NTNU
Norwegian University of
Science and Technology

Implementation of hydrogen as a fuel in the maritime sector

Seminar for master course “Machines” at University of Trieste

Federico Ustolin

04.12.2023

NTNU

- Main profile in science and technology
- Academic breadth: humanities, social sciences, medicine, health sciences, science of education, architecture, fine arts and performing arts
- Headquarters in Trondheim with campuses in Gjøvik and Ålesund

Trondheim

Gjøvik

Ålesund

NTNU

Key figures

- 8 faculties, 55 departments and NTNU University Museum
- 7,761 person-years (2020)
- More than 44,000 students (2020)
- 7,889 completed bachelor’s and master’s degrees (2020)
- 415 doctoral degrees (2020)
- Owned or rented facilities 734,000 m^2

NTNU RAMS

Reliability Availability Maintainability Safety

- Faculty of Engineering (IV)
- Department of Mechanical and Industrial Engineering (MTP)
- Gløshaugen campus (Trondheim)
- RAMS lab (not hydrogen yet)
- Supervisors: 7
- Postdocs: 1
- PhD students: 20+

Professor
Jørn Vatn

Professor
Shen Yin

Ass. Professor
Federico Ustolin

Professor
Nicola Paltrinieri

Professor
Yiliu Liu

Ass. Professor
Hyungju Kim

Assistant professor
Viggo Gabriel Borg Pedersen

NTNU RAMS

Pillar research directions and sub-directions

Reliability Engineering

- Reliability assessment of critical systems/infrastructure
- Experimental reliability tests and data analysis
- Maintainability and resilience analysis
- Digital twin modeling and qualification

Risk Management

- Accident investigation and analyses
- Dynamic risk analysis and real-time decision support
- Risk-informed decision-making and barrier analysis
- Consequence analysis

Maintenance

- Modeling and data analysis for system operation and maintenance
- Health monitoring, fault diagnosis and predictive maintenance
- Integrated planning and asset management
- Digital solutions for maintenance

Social Security and Sustainability

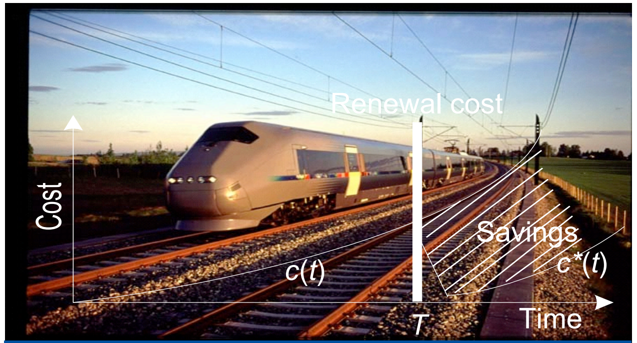
- Robustness of Infrastructure
- ICT/CPS security and attack-resilient control
- NATECH disaster management
- Uncertainty assessment in the value chain

NTNU RAMS

Offshore

Wind

Hydrogen



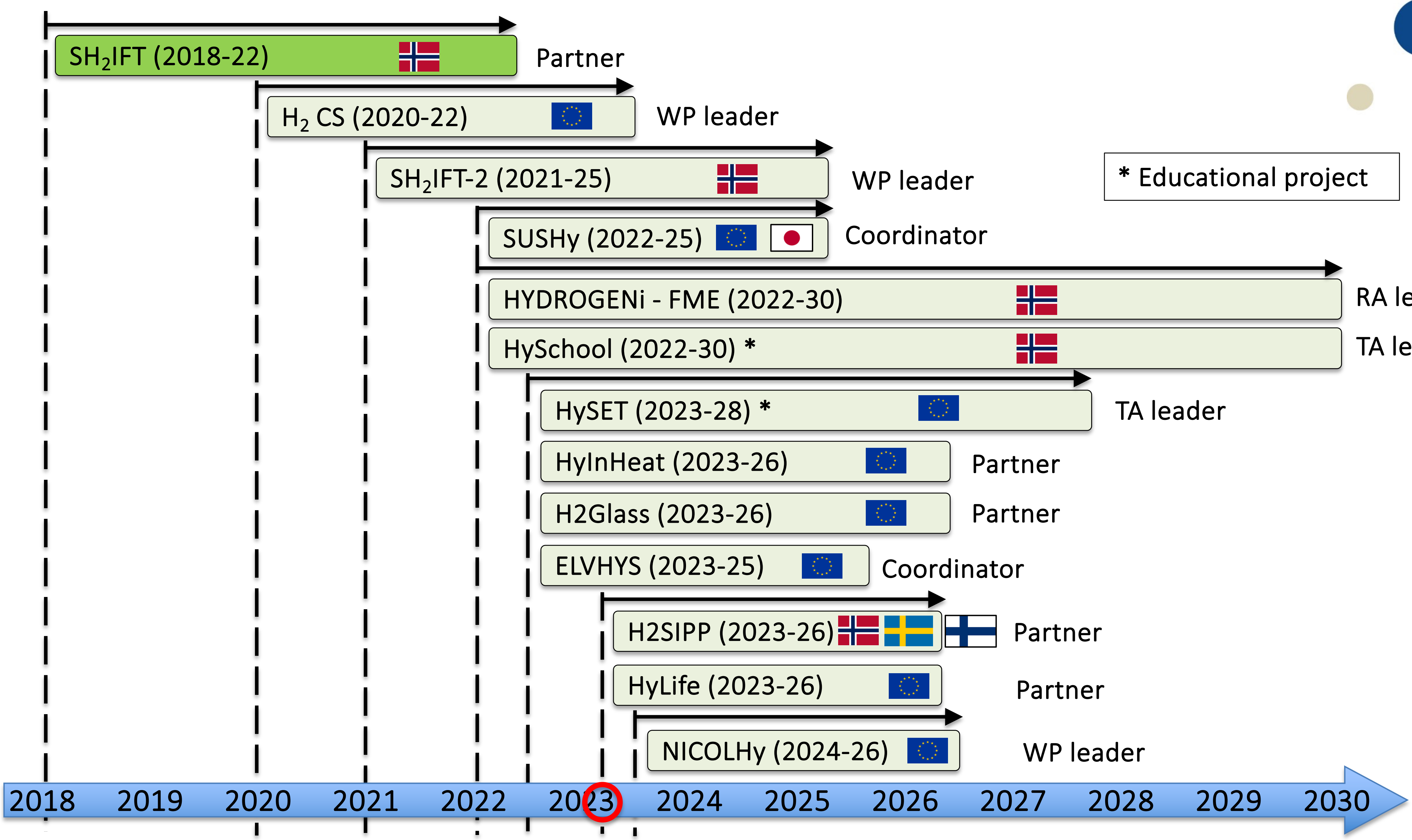
Transportation

Healthcare

Production

- Reliability engineering
- Maintenance
- Risk assessment
- Social security & sustainability

NTNU RAMS projects on hydrogen



NTNU RAMS H2 safety team

Supervisors


Prof Nicola Paltrinieri


Ass Prof Federico Ustolin


Prof Yiliu Liu


Ass. Prof Hyungju Kim

Postdoc


Dr Dimitrios Tzioutzios

PhDs


Alessandro Campari


Leonardo Giannini


Federica Tamburini

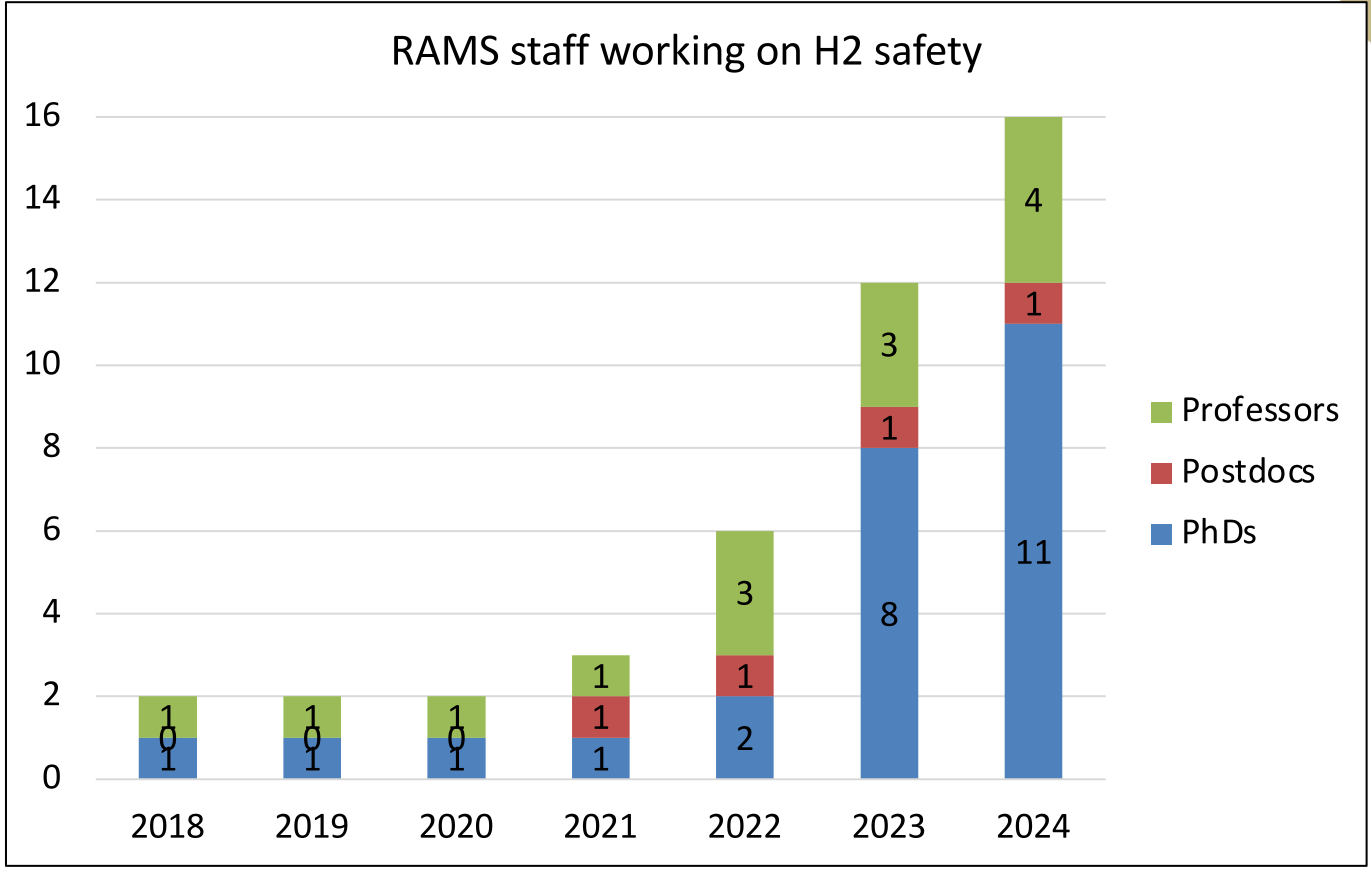

Alice Schiaroli


Giulia Collina


Farhana Yasmine Tuhi


Elena Baboi


Lucas Claussner



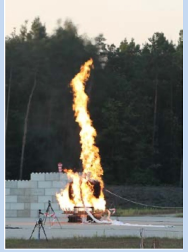
NTNU RAMS expertise on hydrogen

Consequence analysis

Modelling of hydrogen releases and explosions (projects: **SH2IFT-1**, **H2CS**, **ELVHYS**)

Cryogenic technologies

Liquid H2 safety during normal operations (e.g. transfer) & accidents (projects: **SH2IFT-1**, **ELVHYS**)



Material degradation

Risk-based inspection & maintenance methodologies (projects: **SH2IFT-2**, **HYDROGENi**, **H2GLASS**)

Quantitative Risk Analysis

Risk perception of hydrogen refueling stations (projects: **SUSHy**)

Training & education

Training of personnel (**HyInHeat**) & education of master students (**HySET**) and PhD (**HySchool**)

Content

1. Introduction on hydrogen
2. Hydrogen implementation in the maritime sector
    2.1. Storage (compressed gas, liquid)
    2.2. Materials
    2.3. Hydrogen utilization on board
    2.4. Infrastructures (bunkering)
    2.5. Recommendations, codes and standards
    2.6. Research and demonstration projects
3. Hydrogen safety projects

Hydrogen properties

Lower heating value: 119.96 MJ/kg

Combustion products: H2O, NOx

Toxicity: none

Density at NTP: 0.0883 kg/m^3

Flame visibility: Scarce
Colour and/or odour: none

Minimum ignition energy: 0.017 mJ

Flammability range in air: 4 ÷ 75 %vol

Molecule diameter: 120 pm

Hydrogen colour codes

Colour	H2 source	Energy source	Carbon capture & storage
Green	Water	Electricity (renewables)	No
Yellow	Water	Electricity (grid)	No
Purple	Water	Electricity (nuclear)	No
Pink	Water	Thermal + Electricity (nuclear)	No
Red	Water	Thermal (nuclear)	No
White	Water	Thermal (solar)	No
Blue	Natural gas	Thermal (steam)	Yes
Gray	Natural gas	Thermal (steam)	No
Black/brown	Coal	Thermal	No
Aqua	Oil reservoir	Thermal (steam)	No

Hydrogen colour codes

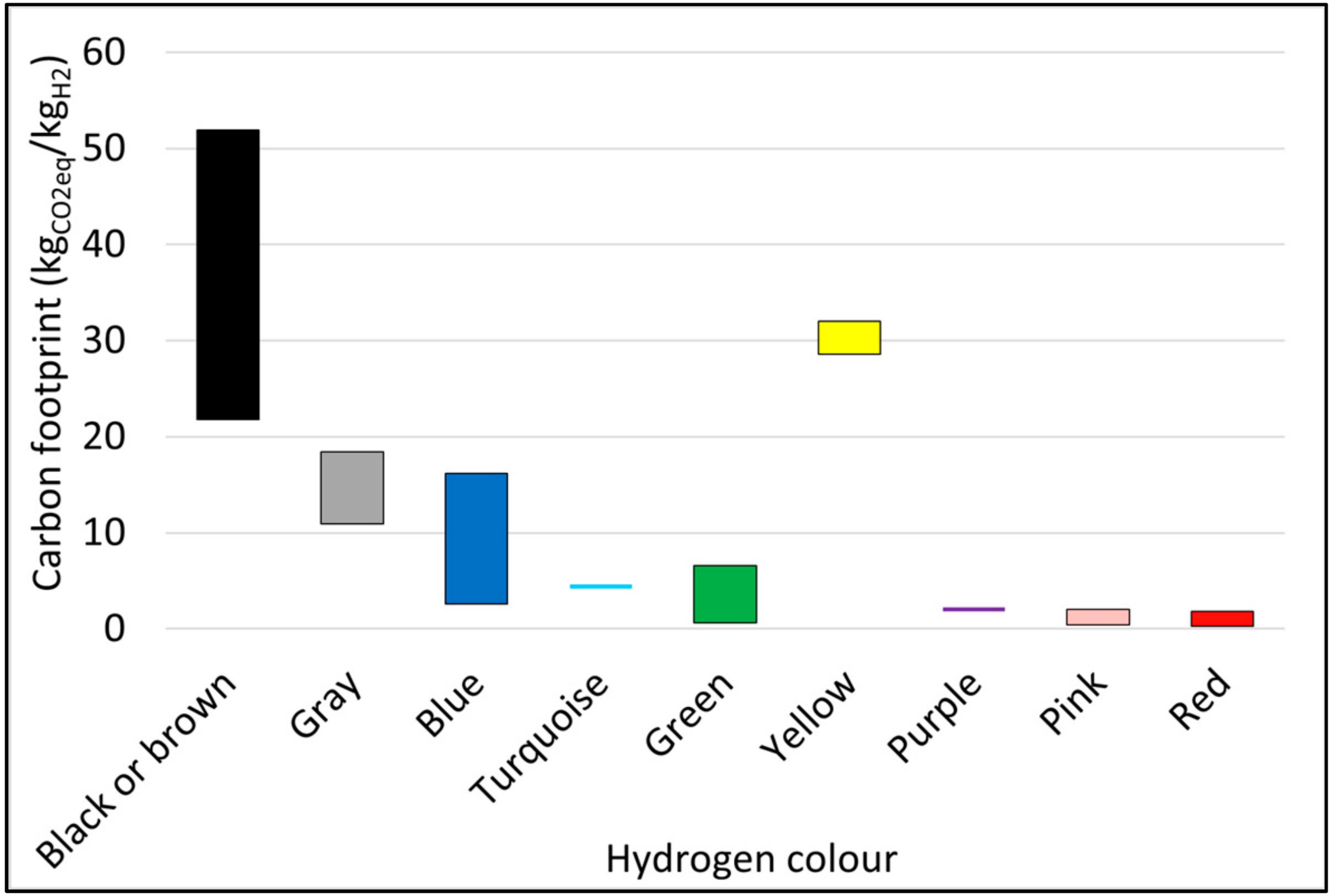
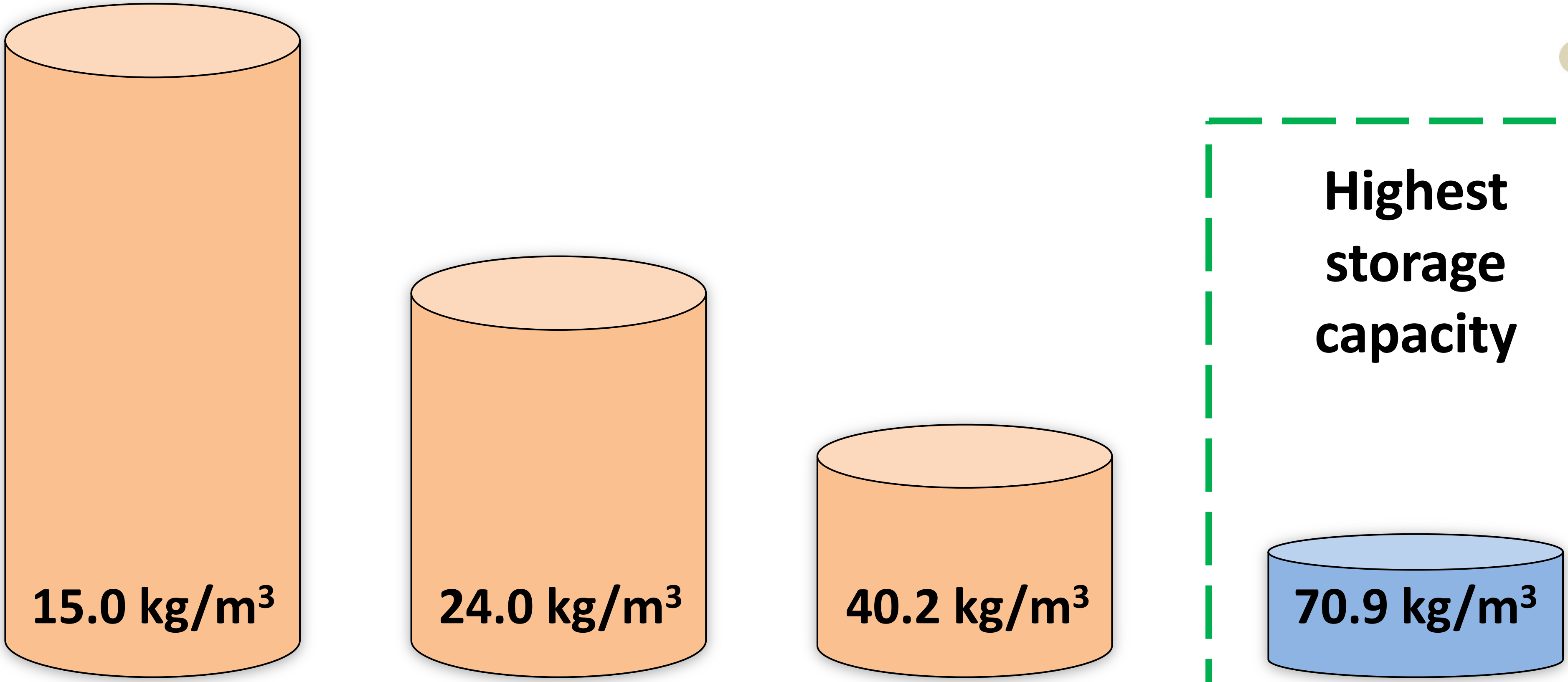


Figure 1. Carbon footprints of various hydrogen colors.

[Ustolin F, Campari A, Taccani R, An Extensive Review of Liquid Hydrogen in Transportation with Focus on the Maritime Sector, J. Mar. Sci. Eng. 2022, 10, 1222]

Hydrogen density comparison

Density



Compressed gaseous hydrogen (200 bar)

Compressed gaseous hydrogen (350 bar)

Compressed gaseous hydrogen (700 bar)

Highest storage capacity

Liquid hydrogen (1÷10 bar, **20 K**)

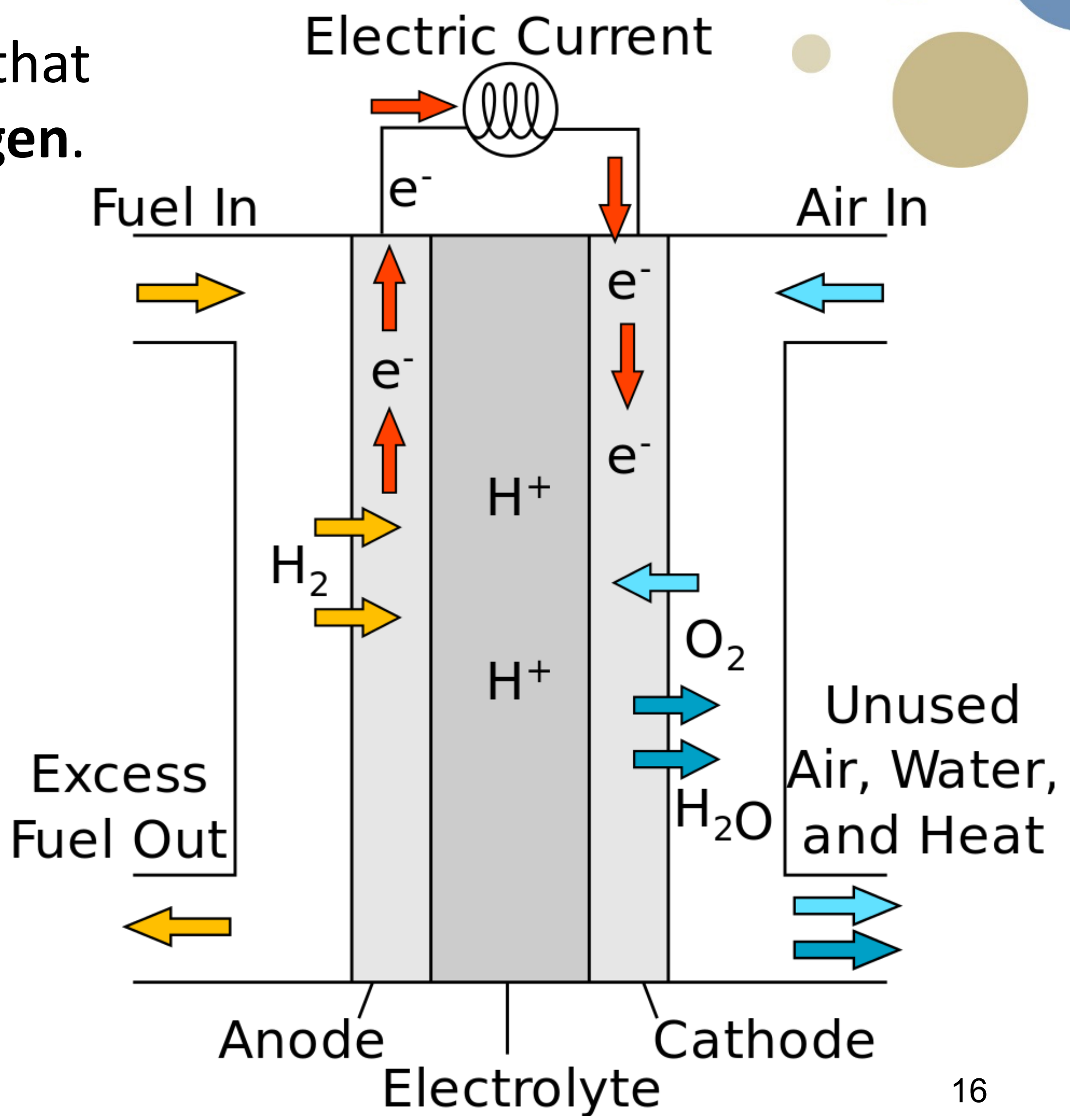
Hydrogen leakages

Hydrogen releases and leakages must be avoided due to the following reasons:

1. Environmental: hydrogen is a indirect greenhouse gas
2. Economic: hydrogen disperse in the atmosphere
3. Safety: hydrogen might ignite if released close to ignition sources

Fuel cell technology

Fuel cells (FCs) are **electrochemical devices** that produce electric energy using **hydrogen** and **oxygen**.



Advantages

- Water and heat (reusable) as products
- High electrical efficiency (more than **50%**)
- No moving parts

Drawbacks (when compared with ICE)

- High cost
- Reduced lifetime
- System mass increases considered
- all the Balance of Plants (BoP): tank, valves,
- pipes, pumps, cooling and control systems

Fuel cell types

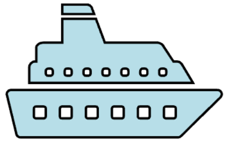
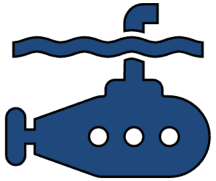
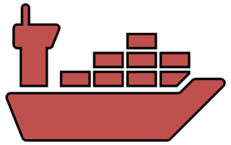
Fuel cell type	Electrolyte	Catalyst	Operative temperature (°C)	Fuel
Polymer Electrolyte Membrane (PEM)	Polymer membrane	Platinum, ruthenium	50 - 100	Pure H_2
Direct methanol	Polymer membrane	Platinum, ruthenium	60 - 200	H_2, methanol
Alkaline (AFC)	Potassium hydroxide	Platinum	60 - 120	Pure H_2
Phosforic Acid (PAFC)	H_3PO_4	Platinum	150 - 220	Pure H_2
Molten Carbonate (MCFC)	Molten alkaline carbonate ($NaHCO_3$)	Non-precious metals	600 - 650	H_2, CH_4
Solid Oxide (SOFC)	Ceramic oxide (ZrO_2)	Non-precious metals	700 - 1000	H_2, CH_4, Diesel

Content

Hydrogen as fuel on board ships

Different challenges must be faced when implementing hydrogen as a fuel on board ships and boats. In this seminar, the focus is placed on:

1. Storage: compressed gaseous, liquid hydrogen, ammonia
2. Materials: hydrogen components must be built with materials compatible with hydrogen and maritime environment
3. Hydrogen utilization on board: fuel cells, electric motors,internal combuston engines, propellers, etc.
4. Infrastructures: required to handle hydrogen and refuel the ships
5. Codes, regulations, standards: to build and operate the hydrogen vessels and infrastructures
6. Research and demonstration projects: examples of ships where hydrogen is already used as a fuel


Content

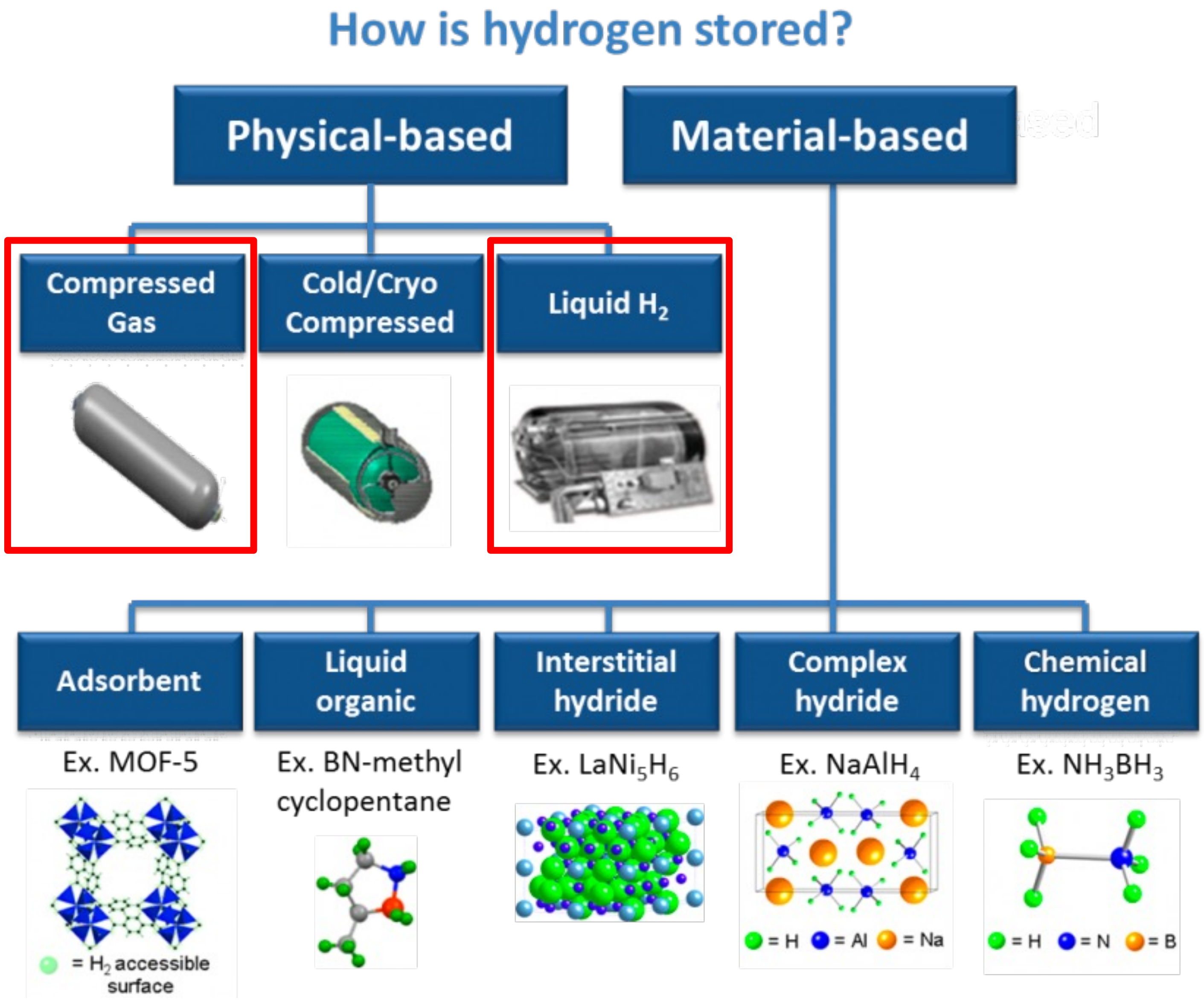
Hydrogen storage

Hydrogen is the lightest element, i.e. it requires a large volume to be stored. Therefore its density must be increased

To store hydrogen on board ships there are different constrains:

1. Volume requirement
2. Materials used to store and transfer hydrogen
3. Codes, regulations and standards to:
    a. build hydrogen components for the maritime sector
    b. handle hydrogen (e.g. bunkering)
    c. etc.

Hydrogen storage



Other fuels that contain hydrogen may be used in fuel cells by using a reformer to produce hydrogen (not for methanol and diesel in SOFC)

- ❑ Ammonia
- ❑ Natural gas
- ❑ Methanol
- ❑ Diesel

Hydrogen storage

Compressed hydrogen

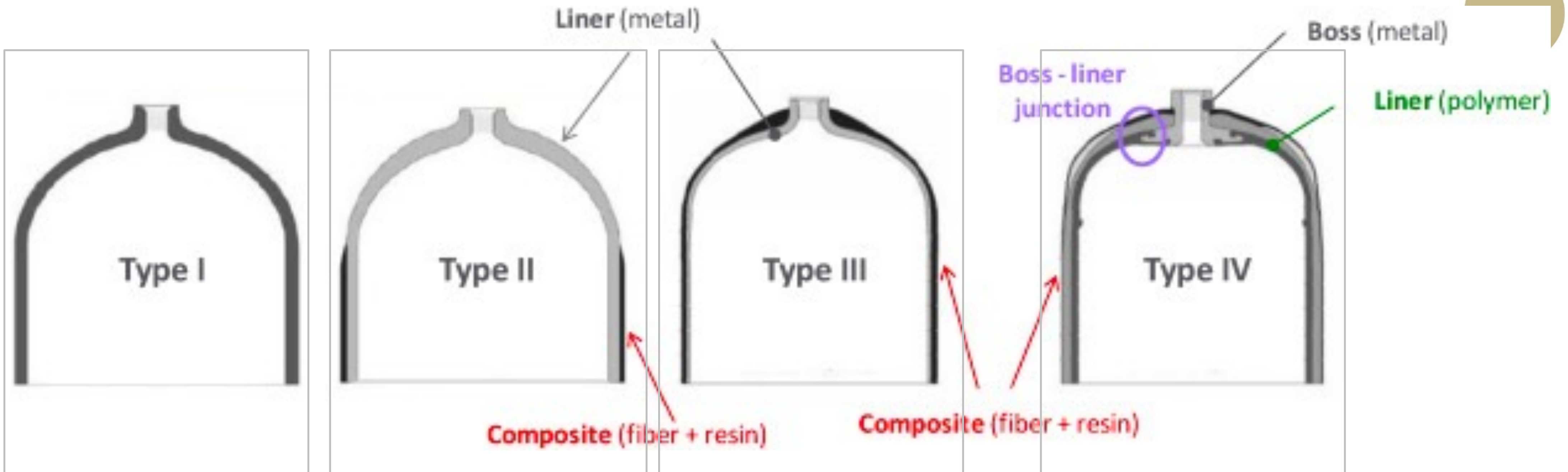
Theoretical energy to compress hydrogen isothermally from **20** to **350 bar** is 1.05 kWh/kg_{H2} and only 1.36 kWh/kg_{H2} for **700 bar**.

Data for compression from on-site H_2 production is 1.7 to 6.4 kWh/kg_{H2} (LHV of H2 = 33.3 kWh/kg)

https://www.hydrogen.energy.gov/pdfs/9013_energy_requirements_for_hydrogen_gas_compression.pdf

Hydrogen storage

Compressed hydrogen tanks

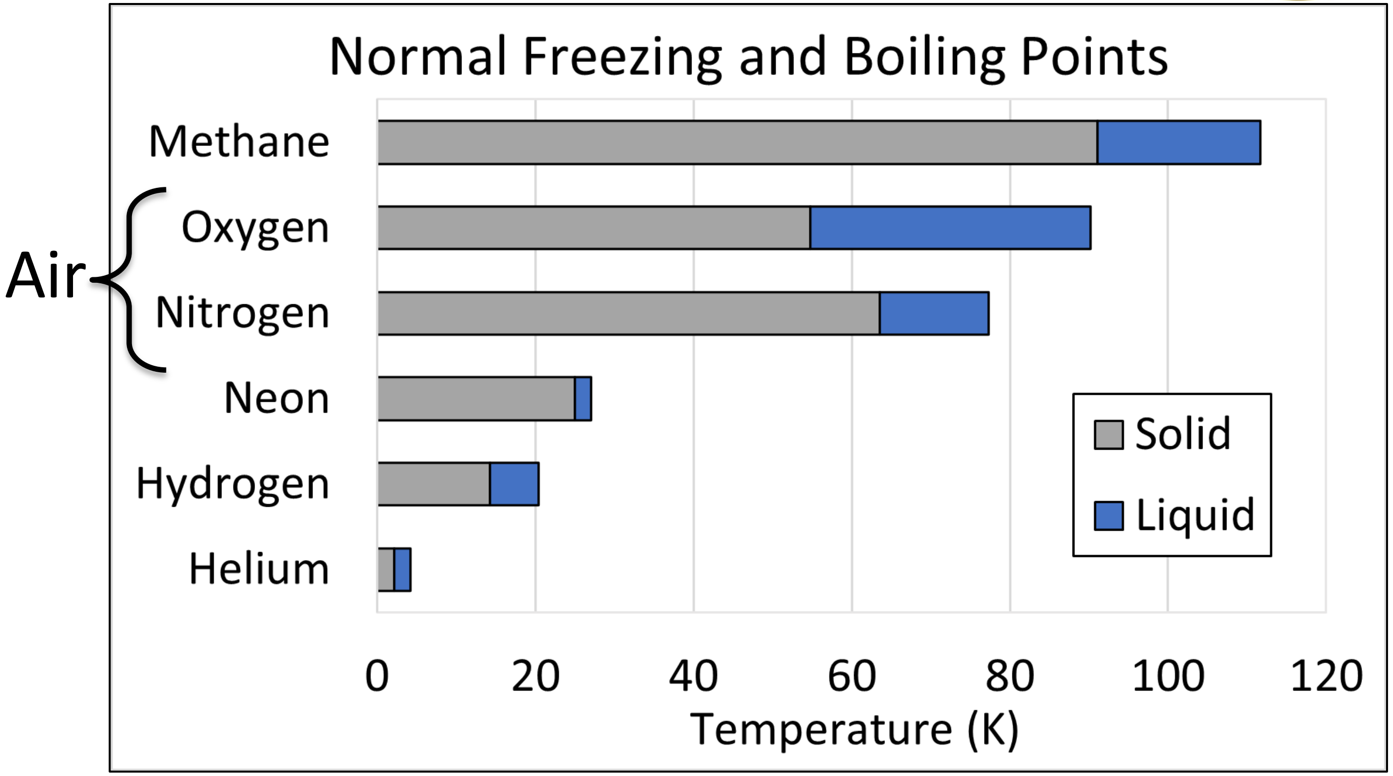


All metal	Metal with composite wrap	Metal liner with composite wrap	Plastic liner with composite wrap
P = 200 bar	P = 300 bar	P = 700 bar	P = 700 bar
Low cost	Low cost	Medium cost	High cost
High recyclability	High recyclability	Good recyclability	Low recyclability
Heavy weight	Heavy weight	Medium weight	Light weight

Hydrogen storage

Liquid hydrogen is a cryogenic fluid stored at atmospheric pressure

Cryogenic: the temperature separating cryogenics from conventional refrigeration is -150°C (123 K) (NIST)



Normal means atmospheric pressure

[NIST Chemistry WebBook 2019. webbook.nist.gov/ (accessed March 19, 2019)]

Hydrogen storage

Liquid hydrogen

Lower temperatures must be reached compared with other substances (e.g. nitrogen, oxygen, natural gas)

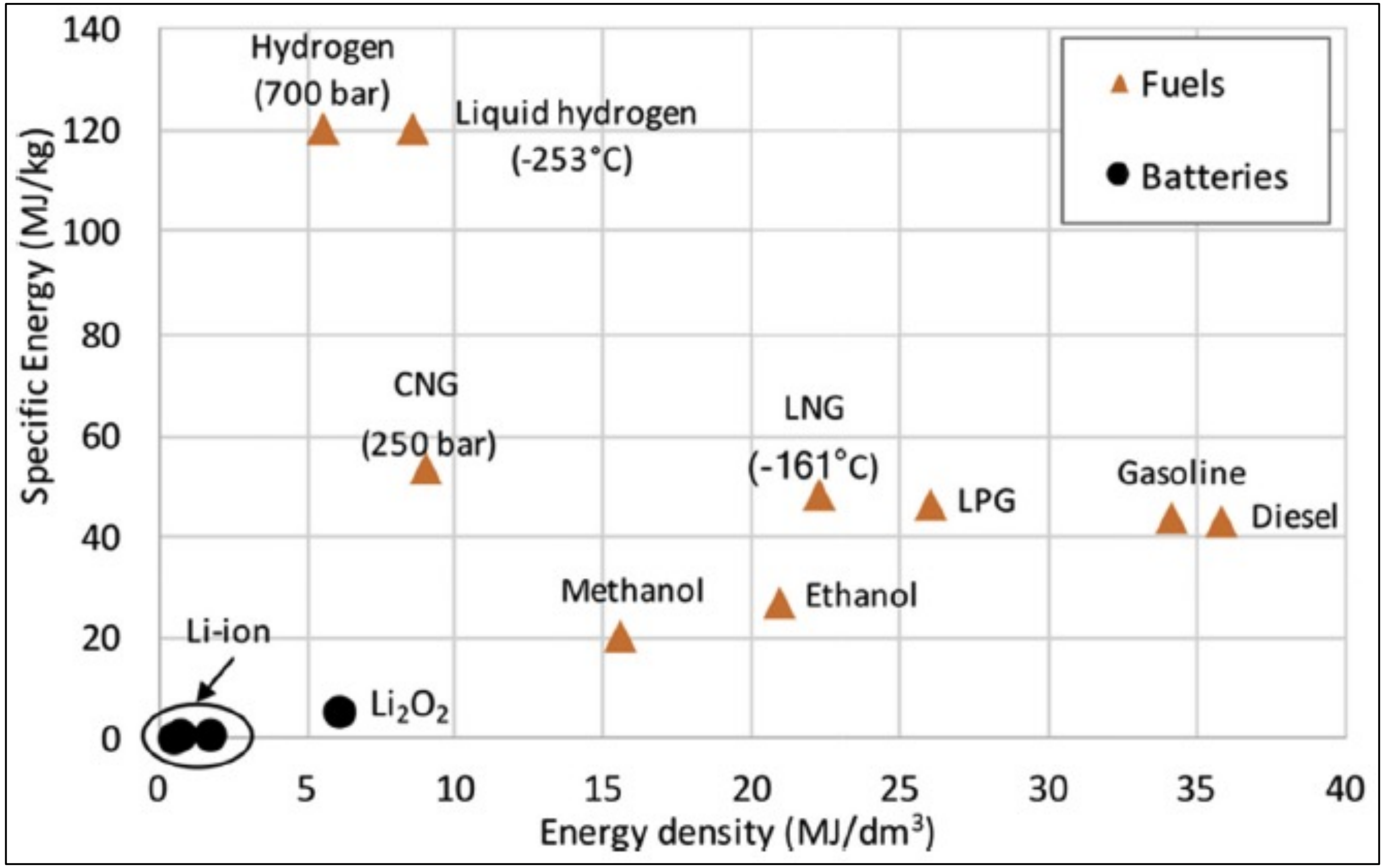
Minimum theoretical energy 3.3 kWh/kg_{LH2} or 3.9 kWh/kg_{LH2} with conversion to para-LH_2 (DOE, 2009). Typically, 10-13 kWh/kg_{LH2} 30% of H_2 LHV (33 kWh/kg).

Novel liquefaction methods such as an active magnetic regenerative liquefier may require as low as 7 kWh/kg_{LH2}

Energy may be recovered when vaporizing and heating LH2 to use it

Hydrogen storage

Liquid hydrogen



- Liquefaction purpose: increase the gas density to maximise the storage capacity.
- Energy demanding
- Liquefaction plants are expensive
- Done for large amounts of fluid

CNG: compressed natural gas; **LNG**: liquefied natural gas; **LPG**: Liquefied Petroleum Gas

[Ustolin F, Taccani R. Fuel cells for airborne usage: Energy storage comparison. Int J Hydrogen Energy 2018;43.]

Hydrogen storage

Cryogenic fluids are usually stored in double walled vessel to reduce heat transfer and evaporation of the liquid

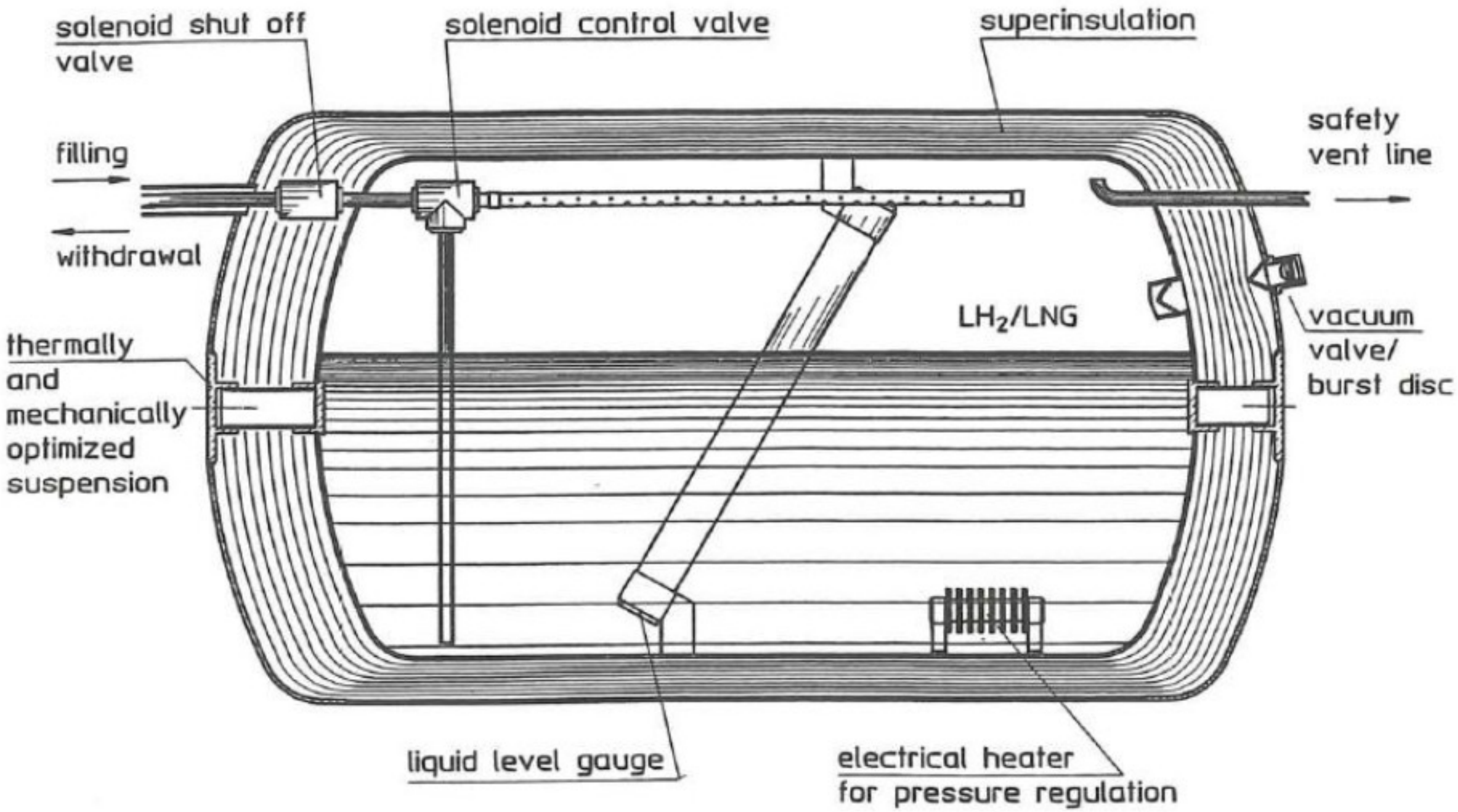
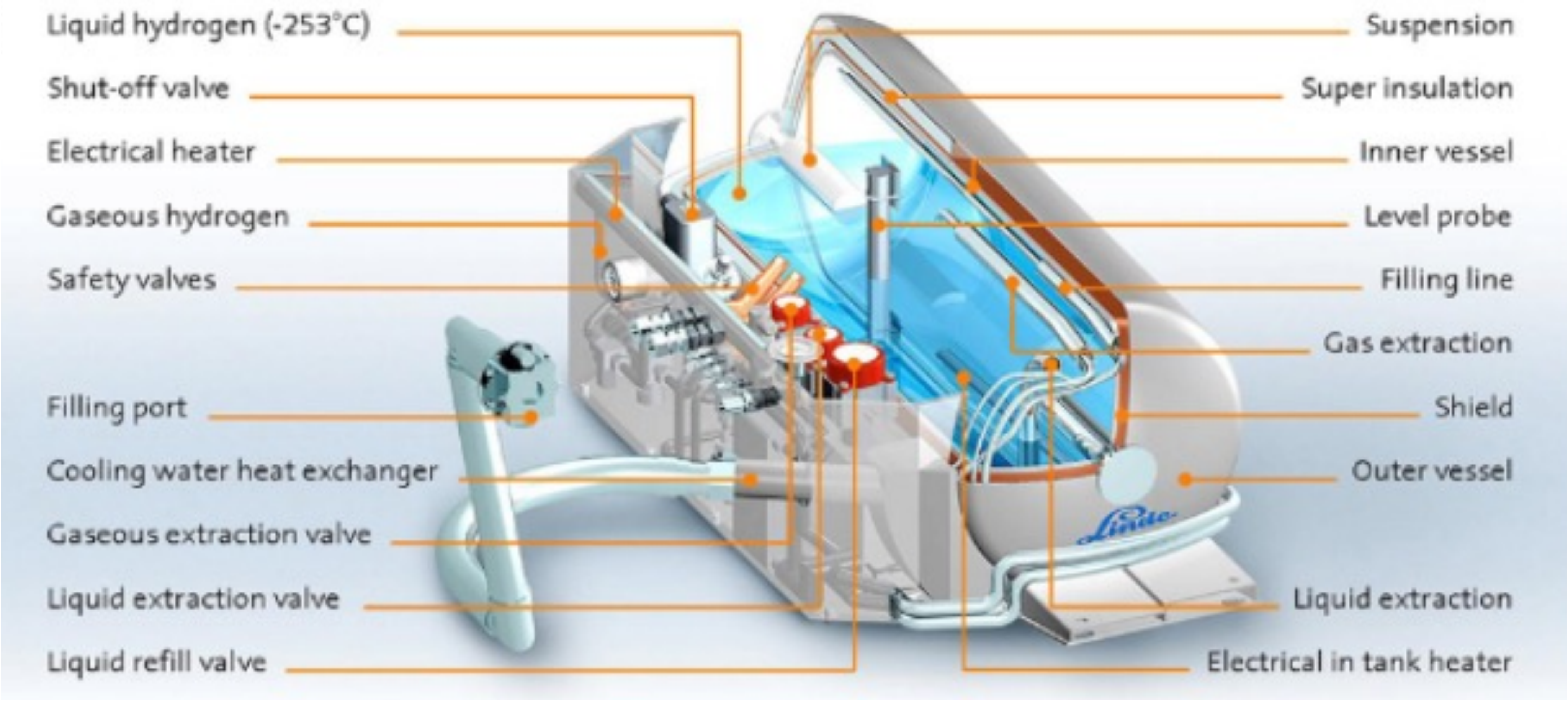


Fig. 1: Schematic drawing of a tank for LH2 or LNG source: Messer Griesheim

[Pehr K. Experimental examinations on the worst-case behaviour of LH2/LNG tanks for passenger cars. Proc. 11th World Hydrog. Energy Conf. Stuttgart 23–28 June 1996, Stuttgart: 1996, p. 2169–87.]

Hydrogen storage

Cryogenic tank – Components



[von Helmolt R, Eberle U. Fuel cell vehicles: Status 2007. J Power Sources 2007;165:833–43.]

Hydrogen storage

Cryogenic tank – Thermal insulation

Aim of thermal insulation is to avoid boil-off gas (BOG) formation, for environmental, economical and safety reasons

The most common insulation types for cryogenic vessels are:

- expanded closed-cell foams (e.g. polyurethane, polystyrene and glass foam);
- gas-filled powders and fibrous materials: fiberglass, **perlite** (a silica powder), silica aerogel, rock wool, and vermiculite;
- aerogel insulation;
- evacuated powders and fibrous materials;
- opacified powder insulations;
- microsphere insulation
- **multilayer insulation** (MLI).

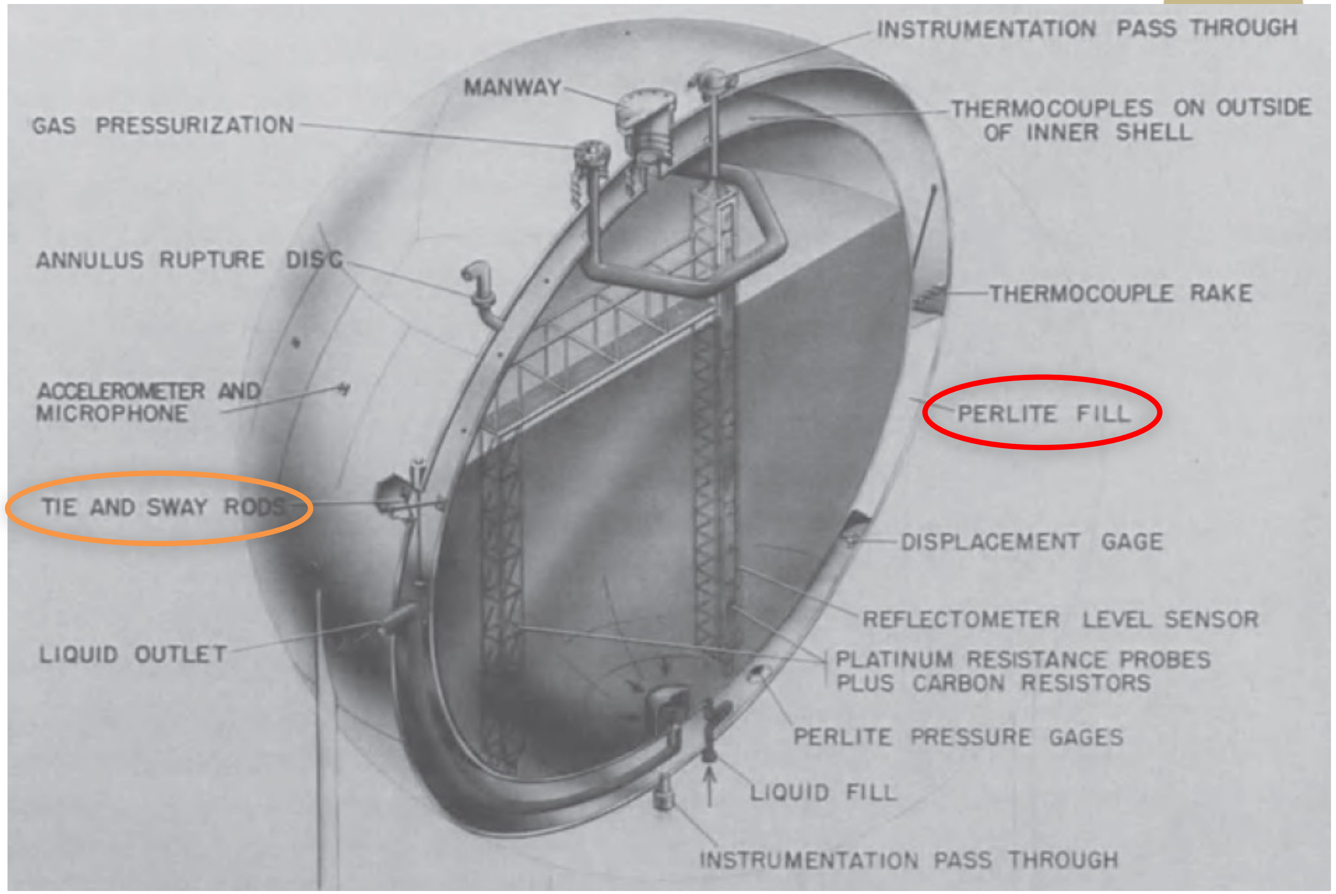
Hydrogen storage

Cryogenic tank – Perlite insulation

Evacuated perlite insulation is usually employed for large size tanks

Perlite tanks weight more than MLI tanks (used for automotive, aeronautics)

Critical components



Interior view of a typical large container with a capacity of 1,800 m^3 for liquid hydrogen (Source: Los Alamos National Laboratory)

Hydrogen storage

BOG rates estimated for different LH_2) tank sizes in 1992

BOG rate	Tank size	Application and insulation
1.0%vol./day	Small (< 5 m^3)	Research, laboratory (MLI)
< 1.0%vol./day	Small (< 5 m^3)	If cooled with liquid nitrogen (MLI)
0.3÷0.5%vol./day	30 ÷ 70 m^3	Road tanker (truck). Vacuum perlite insulation.
0.2%vol./day	105 m^3	Rail transport. Vacuum perlite insulation.
< 0.1%vol./day	Large (> 100 m^3)	Aerospace and nuclear research fields. Insulation cooling through vapour cooled shields (VCSs).

[Peschka W. Liquid Hydrogen - Fuel of the Future. 1st editio. Wien: Springer-Verlag; 1992.]

Hydrogen storage

Compressed hydrogen is suitable for short range ships (ferries, boats) due to high space requirement and high weight

Liquid hydrogen is more suitable for medium - long range ships and to deliver large amounts of hydrogen. However, due to the very cold temperature (-253°C), many challenges must be tackled.

Content

Materials for hydrogen components

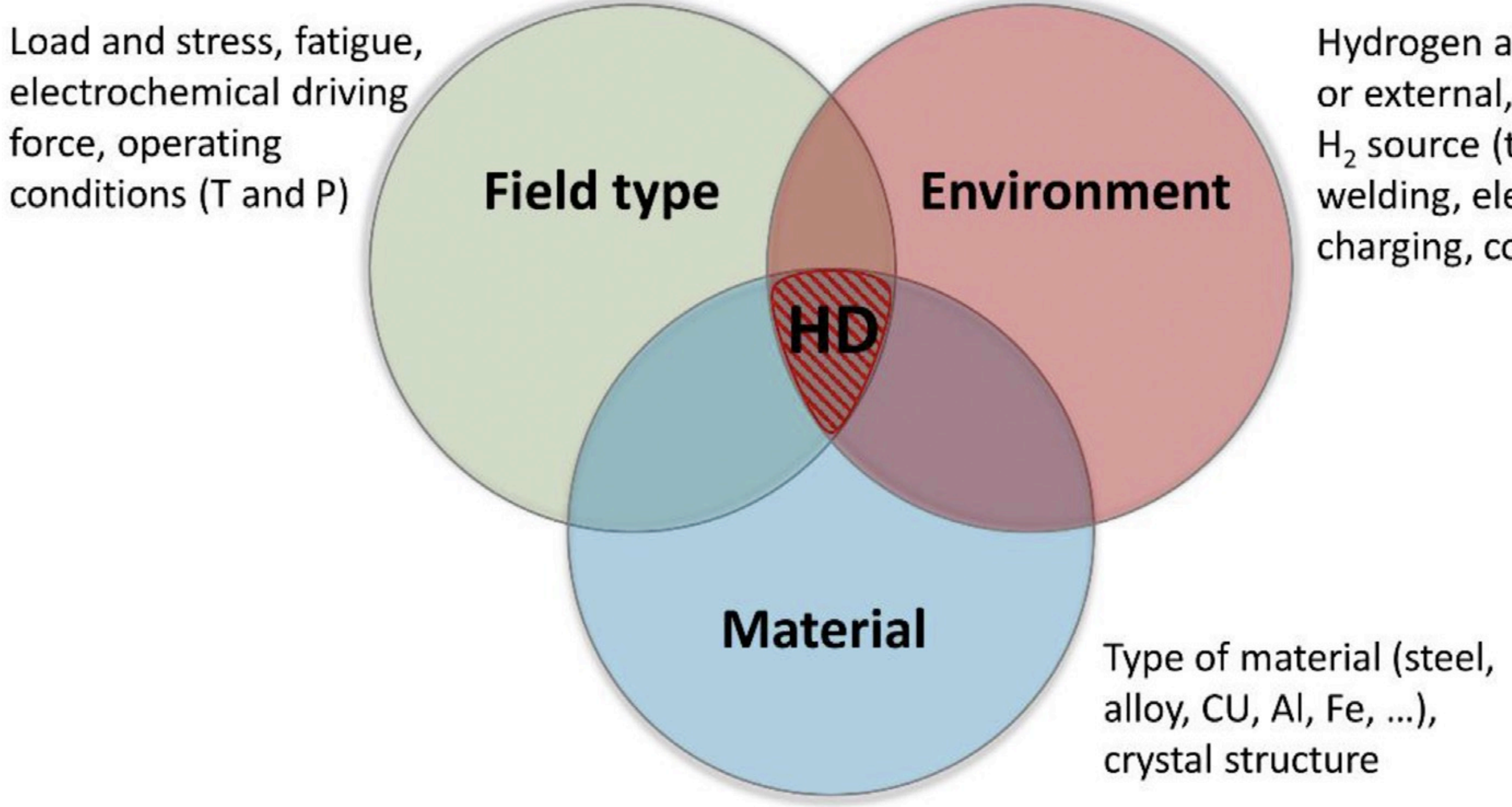
Loss of integrity of H_2 equipment

Loss of integrity of a cryogenic piece of equipment is a dangerous and undesired event which can be cause by different phenomena:

- Hydrogen damage (HD)
- Low temperature embrittlement
- Stresses cause by thermal gradient, dilatation and contraction
- Fatigue cycles

Materials for hydrogen components

Hydrogen damages (HDs)



[Ustolin F, Paltrinieri N, Berto F. Loss of integrity of hydrogen technologies: A critical review. Int J Hydrogen Energy 2020;45:23809–40.]

Materials for hydrogen components

Hydrogen damages (HDs)

Hydrogen is a very peculiar substance. Its molecule is the smallest one. This means that it can penetrate in microscopic holes. Moreover, it reacts with different substances since it is missing one electron in its outer shell.

Table 9 – Hydrogen damage phenomena (adapted from Ref. [163]).

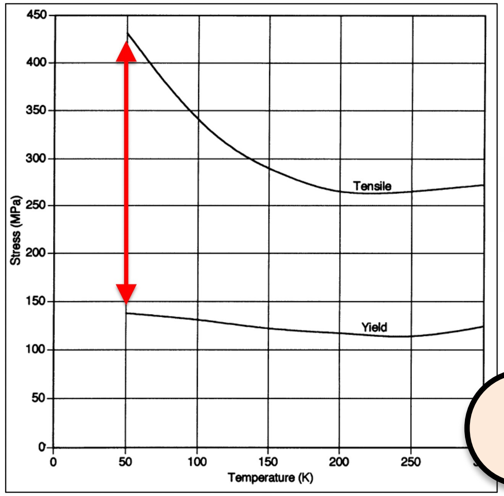
	Hydrogen embrittlement								
	Hydrogen environment embrittlement	Hydrogen stress cracking	Loss in tensile ductility	Hydrogen attack	Blistering	Shatter cracks, flakes, fisheyes	Micro-perforation	Degradation in flow properties	Metal hydride formation
Materials	Steels, Ni-base alloys, metastable stainless steel, Ti alloys	Carbon and low alloy steels	Steels, Ni-base alloys, Be–Cu bronze, Al alloys	Carbon and low alloy steels	Steels, Cu, Al	Steels (forgings and castings)	Steels (compressor)	Fe, steels, Ni-base alloys	V, Nb, Ta, Ti,Zr, U
Source of hydrogen	GH_2	Thermal processing, electrolysis, corrosion	GH_2, internal hydrogen from electrochemical charging	GH_2	H_2S corrosion, electrolytic charging,GH_2	Water vapor reacting with molten steel	GH_2	GH_2 or internal H_2	Internal H_2 from melt; corrosion,electrolytic charging, welding
Conditions	$10^{-12} \div 10^2$ MPa, $-100 \div 700$ °C	$0.1 \div 10$ ppm H_2 content, $-100 \div 100$ °C	$0.1 \div 10$ ppm H_2 content, $-100 \div 700$ °C	Up to 10^2 MPa at $200 \div 595$ °C	H_2 activity $0.2 \div 1 \times 10^2$ MPa at $200 \div 595$ °C	Precipitation of dissolved ingot cooling	$2 \div 8 \times 10^6$ MPa at $20 \div 100$ °C<	$1 \div 10$ ppm H_2 content, up to 10^2 MPa	$0.1 \div 10^2$ MPa

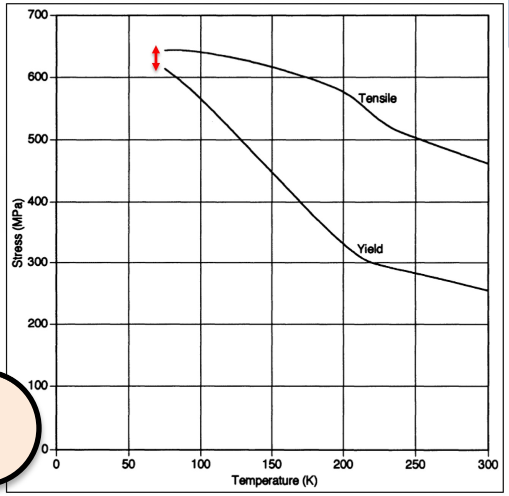
[Ustolin F, Paltrinieri N, Berto F. Loss of integrity of hydrogen technologies: A critical review. Int J Hydrogen Energy 2020;45:23809–40]

Materials for hydrogen components

Other phenomena

1. Low temperature embrittlement: ductile to brittle (at nil-ductility temperature) behaviour
2. contraction: stress caused by dimensional change (Steady-State Temperature)
3. Thermal gradient stress: e.g. two-phase flow

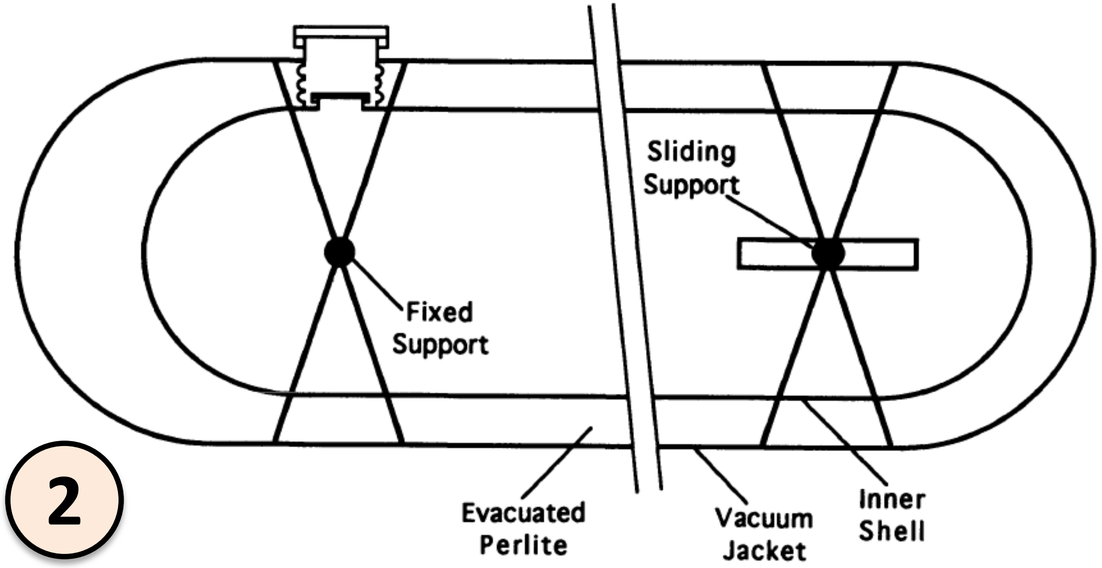




1

5086 aluminum **AISI 430 stainless steel**

[Edeskuty F, Stewart W. Safety in the Handling of Cryogenic Fluids. Springer Science +Business Media, LLC; 1996.]



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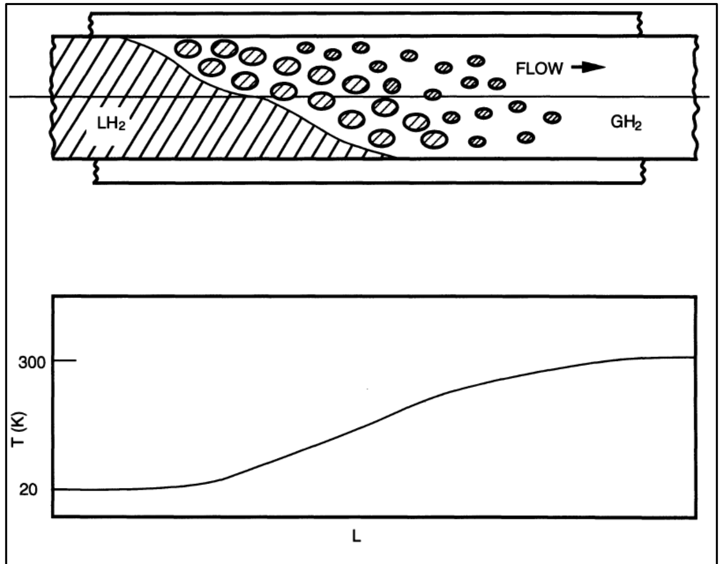


Fig. 4.8. Cool-down model, representing the average behavior of a typical section of a long cryogenic transfer line during the cool-down process.[8]

3

Materials for hydrogen components

Material selection

→ Suitable for LH_2

Other aspects such as cost and availability must be considered for the selection

[NASA. Safety standard for hydrogen and hydrogen systems, Guidelines for Hydrogen System Design, Materials Selection, Operations, Storage, and Transportation - NSS 1740.16. 2005.]

Table A5.1

Summary of Material Compatability for Hydrogen Service

Material	Service			Remarks
	GH_2	LH_2	SLH_2	
→ Aluminum and its alloys	Yes	Yes	Yes	
→ Austenitic stainless steels with > 7% nickel (such as, 304, 304L, 308, 316, 321, 347)	Yes	Yes	Yes	Some make martensitic conversion if stressed above yield point at low temperature.
Carbon steels	Yes	No	No	Too brittle for cryogenic service.
→ Copper and its alloys (such as, brass, bronze, and copper-nickel)	Yes	Yes	Yes	
Gray, ductile, or cast iron	No	No	No	Not permitted for hydrogen service.
Low-allow steels	Yes	No	No	Too brittle for cryogenic service.
~~Nickel and its alloys~~ (such as, Inconel® and Monel®)	~~No~~	~~Yes~~	~~Yes~~	~~Susceptible to hydrogen~~ embrittlement
Nickel steels (such as, 2.25, 3.5, 5, and 9 % Ni)	No	No	No	Ductility lost at LH_2 and SLH_2 temperatures.
→ Titanium and its alloys	Yes	Yes	Yes	
~~Asbestos impregnated with Teflon®~~	~~Yes~~	~~Yes~~	~~Yes~~	~~Avoid use because of carcinogenic~~ hazard.
Chloroprene rubber (Neoprene®)	Yes	No	No	Too brittle for cryogenic service.
Dacron®	Yes	No	No	Too brittle for cryogenic service.
Fluorocarbon rubber (Viton®)	Yes	No	No	Too brittle for cryogenic service.
Mylar®	Yes	No	No	Too brittle for cryogenic service.
Nitrile (Buna-N®)	Yes	No	No	Too brittle for cryogenic service.
Polyamides (Nylon®)	Yes	No	No	Too brittle for cryogenic service.
→ Polychlorotrifluorethylene (Kel-F®)	Yes	Yes	Yes	
→ Polytetrafluorethylene (Teflon®)	Yes	Yes	Yes	

Materials for hydrogen components

Material selection

Table 12 – Materials suitable for the hydrogen equipment (adapted from Ref. [85]).

Component	CGH_2	$CcGH_2/LH_2/SLH_2$
Valves	Appropriate material[a]	Forged, machined, and cast valve bodies (304 or 316 stainless steel, or brass) with extended bonnet, and with other materials inside
Fittings	Appropriate material[a]	Stainless steel bayonet type for vacuum jackets
O-rings	Appropriate material[a]	Stainless steel, Kel-F®, or Teflon®
Gaskets	Appropriate material[a]	Soft Aluminium, lead, or annealed copper between serrated flanges; Kel-F®; Teflon®; glass-filled Teflon®
Flexible hoses	Stainless steel braided with Teflon-lining	Convoluted vacuum jacketed 316 or 321 stainless steel
Rupture disk assembly	304, 304 L, 316, or 316 L stainless steel	304, 304 L, 316, or 316 L stainless steel
Piping	300 series stainless steel, carbon steel [180]	304, 304 L, 316, or 316 L stainless steel
Outer tank of Dewar or tank (CGH_2)	304, 304 L, 316, 316 L stainless steel, carbon fibre epoxy	304, 304 L, 316, or 316 L stainless steel
Inner tank of Dewar	–	austenitic chrome-nickel steel with a high nickel content; aluminium alloys with very good weldability; copper and copper alloys, fcc metals
Insulation	–	Rockwool, perlite, mylar, aluminium and fiberglass
Lubricants	Dupont Krytox 240AC, Fluoramics OXY-8, Dow Corning DC-33, Dow Corning FS-3452, Bray Oil Braycote 601, General Electric Versilube, Houghton Cosmolube 5100, Braycote 640 AC, Dupont GPL 206, Halocarbon Series 6.3 oil, and Kel-F® oil	PTFE, PTFE carbon, PTFE bronze, fiberglass-PFTE graphite [60]. Graphite and molybdenum disulfide permit only very limited service life for bearings [181].

[a] Different commercial materials and product compatible with gaseous hydrogen at different conditions are available.

CGH_2: compressed gaseous H_2; **$CcGH_2$**: cryo-compressed gaseous H_2; **LH_2**: liquid hydrogen; **SLH_2**: slush H_2 (mixture of solid and liquid)

[Ustolin F, Paltrinieri N, Berto F. Loss of integrity of hydrogen technologies: A critical review. Int J Hydrogen Energy 2020;45:23809–40.]

Materials for hydrogen components

Material selection – Notes

Insulating materials, powder and multilayer insulation should be made of non-combustible materials for safety reasons (danger of explosion).

Clad materials can be used in hydrogen technology. These may be difficult to weld. Welds are susceptible to H2 embrittlement in all H2 environments.

It is best to use room temperature material properties to design cryogenic equipment because:

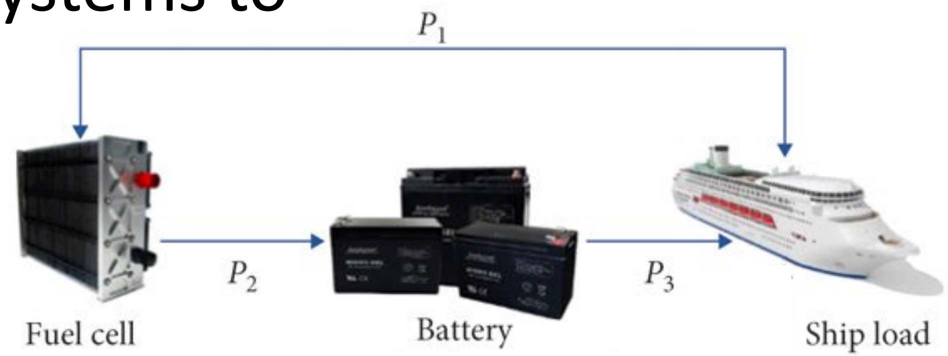
- ✓ strengths of materials tends to increase as their temperature is lowered;
- ✓ these must also operate at room (or higher) temperature.

Forbidden materials: gray, ductile or cast iron.

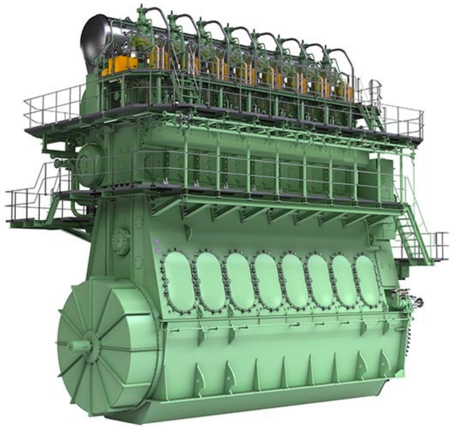
Content

Hydrogen utilization on board

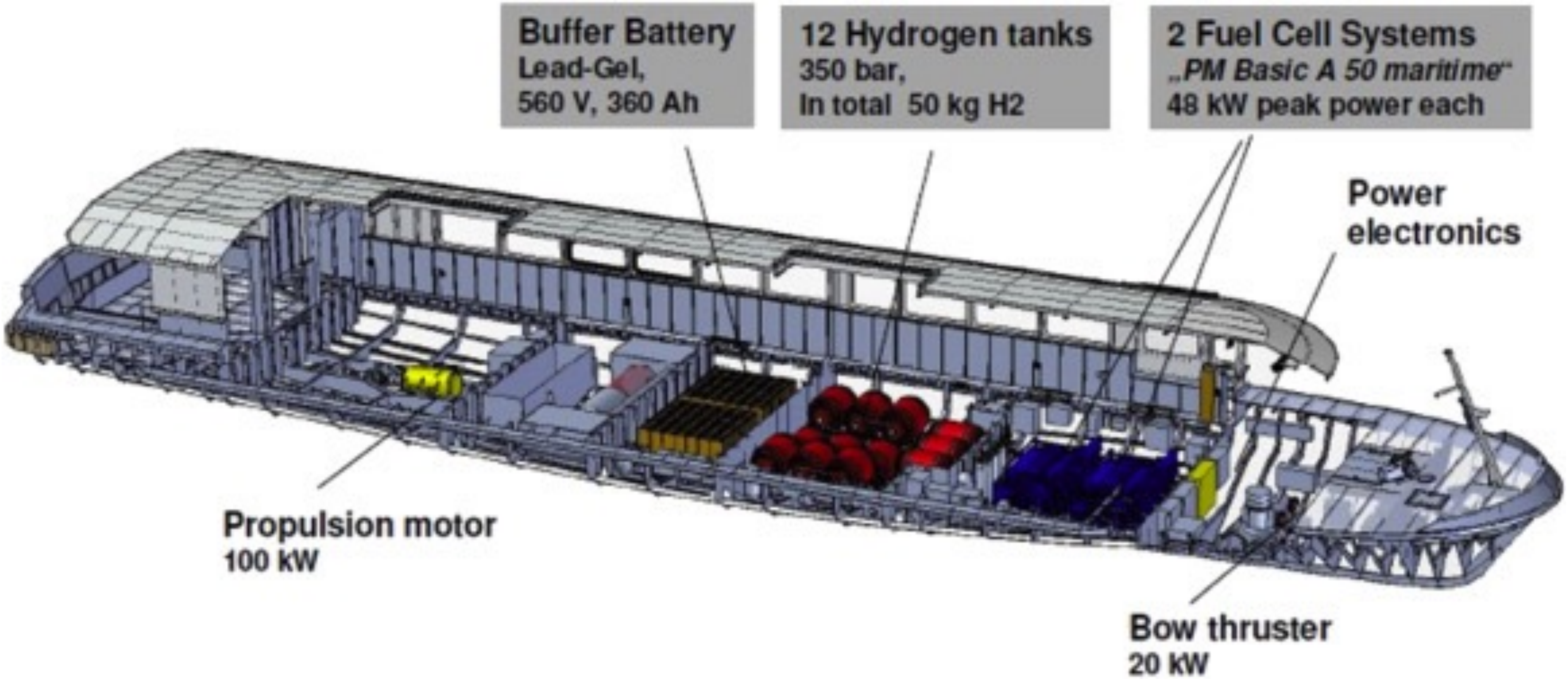
- Hydrogen should be used to supply fuel cell systems to generate electricity and use it to either:
    a. Power the ship service
    b. Or propel the ship



- Hybrid systems (hydrogen + batteries) are usually developed when using fuel cells
- Internal combustion engines might be used, especially in a transition phase, however:
    a. their efficiency may be lower than the fuel cells one
    b. and the generation of NOx (during hydrogen combustion) must be avoided or abated



Hydrogen utilization on board



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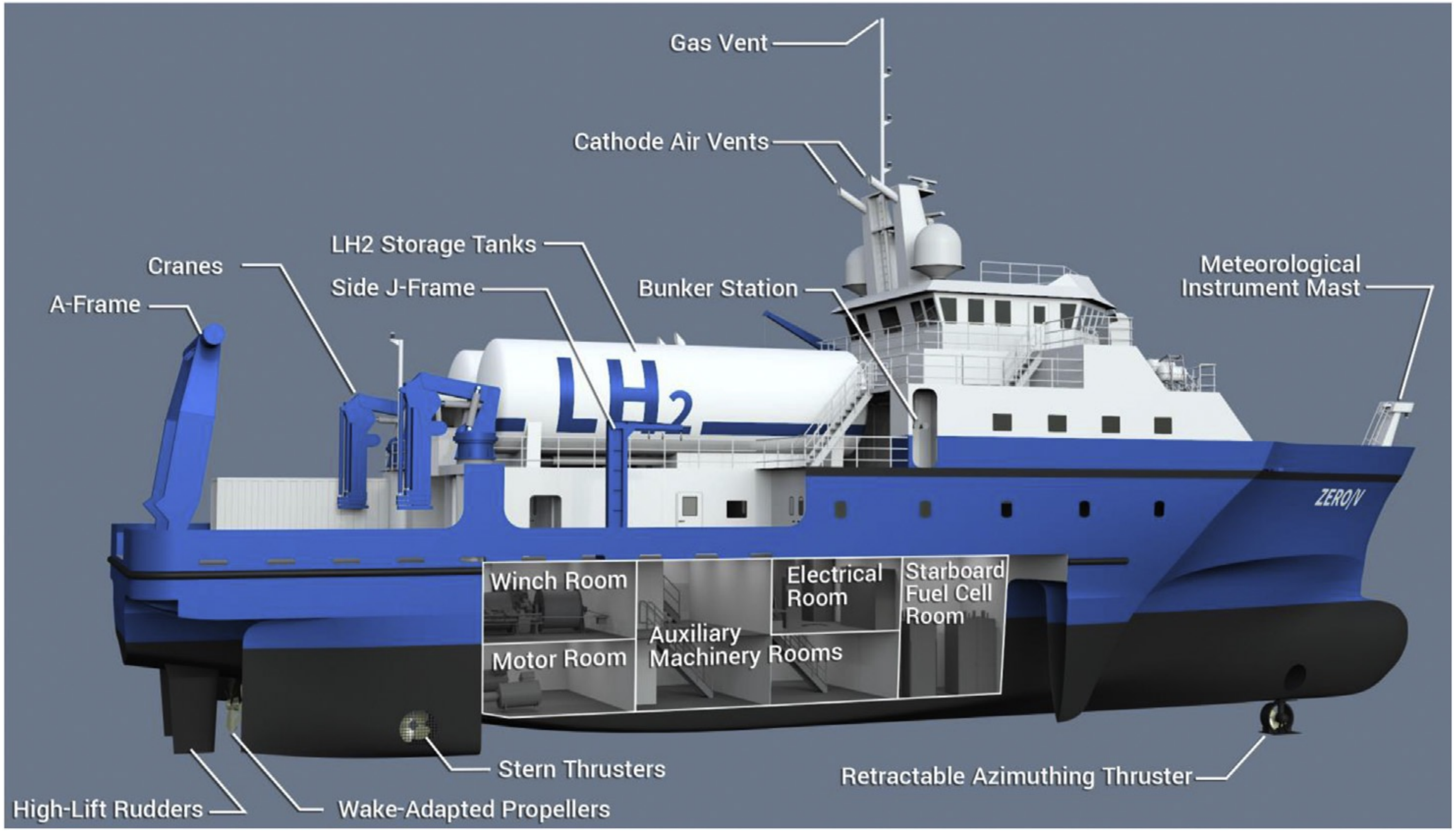
Hydrogen utilization on board



[Madsen, R. T., Klebanoff, L. E., Caughlan, S. A. M., Pratt, J. W., Leach, T. S., Appelgate, T. B., Kelety, S. Z., Wintervoll, H. C., Haugom, G. P., Teo, A. T. Y., & Ghosh, S. (2020). Feasibility of the Zero-V: A zero-emissions hydrogen fuel-cell coastal research vessel. International Journal of Hydrogen Energy, 45(46), 25328–25343]

Hydrogen utilization on board

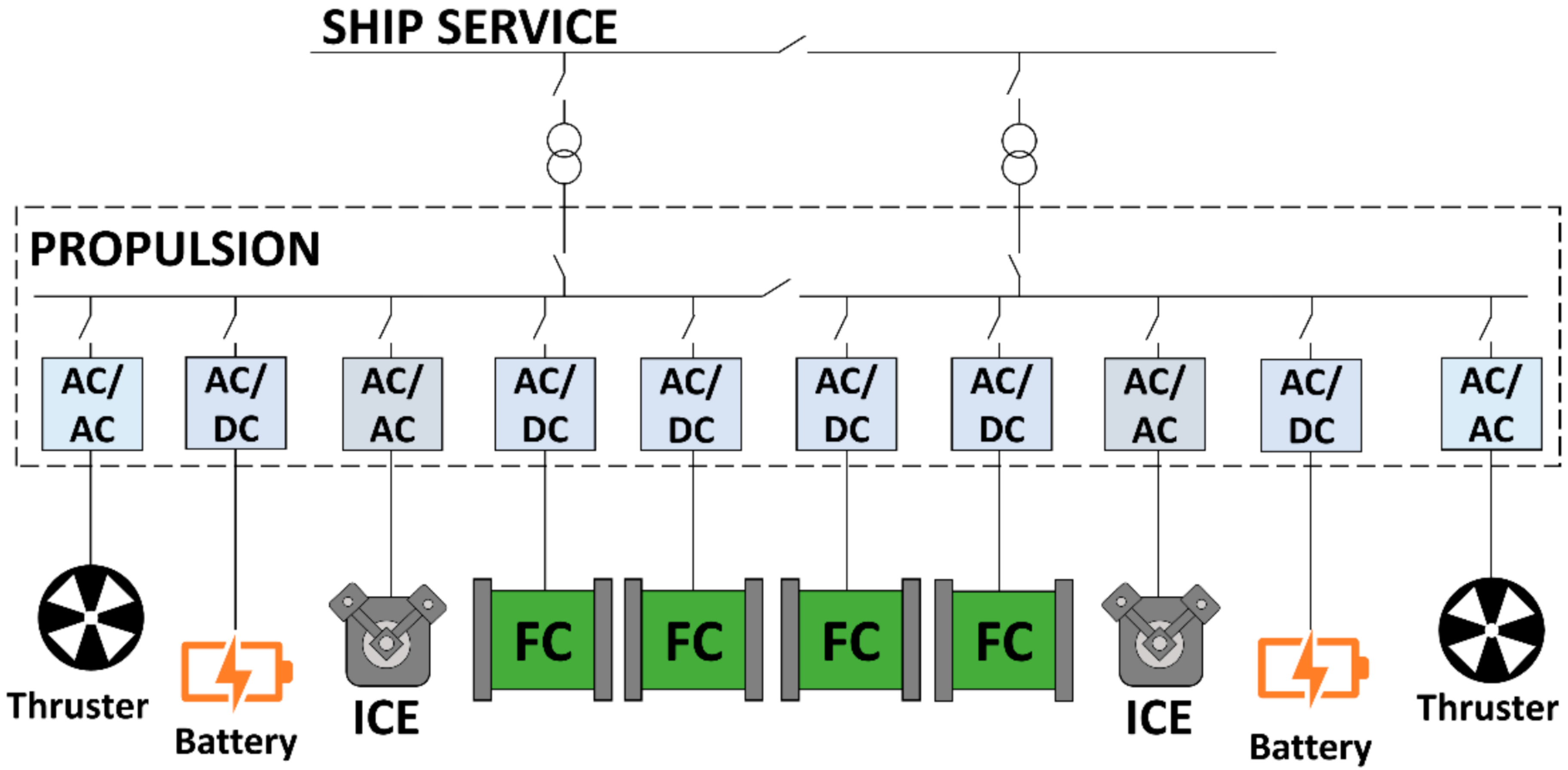


Figure 4. Propulsion and service system block diagram for a hybrid (fuel cells, batteries, and internal combustion engines) system (adapted from [108]; abbreviations: AC: alternative current, DC: direct current, FC: fuel cell, ICE: internal combustion engine).

Hydrogen utilization on board

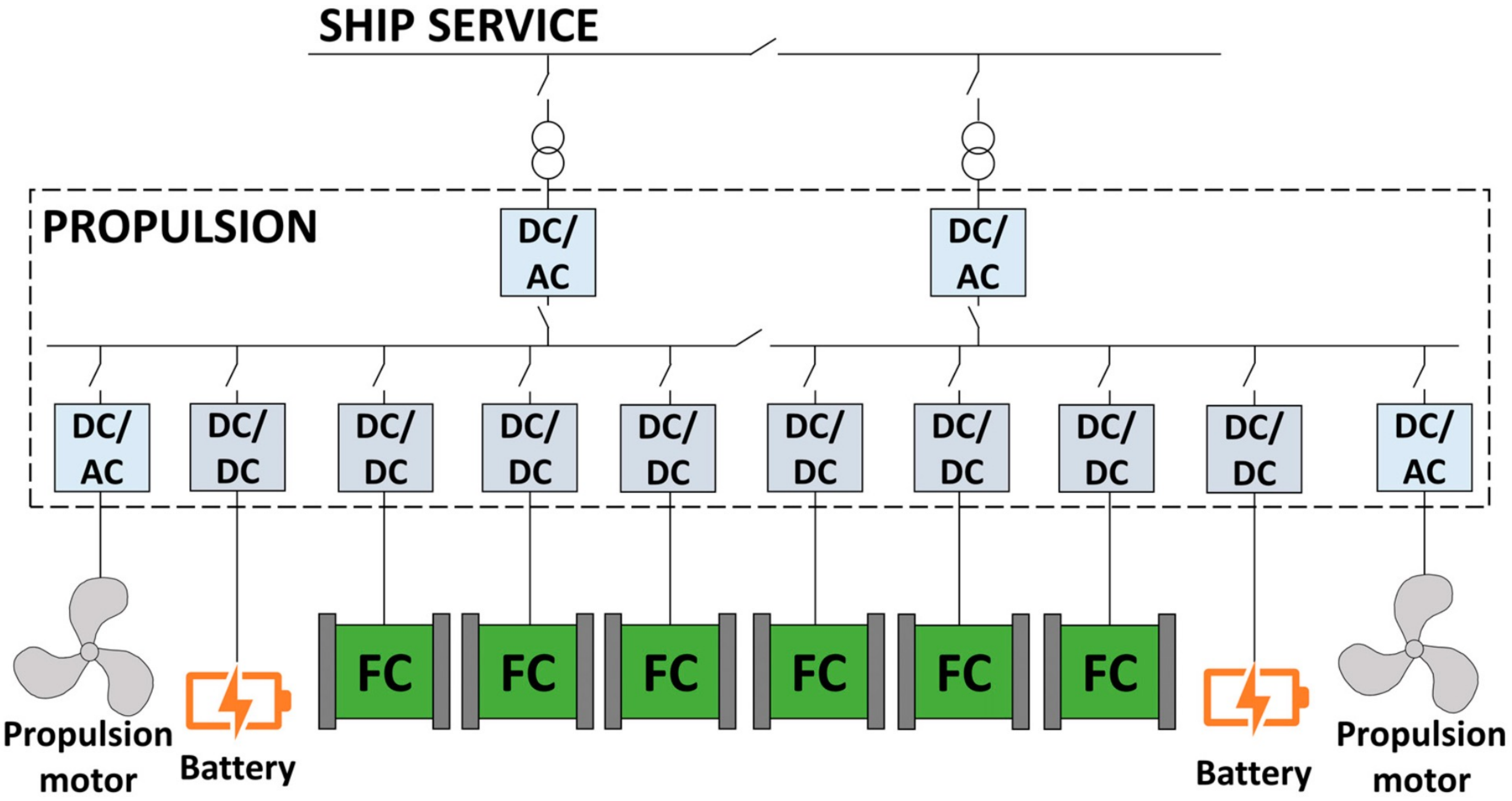
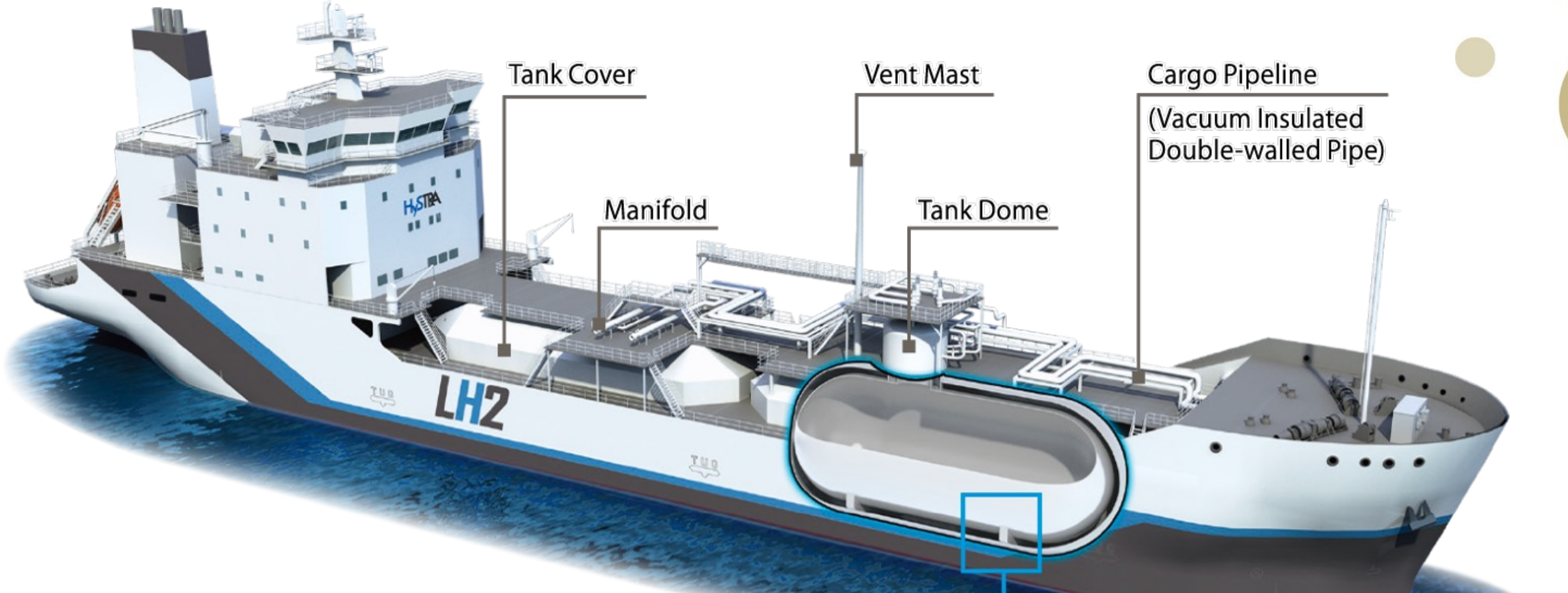


Figure 3. Propulsion and service system block diagram for a hybrid (fuel cells and batteries) system (adapted from [107]; abbreviations: AC: alternative current, DC: direct current, FC: fuel cell).

Hydrogen utilization on board

Hydrogen carriers

Suiso Frontier
(liquid hydrogen)

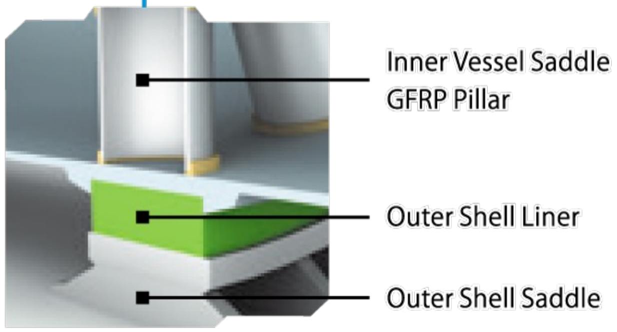


Overall length	: 116.0 m	Gross tonnage	: 8,000 tonnes
Overall width	: 19.0 m	Vessel speed	: 13 knots
Depth	: 10.6 m	Draft	: 4.5 m
Maximum crew	: 25 persons	Tank capacity	: 1,250 kL

https://www.hystra.or.jp/en/project/

Liquefied hydrogen tanks for marine transportation

A vacuum insulated double-walled structure provides ultimate insulation properties.
Using glass fiber reinforced plastic (GFRP) for the support structure enables heat transfer to be reduced.



Content

Hydrogen infrastructures

Bunkering (refuelling of ship) can be carried out with different techniques:

1. Truck-to-ship (TTS) bunkering
2. Ship-to-ship (STS) bunkering
3. Bunker stations

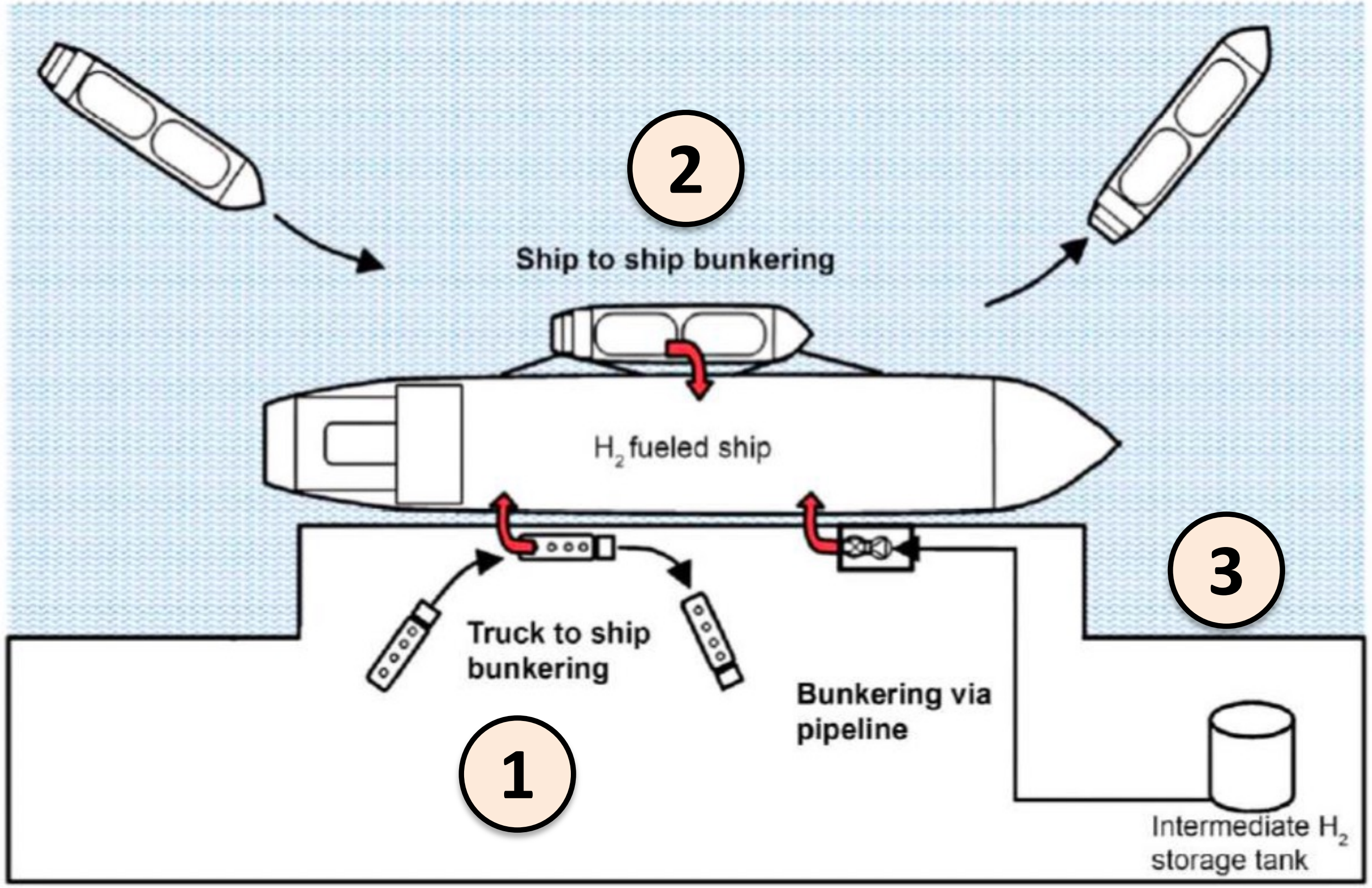


Figure 2: Illustration of different bunkering configurations (source: DNV report ref. /6/)

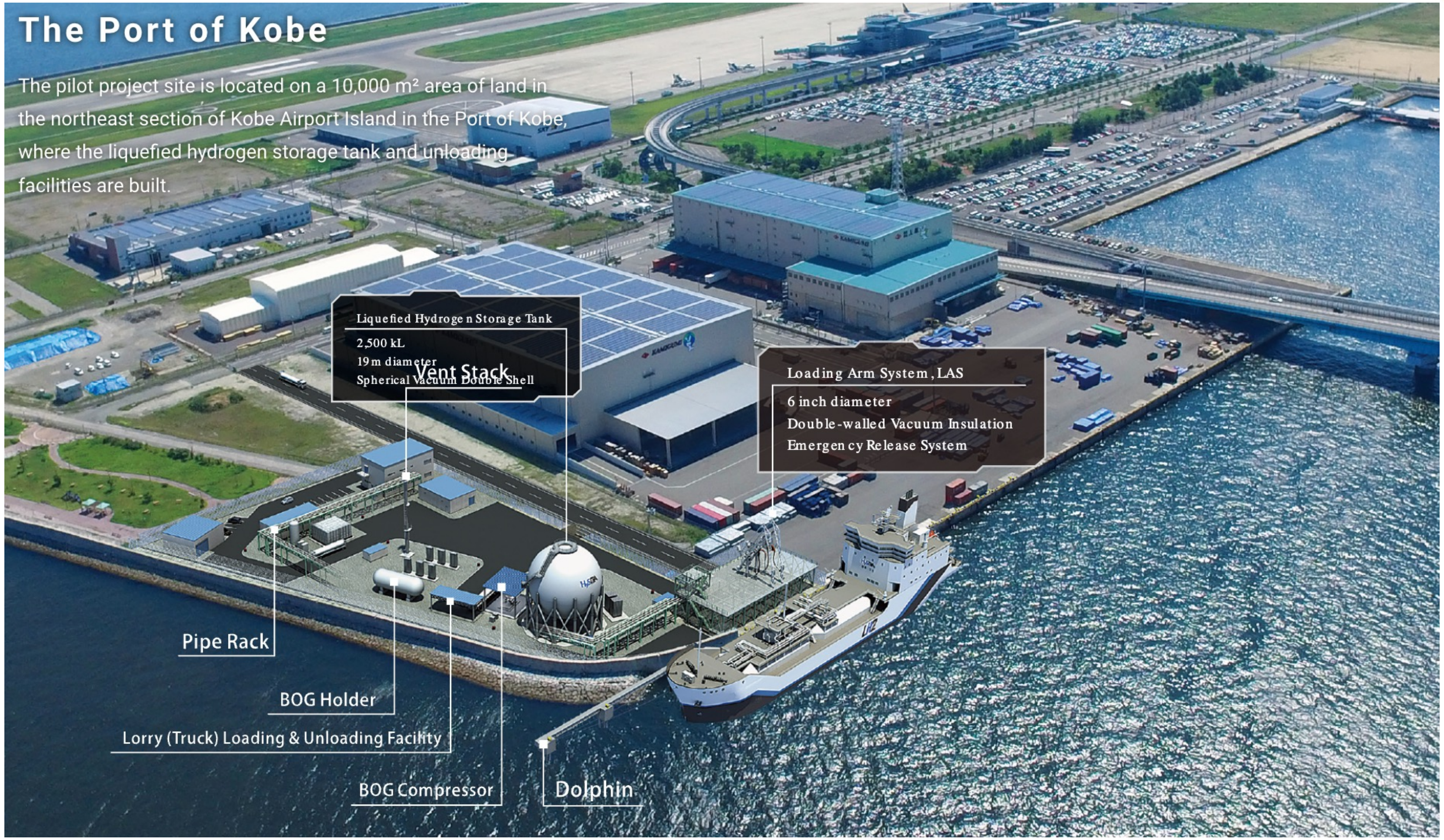
Hydrogen infrastructures

Currently, few bunkering facilities to refuel hydrogen ships exist

Example:

Liquid hydrogen at Kobe terminal built within the HySTRA project

https://www.hystra.or.jp/en/project/



Content

Recommendations, codes and standards

Recommendations, codes and standards (RCS) are necessary to safely design, build and operate hydrogen facilities

Example of Codes and Standards

CENTER FOR Hydrogen SAFETY
Connecting a Global Community

Equipment	ISO Standard	CSA Group Standard	Other NA Standard
Fueling Stations	ISO 19880-1	CSA HGV 4.9	NFPA 2 BNQ 1784
Cylinders & Tubes for Stationary Storage	ISO 19884	---	ASME
Vehicle Fuel Tanks	ISO 19881	CSA HGV 2*	---
Pressure Relief Devices	ISO 19882	CSA HPRD 1*	---
Dispensers	ISO 19880-2	CSA HGV 4.1*	---
Station Valves	ISO 19880-3.2	CSA HGV 4.4* CSA HGV 4.6* CSA HGV 4.7*	---
Station Compressors	ISO 19880-4	CSA HGV 4.8*	---
Station Hoses	ISO 19880-5	CSA HGV 4.2*	---
Fueling Connection Device	ISO 17268	---	SAE J2600
Hydrogen Generators - Electrolysis	ISO 22734	CSA IR-4-14	---
Hydrogen Generators – Fuel Processing	ISO 16110	CSA FC 5 CSA 5.99	---
Hydrogen Fuel Quality	ISO 14687	----	SAE J2719 CGA G5.3

Info source: CSA Group

* CSA Group provided to ISO as a seed document

January 24, 2022 / 14

Recommendations, codes and standards

Many RCS were not developed yet for hydrogen (both gaseous and liquid) in new applications

In the maritime sector, there is a particular need to develop RCS for the:

1. Design and operation of the ships
2. Design and operation of the infrastructures (e.g. bunkering facilities)

Most of the RCS are based on safety considerations to decrease the risk for accidents and increase the efficiency of the systems

Content

Research and demonstration projects

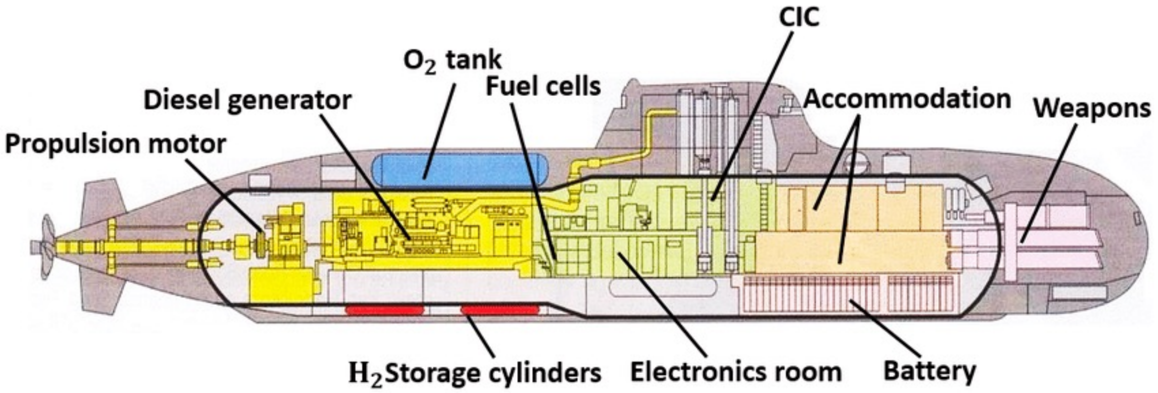
Table 3
An overview of the most noticeable maritime fuel cell application research projects.

Program	Period	Fuel cell type	Logistic fuel	Application	Project lead	References
Class 212	1980–1998	PEMFC	Hydrogen	Submarine AIP	Howaldtswerke-Deutsche Werft	[17,188]
SSFC	1997–2003	MCFC/PEMFC	Diesel	Naval ship	Office of naval research	[41,42,138]
DESIRE	2001–2004	PEMFC	Diesel	Naval ship	Energy research centre Nld	[40]
FCSHIP	2002–2004	MCFC	Diesel		Norwegian Shipowners' Ass.	[46]
FellowSHIP	2003–2013	MCFC	LNG	Offshore supply	DNV research and innovation	[139,189]
FELICITAS	2005–2008	SOFC/GT	Diesel, LPG, CNG	Mega yacht	Frauenhofer institute	[143]
MC-WAP	2005–2011	MCFC	Diesel	RoPax, RoRo	CETENA	[43,44]
ZEMSHIP	2006–2010	PEMFC	Hydrogen	Passenger	ATG Alster Touristik GmbH	[190,172]
METHAPU	2006–2009	SOFC	MeOH	Car carrier	Wärtsilä corporation	[191,79]
Nemo H_2	2008–2011	PEMFC	Hydrogen	Passenger	Fuel Cell Boat BV	[188,172]
SchIBZ	2009–2016	SOFC	Diesel	Multipurpose	ThyssenKrupp marine systems	[16,192,193]
PaXell	2009–2016	HT-PEMFC	MeOH	Cruise ship	Meyer Werft	[192,193]

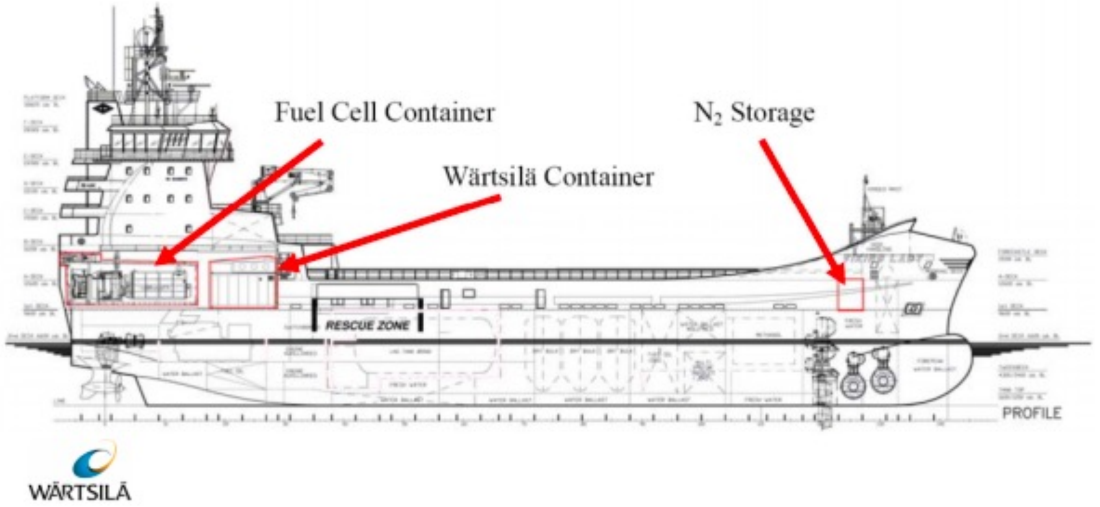
PEMFC: polymeric electrolyte membrane fuel cell
HT-PEMFC: high temperature polymeric electrolyte membrane fuel cell
MCFC: molten carbonate fuel cell
SOFC: solid oxide fuel cell
GT: gas turbine

Research and demonstration projects

Class 212 (submarine) - Air-Independent Propulsion



FellowSHIP - Viking Lady (offshore supply vessel) – Auxiliary Power Unit (LNG)



Research and demonstration projects

Other examples

ZEMSHIPS project – FCS ALSTERWASSER (hydrogen)

SMART-H2 project – Whale Watching Boat ELDING I (hydrogen)

e4ships project - MS MARIELLA (methanol)

e4ships project - MS Forester (diesel)

Research and demonstration projects

Liquid hydrogen

- **Suiso Frontier**: LH2 tanker between Australia and Japan (in operation)
- **MF Hydra**: LH2 ferry in Norway (testing)
- Many feasibility projects and designs (e.g. Kawasaki LH2 carrier)

Content

1. Introduction on hydrogen
2. Hydrogen implementation in the maritime sector
    - 2.1. Storage (compressed gas, liquid)
    - 2.2. Materials
    - 2.3. Hydrogen utilization on board
    - 2.4. Infrastructures (bunkering)
    - 2.5. Recommendations, codes and standards
    - 2.6. Research and demonstration projects
3. Hydrogen safety projects

SH_2IFT project

Safe Hydrogen Fuel Handling and Use for Efficient Implementation

Funding: 25.480 MNOK

Duration: 2018-2022

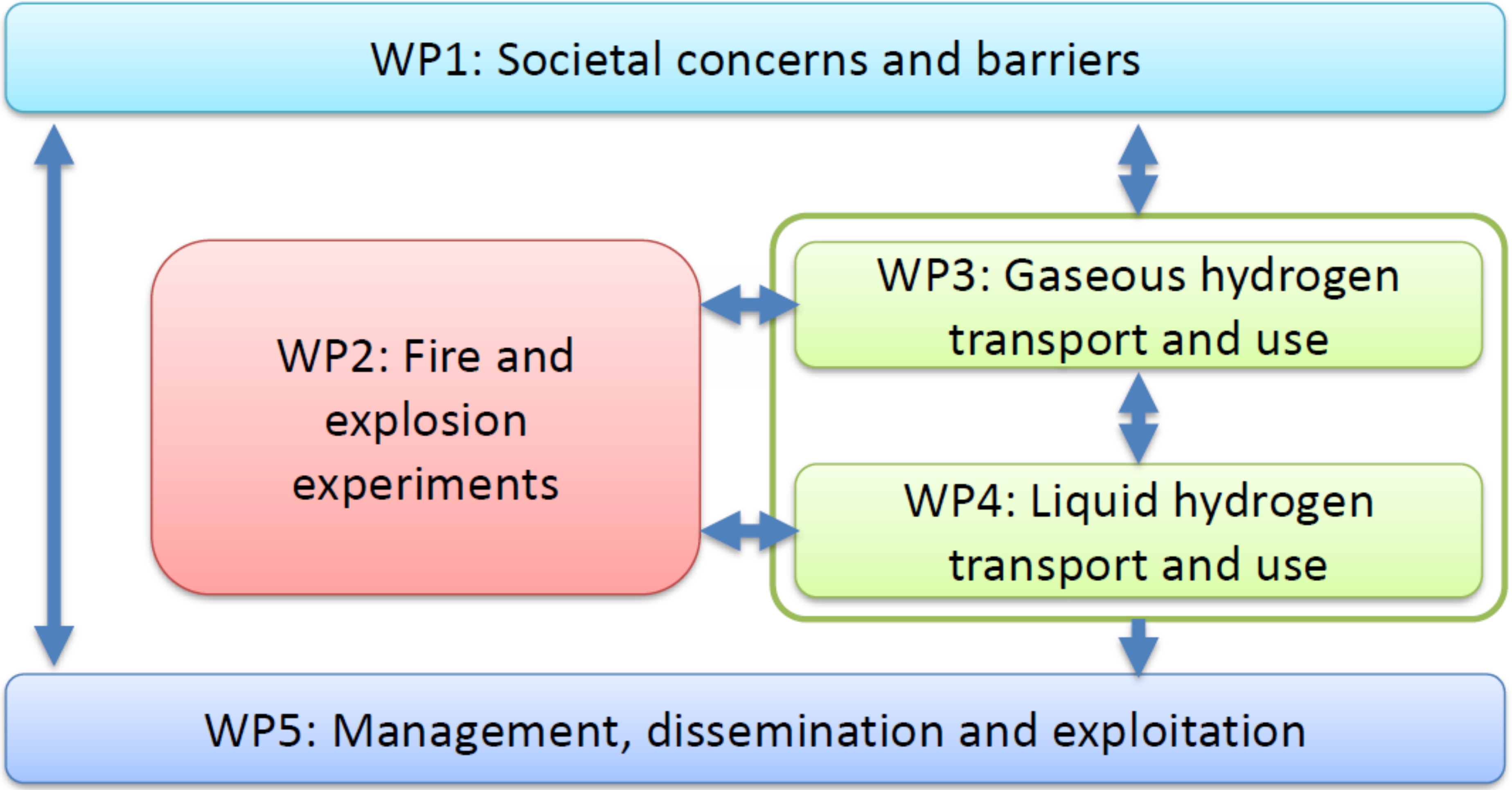
Partners: SINTEF Industry, SINTEF Energy, NTNU, RISE Fire Research, Institute of Transport Economics TØI, Christian Michelsen Research CMR (Prototech & Gexcon), Equinor, Shell, NASTA, Statkraft, ArianeGroup, Air Liquide, Nye Veier

Objectives: societal concern, develop new models, perform large-scale fire and explosion experiments, and provide guidelines for use of hydrogen in industry and transport

NTNU role: project partner (WP4 "Liquid hydrogen transport and use")

SH_2IFT project

Work plan



SH_2IFT project

Work packages 2, 3 & 4

Jet fire

Compressed gas H2

WP2: experiments (RISE)

WP3: modelling (Gexcon)

BLEVE

Liquid H2

WP2: experiments (Gexcon, BAM)

WP4: modelling (NTNU)

RPT

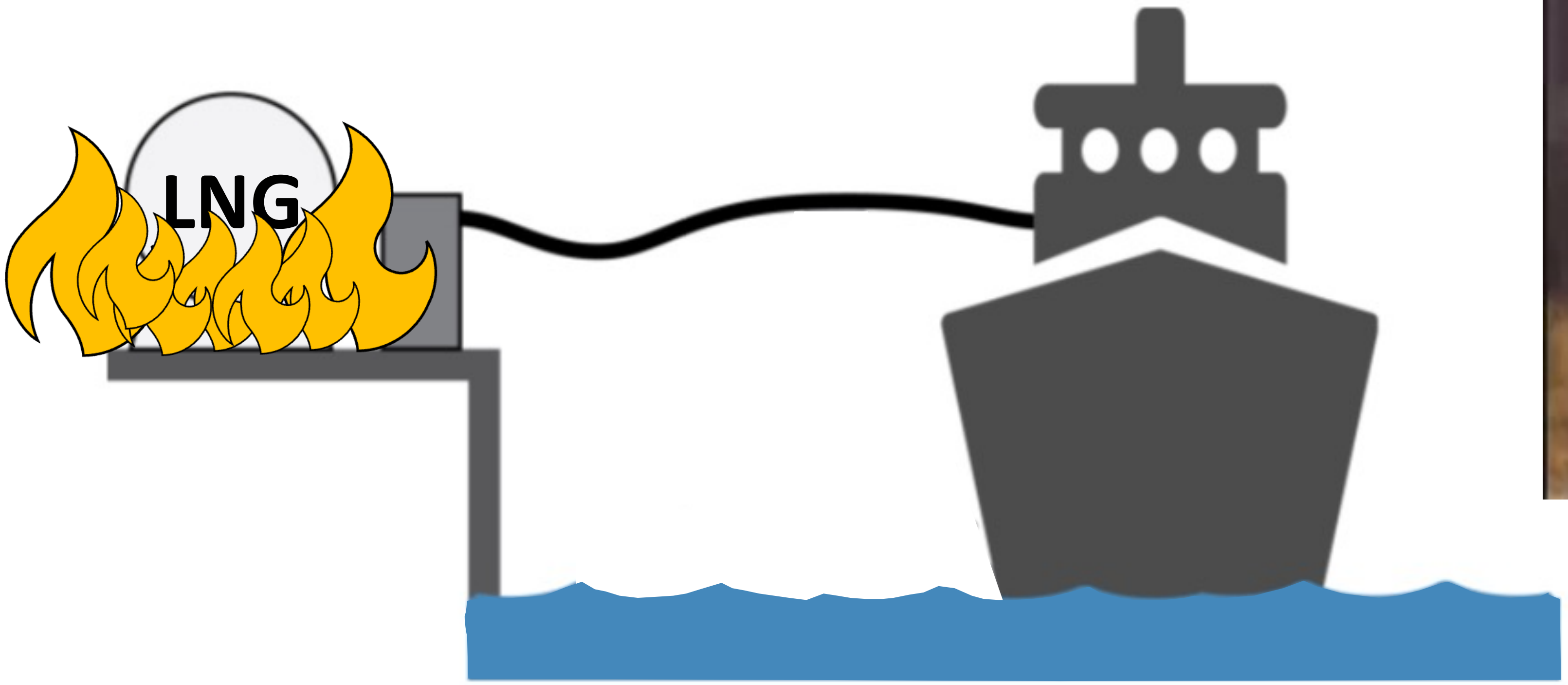
Liquid H2

WP2: experiments (Gexcon, BAM)

WP4: modelling (SINTEF)

Boiling Liquid Expanding Vapour Explosions

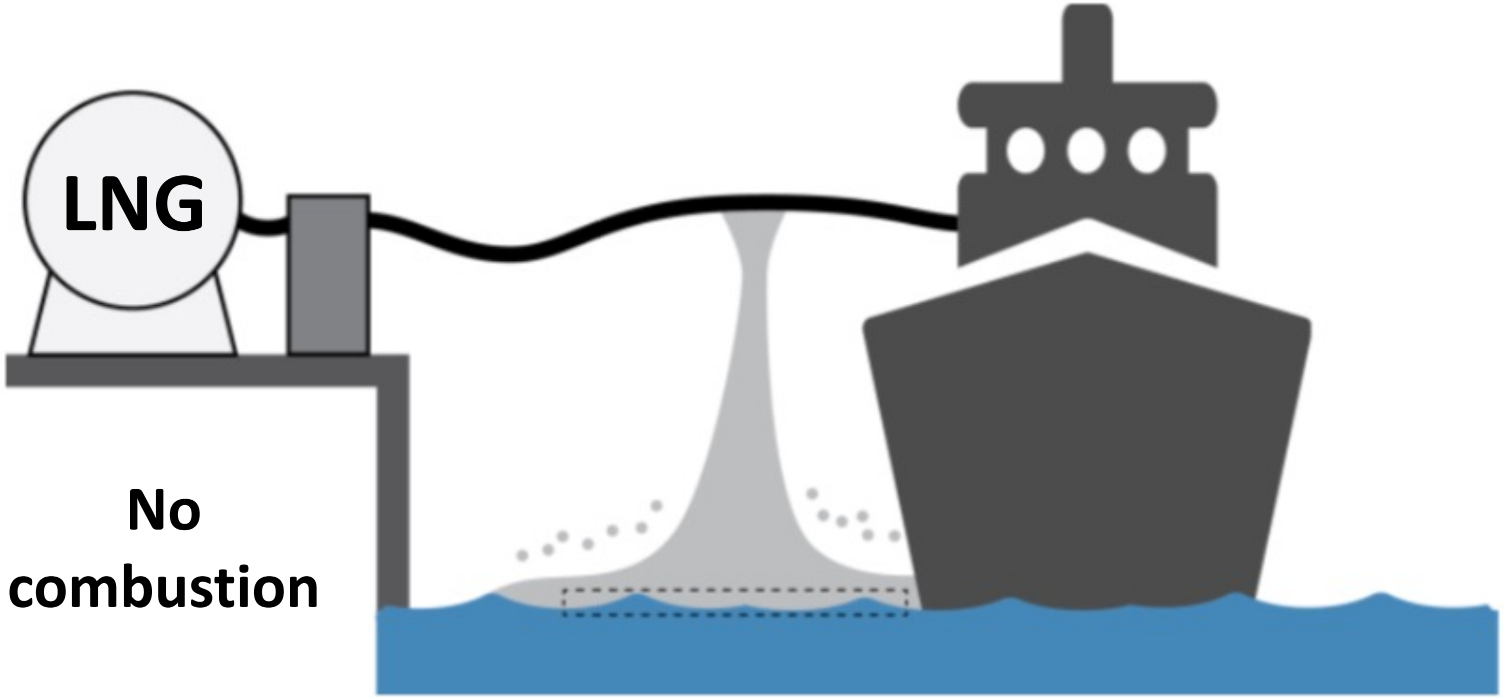
BLEVE is a physical explosion might result from the catastrophic rupture of a tank containing a superheated liquid due to the rapid depressurization



BLEVE of 5,000 tons of Propane (Berlin, 1999)

Rapid Phase Transition

RPT is a physical explosion that can be generated after the interaction of two liquids at different temperatures, and the expansion of the cold one (sudden phase change from liquid to vapour) due to the sudden heat transfer.



No combustion

Gaz de France - Lorient
LNG RPT tests (1981)

SH_2IFT project - BLEVE experiments

Setup

Three double walled vacuum-insulated tanks were tested (engulfed in propane fire, with PRV closed) at the Bundesanstalt für Materialforschung und –prüfung (BAM) in Horstwalde, Germany.

The maximum allowable working pressure of the vessels was 10 bar (burst pressure 36 bar).

Test no.	Degree of filling	Orientation	Insulation
1	35-40%	Horizontal	Perlite
2	35-40%	Horizontal	MLI
3	35-40%	Upright	Perlite

SH_2IFT project - BLEVE experiments

Results

Test 01: tank reached 23 bar. Leakage started through seal of the blind flange connection at the filling valve on top of the vessel after 1 h 15 min

Test 02: PRV opened at 40 min when the pressure was 50 bar. Tank failed after 68 min

Test 03: tank reached 60 bar and resisted for 4 h without failing. No leakages occurred

Test 01

SH_2IFT project - RPT experiments

Setup

Liquid hydrogen spills onto/into water tests performed at Bundesanstalt für Materialforschung und –prüfung (BAM) in Horstwalde, Germany

Water basin was 10 X 10 X 1.5 m. A total of 75 LH2 releases (max mass flowrate = 1.1 kg/s → 10 bar in road tanker) were performed:

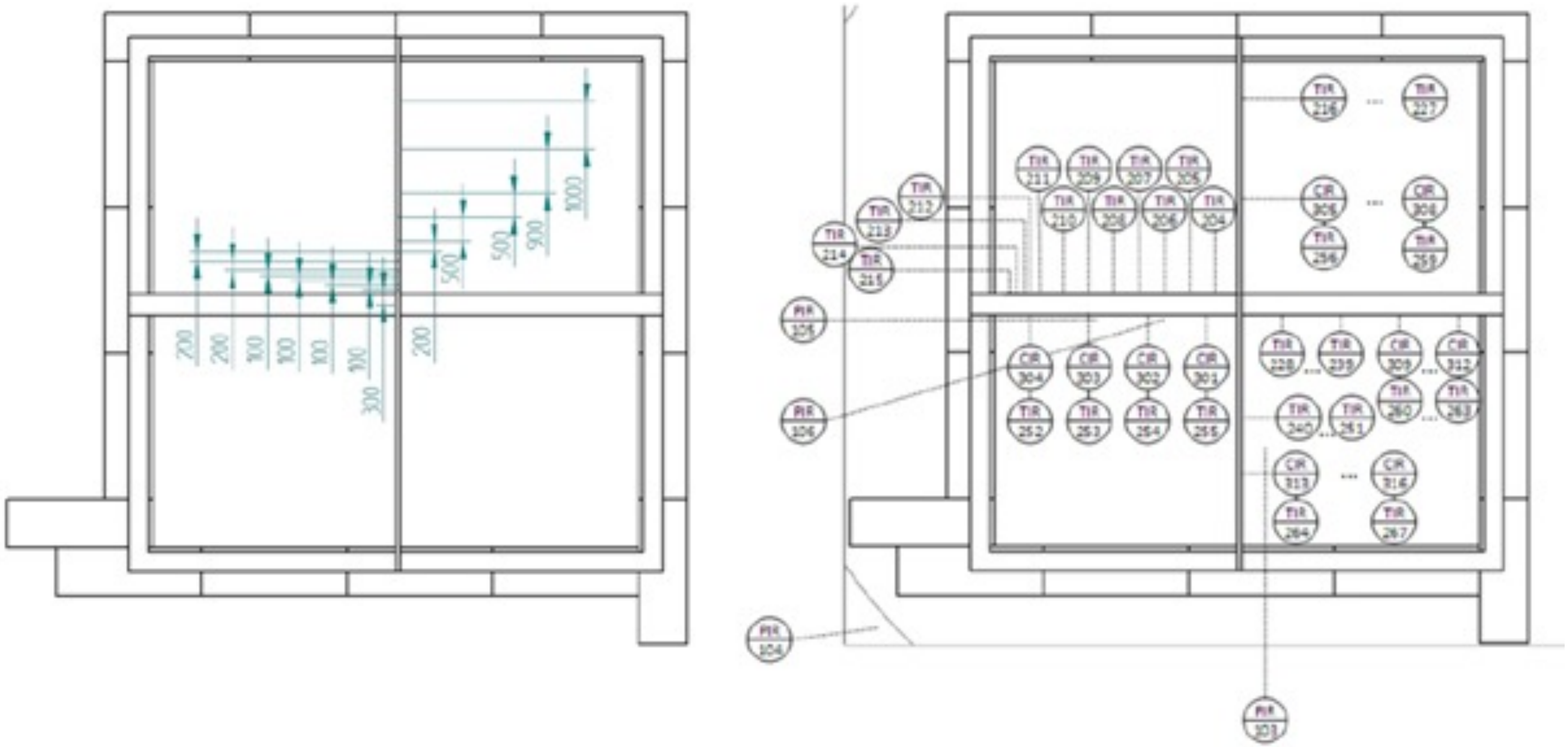
- 50 cm over the water, vertically down
- 30 cm under the water, vertically down
- 30 cm under the water, horizontally

SH_2IFT project - RPT experiments

Setup

Measurements:

- Temperature
- Concentration of hydrogen in air
- Wind speed and direction
- Heat radiation
- Video



Schematic view of the sensor positions over the water surface (TIR = Thermocouple, CIR = Gas Sensor, PIR = Pressure Sensor)

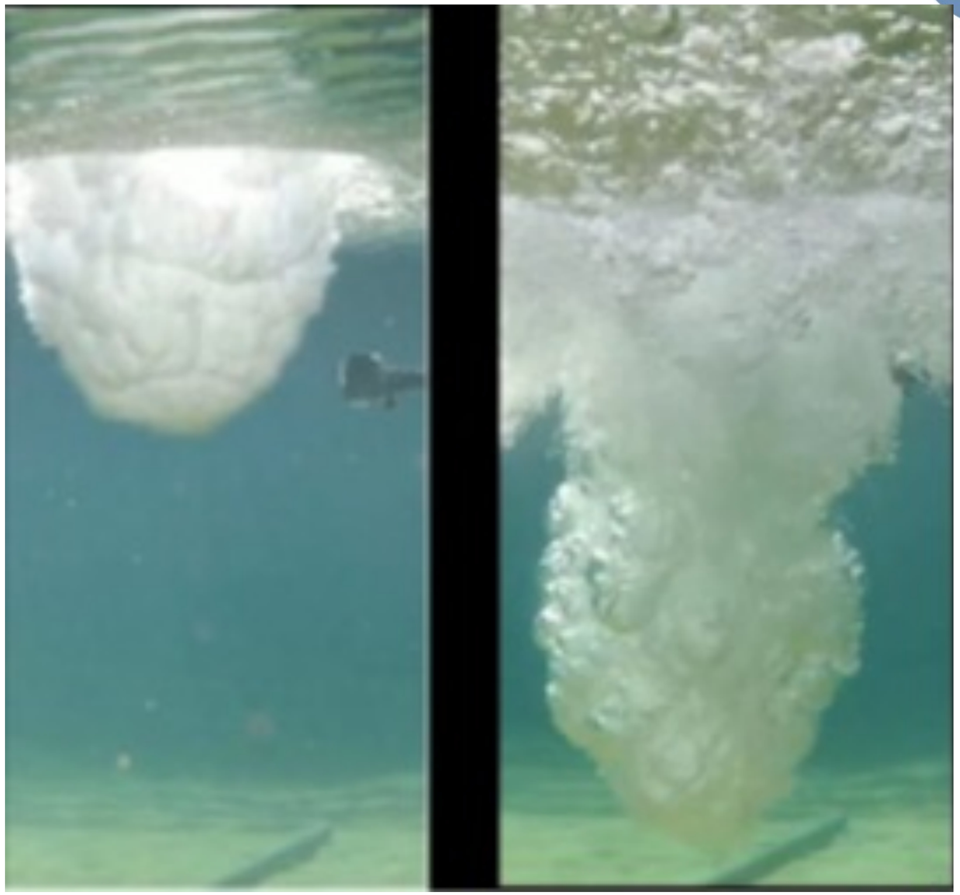
SH_2IFT project - RPT experiments

Results

High-momentum LH2 jet penetrating deep into the water basin, also when the release occurred above the water surface

Massive evaporation, but no sudden bursts typical for an RPT

Very chaotic mixing zone that seem to pulsate due to the interplay between volume production from evaporation, buoyancy and the continuously incoming jet

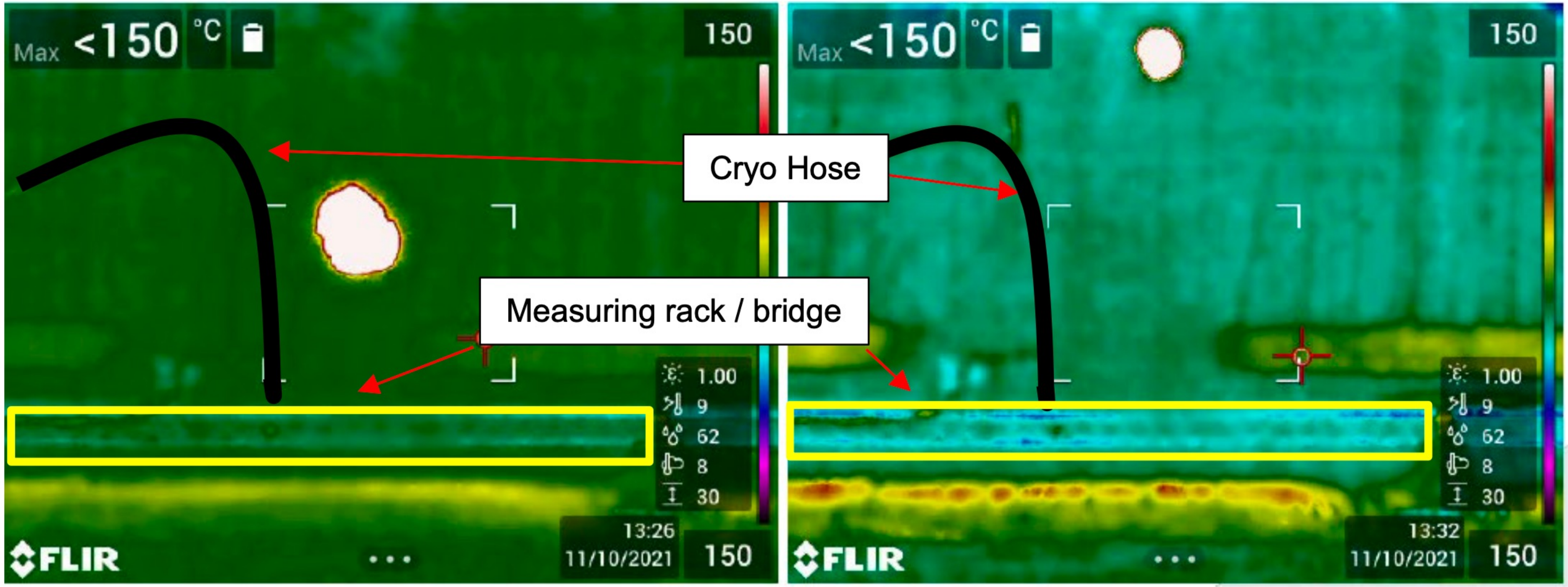


LH2 jet penetrating the water (release rate 0.8 kg/s, release location 50 cm above the water pointing downwards)

SH_2IFT project - RPT experiments

Results

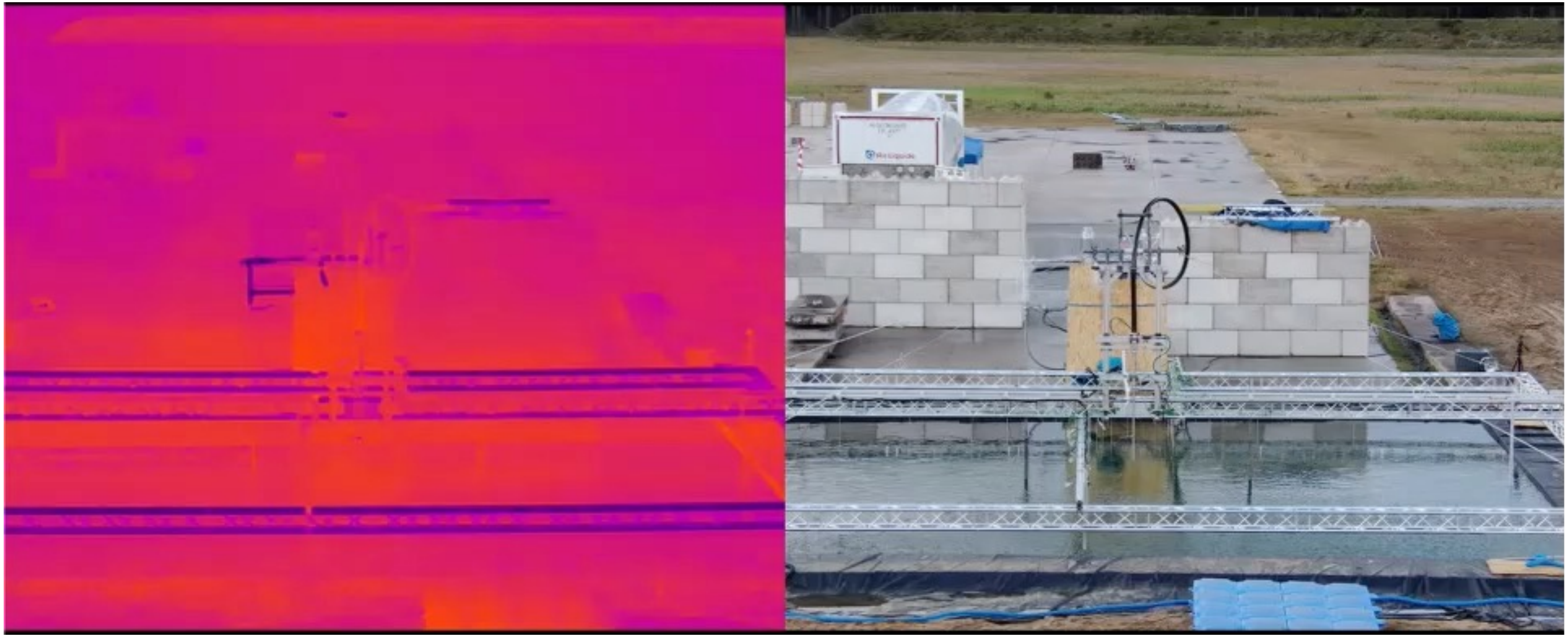
- Frequent geyser-like jets propel out of the water
- Hydrogen self-ignition few seconds after the release started



Moment of initial flame propagation in hydrogen-air clouds (“white spots”) The ignition location appears to be somewhere in the cloud at a distance from any physical object.

SH$_2$IFT project - RPT experiments

Results



SH_2IFT project - Conclusions

BLEVE

- All three LH2 vessels withstood the fire for more than 1 hour (PRV blocked). Only one vessel (with MLI) failed catastrophically and exploded.
- Further studies on vessel heat-up (e.g. insulation) and BLEVE
- More work on the development on barriers is recommended

RPT

- RPT as a consequence of LH2 spills onto or into water is not found to be a major issue for safe implementation of LH2
- Still, any spill of hydrogen should be avoided due to: (i) risk of ignition, (ii) evaporation and spreading of gas cloud, (iii) cryogenic hazards
- High momentum releases of LH2 onto and into water may cause ignition in free air of the evaporated gas cloud (must be studied further)

ELVHYS - Enhancing safety of liquid and vaporised hydrogen transfer technologies in public areas for mobile applications

2nd Stakeholders' Workshop – HSE, Buxton (UK)

Federico Ustolin (NTNU) et al

29.11.2023

ELVHYS project No. 101101381 is supported by the Clean Hydrogen Partnership and its members and the European Union. UK participants in Horizon Europe Project ELVHYS are supported by UKRI: University of Ulster (grant number 10063519) and Health and Safety Executive.

Pre - ELVHYS

Progress / Closed gaps

Fundamental/Modelling “Release”:
- ✓ Discharge coefficients for cryo- and cryocompressed releases
- ✓ Rainout phenomena better understood
- ✓ Fundamental data for mixing of large scale releases

Fundamental/Modelling “Ignition”:
- ✓ MIE and hot surface T determined for cryogenic conditions
- ✓ Empirical tests for RPT without fast reaction
- ✓ Electrostatics of cryogenic releases
- ✓ Worst case effects for small cryogenic inventories determined via variation of ignition time and position

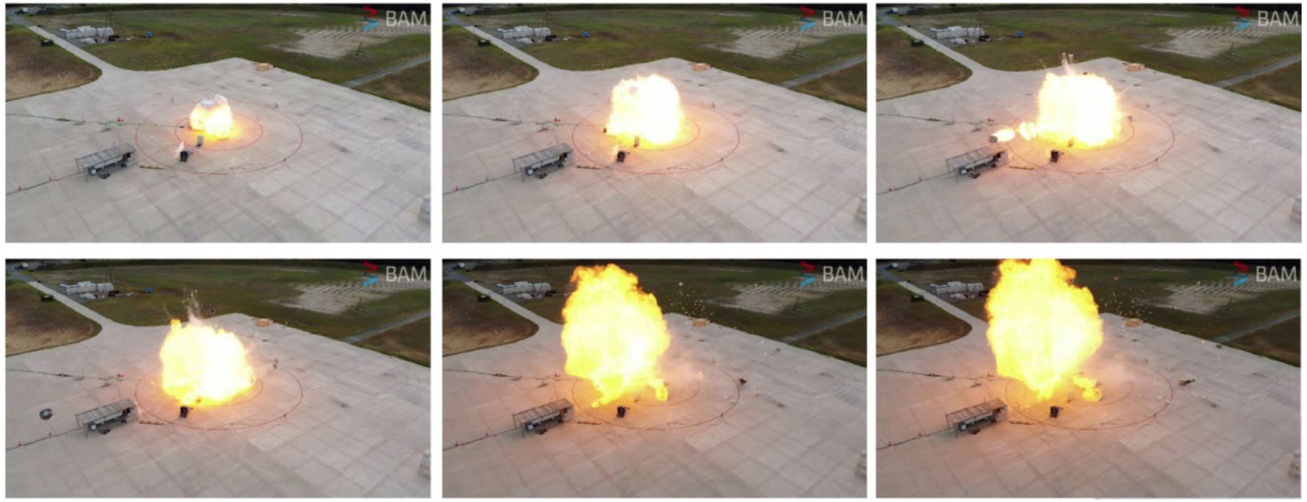
Fundamental/Modelling “Combustion”:
- ✓ Flame length correlations validated
- ✓ σ, σcrit and run-up distance for DDT determined at cryogenic conditions
- ✓ …

PRESLHY

SH2IFT Project Findings

Fundamental/Modelling “BLEVE”:

✓ Experiments performed and BLEVE observed at BAM
(see van Wingerden, Kees, et al. *Chemical Engineering Transactions*, 2022, 90. Jg., S. 547-552)



Fundamental/Modelling “RPT”:

✓ RPT observed in BAM tests spilling LH2 on water
(see van Wingerden, Kees, et al. "Experimental Investigation into the Consequences of Release of Liquified Hydrogen onto and under Water." (2022))

ELVHYS

Enhancing safety of liquid and vaporised hydrogen transfer technologies in public areas for mobile applications

Funding: 2.0 M€

Duration: 2023-2026

Coordinator: NTNU

Partners:

NTNU Norwegian University of Science and Technology

Ulster University

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA

DLR

HSE Health & Safety Executive

KIT Karlsruher Institut für Technologie

Air Liquide

Website

Objective: provide indications on inherently safer and efficient cryogenic hydrogen technologies and protocols in mobile applications by proposing innovative safety strategies including selection of effective safety barriers and hazard zoning strategies, which are the results of a detailed risk analysis.

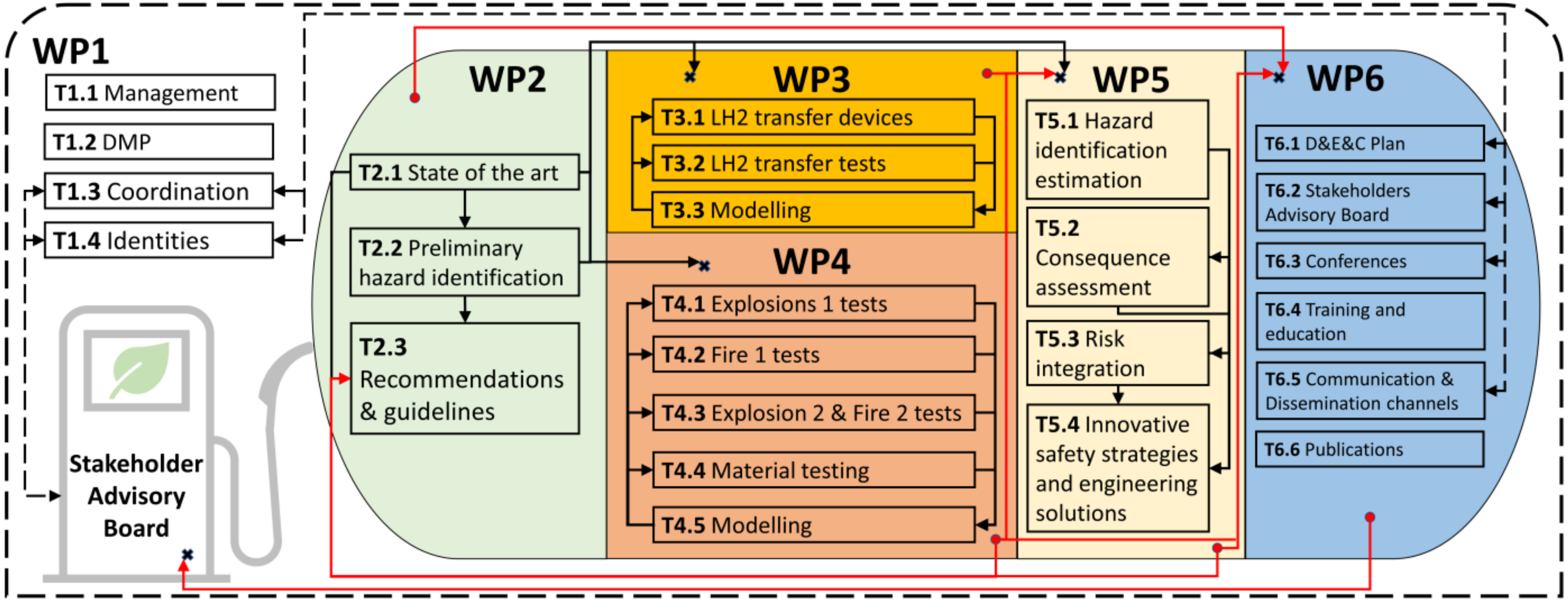
NTNU role: coordinator, consequence analysis, risk analysis

ELVHYS

Expected outcomes & objectives

1. Detailed risk analysis for LH_2 transferring operations for mobile applications (ships, trucks, stationary tanks) fillings
2. Generic hazard distances for LH_2 transferring operations in the different applications, also addressing SimOps
3. Guidelines for design of LH_2 transferring facilities
4. Consensual loading procedures for LH_2 transferring operations
5. Provide inputs for developing Standards, Technical Specifications, or Technical Reports at the international level

ELVHYS – Work Plan

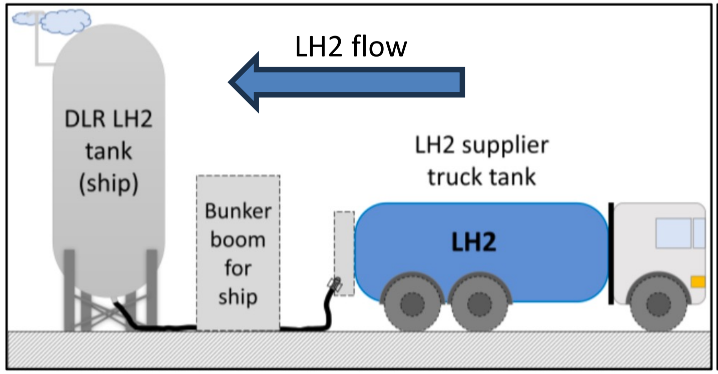


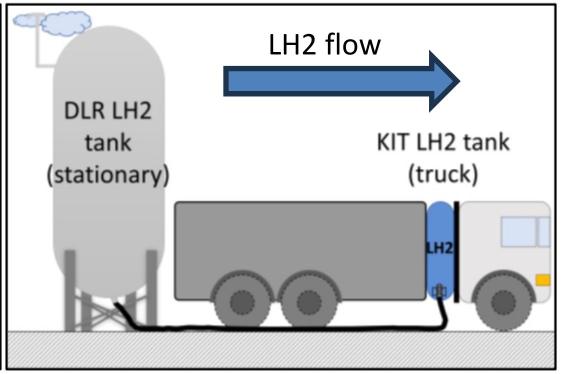
- WP1 - Project Management & Coordination
- WP2 - From industrial background and strategy to findings application
- WP3 - Cryogenic hydrogen transfer facilities performance
- WP4 - Fires & explosions from cryogenic hydrogen transfer facilities
- WP5 - Risk Analysis for selected cryogenic hydrogen transferring operations
- WP6 - Dissemination, exploitation and communication

ELVHYS – Tasks

WP3 - Cryogenic hydrogen transfer facilities performance

- **Task 3.1** - LH2 transfer devices definition
- **Task 3.2** - LH2 transfer tests: bunkering, fuelling, refuelling, defueling
- **Task 3.3** - Support by theoretical and numerical studies for experimental setup, and numerical experiments to formulate cryogenic hydrogen transfer protocols





Tests will be carried out by DLR in Germany in 2024

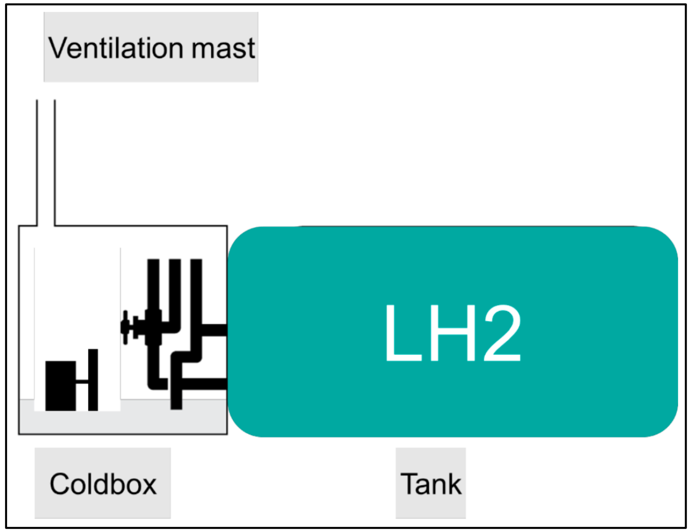
ELVHYS – Tasks

WP4 - Fires and explosions from cryogenic hydrogen transfer facilities

- **Task 4.1** – Oxygen enrichment and condensed phase explosions
- **Task 4.2** – Leakage into cold room/tank connection space considering barriers and obstacles

HSE test (Hooker et al., 2012)

Tests will be carried out by HSE in UK in 2024



DNV test (Aaneby et al., 2021)

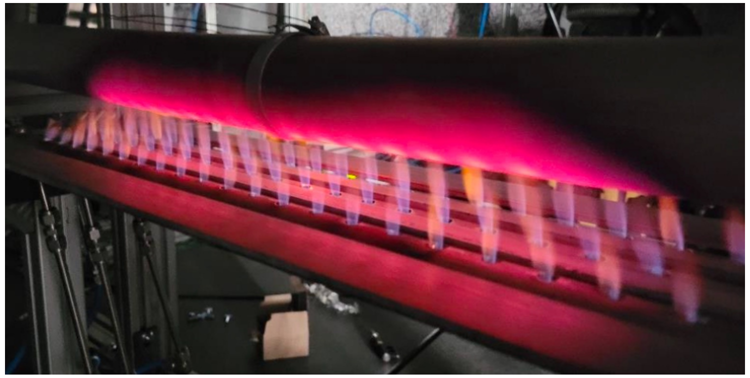
ELVHYS – Tasks

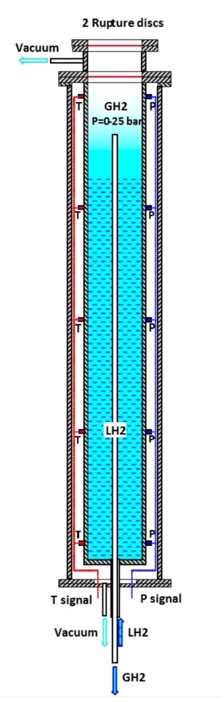
WP4 - Fires and explosions from cryogenic hydrogen transfer facilities

- **Task 4.3** – Performance of LH2 components and explosion consequences
- **Task 4.4** – Material testing against unignited and ignited jets (MLI, glass spheres, perlite layers and fire protecting wall) according to ISO 20088
- **Task 4.5** – Modelling in support of and utilising WP4 experimental activities

Tests will be carried out by KIT in Germany in 2024

SH2IFT test (Ødegård et al., 2022)





ELVHYS – Tasks

WP5 - Risk Analysis for selected cryogenic hydrogen transferring operations

- **Task 5.1** – Hazard identification and damage state estimation
  - Sub-Task: 5.1.1 Hazard identification
  - Sub-Task: 5.1.2 Damage state of the installation resulting in the release of hydrogen
- **Task 5.2** – Consequence assessment
  - Sub-Task: 5.2.1 Modelling of accidental phenomena
  - Sub-Task 5.2.2: Vulnerability assessment
- **Task 5.3** – Frequency assessment and risk integration
  - Sub-Task: 5.3.1 Frequency of incident occurrence
  - Sub-Task: 5.3.2 Risk integration
- **Task 5.4** – Innovative safety strategies and engineering solutions
  - Sub-Task: 5.4.1 Safety barriers
  - Sub-Task: 5.4.2 Safety zoning strategies

ELVHYS – News

Some selected news from the last newsletter published on the project website

- ELVHYS project shortlisted for the Best Success Story Award 2023 by the Clean Hydrogen Partnership!

- ELVHYS first research outcomes were presented at International Conference of Hydrogen Safety (ICHS) 2023

ELVHYS

Thank you for your attention

federico.ustolin@ntnu.no

Co-funded by the European Union

Clean Hydrogen Partnership

UK Research and Innovation

ELVHYS project No. 101101381 is supported by the Clean Hydrogen Partnership and its members. UK participants in Horizon Europe Project ELVHYS are supported by UKRI grant numbers 10063519 (University of Ulster) and 10070592 (Health and Safety Executive).

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BLEVE

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