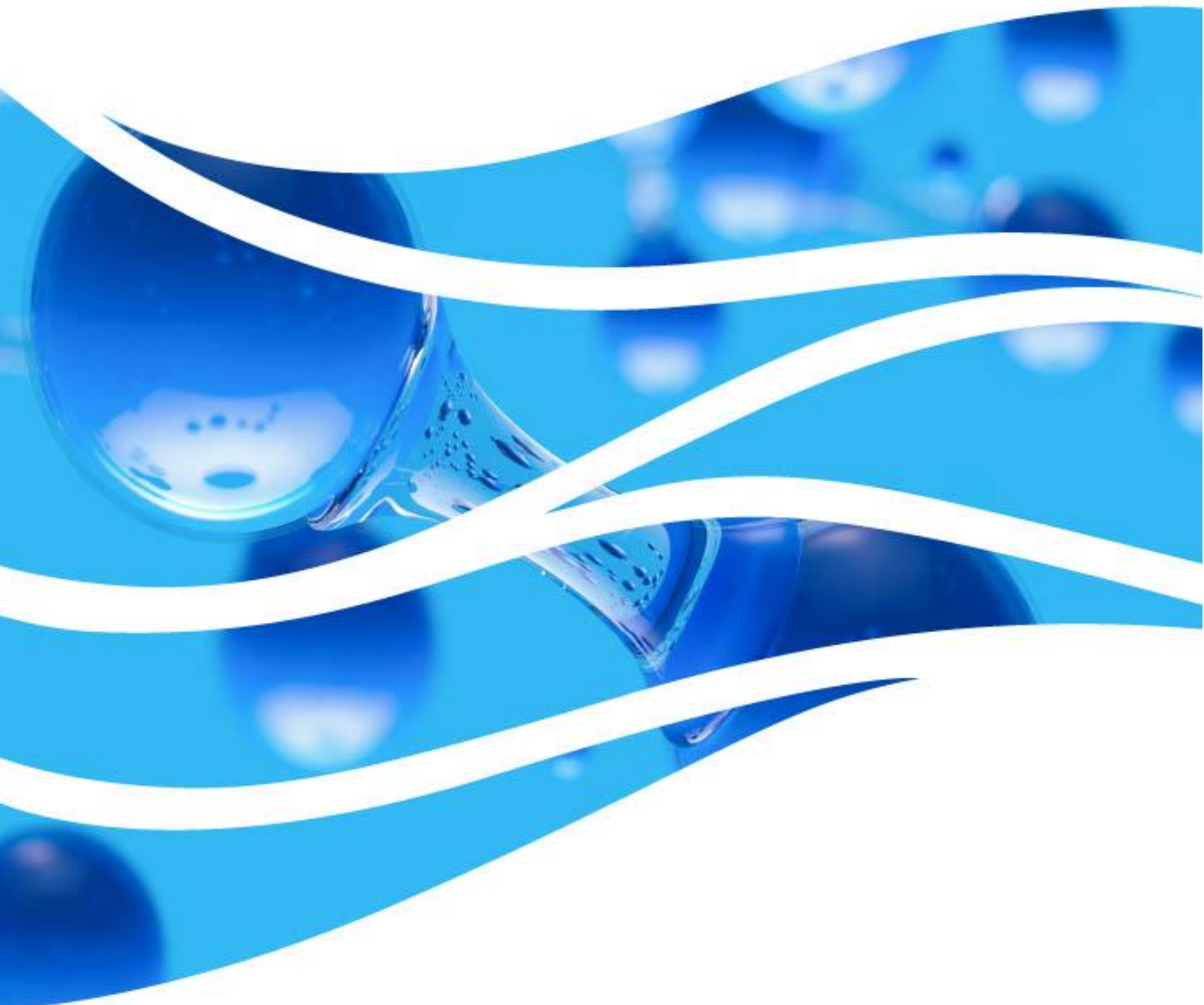




FATE, BEHAVIOUR AND POTENTIAL LIABILITIES ARISING FROM A SPILL OF HYDROGEN INTO THE MARINE ENVIRONMENT

Report for the International Group of P&I Clubs Alternative Fuels Working Group

May 2024



I. Introduction

ITOPF, as part of the International Group of P&I Clubs Alternative Fuels Working Group, has been requested to provide a series of brief summary documents to describe the expected fate and behaviours of the following alternative fuels and to outline the possible damage and liabilities that may arise from incidents involving vessels carrying these fuels as bunkers.

The alternative fuels covered are:

- Biofuels
- Liquefied Natural Gas (LNG)
- Liquefied Petroleum Gas (LPG)
- Hydrogen
- Ammonia
- Methanol

ITOPF has also been requested to provide a summary document for lithium-ion batteries as a new technology for vessel propulsion.

A review of Nuclear as a means of vessel propulsion will be described separately, with the summary report provided by ENCO.

This report shall focus on **hydrogen** as a non-traditional marine fuel, more specifically **compressed hydrogen** and **liquid hydrogen (LH₂)**.

Hydrogen has been viewed as a viable option for shipping's decarbonisation journey as it is the one of the few alternative fuels that can be classed as 'emission-free' (only if the hydrogen is produced by the electrolysis of water using renewable energy, i.e. 'green hydrogen').^{1,2} The use of hydrogen as a fuel for shipping can be used in multiple states, such as liquefied or compressed hydrogen within internal combustion engines, or using LH₂ within fuel cells. Due to the economic and technical barriers facing hydrogen technology and infrastructure development, the industry is immature when compared to other marine alternative fuels and therefore these technologies may develop in the future, with one format potentially being more technically viable than others.

For the purpose of this report, the fate, behaviour, damages and liabilities of compressed hydrogen and LH₂ will be outlined.

Small scale R&D projects are being undertaken in the United States, Belgium, Norway and France, and the first use of LH₂ as a marine fuel was observed in the MF HYDRA ferry in Norway. In addition, four ports in Europe and one in Japan are developing hydrogen import plans.

The use of dual-fuel engines is increasingly commonplace within the shipping industry and allows for flexibility between alternative fuels such as hydrogen and more conventional fuel oils (e.g. heavy fuel oil, marine diesel oil or even biofuels). In the future, there may be potential for multiple alternative fuels to be used on the same vessel. This means that, in the event of an incident, there may be potential for multiple alternative fuels to be spilled simultaneously, which could combine the risks outlined in these summary documents. An incident of this type would require a complex and highly specialised response to be mounted to counteract these risks.

Unlike biofuels, LNG, LPG, ammonia and methanol, hydrogen is not globally transported as a marine cargo and therefore experience in handling, transportation, storage and loading/unloading is currently limited. Therefore, general understanding of hazards and risks associated with hydrogen as a marine fuel, and particularly LH₂, is limited. To date, ITOPF has not been involved in a case involving a spill/release of hydrogen.

II. Storage and Transportation

At ambient conditions, hydrogen is a colourless, odourless, non-toxic gas. Due to its very low density, hydrogen is typically liquefied or compressed for storage and transport as it takes about 1/850th of the volume of hydrogen

¹ Van Rheenen E. Scheffers E. Zwaginga J. Visser K. 2023. "Hazard identification of hydrogen-based alternative fuels onboard ships." Sustainability. 2023. 15,16818

² DNV-GL. 2023. "Energy Transition Outlook 2023: Maritime Forecast to 2050", DNV-GL. Høvik, Norway

gas. Pure hydrogen would require cooling ranging from -254 °C under 1 bar to -240 °C under 13 bars to be stored as LH₂. It can also be stored as a compressed gas if subjected to very high pressures (250 – 700 bar).^{3,5} However, LH₂ has approximately 4.5 times higher energy density than compressed hydrogen gas, making LH₂ a more attractive storage option for shipping applications.⁴ Efforts are being made to use a combination of the two dominant storage options to optimise the cost and volume of storage.⁵

III. Fate and behaviour of hydrogen when spilled in the marine environment

The Standard European Behaviour Classification (SEBC) categorises hydrogen as a gas (G). During an incident, hydrogen’s hazards will be the drivers for the first actions and emergency response, followed by specific actions linked to its behaviour classification. Some of hydrogen’s key properties that play a role in its hazards, fate and behaviour when spilled are listed in Table 1.

Table 1: Summary of key hydrogen properties dictating its hazards, fate and behaviour.⁶

	Properties	Behaviour
Boiling Point	-253 °C	At ambient conditions, hydrogen is a gas.
Liquid Specific Gravity (@-253 °C)	0.071	Hydrogen is approximately 14 times less dense than water; therefore, as a liquid, LH ₂ will float if spilled on water.
Gas Specific Gravity (@-253 °C)	1.338	Saturated vapour is heavier than air and will remain close to the ground until the temperature rises
Vapour Specific Gravity (@ ambient Temp)	0.067	Vapours of hydrogen at ambient conditions are significantly lighter than air (buoyant) and will easily disperse in open or well-ventilated areas.
Solubility	Insoluble	Hydrogen will not mix with water (run-offs) or seawater.
Flammability Range	4.0 – 75.0 (v/v) %	Outside of this range, hydrogen/air vapour mixture is not flammable.

In its transported and stored form as a liquid, when the LH₂ storage tank temperature rises above hydrogen’s boiling point or when LH₂ is exposed to ambient conditions, it vaporises. As hydrogen vapours warm to ambient conditions, due to their extremely low densities, they will disperse rapidly into the atmosphere.

If LH₂ spills on or above the waterline, it will first float and rapidly vaporise on the surface of the water. Unlike a spill of LNG, cryogenic pools on the surface of the water are not likely to form as the temperature difference between LH₂ and ambient conditions is so large (>250 °C) that the rate of transition from liquid to gas would be too rapid. There is potential for some of the seawater in the immediate vicinity of the release to freeze due to LH₂’s low temperature, causing localised ice patches to form, which would be short-lived as water temperatures would return to pre-spill levels quickly.

If released below the waterline, due to its specific gravity it will rise to the surface of the water before rapidly boiling and volatilising into the atmosphere as its temperature increases in contact with seawater and the atmosphere.

³ College of the Desert. 2001. “Module 1: Hydrogen Properties.” Hydrogen Fuel Cell Engines and Related Technologies: Rev 0

⁴ SINTEF, “Which role will liquid hydrogen play? Liquid, compressed or something inbetween?” SINTEF Trondheim, Norway

⁵ European Maritime Safety Agency (EMSA) 2023. “Potential of Hydrogen as Fuel for Shipping” EMSA, Lisbon

⁶ NOAA. 1999. “Liquefied hydrogen – CAMEO chemicals profile”. June 1999, NOAA. Washington DC, USA

When vaporising, the cold hydrogen vapours are heavier than air and will remain close to the ground until the temperature rises. The cold vapour condenses the moisture in the air, forming a visible white cloud of water vapour (or fog), mixed with gaseous hydrogen, close to the ground or sea. As the gas mixture warms up and its overall specific gravity decreases, it rapidly rises and dissipates into the atmosphere within a very short time period. It is likely that the water vapour cloud will persist for longer than the hydrogen plume and stay closer to the ground or surface at the point of release.

The footprint and height of the vapour cloud depends on the rate of the spill and the metocean conditions at the time of the release. In low wind conditions (<5 mph), the vapour cloud footprint is smaller on the sea surface and is expected to dissipate at a higher altitude (Figure 1a), whereas in moderate wind conditions (>5 mph), the vapour cloud plume is likely to be knocked down on the sea surface, therefore being more low-lying and spreading over a larger footprint on the sea surface (Figure 1b). Even in moderate wind speeds, an ignition of the vapour cloud may still be able to propagate back to the leak source until all hydrogen is consumed below the lower flammability limit (LFL) or is extinguished. As hydrogen is less dense and more volatile than spills of LNG, it will disperse at a much faster rate. Therefore, the resulting vapour cloud will have a significantly smaller sea surface footprint and will have a smaller flammability area than LNG⁷. If ignition were to occur following a spill of LH₂, no visible condensed water vapour cloud will form.

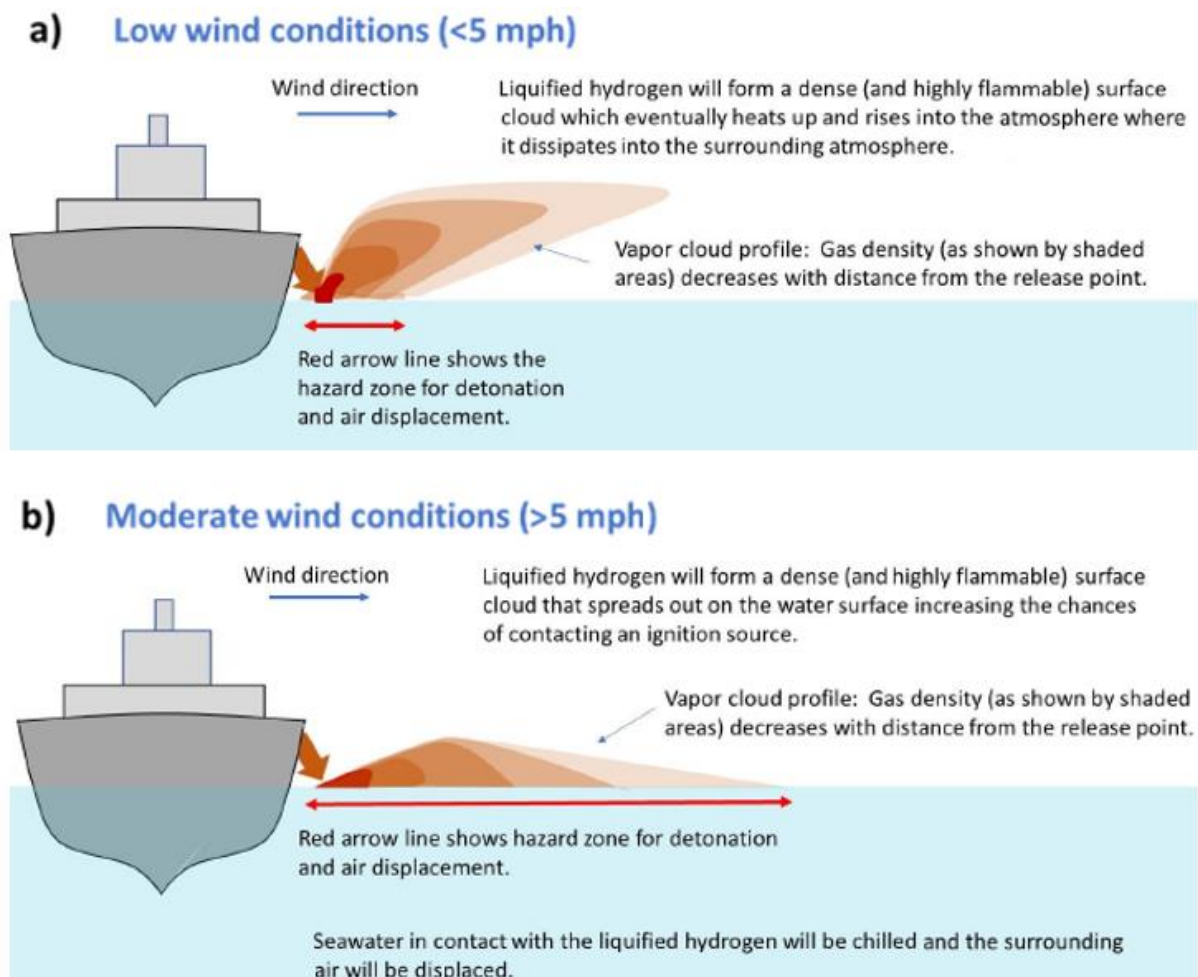


Figure 1: Comparison of expected fate and behaviour of a LH₂ spill from a ship in a) low wind conditions (<5 mph) and b) moderate wind conditions (>5 mph)⁷. Blue arrows show wind direction, orange arrows show hydrogen release direction, and red arrows show the extent of hazard zone that increases with increasing wind speed.⁷

⁷ Kass, M. D., Sluder, C. S., & Kaul, B. C. 2021. *Spill Behavior, Detection, and Mitigation for Emerging Nontraditional Marine Fuels* (No. DTMA91X20A65). United States. Department of Transportation. Maritime Administration.

Previous studies have indicated that vapour clouds spread roughly at the same rate as wind speed and are likely to persist in the order of tens of minutes, depending on multiple factors such as hull puncture size, location of the breach, discharge rate and environmental conditions at the time of the spill. However, due to the small size and extremely light nature of hydrogen molecules, buoyancy and diffusivity are much higher resulting in rapid atmospheric dilution, especially in unconfined areas.

IV. Hazards of hydrogen when spilled in the marine environment

Hydrogen's hazards can lead to direct impacts on health and safety, mainly through its flammability and explosivity.

Flammability

LH₂ is not flammable, however, its vapour has a flammability range of 4 – 75 (v/v) %, which can be detected with specialised equipment.⁶ Outside of this range, the hydrogen/air mixture is not flammable. This is greater than conventional fuels such as diesel, which has a much smaller flammability range of 0.6 – 5.5 (v/v) %.

In an unconfined space, a release of LH₂ from a tank or pipeline will rapidly mix and dissipate into the atmosphere reaching concentrations below the 4% LFL. Only a small area near the immediate leak would likely reach the concentration that would allow hydrogen to ignite.

In a confined space, where flammable vapours cannot dissipate, a small leak would result in a stratified layer of hydrogen at high points in that space (e.g. at ceiling height), which could lead to a flammable vapour/air mixture.⁸ Note that inside a fuel storage tank, the percentage of hydrogen is almost pure and, as such, the conditions are not in its flammable range. However, following a leak/rupture, a vapour cloud will form and once it has mixed with air, when its concentration reaches between the LFL (4% volume) and the upper flammability limit (UFL) (75% volume), the mixture can sustain a flame if ignited. If ignition occurs immediately, a flash fire is likely to result and continue until all the fuel is consumed. It should be noted that hydrogen-air flames are colourless and therefore have a low visibility, especially in daylight conditions.³ Hydrogen fires also have a low radiant heat and therefore, it is difficult to sense the location of the fire until in close proximity.

Explosivity

Hydrogen has a wide range of explosivity limits (15 – 59 (v/v) %) and as a result of this, even small leaks have the potential to burn or explode.³ If leaked, hydrogen concentrates in a confined space, there is a significant risk of combustion and explosion, meaning that even an invisible spark or static electricity discharge may cause ignition. Ignition of a flammable vapour/air mixture may result in a possible deflagration to detonation transition (DDT) and a subsequent large explosion due to high burning velocities of hydrogen-air flames and shorter burning distances needed to initiate a DDT event.⁸ These have been reported in the past but are unpredictable and not well understood at this time.

Compressed hydrogen

Hydrogen released in sufficient quantities can create a harmful overpressure which may result in direct and indirect hazards from building damage or flying debris. Overpressures can occur as a result of unignited releases of pressurised gas or as a result of ignition of a cloud of released flammable gas.

Liquid hydrogen

In particular conditions, LH₂ could potentially undergo a boiling liquid expanding vapour explosion (BLEVE), which is an explosion caused by the rupture of a tank containing a pressurised liquid that has reached a temperature above its boiling point of -253 °C. This would be the case if the temperature of the tank were to raise and gas release systems were to fail.

⁸ DNV-GL. 2021. "Handbook for hydrogen-fuelled vessels" MarHySafe JDP Phase 1, 1st Edition (2021-06). DNV-GL. Høvik, Norway

When exposed to ambient conditions, there is a possibility that spilled LH₂ may result in a rapid phase transition (RPT), which is a flameless overpressure due to a very fast change of phase, in this instance from liquid to gas. The vapour cloud expands so quickly that a sonic boom and localised overpressure occurs. It should be noted that no LH₂ RPT incidents have been reported. With some studies, indicating the likelihood of an RPT event caused by LH₂ is considered to be considerably smaller than LNG.⁹ Similar to DDT events, RPT events involving LH₂ are not well understood at this time.

Asphyxiant

Like with any gas in a confined environment, high concentration of hydrogen vapours displace oxygen in the air, decreasing oxygen availability and therefore leading to asphyxiation to those present in these confined environments.

Temperature

The cryogenic temperature of LH₂ will result in the freezing of any tissue (plant or animal) upon contact and can cause materials to become brittle and lose their strength or functionality.

V. Damage and liabilities arising from incidents involving hydrogen

LH₂ carried as bunkers is not covered specifically by an International Convention at present, with liabilities relating to a release, or risk of a release, a result of national legislation. LH₂, carried as cargo in bulk, is covered by the International Convention on Liability and Compensation for Damage in Connection with the Carriage of Hazardous and Noxious Substances by Sea, 2010 (2010 HNS Convention). While not in force at the time of writing, this Convention sets out the potential liabilities arising from damage caused by HNS substances. Furthermore, while this Convention does not apply to HNS carried as bunker fuel, the same damage can be expected equally from an incident involving LH₂ carried on-board to power the ships' engines and are set out below.

Clean-up and Preventive Measures

In comparison to the costs associated with clean-up and preventive measures from a traditional spill of persistent hydrocarbon bunker fuel oil, the costs for this claim heading for a spill of LH₂ would likely be for different measures, primarily source control.

LH₂'s non-persistence in the marine environment, means established oil pollution clean-up measures are inappropriate (e.g. collection and recovery using booms and skimmers). Spilled LH₂ is not recoverable and therefore allowing natural attenuation to occur is the only appropriate option. For this reason, no protracted clean-up operations extending over a large geographic area, as is often seen with traditional persistent hydrocarbon oil spills, are required. Similarly, waste management is expected to be negligible in comparison to persistent hydrocarbon oil spills.

Due to the flammability of hydrogen vapours and possible resulting explosions, the main focus of this claim heading would be i) detection and monitoring, ii) prevention and control of fire and iii) possible bunker fuel removal.

- i) Monitoring would include the use of expert atmospheric plume modelling, use of multi-gas monitors, sensors, mounted possibly on drones (UAVs) to evaluate the potential presence of a flammable vapour/air mixture, which may pose a risk to local environmental and economic sensitivities. This can lead to the delimitation of exclusion zones. In addition, due to the spillage of cryogenic substances in

⁹ Odsæter, L.H. Skarsvåg, H.L. Aursand, E. Ustolin, F. Reigstad, G.A and Paltrinieri, N. 2021. "Liquid hydrogen spills on water – risk and consequences of rapid phase transition." *Energies*, 2021, 14, 4789.

the water column, ROVs installed with temperature sensors may be deployed to assess the extent of localised temperature reductions.

- ii) Costs associated with controlling the leak (e.g. stopping/controlled release/concentration reduction), without posing a risk to the lives of responders, could be a technically reasonable and effective way of mitigating against fire, preventing further releases and reducing the risk to sensitivities. In addition, water curtains, water spray, water cannons or fog are techniques that can be used to fight fire or reduce the risk of fire. These are typically deployed from specialised firefighting vessels. In comparison to oil spills, responders will need to be highly trained for HNS incidents.
- iii) The removal of LH₂ bunker fuel from a casualty could come under the 2007 Nairobi Convention if so decided, although note this convention refers only to bunker fuel oil.

The above clean-up and preventive measures rely on availability of specialist equipment (e.g. HAZMAT PPE, UAVs and ROVs for monitoring, etc.), modelling capabilities and specialist trained personnel. These resources may not be commonly available across the world and therefore these actions may only be possible in highly prepared areas, where immediate deployment of this equipment would be possible. Due to possible lack of available mitigation measures, the below damages related to these incidents may be increased in these circumstances.

The cleaning and rehabilitation of wildlife is another potential cost associated with clean-up and preventive measures. These could come from the impacts from: fire hazard and extremely low temperatures in the water body in the immediate vicinity of an incident. Both mechanisms could result in mortality for wildlife in the immediate proximity to the incident or other sublethal effects including burns and fire damage.

Rehabilitation for burns and fire damage may be possible by wildlife responders, in addition to the potential recovery of dead wildlife and any associated costs related to this would fall under clean-up and preventive measures.

Personal Injury and Loss of Life

This claim heading is included within the HNS Convention for LH₂ cargoes and has particular relevance to spills involving LH₂ bunkers.

Due to the flammability and explosivity hazard of hydrogen, a clear and acute risk exists to people near an LH₂ release. Vapours, from large unignited LH₂ spills near developed (residential or industrial) areas would quickly encounter an ignition source, ignite and the vapour cloud fire could potentially burn back to the source, and depending on confinement, result in an explosion. Populations, present outdoors, within the flammable and explosive boundaries of the vapour cloud would be at risk of loss of life or injuries due to high thermal radiation (heat from the fire), the contact with the flame (burn), force exerted from an explosion and inhalation of hot combustion products. People inside buildings are less likely to be directly impacted by direct thermal impact injuries from a fire but could be at risk of structural collapse in the event of an explosion.

The list of those at high risk include the ship's crew, bunkering operators, stevedores, passengers and other relevant nearby parties (e.g. surveyors, port operators). This is the most likely public safety impact of a hydrogen spill.

The asphyxiant risk due to displacement of oxygen by hydrogen vapours, and cryogenic-induced injuries would be restricted to those on-board the vessel or first responders where vapours aggregate in confined spaces or in very close proximity of the source of the spill.

People can sustain cryogenic damage from direct contact with spilled LH₂. If directly exposed to a cryogenic liquid or depending on the exposure levels of cold hydrogen vapours there may be risk of long-term, life changing injuries, such as blindness from crystallising moisture in the eye, severe cryogenic burns (frostbite), lung damage from inhaling cold vapour, in addition to hypothermia and possible brain damage and death.

The costs associated with these may be extensive, dependent in part on applicable international conventions and local legislation and should therefore be considered when dealing with liability and compensation.

Environmental Damage

The environmental impact of LH₂ in the marine environment is not as widely researched as the impact associated with spills of other, more persistent, hydrocarbon oils. However, due to the fate, behaviour and chemical characteristics of LH₂, only a short-term, acute negative impact in the immediate vicinity of the incident location is expected. Water temperatures are expected to return to pre-spill levels quickly, especially with increasing distance from the vessel.

Post spill studies to establish the severity and extent of environmental damage may be technically reasonable. For instance, if the vessel were to ground on a coral reef causing a release of bunkers, there is potential for localised mortality/harm and subsequent studies could be appropriate. Due to the acute and localised nature of any environmental impact, restoration projects would likely be minimal and, if any, confined to a small area.

Property Damage

Costs arising for property damage will be spatially confined to properties in close proximity to the incident. For example, if a catastrophic fire or explosion were to result from a LH₂ spill, significant property damage to port structures, vessels (commercial, leisure or fishing), buildings and aquaculture facilities may occur if located near the casualty. In addition, any items/objects subjected to cryogenic temperatures may occur material embrittlement. This could potentially compromise the integrity of vessels and their structure.

Types of property damage experienced during a persistent hydrocarbon oil spill are not relevant in a spill of LH₂, in particular coating by oil of vessel hulls, shoreline infrastructure, surface fishing and aquaculture gear. Instead, replacement of, or structural repair to damaged property may be necessary in the aftermath of a fire or explosion and could be significant. Due to the likely short timeframes of a LH₂ spill, mitigation measures (e.g., placement of water curtains, lift out of vessels) would be more difficult to put in place. However, with sufficient notice of an LH₂-fuelled vessel in distress, safety zones could be assigned, limiting entry to permitted vessels only. This would mitigate against damage to vessels.

Economic Loss

Economic loss can be split into “consequential loss”, whereby compensation is payable for loss of earnings suffered by the owners of property, which have been impacted and “pure economic loss”, whereby compensation is payable for loss of earnings suffered by persons whose property has not been impacted. In the event of a LH₂ incident, both consequential and pure economic loss could be experienced.

In the event of a fire/explosion, loss of earnings/income claims from damaged commercial, leisure or fishing vessels, factories, and other commercial etc. property, could be liable for compensation. If the incident was in the immediate vicinity of aquaculture facilities, localised reduction in seawater temperatures or a fire/explosion could lead to mortality of stock and associated loss of earnings. Pure economic loss could be experienced from loss of earnings from those impacted by any fishing bans imposed by authorities. Despite the very short residence time of LH₂ in the environment and the non-toxic nature of the substance, there is a possibility that fishing bans may still be imposed, due to the lack of understanding of the impacts of LH₂.

In addition, if vessels are delayed due to port closures or impacts to their journey to abide by safety zones, demurrage costs may apply, which could be significant. Losses due to the closure of ports and other areas identified as being at potential risk as a result of safety zones demarcated during an emergency may potentially be claimed also. An interruption of flow to water intakes may also cause pure economic loss claims, however due to the short residence of LH₂ in the environment, these are likely to be short-lived.

Finally, impact to the local tourism industry is expected to be less in comparison to areas impacted by an oil spill. There might be claims arising from organisations impacted in the immediate vicinity of the incident location, however these are to be short-lived and in the order of days rather than weeks to months, unless significant impact from a fire/explosion occurs.

VI. Conclusions

In conclusion, LH₂'s short residence time in the marine environment and high volatility means that claims arising from incidents involving this alternative fuel would greatly contrast those associated with conventional persistent hydrocarbon oil spills.

Claims from **clean-up and preventive measures** are expected to arise from different measures, such as source control, fire-fighting measures, monitoring via expert modelling or sensors mounted on UAVs/ROVs and possible bunker fuel removal. Traditional clean-up measures will not be possible and therefore, claims from a protracted spill clean-up operation will not arise. However, **personal injury and loss of life** claims may be significant. Risks from fire, explosions, cryogenic damage and asphyxiating vapours could lead to death or life-altering injuries to crew, passengers, nearby operators and members of the public.

Claims arising from **environmental damage** are likely to be geographically confined in comparison to damage from oil spills. Post spill studies may be undertaken, in certain circumstances, to establish the severity and extent of damage. Restoration measures are likely to be minimal and confined to a small area. Rather than **property damage** claims involving cleaning and cosmetic repair of oiled property, LH₂ claims are likely to be a result of fire, explosion or cryogenic damage and therefore, structural repair or replacement may be required, which would likely be more costly and potentially time-consuming. **Economic loss** claims resulting from a fire or explosion could include port closure/disruption and associated demurrage costs, losses from damaged/destroyed property, local aquaculture losses from mortality of stock, and local losses resulting from fishing bans. Impacts to commercial water intakes and tourism may also occur.