such as concussion with or without skull fractures with up to 12 hours of unconsciousness, paradoxical breathing;
- AIS 5: critical injuries (life-threatening, survival uncertain) such as spinal fractures below the fourth cervical vertebra with damage to the spinal cord, intestinal tears, cardiac tears, more than 12 hours of unconsciousness including intracranial bleeding;
- AIS 6: extremely critical or fatal injuries such as fractures of the cervical vertebral above the third cervical vertebra with damage to the spinal cord, extremely critical open wounds of body cavities (thoracic and abdominal cavities), etc

System description

- Node 1.1, 1.2 and 1.3

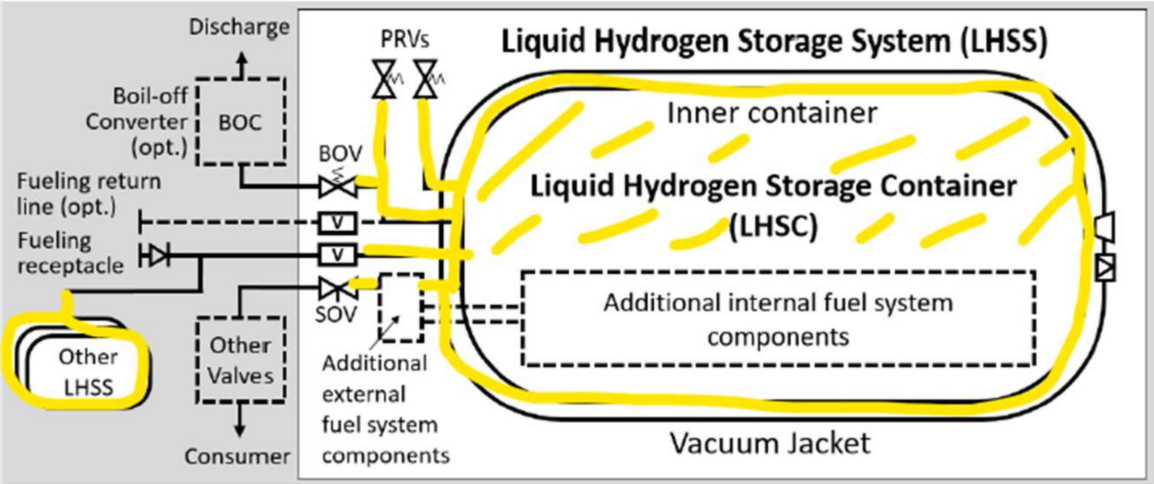


- Vehicle Start-up
- Vehicle Driving/Operating
- Vehicle Shut-down

This three phases and related nodes correspond to the ramp-up, operation and ramp-down of the power train using hydrogen supplied by the storage

System description

- Node 2

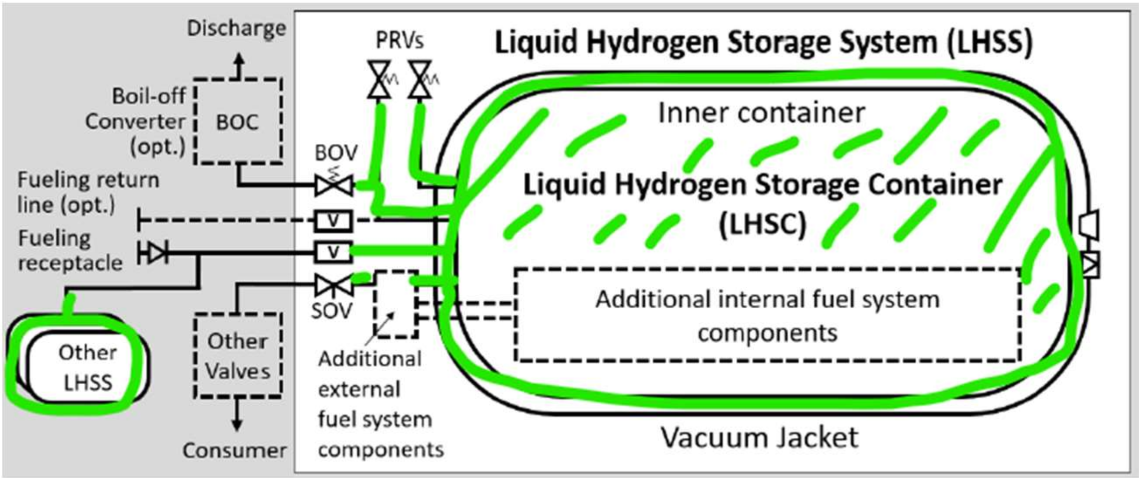


- Vehicle Idle

This phase and related nodes correspond to the vehicle operating but without supply requested from the storage system

System description

- Node 3



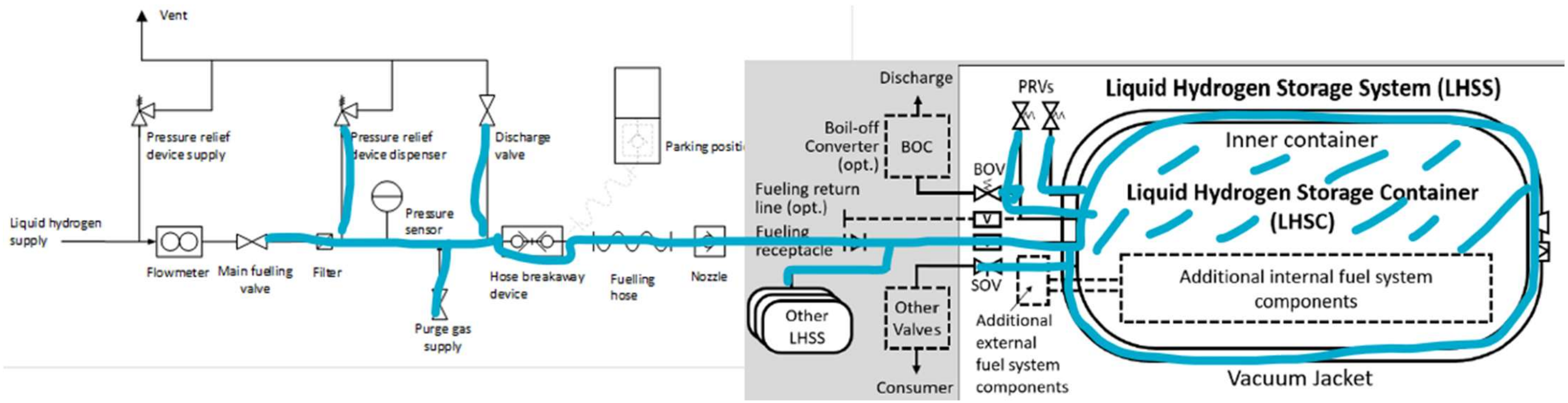
- Vehicle Parking

This phase and related nodes correspond the vehicle power train shut down, i.e. not rolling and without supply requested from the storage system

System description

- Node 4.1, 4.2 and 4.3

- Fuelling Start-up
- Main Fuelling
- Fuelling Shut-down

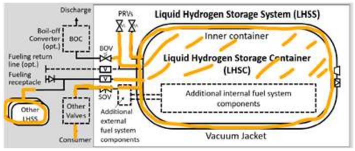


This phase and related nodes correspond to the different fuelling steps of the vehicle at a hydrogen fuelling station

HAZID matrix overview

Phase 1 - Identification							Phase 2 - Ranking						
Node	*Parameter*	*Guideword*	*Deviation*	*Cause*	*Effect*	*Consequence*	*Severity S1, S2, S3*	*Probability E1, E2, E3, E4*	*Controlability C1, C2, C3*	*ASIL QM, A, B, C*	*Countermeasures*	*Discussion on residual risk (ALARP)*	
1.2	Temperature	No	No Temperature	Temperature sensor fault	Operation	Missing information on tank conditions and state of charge	S0	E3	C2	FALSCH			
	Temperature	More	More Temperature	Major tank insulation fault (e.g. vacuum loss)	Safety	Fast pressure increase of the tank leading to a rupture and major H2 release (cryo spill, explosion, major jet fire, extended flash fire)	S3	E2	C3	B	**- PSV redundancy designed to handle vacuum loss** -> vacuum loss test - end of line test (first fill with LH2) - pressure cycling of the tank - mechanical qualification (adressed below) - material design / qualification (adressed below)	Residual risk ok	E2: in terms of operation the probabilty of failure is fairly low and field experience is positive. On the other hand considering manufacturing constraints, the probability of having products failing in the field might be higher. Chosen here in a conservative view Detection mean to prevent permanent release
	Temperature	More	More Temperature	Major heating supply system control failure	Safety	Fast pressure increase of the tank leading to a rupture and major H2 release (cryo spill, explosion, major jet fire, extended flash fire)	S3	E3	C3	C	**- Boil-off management system + detection of activation -> Boil-off flowrate to be discussed (boil-off management is designed at least to the highest consumption of the heater)** **- PSV redundancy** **-Control loop of the heater** **- Fuse of the heater**	Residual risk ok	Heater loop sufficiently controlled if trespassing maximum design pover
	Pressure	More	More Pressure	Ice build up limiting the relief of H2	Safety	Fast pressure increase of the tank leading to a rupture and major H2 release (cryo spill, explosion, major jet fire, extended flash fire)	S3	E4	C3	D	- Validation scenario - Design - Recommendation for extinguishing fire **- Redundancy of the safety valve** **- Water protection**	Residual risk can only be reduced through strict design rules	Protection from atmospheric conditions for the inner part. Design external parts not to be affected by ice freezing
	Vibration	More	More Vibration	Fluctuations due to driving profile, causing fluid dynamic shaking, impacting the tank wall and accelerating the boil-off rate	Safety	Fast pressure increase of the tank leading to a rupture and major H2 release (cryo spill, explosion, major jet fire, extended flash fire)	S3	E2	C3	B	- Testing and design (Shaker test with LH2 or equivalent fluid) - Design of the Boil-Off valve - PSV	Residual risk ok	Shaking might even contribute to reduce pressure
	Errosion/Corrosion	More	More Errosion/Corrosion	Excessive supply flow to fuel-cell/engine causing errosion in the pipeline	Safety	Material damage leading to H2 release (cryo spill, explosion, major jet fire, extended flash fire)	S3	E1	C3	A	- Qualify the components for the maximum flowrate	Residual risk ok	
	Errosion/Corrosion	Less	Less Errosion/Corrosion	No relevance						FALSCH			
	Errosion/Corrosion	As Well As	As Well As Errosion/Corrosion	No relevance						FALSCH			
	Errosion/Corrosion	Part of	Part of Errosion/Corrosion	No relevance						FALSCH			

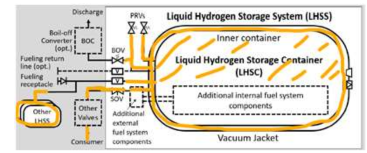
Key results outlook



- Node 1.1, 1.2, 1.3, 2 and 3 => ISO 13985

Identified scenarios with specific attention	Proposed countermeasures
Cryogenic leak towards non-cryogenic parts	- **External leaks**: components qualification, minimisation of interfaces and leak detection - **Internal leaks**: component design and qualification, even if not intended for cryogenic uses
Icing of relief devices	- **Protect inner** parts from atmospheric influence - External parts designed **not to be affected by freezing**
Venting system not reclosing	- Design, qualification, maintenance & inspection - **Installation rules** - Additional barriers possible for boil-off system
Extreme road and environmental conditions	Individual assessment by manufacturers
External leakage	Combination of **design & qualification**, **inspection & maintenance** and **leak detection**

Key results outlook



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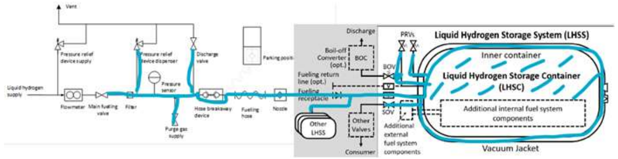
Scenarios with the highest risk level	Mitigation
Ice build up, limiting pressure relieve	**Design rules, redundancy of relief devices, protection against water, recommendations for fire extinguishing**
Tank or components materials not appropriate	**Choice and design of material, qualification of materials, especially accounting for cryogenic conditions**
Vehicle dynamics, shock or braking, causing excessive mechanical stresses	**Mechanical acceleration tests, design of the structure and crash simulations and tests**

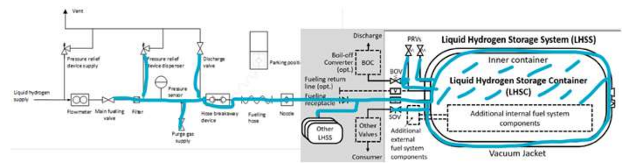
Key results outlook



- Node 4.1, 4.2 and 4.3 => ISO 13984

Identified scenarios with specific attention	Proposed countermeasures
Components or storage too warm	- **Vehicle side**: qualification for warm tank situation, detection and preliminary countermeasures, pressure relief devices - **Station side**: initial fuelling routine, warm tank detection, measurement
Initial pressure conditions: - storage pressure > station pressure - storage pressure < station pressure	- **Boil-off management** and **relief devices** - Design of maximum allowable working pressure **- Initial procedures** **- Purge** against contamination
Pressure sensor upward deviation - fuelling of an empty storage	- **Vehicle detection** and fuelling prevention - **Redundancy**, safety level of station pressure sensor - Leak test - Maintenance

Key results outlook



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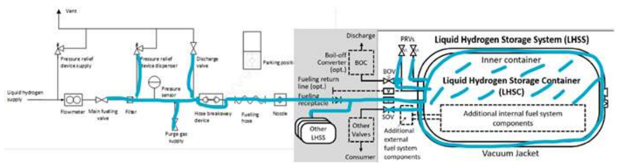
Identified scenarios with specific attention	Proposed countermeasures
Purge and leak test system: - pressure increase through leak - contamination	- **Constructive** and **design measures** **- Supply control** (pressure, flowrate) **- Helium** or **hydrogen** for purge - Pressure relations between sub-systems
Check-valve issues: - chattering - receptacle check-valve remaining open at disconnection	- **Design** and receptacle check-valve neutralization - **no stop and flow** behaviour - **Connector qualification** - **Locking pin safety** - User information
Excessive flowrate	- **Relief devices design** - Pressure control - Flowrate direct or indirect safety loop
Air ingress	- **Vehicle leak detection** **-** Initial **purge and leak test**

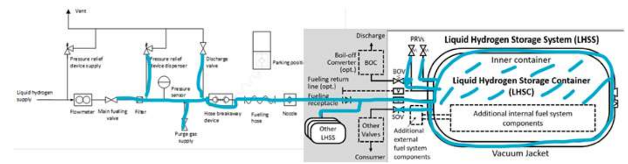
Key results outlook



- Node 4.1, 4.2 and 4.3 => ISO 13984

Scenarios with the highest risk level	Mitigation
Components or storage too warm	**Qualification of components and storage, redundancy and setting of relief devices** **Initial warm tank procedure**
Components materials not appropriate	**Choice and design of material, qualification of materials, especially accounting for cryogenic conditions**
Lifetime and full environmental range	**Design measures and sufficient qualification of the components**
Too fast temperature variations	**Appropriate design rules (e.g. limiting sharp bends) and qualification** **Controlled cool down station procedure**
Initial pressure relations	*See previous slides*

Key results outlook



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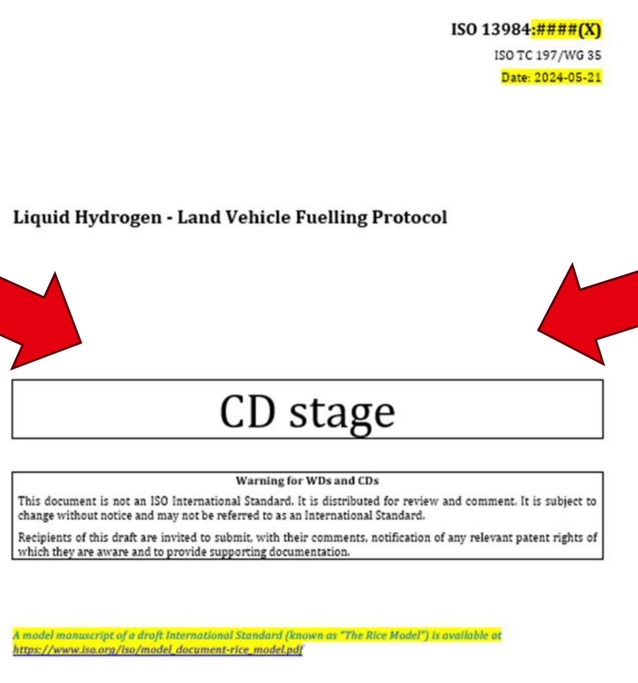
Scenarios with the highest risk level	Mitigation
Remaining contamination from previous fuelling	**Nozzle design, as well as docking of the station and systematic purge procedure**
Vehicle drive away while still connected	**Breakaway device** **Possible additional measures**
Nozzle misconnection or damaged	**Standardized design and specification of the connector** **Protection and qualification against drop** **Systematic initial purge and leak test procedure**
Check valves not properly closed at connection or disconnection	**Check valve design and qualification, including independency/redundancy** **Safety Integrity Level on the locking pin function**

Where to find information

- Available in ISO 13984 to come next year

Integrated in the main document



ISO 13984:####(X)

ISO TC 197/WG 35

Date: 2024-05-21

Liquid Hydrogen - Land Vehicle Fuelling Protocol

CD stage

Warning for WDs and CDs

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A model manuscript of a draft International Standard (known as "The Rice Model") is available at https://www.iso.org/iso/model_document-rice_model.pdf

Specific summary in Annex G

Thank you.

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Questions