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Risk Assessment Of Liquid Hydrogen In Marine Transportation

Olga Aneziris, Ioanna Koromila, Zoe Nivolianitou

National Center for Scientific Research "DEMOKRITOS", Aghia Paraskeui, Athens, Greece

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This paper presents the major steps of the risk assessment methodology for liquid hydrogen bunkering and a preliminary assessment of safety distances. European and international shipping regulations are becoming increasingly strict to contribute to a neutral climate where Sulfur and Nitrogen Oxides, Carbon Dioxide, and greenhouse gas emissions will be considerably reduced (European Commission, 2019; IMO, 2008). New technologies to adopt alternative low-flashpoint fuels have been already considered to reduce such hazardous emissions from ships, including low-carbon fuels such as Liquefied Natural Gas (LNG), Liquefied Petroleum Gas (LPG) and methanol. A long-term solution is hydrogen, which will enable a zero-carbon shipping industry in the future. IMO, through the IGF code, allows the application of hydrogen as an alternative fuel for ships (IMO, 2015). Vessels that use hydrogen as a fuel shall be designed with the specific requirements contained in the SOLAS alternative ship design regulation (IMO, 2009). In addition, some guides have already been developed by classification societies encouraging the use of LH_2 (DNV, 2021a; IMO, 2021; ABS, 2021). In parallel, recommendations for ships carrying hydrogen as a cargo have been developed (IMO, 2016; ClassNK, 2017).

Hydrogen is a pure substance that is produced by steam reforming of methane or water electrolysis. It is an almost zero-carbon alternative, since its combustion merely produces hydrogen or water depending on the production method. To store and transport hydrogen in large quantities, it needs to be liquefied at -253℃. Its high energy density requires storage tanks 5 times larger in volume compared to petroleum-based fuels and therefore liquid hydrogen (LH_2) would be practical only for small ships that travel short distances. Nevertheless, regardless of the environmental sustainability, the use of LH_2 can pose a significant risk to human life and infrastructure. Primarily, human exposure to extreme temperatures poses a significant cryogenic risk. In addition, it is a flammable substance, especially when mixed with pure oxygen, that requires major measures to be taken to prevent large-scale accidents. Indeed, when LH_2 is released into the open air, a flammable gas mixture is formed that produces invisible flames posing a serious fire hazard (ABS, 2021). The result is either a jet fire or an explosive gas cloud and may lead to detonation.

The current study utilizes the methodology already presented by Papazoglou et al. (1992) to quantify the risk associated with LH_2 handling in port areas, and particularly it is performed a risk assessment considering truck to ship (TTS) and ship to ship (STS) bunkering. The adopted methodology consists of the next three major phases: a) assessment of damage states and their frequency of occurrence, b) assessment of consequences of flammable or toxic substances release, and c) risk integration. In the first phase of the risk assessment methodology, master logic diagrams (MLDs) are constructed to determine the initial events that are likely to occur during TTS or STS bunkering. MLDs initiate with the top event "Loss of Containment" which is decomposed into simpler events. Inadequate purging or ventilation, external heat owning to external fire, tank rupture owning to corrosion, embrittlement or weld failures, and overfilling are identified initial events in case of LH_2 leakage during bunkering (Ringland, 1994; NASA, 2005). As soon as the initial events are identified, the safety functions and systems for preventing release, and the damage states are identified. Herein, it is examined merely the case of the LH_2 release owning to hose rupture during bunkering. The frequency of the occurrence of hose rupture can be calculated by the Event Tree and/or Fault Tree methodology, or by using accident frequency data from the literature. In this study, the data incorporated by HYRAM+ (Ehrhart and Hecht, 2022) and DNV (2021c) are used.

The second major step involves the assessment of the consequences owing to the LH_2 release. As a matter of fact, in case of hose rupture there are two possibilities: a) an immediate ignition will occur at the time of the release thus a jet fire will take place, and b) in case an immediate ignition does not occur, LH_2 will evaporate, spread and eventually form a vapor cloud dispersing into the atmosphere that may result in vapor cloud explosion, if ignited. The consequences are directly related to the bunkering rate that differs among the various bunkering modes. Assuming TTS, low and high bunkering rates can be considered to be 14 m^3/h to 56 m^3/h respectively (DNV, 2021b), while in STS the respective low and high bunkering rates are 400 m^3/h and 1000 m^3/h (DNV, 2021c).

Finally, the third major step involves the integration of the results of all previous phases to estimate the total individual risk. Assuming LH_2 release and the associated physical phenomena, heat radiation and the maximum impulse are calculated by using the HYRAM+ software. Table 1 shows the damage states as well as the distances where individual risk equals to 10^{-6}, in case of a full bore hose rupture and pressure 10 bar. It is also assumed that after the full bore hose rupture either a jet fire will occur, or a vapour cloud explosion each with 50% probability. Two sets of calculations have been performed. In the first one the frequency of the full bore rupture was equal to 6.0 10^{-5}/y, according to HYRAM+ data and in the second one it was equal to 2.64 10^{-2}/y for small releases and 2.64 10^{-3} for larger ones, according to (DNV, 2021c). The most serious accident is a hydrogen vapour cloud explosion during STS bunkering at high flow rate.

Table 1. Distances where individual risk is equal to 1.0 10-6.

Damage State - LH_2 hose full rupture	Bunkering Rate (m^3/h)	Hose Inner Diameter (mm)	Frequency of occurrence/y (HYRAM)	Distance (m)	Frequency of occurrence/y (DNV)	Distance (m)
TTS and jet fire or explosion	14	10	3.10 10^{-5}	3.5	1.32 10^{-2}	7
	56	18	3.10 10^{-5}	18	1.32 10^{-2}	45
STS and jet fire or explosion	400	50	3.10 10^{-5}	63	1.32 10^{-3}	134
	1000	80	3.10 10^{-5}	101	1.32 10^{-3}	215

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