Deputy Commandant for Systems

Research and Development Center

Operational Guide for Response to Alternative Fuels Incidents

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Homeland Security

NOTICE

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16. Abstract (MAXIMUM 200 WORDS)

Fossil fuel use within the maritime industry is prevalent and will continue in the near future, but the global energy landscape is evolving. The U.S. Coast Guard (USCG) expects a significant increase in the use and transport of alternative fuels in U.S. waterways that are less carbon intensive or reduce air pollutants in order to meet global emission targets. The Coast Guard Office of Marine Environmental Response Policy (CG-MER) is concerned that without adequate awareness, training, and preparation, alternative fuel spillage in U.S. waterways can pose risks to responders' safety and health, port and vessel safety, and environmental damage. The USCG Research and Development Center (RDC) aimed to fill this knowledge gap by conducting a literature review of alternative fuels that pose both the highest probability for spillage and risk to responders' safety and health. After consulting with subject matter experts (SMEs) and field responders throughout the U.S., RDC determined that certain alternative fuels needed immediate response guidance for incident response: liquefied natural gas, methanol, ammonia, hydrogen, liquefied petroleum gas, and biofuels. USCG Federal On-Scene Coordinators (FOSCs) can use this operational guide to identify safety and health hazards associated with each priority alternative fuel. This document provides technical information and quick response guidance for those fuels.

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Alternative fuels, methanol, liquefied natural gas, ammonia, hydrogen, response, incident, safety, petroleum, biofuels, biodiesel, FAME, HVO, hazards, guide, liquefied petroleum gas, detection

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EXECUTIVE SUMMARY

Fossil fuel use within the maritime industry is prevalent and will continue to be in the near future, but the global energy landscape is evolving. The U.S. Coast Guard (USCG) expects a significant increase in the use and transport of alternative fuels in U.S. waterways that are less carbon intensive or reduce air pollutants in order to meet global emission targets. Alternative fuels being considered include but are not limited to liquefied natural gas (LNG), methanol, liquefied petroleum gas (LPG), biofuels and zero-carbon fuels (such as ammonia and hydrogen). Since there is a wide range of alternative fuels still being considered by the shipping industry, each of their fate and behavior in the maritime and port environments have not yet been thoroughly studied. The Coast Guard Office of Marine Environmental Response Policy (CG-MER) is concerned that without adequate awareness, training, and preparation, alternative fuel spillage in U.S. waterways can pose risks to responders' safety and health, port and vessel safety, and environmental damage.

To address a knowledge gap in alternative fuel response, the USCG Research and Development Center (RDC) consulted with subject matter experts (SMEs) and Coast Guard field responders throughout the U.S. to prioritize response guidance for specific fuels. Based on this consultation, RDC identified LNG, methanol, ammonia, and hydrogen as the highest priorities. SMEs also cited LPG and biofuels, but to a lesser extent. RDC synthesized the literature review results into an operational guide for quick reference in event of an incident. The guide includes human and environmental health/safety hazards, protective measures, and safety precautions for responding to incidents involving LNG, methanol, ammonia, hydrogen, LPG, and biofuels. It also identifies research gaps/other unknowns about each alternative fuel for future work. This operational guide is mostly based on information from a report prepared by Oak Ridge National Laboratory (ORNL) in 2021 and the International Tanker Owners Pollution Federation's (ITOPF) 2024 report series about alternative fuels risks and response measures.

USCG Federal On-Scene Coordinators (FOSCs) and other spill responders can use this operational guide to identify safety and health hazards associated with each priority alternative fuel. It can also assist CG-MER in determining whether field research will be necessary to evaluate response technologies with specific alternative fuels, such as low-sulfur fuel oils (not included in this document). With public dissemination, this operational guide will improve awareness and readiness for alternative fuel incident response.

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LIST OF ACRONYMS, ABBREVIATIONS, AND SYMBOLS

AOR	Area of Responsibility
AR-AFFF	Alcohol-Resistant Aqueous Film-Forming Foam
ARISE	Ammonia Response in Sea Emergencies
BLEVE	Boiling Liquid Expanding Vapor Explosion
CAMEO	Computer Aided Management of Emergency Operations
CGI	Combustible Gas Indicator
CG-MER	Coast Guard Office of Marine Environmental Response Policy
CG-OES	Coast Guard Office of Operating and Environmental Standards
CHRIS	Chemical Hazards Response Information System
cm	Centimeter(s)
COD	Chemical Oxygen Demand
COTP	Captain of the Port
CSAC	Chemical Security Analysis Center
°C	Degree Celsius
°F	Degree Fahrenheit
DHS	Department of Homeland Security
DNV	Det Norske Veritas
DOE	U.S. Department of Energy
DRAT	District Response Advisory Team
eV	Electronvolt
FAME	Fatty Acid Methyl Esters
FLIR	Forward-Looking Infrared
FOSC	Federal On-Scene Coordinator
FOUO	For Official Use Only
HVO	Hydrotreated Vegetable Oil
IGC Code	International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk
IGF Code	International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels
IMAROS 2	IMpacts and Response OptionS
IMO	International Maritime Organization
IR	Infrared
ITOPF	International Tanker Owners Pollution Federation
L	Liter(s)
LFL	Lower Flammability Limit
LGC NCOE	Liquefied Gas Carrier National Center of Expertise
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
LSFO	Low-Sulfur Fuel Oil
MEPC	Marine Environment Protection Committee
MGO	Marine Gas Oil
MJ	Megajoule(s)
mph	Mile(s) Per Hour

LIST OF ACRONYMS, ABBREVIATIONS, AND SYMBOLS (Continued)

NCA	Norwegian Coastal Administration
NRT	National Response Team
NSF	National Strike Force
ORNL	Oak Ridge National Laboratory
OSRO	Oil Spill Removal Organization
PID	Photoionization Detector
PPE	Personal Protective Equipment
QRG	Quick Response Guide
RDC	Research and Development Center
ROV	Remotely Operated Vehicle
RPT	Rapid Phase Transition
RRT	Regional Response Team
SCBA	Self-Contained Breathing Apparatus
SDS	Safety Data Sheet
SGMF	Society for Gas as a Marine Fuel
SME	Subject Matter Expert
S&T	Science and Technology Directorate
UAS	Uncrewed Aircraft System
U.S.	United States
USCG	United States Coast Guard
UV	Ultraviolet
VLGC	Very Large Gas Carrier
VLSFO	Very Low Sulfur Fuel Oil
VOC	Volatile Organic Compound

1 INTRODUCTION

The U.S. Coast Guard (USCG) expects a significant increase in the use and transport of alternative fuels in the maritime industry (Figure 1). Title 42 U.S. Code § 13211 defines alternative fuel as pure methanol, ethanol, and other alcohols; blends of 85% or more of alcohol with gasoline; natural gas and liquid fuels domestically produced from natural gas; propane; coal-derived liquid fuels; hydrogen; electricity; pure biodiesel; fuels, other than alcohol, derived from biological materials; and P-Series fuels (Alternative Fuels, 1999).

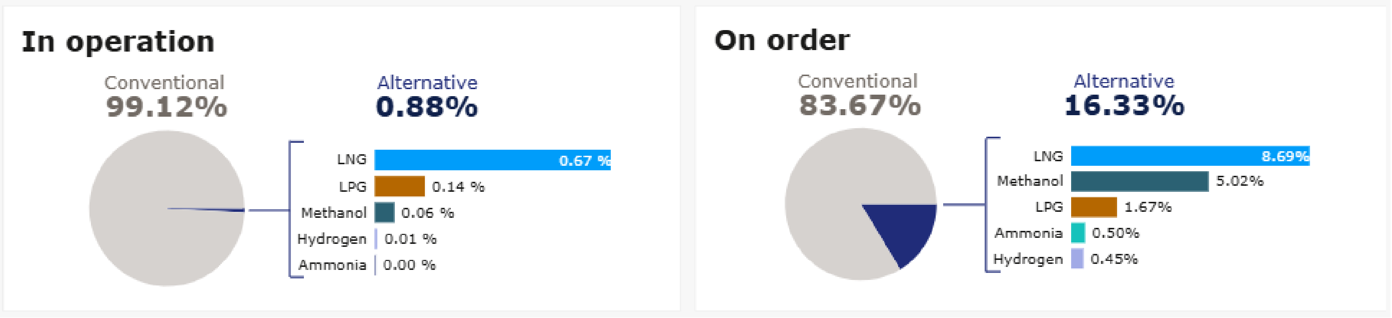

Figure 1. Percent of world fleet currently in operation and on order using conventional vs. alternative fuels, as of 21 May 2025 (DNV, 2025)[1].

In recent years, the shipbuilding industry has ramped up new-vessel builds or vessel retrofits for powering by alternative fuels. According to Lloyd's Register, shipowners ordered approximately 600 vessels capable of using alternative fuels in 2024. There were 119 orders for methanol-fueled vessels, 22 for ammonia-fueled vessels, and 12 for hydrogen, but liquefied natural gas (LNG) as fuel topped the list with more than 350 vessels, including LNG carriers (Lloyd's Register, 2025). Between new orders and the existing in-service alternative-fueled fleet, the total number stands at 3,597 vessels, which accounts for 4.8% of all vessels in-service and on order (Lloyd's Register, 2025).

The Department of Homeland Security (DHS) Science and Technology Directorate (S&T) Chemical Security Analysis Center (CSAC) conducted a market assessment to better understand the details of production, storage, and transportation of alternative fuels in U.S. ports and assess the associated hazards (DHS S&T, 2024). The report is marked as For Official Use Only (FOUO) but qualified persons seeking the report's content should contact DHS S&T for more information about projected alternative fuel activities in U.S. ports.

Det Norske Veritas (DNV) provides a subscription-based data platform called "Veracity" for the maritime and energy sectors. Veracity collects and verifies operational data from over 11,000 vessels, with connections to over 60,000 through its Integrated Partner program. This data undergoes quality assurance and independent verification by DNV. The platform calculates fuel consumption and emissions for the entire global fleet, and includes data for both in-service and on-order vessels. It also offers advanced

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[1] DNV collects data from publicly available information, S&P Global Market Intelligence, and directly from shipowners. DNV updates data monthly and includes only seagoing vessels. For hydrogen-powered vessels, vessels in operation that have completed testing with hydrogen as fuel are distinguished from vessels in operation where testing has not yet taken place.

emissions simulations and predictions. Figure 2 shows the steady growth of vessels powered by alternative fuels and the number of vessels on order through to 2033.

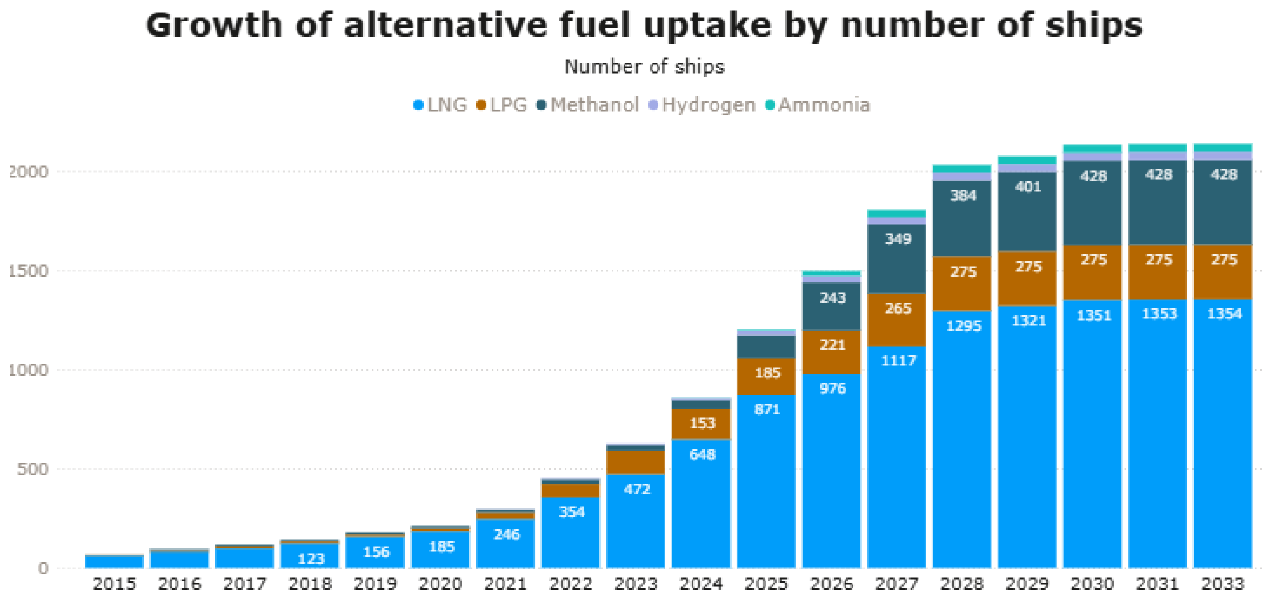

Figure 2. Growth of alternative fuel uptake by number of ships from 2015 to 2033 (DNV, 2025).[2]

There are uncertainties among shipowners about which alternative fuel will see widespread use. Some reasons include complex and costly supply chain management challenges and needed specialized infrastructure for each alternative fuel (MARPRO, 2023). There are different safety risks/considerations associated with handling and storage of each fuel on a vessel. They also have different energy densities, which directly impacts the storage volume needed for a voyage (Table 1).

Table 1. Volumetric energy density of each alternative fuel on a lower heating value basis (SGMF, 2024b).

Fuel	Volumetric Energy Density (MJ/L)
Biodiesel	33
LPG*	25
LNG	21
Methanol	16
Liquid Ammonia	13
Liquid Hydrogen	9
Compressed Hydrogen	5

*LPG density can vary depending on the propane/butane mixture.

Alternative fuels with lower energy densities are most appropriate for vessels traversing shorter distances with adequate shoreside infrastructure support, for example passenger ferries powered by hydrogen. Figure 3 gives an insight on which type of alternative fuel is currently being used by specific ship types.

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[2] Liquefied petroleum gas (LPG) is a flammable mixture of hydrocarbon gases, primarily propane and butane, that is liquefied for storage and transportation.

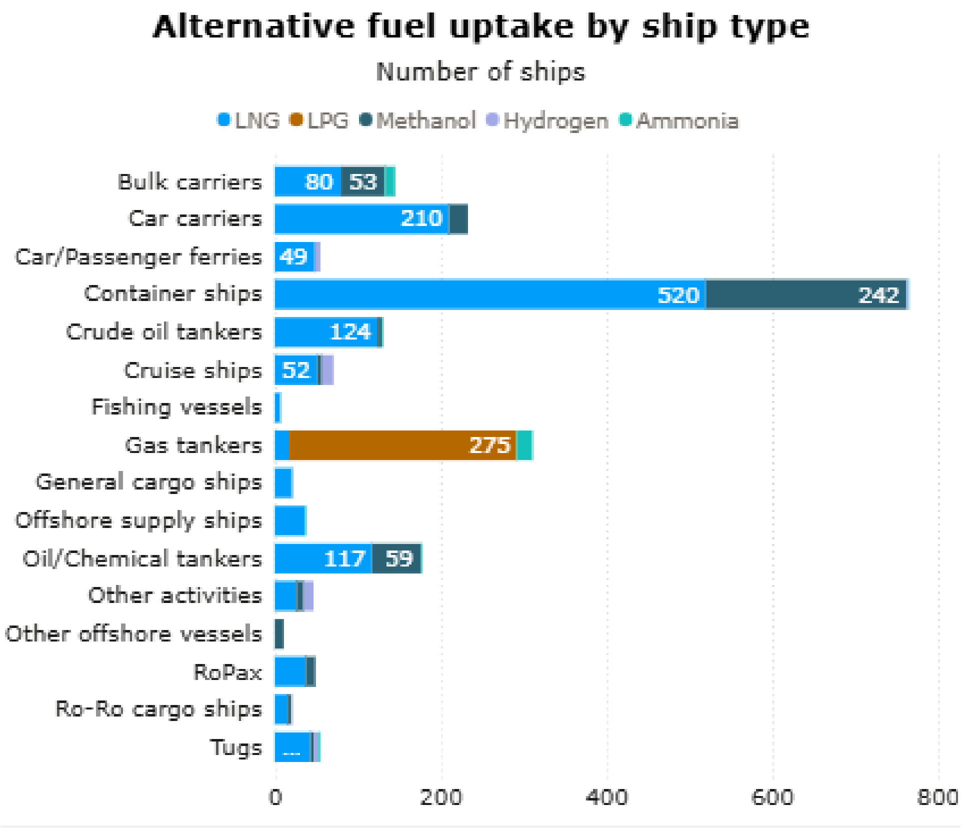

Figure 3. Alternative fuel uptake by ship type, as of 21 May 2025 (DNV, 2025).

The shipping industry is mostly in agreement that LNG is an essential, affordable transition[3] fuel until zero-carbon alternatives become more widely available (SGMF, 2023b). Vessel data from Lloyd's Register and DNV support this sentiment and there is no uniform agreement on how long this transition to less carbon-intensive fuels is expected to take.

The fate and behavior in maritime and port environments have not yet been thoroughly studied for each alternative fuel being considered by the shipping industry. The Computer Aided Management of Emergency Operations (CAMEO) software and the Chemical Hazards Response Information System (CHRIS) provide the Coast Guard basic information about most alternative fuels except for biofuels. There is also ongoing research being conducted by academia, industry, other Government organizations such as the Department of Energy, and foreign Governments. However, further knowledge is urgently needed for USCG Federal On-Scene Coordinators (FOSCs) and other spill responders, especially for response techniques and strategies. Specifically, there is inadequate data about the effectiveness of oil spill response equipment, typically used for crude petroleum and refined products, on alternative fuels.

Within the Coast Guard, the Liquefied Gas Carrier National Center of Expertise (LGC NCOE) based in Galveston, TX is a trusted source of knowledge about alternative fuels, especially LNG and other liquefied gases. Established in 2009, LGC NCOE serves as an in-house consultant to the Coast Guard for its involvement with the liquefied gas shipping industry. The scope of its expertise includes: foreign and

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[3] Transition fuel refers to a fuel that "bridges" current reliance on fossil fuels to a future powered by zero-to-low emission fuels. Transition fuels produce less emissions but still require infrastructure similar to existing fossil fuels.

domestic flagged vessels and barges that carry liquefied gases in bulk, commercial ships that use LNG as a fuel, and the safety and engineering systems associated with LNG/LPG storage facilities (LGC NCOE, 2025). LGC NCOE works closely with USCG technical and program offices, equipment manufacturers, ship owners/operators, and classification society representatives. LGC NCOE trains prevention staff at USCG Sectors in major ports to ensure Coast Guard inspectors are well-versed on appropriate examination protocols for alternatively fueled ships (LGC NCOE, 2025). However, LGC NCOE is not tasked to develop response strategies for alternative fuel incidents in the maritime environment.

1.1 Research Objective

The Coast Guard Office of Marine Environmental Response Policy (CG-MER) has concern that without adequate awareness, training, and preparation, alternative fuel spillage in U.S. waterways can pose risks to responders' safety and health, port and vessel safety, and environmental damage. The USCG Research and Development Center (RDC) aimed to fill this knowledge gap by conducting a literature review of alternative fuel spill response methodologies. RDC synthesized those results into this operational guide that responders can quickly refer to in the event of an incident.

1.2 Literature Review

RDC contacted USCG Captains of the Port (COTPs), District Response Advisory Teams (DRATs), and prevention staff at USCG Sectors and Districts throughout the U.S. From the field input, RDC determined which alternative fuel(s) were most concerning or least known, prioritizing them for further review. Other points-of-contact included state agencies, spill response organizations such as the International Tanker Owners Pollution Federation (ITOPF), classification societies, Oil Spill Removal Organizations (OSROs), National Response Team (NRT) and Regional Response Team (RRT) members, and other USCG program offices such as the Office of Operating and Environmental Standards (CG-OES) and LGC NCOE. RDC became a member of the Society for Gas as a Marine Fuel (SGMF) in order to access their library containing information about alternative fuels. It also subscribed to DNV's Veracity platform for the latest industry data and perused resources from the International Maritime Organization's (IMO) Future Fuels and Technology Project.

RDC participated in webinars pertinent to alternative fuels and became familiar with multiple international research efforts including the Norwegian Coastal Administration's (NCA) Impacts And Response Options (IMAROS 2) regarding low-sulfur fuel oil (LSFO) spills. IMAROS 2 is a working group led by NCA and funded by the European Union. Cedre, a French State-approved association that conducts research of accidental water pollution, was planning a August/September 2025 sea trial to study the impacts of a large-scale ammonia release. RDC joined several meetings held by the Puget Sound Harbor Safety Committee to learn about increased methanol activities in the Ports of Seattle and Tacoma, and the upcoming Pacific Northwest to Alaska Green Corridor project in USCG Northwest and Arctic Districts.

RDC connected with LGC NCOE staff early in the literature review process and was made aware of a report prepared by Oak Ridge National Laboratory (ORNL) for the U.S. Department of Energy (DOE) titled, "Spill Behavior, Detection, and Mitigation for Emerging Nontraditional Marine Fuels." Much of the information here is based on the ORNL report. RDC also conducted a thorough review of publicly-available reports, articles, fact sheets, presentations, and other materials on existing and emerging alternative fuels. RDC attended several technical sessions focused on alternative fuel research at the International Oil Spill Conference in 2024 and established contacts with subject matter experts (SMEs) in this research area.

2 PRIORITY ALTERNATIVE FUELS

Consulting with SMEs and field responders throughout the U.S. RDC indicated a high demand for incident response guidance on LNG, methanol, ammonia, hydrogen, and LPG. Literature mentioned ethanol as one possible alternative fuel being considered by shipowners, but field responders did not note much activity in their Areas of Responsibility (AORs) nor were they aware of future planned bunkering[4] infrastructure in the U.S. The NRT has a quick response guide (QRG) for responding to ethanol incidents already available on its website (https://www.nrt.org/). RDC also identified biofuels (e.g., Fatty Acid Methyl Esters (FAME), hydrotreated vegetable oil (HVO)) as other potential alternative fuels though responders expressed relatively less concern about them compared to other higher-priority alternative fuels.

The MV Wakashio incident in Mauritius in July 2020 was the first major spill of very-low sulfur fuel oil (VLSFO). Although some bunkering of this fuel occurs in the U.S., responders did not cite it as a pressing concern. There have been reports that mechanical recovery of VLSFO or other LSFOs is not as effective as recovery with conventional crude or products, especially in cold climates where VLSFO is more likely to “clump”. Current oil spill equipment is not designed to collect oil clumps. IMAROS 2 staff is currently addressing this challenge. Due to lack of feedback regarding VLSFO or LSFOs and existing ongoing research, RDC did not include this fuel category here. However, there is potential for future collaboration with the IMAROS 2 team to determine how traditional mechanical recovery systems (i.e., oil skimmers) can be modified for improved performance with LSFOs.

This document is arranged with a brief discussion on each priority alternative fuel here in Section 2, followed by APPENDIX A through APPENDIX F as QRGs for each alternative fuel. The QRGs are primarily based on the 2021 Oak Ridge National Laboratory report, “Spill Behavior, Detection, and Mitigation for Emerging Nontraditional Marine Fuels” and ITOPF’s 2024 report series on alternative fuels developed by its International Group of P&I Clubs Alternative Fuels working group. The ORNL report and ITOPF reports represent the latest knowledge about safety and spill mitigation strategies for the identified priority alternative fuels. RDC organized information to be easy to read and quickly referenced before and during incidents. The QRGs contain the most relevant recommendations for response but responders are encouraged to read the original reports. Table 2 summarizes each alternative fuel’s behavior, associated hazards, likelihood of spill response, and QRG location within this guide.

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[4] Bunkering encompasses the logistics of loading and distributing fuel throughout a ship's fuel tanks. Vessels bunker either alongside specific regulated facilities or in a vessel to vessel operation.

Table 2. High level overview of each alternative fuel and QRG location.

Alternative Fuel	State		Longevity in the Environment	Toxicity to Humans	Health & Safety: Main Concerns	Protracted Response to Recover Pollutant	Quick Response Guide Location
	Under Ambient Conditions	During Transport					
LNG	Gas	Liquid (cryogenic)	Hours	Non-toxic	Significant risks linked to flammability, explosivity, asphyxiation, and cryogenic temperatures	Unlikely	Appendix A
Methanol	Liquid	Liquid	Hours to days	Toxic (direct contact & inhalation of vapors)	Significant risks linked to toxicity and flammability	Unlikely	Appendix B
Ammonia	Gas	Liquid (pressurized and refrigerated)	Hours to days	Acutely toxic (vapors and upon direct contact)	Immediate risk in vicinity of substance, high toxicity with particular risk from vapors	Unlikely	Appendix C
Hydrogen	Gas	Liquid (cryogenic), or pressurized gas	Hours	Non-toxic	Significant risks linked to flammability & explosivity	Unlikely	Appendix D
LPG	Gas	Liquid (pressurized and refrigerated)	Hours	Non-toxic	Significant risks linked to flammability, explosivity, asphyxiation, and extreme low temperatures	Unlikely	Appendix E
Biofuels	Liquid	Liquid	Weeks to months	Toxic (direct contact)	Low risk from initial exposure, toxicity poses a risk if exposed for extended periods	Likely	Appendix F

2.1 Liquefied Natural Gas (LNG)

LNG, colorless and odorless, is natural gas that has been cooled sufficiently to condense into a liquid. At atmospheric pressure, this occurs at a temperature of -162 °C (-260 °F) (SGMF, 2023b). As natural gas condenses, approximately 600 volumes of gas become one volume of liquid, improving its energy density and making it commercially feasible to transport large volumes of gas in a vessel. LNG is usually re-gasified by heating at its destination before being fed into a pipeline grid or power station (SGMF, 2023b). Alternatively, LNG is distributed by rail tank car or tanker truck to off-grid customers for industrial use or for use as transport fuel. LNG is a mixture of hydrocarbons, predominantly methane (>85%). Other significant components include other alkanes – ethane, propane and butane. Nitrogen may also be present at levels up to 1%. All of the more complex hydrocarbons, along with carbon dioxide and sulphur compounds, are removed to trace levels during production (SGMF, 2023b).

LNG is widely used as a “transition” fuel for many shipowners until affordable, lower-emission alternatives become available. It has been shipped globally in bulk as cargo for more than sixty years, there is an abundant global supply, and it can be used with dual-fuel engines that can be cost effective to use for many shipowners (ITOPF, 2024d). There has also been a corresponding growth in LNG bunkering infrastructure in U.S. ports. Ports that received major investments for LNG facilities include but are not limited to Jacksonville, FL, Houston, TX, Los Angeles/Long Beach, CA, Port Canaveral, FL, Galveston, TX, and Tacoma, WA. The Port of Houston, for example, has approximately 1 million gallons of storage capacity for LNG (Casey, 2024) and the Port of Jacksonville has a LNG bunkering terminal, truck-to-ship bunkering, and vessel-to-vessel bunkering capabilities. Containerships, Large Passenger Vessels, Roll-on/Roll-off carriers, and Offshore Support Vessels are some of the vessel types using and bunkering LNG in the U.S.

In an effort to keep LNG as a “transition” fuel and not a long-term solution, members at IMO’s Marine Environment Protection Committee (MEPC) 83rd meeting in April 2025 agreed to set limits on LNG’s viability as a marine fuel. They proposed basic penalty fees within the next few years with rapidly growing fees beginning in 2033. If adopted, LNG may no longer be a competitive choice for new shipbuilding projects and existing vessels would likely face residual value consequences (Smith, et al., 2025). MEPC members noted that there may be arguments for LNG being able to operate on bio-methane and synthetic methane. However there is a broad consensus in analysis and models of future fuel prices, that these variants of methane are unlikely to be competitive choices relative to ammonia or even biofuels (Smith, et al., 2025).

2.1.1 LNG Fate and Behavior

When the storage tank temperature rises above LNG’s boiling point or when liquid LNG is exposed to ambient conditions, it vaporizes.

If LNG spills on or above the waterline, it will first float and, depending on the quantity spilled, may form a shallow cryogenic pool on the water surface before vaporizing. There is also potential for some seawater in the immediate vicinity of the release to freeze due to LNG’s low temperature, causing localized ice patches (ITOPF, 2024d). Since methane is not highly soluble with water, there will be little dissolution into the sea (Kass et al., 2021).

If released below the waterline, there will be little dissolution due to methane’s low solubility. LNG will rise to the water surface before rapidly boiling and volatilizing into the atmosphere as its temperature increases due to contact with seawater and the atmosphere. When vaporizing, the cold LNG vapors are heavier than air and stay close to the sea surface. These vapors condense the moisture in the air, forming a visible white cloud of water vapor (or fog), mixed with gaseous LNG (Figure 4).

Figure 4. Formation of white cloud resulting from LNG spillage during vessel refueling (Kass et al., 2021).

As the gas mixture warms up and its overall specific gravity decreases, it rises and dissipates into the atmosphere within a short period of time; approximately 30 minutes for large, discontinuous spills (Kass et al., 2021). It is likely that the water vapor cloud will persist longer than the LNG cloud. The footprint and height of the vapor cloud will depend on the metocean conditions at the time of the release (ITOPF, 2024d).

In low wind conditions (<5 mph), the vapor cloud footprint is smaller on the sea surface and is expected to dissipate at a higher altitude (Figure 5). It is not projected to extend across the water's surface from the release point beyond approximately 30 meters (Kass et al., 2021).

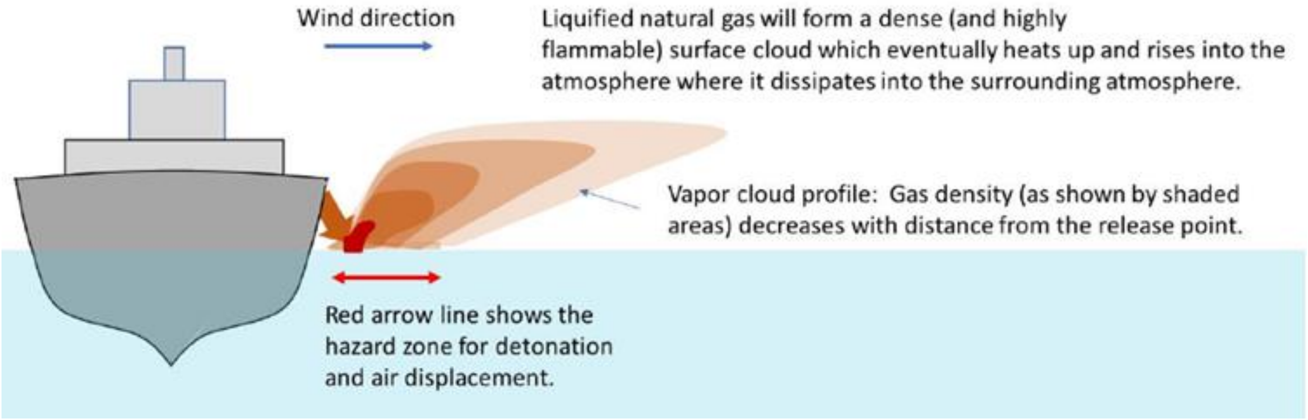

Figure 5. Expected fate and behavior of an LNG spill from a ship in low wind conditions (<5 mph) (Kass et al., 2021).

With moderate wind conditions (>5 mph as defined by Kass et al.), the vapor cloud plume is likely to be knocked down, resulting in a low-lying plume with a larger footprint across the sea surface (Figure 6) (ITOPF, 2024d). Several studies of vapor cloud profiles indicate that higher wind speeds cause an expansion of the cloud footprint, resulting in an expanded hazardous region. Thus, fire and suffocation risks can be higher in windy conditions (Kass et al., 2021).

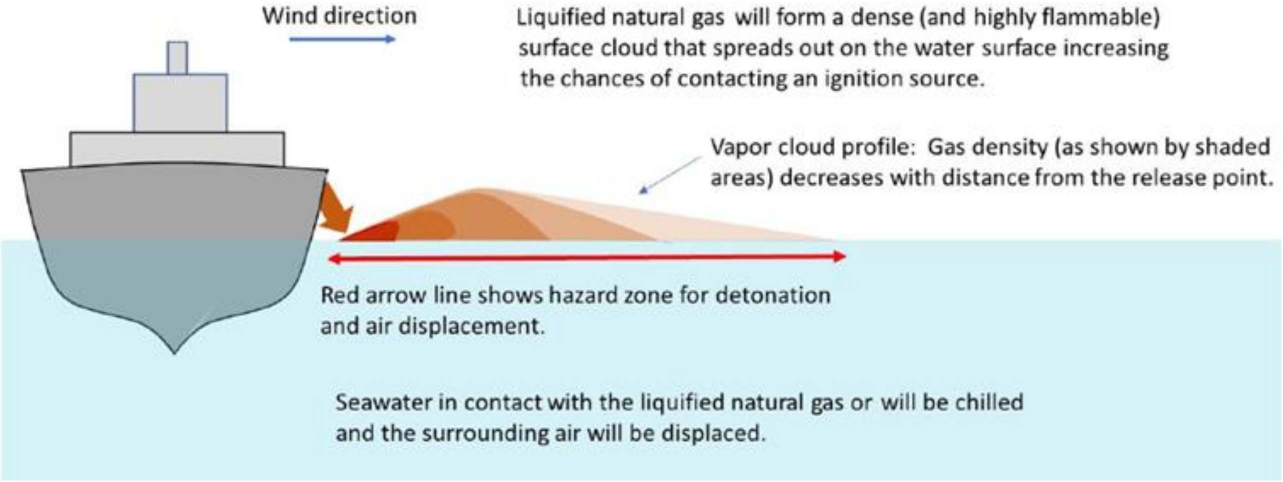

Figure 6. Expected fate and behavior of an LNG spill from a ship in moderate wind conditions (>5 mph) (Kass et al., 2021).

Previous studies have indicated that vapor 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 location of the breach, discharge rate, and environmental conditions at the time of the spill (ITOPF, 2024d). The LNG cloud in its cold state is the most dangerous since it has a high likelihood to ignite when it comes into contact with a heat source (Kass et al., 2021).

With an LNG spill, there is little chance of effective spill response beyond evacuation of personnel from the hazard area. There are some detection devices that may be adaptable to monitor the flammable vapor/air mixture near the spill source. The principal hazard with a LNG spill is the potential to create an explosive cloud, although localized oxygen displacement can also create the potential for suffocation near the point of release (Kass, et al., 2021).

2.1.2 Knowledge Gaps

Environmental impacts of LNG in the marine environment are not as widely researched as impacts associated with traditional oil spills (ITOPF, 2024d). Additional research may be beneficial to better assess pre- and post-spill baselines.

2.2 Methanol

Methanol (CH_3OH), a basic alcohol, is a colorless liquid with slightly sweet odor at ambient temperature and pressure, making it simpler to store and handle compared to cryogenic fuels like LNG, ammonia, and hydrogen. However, it presents a different set of hazards, particularly related to toxicity and flammability (SGMF, 2024b). Methanol is corrosive with some materials, such as aluminum and titanium alloys and shipowners need to consider specific types of materials for storage and transportation (ITOPF, 2024f).

Methanol is gaining traction as an alternative marine fuel due to its potential to significantly reduce greenhouse gas emissions when produced from renewable sources (“green methanol”). However, most of the current world supply relies on the production from fossil fuel feedstocks. It is already transported globally as cargo; the industry has more experience with handling and transporting methanol compared to other emerging alternative fuels except for LNG. There is increasing adoption of methanol as a low-carbon fuel, especially in dual-fuel engines that can switch between methanol and conventional marine fuel oils.

Responders on the U.S. West Coast, especially in USCG Northwest District, note an increase in methanol bunkering activities with *Maersk Alette* recently making a port call at Tacoma in September 2024. It was the largest dual-fuel vessel for Tacoma to date (NWSA, 2024). In 2022, a group of stakeholders from Alaska, Washington, and British Columbia, Canada launched an initative called “PNW2Alaska Green Corridor”. The goal is to establish a maritime route between the Pacific Northwest and Alaska that reduces or eliminates greenhouse gases. In 2024, they launched a feasibility study to focus on evaluating the demand, production, and availability of green methanol for use as a maritime fuel in the region, delivery of cruise ships able to run on green methanol, and the readiness of bunkering green methanol in both Seattle and Vancouver (Port of Seattle, 2024).

2.2.1 Methanol Fate and Behavior

When methanol spills into the marine environment, it will float, spreading rapidly across the water surface. It will then begin to simultaneously evaporate and rapidly dissolve into the water column (Figure 7). Methanol’s high vapor density prevents all but a small fraction of the vapor cloud from rising. This methanol vapor cloud has a larger flammability footprint than less dense LNG and hydrogen vapor clouds that readily rise and disperse (ITOPF, 2024f).

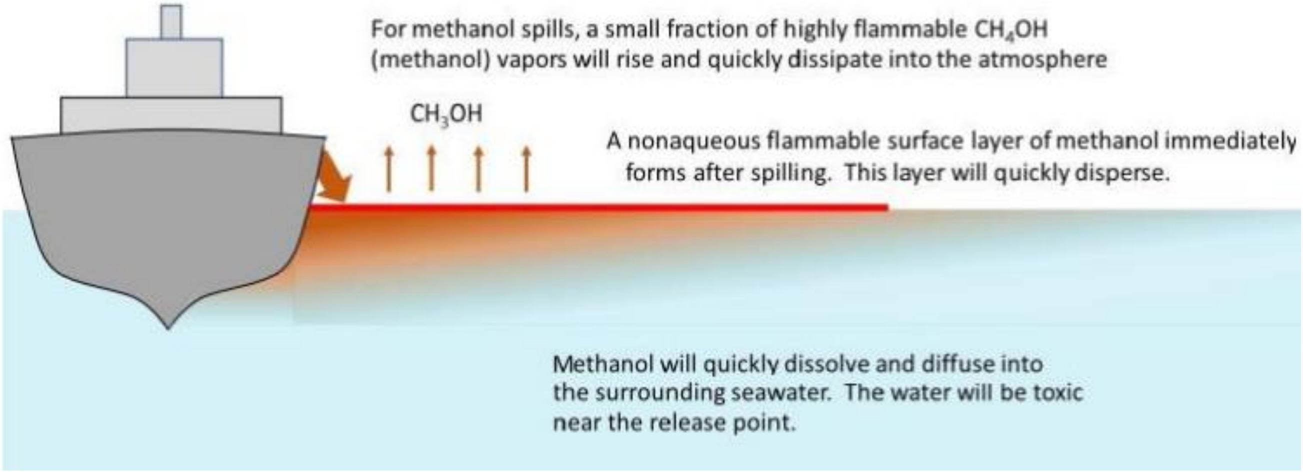

Figure 7. Expected fate and behavior of a methanol spill from a vessel (Kass et al., 2021).

The rate at which methanol dissipates in the water will depend on the sea state conditions at the time of the incident (e.g., currents and wind-induced wave action). Although there are many factors that will influence methanol fate, a release in open water is likely to disperse to non-toxic levels to aquatic life (<%1 concentration) at a much faster rate than petroleum hydrocarbons, with some studies giving methanol a half-life between one and seven days mostly due to biodegradation (ITOPF, 2024f). Since methanol is already naturally occurring in the environment, there are many microorganisms that can process methanol into formic acid (Kass et al., 2021) although a high concentration of methanol at the release point may inhibit microbe activity (Kass et al., 2021) and poses high risk to aquatic life near the point of release.

Methanol’s complete miscibility with water makes physical recovery of spilled methanol impractical. Computer simulations have shown that a 10,000 ton release of methanol at sea would reach a concentration of 0.36% within 1 hour of the spill (Kass et al., 2021), which would mean a clean-up is not feasible. While natural dilution reduces the overall concentration of methanol, it can still pose a toxicity risk to aquatic life in the immediate area of the release point. The principal hazard with a methanol spill is the potential for fire or explosion during the incident or immediately after.

2.2.2 Knowledge Gaps

Environmental impacts of methanol in the marine environment are not as widely researched as impacts associated with traditional oil spills (ITOPF, 2024f). Responders from USCG Northwest District are also concerned with lack of knowledge about water toxicity resulting from methanol incidents; additional research is needed.

2.3 Ammonia

Ammonia is a compound of nitrogen and hydrogen typically stored and transported in its liquefied form (anhydrous ammonia) under pressure or at cryogenic temperatures. At ambient conditions, ammonia is a colorless gas with a strong, irritating odor detectable at very low concentrations (ITOPF, 2024a). Upon contact with water, ammonia rapidly dissolves to form ammonium hydroxide (NH_4OH)—a corrosive (basic) and toxic solution that can cause serious environmental harm.

Ammonia (NH_3) is emerging as a promising zero-carbon marine fuel for deep-sea shipping, especially when synthesized using renewable energy sources ("green ammonia"). Despite its potential, ammonia presents considerable operational and safety risks due to its toxicity, corrosiveness due to its basic (alkaline) nature, and pungent odor. For these reasons, it has consistently been cited by emergency responders as a fuel of concern.

Although ammonia is not yet widely used as a marine fuel, it has been shipped globally as bulk cargo for decades, primarily for the production of fertilizers. It has also been transported and used as a refrigerant at sea. Unlike other low-carbon fuels such as LNG or methanol, ammonia does not emit carbon dioxide (CO_2) during combustion, making it attractive for decarbonization. However, most ammonia today is still produced from natural gas, a process with a high carbon footprint (ITOPF, 2024a).

Globally, several major ports have begun preparing for ammonia bunkering operations by investing in compatible storage infrastructure, transfer systems, and risk management protocols. While ammonia bunkering is not yet established in the U.S., pilot projects, simulation exercises, and feasibility studies are underway in port regions with existing chemical handling capacity. Engine manufacturers are also developing internal combustion systems capable of operating on ammonia, with commercial availability anticipated within this decade (SGMF, 2024a). There has been some limited testing of ammonia-supplied fuel cells as well (SGMF, 2024a). While dual-fuel engines using ammonia are not yet in widespread use, the fuel's commercial viability is growing as shipbuilders, classification societies, and regulators work to develop safety protocols. In May 2024, DNV certified the converted supply vessel Fortescue Green Pioneer, which became the first oceangoing vessel to be fueled by ammonia after completing sea trials (DNV, 2024).

2.3.1 Ammonia Fate and Behavior

If ammonia is spilled above the waterline, a portion of the liquid will rapidly boil off, releasing vapor, while most will dissolve into seawater (Figure 8). For large surface spills, studies indicate that about 60-70% of the volume typically dissolves, while the remaining 30-40% vaporizes (Kass et al., 2021). This evaporation-to-dissolution ratio remains similar for shallow underwater spills, but for deeper releases (greater than 2 meters), only 5–15% of the ammonia volume may escape as vapor, with the majority dissolving into the water column (ITOPF, 2024a).

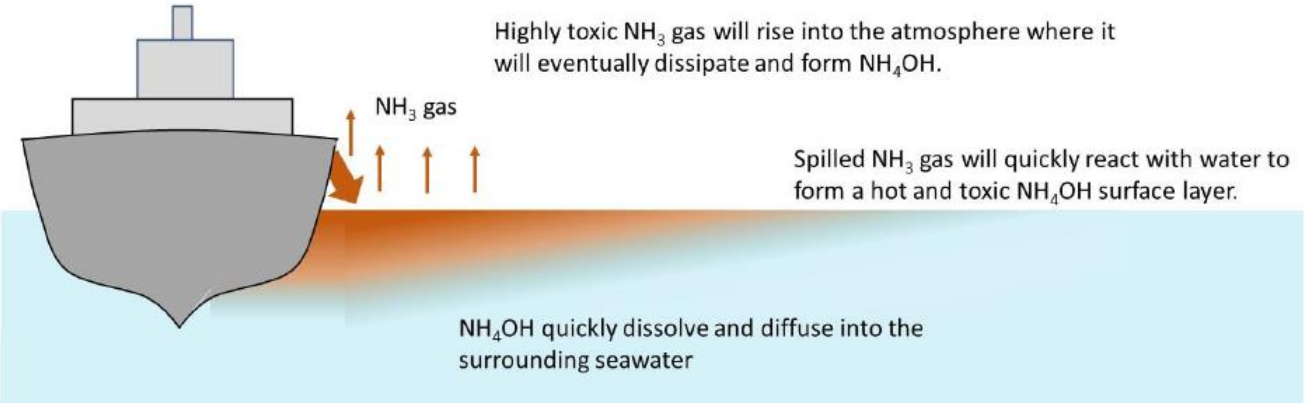

Figure 8. Expected fate and behavior of an ammonia spill from a ship (Kass et al., 2021).

Once dissolved, ammonia forms ammonium hydroxide, a caustic, toxic solution. Since it is less dense than seawater, it will form a layer near the surface. The dissolution is exothermic and can cause a localized temperature increase at the point of release. Most of the ammonia enters the water column, creating an intense but localized heated and toxic zone harmful to marine life. The concentrations and elevated temperatures decrease with distance from the point of release.

The dispersion rate of the ammonium hydroxide plume depends on prevailing environmental conditions such as temperature, tidal currents, and wave action. High-energy environments (e.g., open sea) promote faster dispersion, while low-energy environments like sheltered ports or inland waterways retain higher concentrations for longer durations (ITOPF, 2024a).

In a large, unconfined release, the cryogenic ammonia vapors can condense atmospheric moisture. This cloud consists of tiny water droplets formed by condensation, not ammonia itself, though it may carry ammonia vapor and aerosolized droplets of ammonium hydroxide. Initially, this cloud is denser than air and can travel laterally for hundreds of meters, especially under windy conditions. As the vapor warms to ambient temperatures, it becomes lighter than air, rising and dispersing into the atmosphere (ITOPF, 2024a).

Although ammonia lacks the flammability risks of LNG or methanol under typical marine spill conditions (i.e., ammonia vapor is difficult to ignite in outdoor environments compared to other alternative fuels), ammonia's acute toxicity to humans and marine life, high vapor pressure, and reactivity with water make it an unique hazard (ITOPF, 2024a).

2.3.2 Knowledge Gaps

The environmental impact of ammonia in the marine environment is not as widely researched as the impact associated with traditional oil spills (ITOPF, 2024a). There is a joint industrial partnership called Ammonia Response in Sea Emergencies (ARISE) that was established with the objective of reducing the knowledge gap on cold ammonia and sea water interaction to improve related risk assessment exercises and accurately control impacted risk profiles. Cedre, a French non-profit research organization on accidental water pollution, is part of ARISE and plans to conduct large-scale releases of cold ammonia in sea water in Summer 2025. RDC expects to receive results in January 2026.

2.4 Hydrogen

At ambient conditions, hydrogen is a colorless, odorless, non-toxic gas. Due to its very low density, hydrogen is typically liquefied or compressed for storage and transport as liquid hydrogen takes about 1/850th of the volume of hydrogen gas (ITOPF, 2024c). Pure hydrogen requires cooling ranging from -253 °C under 1 bar to -240 °C under 13 bars to be stored as liquefied hydrogen. It can also be stored as a compressed gas if subjected to very high pressures (250 to 700 bars). With higher energy density compared to compressed hydrogen, liquefied hydrogen is a more attractive storage option for shipowners although both require specialized insulated tanks and venting systems (ITOPF, 2024c).

Liquefied and/or compressed hydrogen is being explored as a zero-carbon marine fuel due to its "clean"[5] combustion if produced by the electrolysis of water using renewable energy ("green hydrogen"). There are increasing orders of vessels using hydrogen as fuel for ferries, tugs, crew transfer vessels, workboats and dredgers using either fuel cells or internal combustion engines. There are some orders for cruise ships intending to install hydrogen fuel cells for auxiliary power (DNV, 2024). In 2023, the Norwegian ferry MF Hydra became the first commercial ship to operate on liquefied hydrogen. Though no commercial oceangoing vessels operate with hydrogen-fueled internal combustion engines, small scale research and development efforts are ongoing (ITOPF, 2024c). However, hydrogen's extremely low ignition energy, broad flammability range, and cryogenic storage requirements make it difficult to safely handle.

A drawback to using hydrogen as fuel is its low volumetric energy density (see Table 1); hydrogen-fueled vessels will need larger fuel storage tanks compared to other potential alternative fuels for the same journey distance (SGMF, 2023a). At this time, hydrogen-powered vessels are likely limited to short shipping routes such as ferries. Additionally, hydrogen is not globally transported as cargo like other alternative fuels so there is limited experience in handling, storage, and loading/unloading. Thus, there is limited understanding of hazards and risks associated with hydrogen as a marine fuel (ITOPF, 2024c).

2.4.1 Hydrogen Fate and Behavior

Liquefied hydrogen is not soluble in water, so if released on or above the waterline, it will first float and then quickly vaporize since ambient temperatures will be well above the hydrogen's boiling point. With extremely low density, hydrogen will disperse rapidly into the atmosphere. Cryogenic pools on the water surface are not likely to occur because of an extremely large temperature difference between hydrogen and the environment (>250 °C); the transition rate from liquid to gas would be too rapid (ITOPF, 2024c). If localized ice patches form, however, they would be short-lived as water temperatures will return to pre-spill levels quickly.

If released below the waterline, hydrogen will rise to the water surface before rapidly boiling and volatilizing into the atmosphere. Overall, liquefied hydrogen's behavior when released in the open water is similar to LNG, but because hydrogen is less dense and more volatile, it has a higher dissipation rate. Thus, the resulting vapor cloud will have a much smaller sea surface footprint compared to LNG and will

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[5] Energy produced during combustion can oxidize nitrogen in the air to form NO_x, so hydrogen is not completely emission free (SGMF, 2023a).

also have a smaller flammability zone. A key difference, however, is since hydrogen is highly reactive, it will ignite much more readily than LNG (Kass et al., 2021).

In low wind conditions (<5 mph), the vapor cloud is expected to dissipate at a higher altitude (Figure 9), whereas in moderate wind conditions (>5 mph), the vapor cloud will not be as high and will spread over a larger footprint on the sea surface (Figure 10). Even in windy conditions, an ignition of the vapor 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 (ITOPF, 2024c).

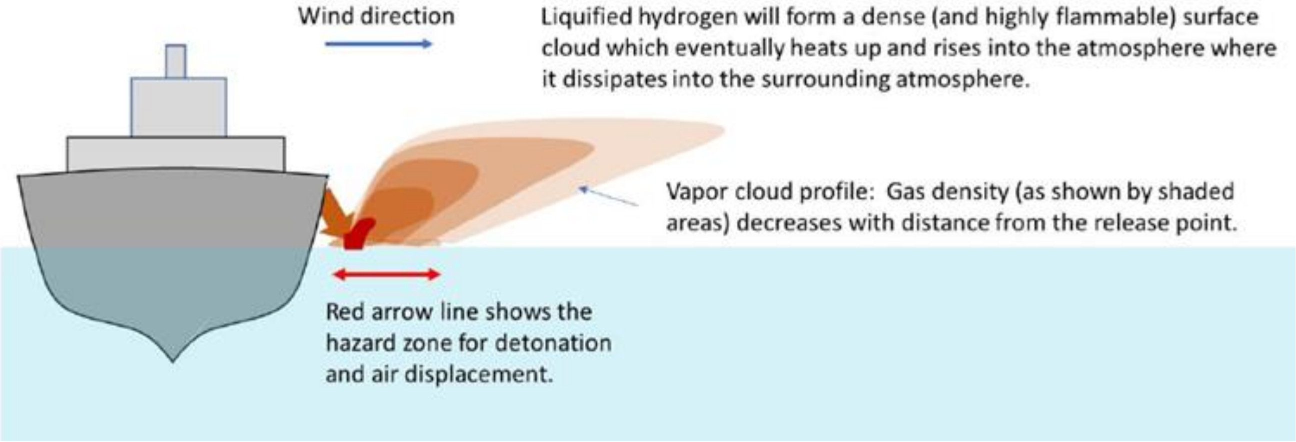

Figure 9. Expected fate and behavior of a liquefied hydrogen spill from a ship in low wind conditions (<5 mph) (Kass et al., 2021).

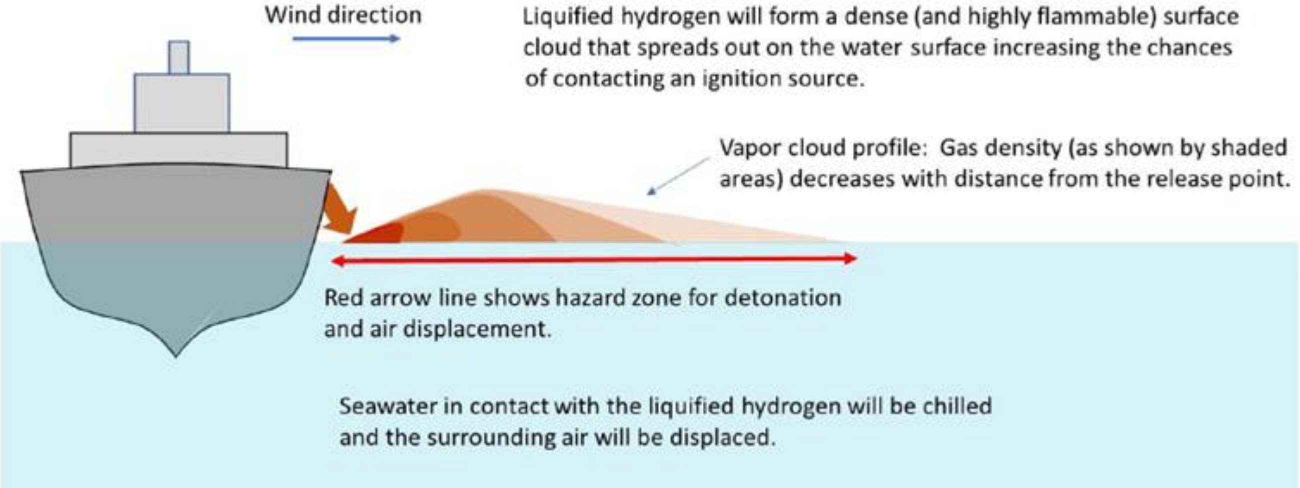

Figure 10. Expected fate and behavior of a liquefied hydrogen spill from a ship in moderate wind conditions (>5 mph) (Kass et al., 2021).

During vaporization, the cold hydrogen vapors have a higher specific gravity than air, and will remain close to the water surface until the temperature rises. The cold vapor condenses the moisture in the air, forming a visible white cloud of water vapor mixed with gaseous hydrogen. As the gas mixture warms and its overall specific gravity decreases, it rapidly rises and dissipates into the atmosphere within a very short time period (ITOPF, 2024c).

Similar to LNG, vapor clouds are expected to spread at approximately the same rate as wind speed and likely will persist in the order of tens of minutes, depending on multiple factors such as 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 than natural gas resulting in rapid atmospheric dilution, especially in unconfined areas (ITOPF, 2024c).

While hydrogen is non-toxic, it can displace the surrounding air and cause suffocation. The biggest concerns for responders with released hydrogen are high explosivity and flammability risks. Exposure to air will allow it to be readily ignited by any hot surface or spark (including static electricity). If the escaping hydrogen is ignited, no cold cloud or condensed water vapor will form. When ignited, more heat will be released per mass and volume than LNG (Kass et al., 2021).

2.4.2 Knowledge Gaps

The environmental impact of hydrogen in the marine environment is not as well studied as that of traditional oil spills. While post-spill assessments are feasible, such studies are rare for hydrogen. For example, a vessel grounding on a coral reef and releasing liquefied hydrogen could cause localized harm, warranting investigation. Unlike biofuels, LNG, LPG, ammonia, and methanol, hydrogen is not widely transported as marine cargo, so experience with its handling, storage, and transfer at sea is limited. As a result, there is limited understanding of the hazards and risks posed by liquefied hydrogen as a marine fuel (ITOPF, 2024c).

2.5 Liquefied Petroleum Gas (LPG)

At ambient conditions, LPG is a colorless, odorless, non-toxic gas, although an odorant is typically added for leak detection. For marine transport, LPG is stored as a liquid for ease of storage and transport (i.e., lower volume space) at moderate pressures or at slightly sub-zero temperatures (-1 °C to -5 °C) under atmospheric pressure. When released, LPG rapidly expands to form a gas that is heavier than air and will tend to accumulate near the ground or water surface, in low-lying areas, or confined spaces, posing a fire and explosion hazard (ITOPF, 2024e).

LPG is a transition fuel that is acquired during the crude oil refining process. It is any mixture of propane and butane in liquid form (ITOPF, 2024e). Similar to LNG, LPG has been shipped in bulk for over 80 years by LPG gas carriers but has recently been explored as an option to be used as a marine fuel due to its relatively low carbon emissions and mature infrastructure for storage and handling. In December 2020, BW LPG's very large gas carrier (VLGC) BW Gemini was the first LPG-powered vessel to be loaded with 590,000 barrels of LPG as cargo and fuel at the Houston Ship Channel in Texas (Richesson, 2021). As Figure 3 shows, gas tankers make up a significant portion of LPG-fueled vessels and they typically use dual-fuel engines capable of burning both LPG and conventional marine fuels (ITOPF, 2024e). This means that experience with handling LPG as cargo and fuel is mostly limited to the LPG shipping industry.

LPG has a high volumetric energy density compared to other alternative fuels (Table 1) and requires less storage space onboard, making it more suitable for long-distance shipping. Its ambient temperature storage as a liquid under moderate pressure (approximately 5–15 bars, depending on the propane/butane mixture) simplifies tank design compared to cryogenic fuels like LNG or hydrogen. Personnel operating on LPG-powered gas carrier are required to comply with Personal Protective Equipment (PPE) requirements under the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code). Other vessel types planning to use LPG as fuel will be required to follow the International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels (IGF Code) (ITOPF, 2024e).

2.5.1 LPG Fate and Behavior

If LPG is released on or above the waterline, it will first float and spread (forming a shallow pool depending on the spilled quantity and/or low temperature/wind conditions) and begin to vaporize as it absorbs heat from the surrounding environment. Since LPG is insoluble in water, it will not mix into the water column. If the spilled LPG was liquefied from refrigeration, there may be temporary local ice formation at the point of release (ITOPF, 2024e).

The initial LPG vapor is denser than air and may travel downwind along the water before dissipating or potentially reaching an ignition source. Unlike LNG and hydrogen vapors, when the temperature of LPG increases due to ambient conditions, it will not become buoyant and disperse into the atmosphere. In low-wind conditions (<5 mph), LPG vapor clouds may remain concentrated and close to the water surface for prolonged periods, increasing the risk of delayed ignition. With higher wind speeds (>5 mph), the vapor cloud can be carried further but will dilute quicker due to the increased turbulent mixing with air. The presence of a visible cloud may not always occur, as condensation of water vapor is less pronounced compared to colder cryogenic fuels like hydrogen or LNG (ITOPF, 2024e).

When released underwater, LPG will rise to the surface due to its low specific gravity and quickly begin volatizing into the atmosphere. Flammable vapors in the vicinity of the spill can still occur with an underwater release. In confined or poorly ventilated areas, this presents a significant hazard but the risk decreases (yet remains present) in open-water environments (ITOPF, 2024e).

With an LPG spill, there is little chance of effective spill response beyond evacuation of personnel from the hazard area. There are some detection devices that may be adaptable to monitor the flammable vapor/air mixture near the spill source. The principal hazard with a LPG spill is its flammability, and the area near the leak source can be ignited by open flames, sparks, or hot surfaces. If ignited, the resulting fire may be intense but typically localized (ITOPF, 2024e). Compared to hydrogen, LPG has a narrower flammability range and higher ignition energy, which means it is less prone to accidental ignition but when ignited, it can cause rapid flame propagation and flash fires.

2.5.2 Knowledge Gaps

While the gas carrier industry has experience handling LPG as cargo, its expanded use as a marine fuel introduces new operational contexts that may involve different failure scenarios, ignition risks, and response needs. Continued research is warranted to understand these scenarios, especially in confined port areas or near populated coastal zones.

2.6 Biofuels

Biofuels[6] cover a wide range of fuels that are produced directly or indirectly from organic materials but this operational guide will focus on biodiesels, particularly Fatty Acid Methyl Esters (FAME) and Hydrotreated Vegetable Oil (HVO) due to currently available resources. They are produced from renewable feedstocks such as used cooking oils, vegetable oils, animal fats, and other waste oils. They offer a low-carbon alternative that can be integrated into the current fuel supply chain. These fuels are already in limited commercial use within the shipping industry, often blended with conventional marine gas oil (MGO).

Both FAME and HVO are colorless liquids, have low toxicity, and are stored and handled at ambient temperature and pressure, which simplifies logistics and bunkering when compared to alternative fuels like LNG, hydrogen, or ammonia that require cryogenic or pressurized systems. However, FAME’s tendency to absorb water and degrade over time means that storage tanks and fuel lines may require more frequent inspection and conditioning to maintain fuel quality, especially in humid environments. FAME may need to be heated to reduce viscosity prior to bunkering or other transfer operations. These issues are less pronounced with HVO, which has excellent storage stability and shelf life (ITOPF, 2024b).

The lower the proportion of biofuels added, the more likely the fuel will behave like a traditional MGO (ITOPF, 2024b). Their appeal lies in their compatibility with existing diesel engines, enabling a relatively straightforward transition with minimal modifications (ITOPF, 2024b). Several vessels are already operating on biodiesel blends, and there have been trials using 100% HVO carried out in various vessel types including ferries, research vessels, and tugs (Lloyd's Register, 2024b).

Among the two biodiesels, HVO is generally considered to be more advantegeous from an operational standpoint. It has a chemical composition and fuel behavior similar to petroleum diesel, allowing for it to act as a drop-in replacement without the need for engine or infrastructure adjustments. In contrast, FAME is more widely available and often less expensive, but it is less chemically stable and has poor cold flow properties. FAME is more prone to oxidative degradation, microbial growth, and fuel system clogging especially when stored for extended periods or exposed to moisture and temperature fluctuations. HVO does not have this issue because its processing method removes any oxygen content (ITOPF, 2024b).

While biofuels offer a viable decarbonization option in the near term, their long-term role remains uncertain due to supply limitations and increasing competition from other sectors such as aviation and land transport. The availability of sustainable feedstocks and variability in regulatory support may all influence their price and commercial viability within the shipping industry (Smith, et al., 2025).

2.6.1 Biofuels Fate and Behavior

When released on water, FAME and HVO will behave similarly to conventional diesel and will remain liquid at ambient conditions. They will spread into a slick and gradually undergo weathering process including biodegradation, oxidation, dissolution, and dispersion (Figure 11) but there are some key differences.

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[6] Some may consider LNG or methanol produced from biomass to be “biofuels”.

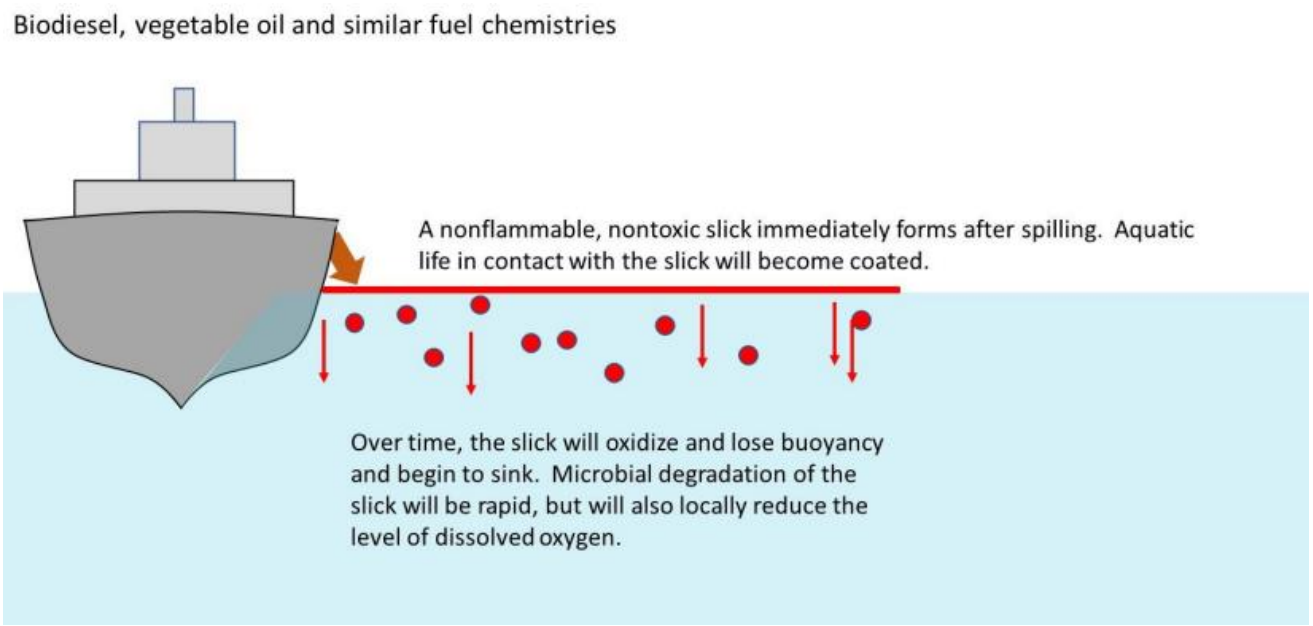

Figure 11. Expected fate and behavior of spilled biodiesels (Kass et al., 2021).

Studies show that biodiesels degrade approximately four times faster than conventional diesel but this depends on numerous factors including temperature, pH and nutrient, oxygen, and microbial availability (Kass et al., 2021). The rate at which biodiesel disperses depends on the meteorological and oceanographic (metocean) conditions at the time of the incident (e.g., tidal currents and wind-induced wave action) but overall studies show there is increased dispersibility compared to conventional diesel (ITOPF, 2024b).

Biodiesels will not mix with water since they are insoluble and unlike conventional fuels, pure biodiesel will not evaporate because of its low vapor pressure and will persist on the water surface longer. HVO is more resistant to oxidation and degradation than FAME. FAME, due to its polar nature, may interact more strongly with water, increasing the likelihood of forming stable emulsions that are more challenging to recover (ITOPF, 2024b).

If spilled in warm water (>10 °C), both FAME and HVO are likely to remain as low viscosity liquids, spreading over a large area to form a slick on the water’s surface under the influence of metocean conditions (ITOPF, 2024b). In cold water conditions (<10 °C), however, both biodiesels’ viscosities would increase, reducing the distance of surface spreading. HVO is likely to remain a liquid since the water temperature will still be above its pour point temperature but with FAME, it is likely to become semi-solid since its pour point temperature is within range of water temperatures in cold regions. ITOPF noted that when vegetable oils were spilled into waters with a temperature below their pour point, they solidified into balls, lumps, or discs up to 60 centimeters (cm) in diameter (ITOPF, 2024b). They remained near the point of release within the first 24 hours, and then broke into smaller pieces (<10 cm) forming small slicks. After 72 hours, the slicks break up into pea/rice-sized pieces scattered over a wide area. ITOPF expects pure biodiesels to behave in a similar manner (ITOPF, 2024b).

If spilled below the waterline, biofuels will rise to the surface due to their lower density and form surface slicks. While biofuels are more biodegradable compared to traditional fuel oils, large spills can still result in oxygen depletion and localized ecological harm, particularly in confined, low-energy environments where dilution and degradation rates are slower. FAME components may degrade more rapidly but also cause more initial disturbance due to slightly higher solubility and dispersion in water compared to HVO. If responders do not take mitigating action, biodiesels can remain in the environment on the order of weeks to months (ITOPF, 2024b).

Compared to other alternative fuels, safety risks associated with FAME and HVO are considerably lower in terms of handling and emergency response. Biodiesel spills will not form cold vapor clouds or rapidly expanding gas plumes, making them significantly less hazardous than LNG or hydrogen in terms of immediate flammability or explosivity. Flammability risk still exists but is generally limited to a very concentrated area near an ignition source due to their high flash points and low vapor pressures (ITOPF, 2024b).

2.6.2 Knowledge Gaps

Compared to traditional petroleum-based fuels, the environmental impacts of biofuels like FAME and HVO in marine settings are less documented. While biodegradability is generally higher, the specific behavior of biofuels in cold, saline environments or sensitive ecosystems is not well understood. A grounding incident causing a large-scale biofuel release may warrant targeted studies to assess localized harm and long-term recovery. Additionally, variability in biofuel composition, especially for FAME, can result in inconsistent performance and behavior, making standardization and regulatory guidance more difficult. Further research is needed to understand how different feedstocks, blends, and additives influence environmental fate, toxicity, and response measures.

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APPENDIX A. LIQUEFIED NATURAL GAS (LNG) QUICK RESPONSE GUIDE

A.1 Overview of Spill Characteristics, Properties, Behaviors, and Hazards

Table A-1, Table A-2, and Table A-3 provide a high-level overview of liquefied natural gas (LNG) spill characteristics, properties, behaviors, and hazards.

Table A-1. LNG spill characteristics (Kass et al., 2021).

Behavior when Spilled	Dissipation or Degradation Rate	Ecological Impacts	Flammable/ Explosion Risk	Toxicity	Air Displacement and Suffocation Risk	Spill Cleanup
Will form a cold cloud on the water surface	Fast	Marine life at the water surface in the spill zone may suffocate or become chilled	High	Low	Possible	Will dissipate before cleanup can begin

Table A-2. Summary of key LNG properties and behaviors (ITOPF, 2024d).

	Properties	Behavior
Chemical Composition	Usually >85% methane with small quantities of ethane, propane, butane, carbon dioxide and nitrogen	LNG properties vary slightly depending on the exact composition.
Boiling Point	-162 °C	At ambient conditions, LNG is a gas.
Liquid Specific Gravity (@ -162 °C)	0.415 - 0.450	LNG has less than half the density of water; therefore, as a liquid, LNG will float if spilled on water.
Vapor Specific Gravity (@ -106 °C)	1.5	The vapor is heavier than air when the vapor temperature is less than -106 °C, i.e., when LNG initially vaporizes.
Vapor Specific Gravity (@ ambient temp)	0.55 - 1.0	Vapors of LNG at ambient conditions are lighter than air (buoyant) and will easily disperse in open or well-ventilated areas.
Solubility	Insoluble	Liquid LNG will not mix with water (run-offs) or seawater.
Flammability Range	5 - 15 %volume per volume (v/v)	Outside of this range, the LNG/air vapor mixture is not flammable.

Table A-3. High-level overview of hazards associated with LNG (ITOPF, 2024g).

State		Longevity in the Environment	Toxicity to Humans	Health & Safety: Main Concerns	Protracted Response to Recover Pollutant
Under Ambient Conditions	During Transport				
Gas	Liquid (cryogenic)	Hours	Non-toxic	Significant risks linked to flammability, explosivity, asphyxiation, and cryogenic temperatures	Unlikely

A.2 Responder Safety Considerations

LNG vapors are highly flammable within a narrow range (5-15% by volume in air). Although vapor clouds disperse quickly in open areas, the zone near the spill may reach flammable concentrations. Ignition sources must be controlled or eliminated. Unconfined vapor clouds can ignite if the right concentration is reached, especially in low-lying or wind-affected areas. The flame is visible and burns cleanly.

Responders should always approach from upwind and remain outside the visible vapor cloud.

Principal hazards include:

- Flammability and explosion risk: Methane vapors can ignite in the flammable range; ignition sources must be eliminated.
- Cryogenic exposure: Direct contact with LNG can cause severe frostbite and embrittlement of materials
- Oxygen displacement and asphyxiation: High vapor concentrations can displace breathable air in confined or low-lying areas.

Personal Protective Equipment (PPE):

- Self-contained breathing apparatus (SCBA) must be used in areas with suspected high vapor concentrations due to the risk of asphyxiation.
- Thermal protective clothing and cryogenic gloves essential when operating near cold zones.
- Mandatory use of intrinsically safe equipment.

Personnel must be trained in recognizing symptoms of cryogenic exposure and oxygen deficiency.

A.3 Detection and Monitoring

Table A-4 shows how effective existing detection methodologies are for identifying LNG releases into seawater. Responders have the added challenge of deploying detecting and monitoring instruments into the field in a timely manner as the cloud vapor resulting from a release of liquid LNG into seawater quickly dissipates.

Table A-4. Summary of detection methodologies for LNG (Kass et al., 2021).

Visible	Radar	Infrared	Fluorescence	Chemical Analysis
Yes, will form a cold cloud on the water surface that will quickly dissipate	No	Potentially yes, depends on temperature reduction of ship and water surface	No	Yes, but only by sampling surface airspace

Visual indicators such as vapor clouds, frost on surfaces, and the sound of escaping gas can assist in initial identification. Technologies such as combustible gas indicators (CGIs) are used to measure the concentration of flammable vapors and help define hot, warm, and cold zones. Photoionization detectors (PIDs), commonly used for detecting volatile organic compounds (VOCs), are not effective for methane detection and should not be relied upon for LNG-specific response. Methane is better detected using catalytic bead sensors, infrared gas detectors, or methane-tuned electrochemical sensors that are intrinsically safe.

Multiple detectors should be positioned at various elevations to track vertical and horizontal movement of the vapor cloud. Remote sensing devices, such as Forward-Looking Infrared (FLIR) cameras, can visualize gas clouds that may not be easily seen. FLIR may be useful when other detection systems are unavailable.

Uncrewed aircraft systems (UAS) equipped with gas detection payloads can be deployed for plume modeling and monitoring over inaccessible or wide areas. Remotely operated vehicles (ROVs) with temperature sensors can be used underwater to detect localized temperature reductions associated with submerged LNG releases. Given the potential for UAS to act as ignition sources, all monitoring activities require careful coordination to establish a safe perimeter and effectively mitigate exposure.

A.4 Fire Fighting

LNG fires are classified as flammable gas fires and require a specialized approach. If a vapor cloud ignites, it may result in a flash fire, jet fire, or pool fire. Pool fires on water may occur when liquid LNG spreads and burns on the surface. These fires produce intense heat and can be prolonged if fuel supply is sustained.

The preferred strategy is to isolate the fuel source and allow the fire to burn out.

Concerns/considerations:

- Water should never be applied directly to LNG fires, as it accelerates vaporization and can intensify the fire.
- Fire suppression systems should include dry chemical agents (such as dry powder) suitable for gas fires.
- Apply water spray to cool surrounding equipment/structures/vessels to prevent heat damage or escalation.

A.5 Spill Response

Due to its volatile nature and rapid dissipation, traditional mechanical recovery methods such as absorbents, booms, and skimmers are ineffective. Response priorities focus on hazard isolation, public safety, vapor cloud monitoring, and environmental monitoring.

Response actions include the establishment of exclusion zones, rerouting of traffic, securing ignition sources, and air monitoring. Emergency responders should set up perimeter controls based on real-time gas concentration data, metocean conditions, and predictive modeling. Vapor cloud mapping can guide evacuation and inform dynamic risk assessments.

Cryogenic containment of the spill is not feasible in open water conditions. Any attempt to trap or retain the liquid phase may increase fire and explosion risk by promoting concentrated, rapid vaporization. Since the natural process of dissipation reduces these risks, containment efforts can be counterproductive. Although the spill footprint is typically small and short-lived, coordinated incident command is essential to manage secondary risks such as fire, infrastructure exposure, and public safety. Training and tabletop exercises are critical to ensure readiness.

A.6 Environmental Impacts

The environmental impact of LNG spills is generally considered low in persistence and toxicity, but acute effects may occur. The primary concern is localized oxygen displacement and thermal shock to aquatic organisms at the sea surface. Contact with the cryogenic liquid can cause rapid chilling and potential mortality in fish, plankton, and benthic organisms within the immediate spill zone.

Methane has low aquatic toxicity and limited solubility, reducing the potential for long-term contamination. Unlike oils or persistent biofuels, LNG does not leave a residue or sheen, and biodegradation is not a significant factor due to its rapid evaporation.

The physical effects of a spill, such as freezing of seawater and brittle failure of marine infrastructure, may cause secondary damage. Materials exposed to cryogenic temperatures, including steel pilings, dock structures, and piping, can experience thermal contraction and loss of integrity. Damage to facilities, vessels, or port equipment may occur if exposed directly to spilled LNG or fire.

Given the transient nature of LNG in the environment, restoration efforts are rarely needed. Post-incident assessments may be warranted to document ecological effects, infrastructure impacts, or to inform improvements to preparedness and risk mitigation protocols.

APPENDIX B. METHANOL QUICK RESPONSE GUIDE

B.1 Overview of Spill Characteristics, Properties, Behaviors, and Hazards

Table B-1, Table B-2, and Table B-3 provide a high-level overview of methanol spill characteristics, properties, behaviors, and hazards.

Table B-1. Methanol spill characteristics (Kass et al., 2021).

Behavior when Spilled	Dissipation or Degradation Rate	Ecological Impacts	Flammable / Explosion Risk	Toxicity	Air Displacement and Suffocation Risk To Crew	Spill Cleanup
Will rapidly spread out and dissolve into water	Fast	No long term impacts, but aquatic life in contact with spill may be poisoned	High	Yes, but limited to spill zone	Low	Will dissipate before cleanup can begin

Table B-2. Summary of key methanol properties and behaviors (ITOPF, 2024f).

	Properties	Behavior
Boiling Point	64.5 °C	At ambient conditions, methanol is a liquid.
Liquid Specific Gravity (@ 20 °C)	0.792	Methanol is less dense than water; therefore, as a liquid, methanol will float if spilled on water.
Vapor Specific Gravity (@ 20 °C)	1.1	Vapors of methanol at ambient conditions are denser than air and will spread above the ground/water surface when spilled.
Solubility	Fully miscible	Methanol has no limit to its solubility in water.
Flammability Range	6.0 - 36.5 (v/v) %	Outside of this range, the methanol/air vapor mixture is not flammable.
Flash Point	12 °C	Above this temperature, highly flammable methanol vapors are produced.

Table B-3. High-level overview of hazards associated with methanol (ITOPF, 2024g).

State		Longevity in the Environment	Toxicity to Humans	Health & Safety: Main Concerns	Protracted Response to Recover Pollutant
Under Ambient Conditions	During Transport				
Liquid	Liquid	Hours to days	Toxic (direct contact & inhalation of vapors)	Significant risks linked to toxicity and flammability	Unlikely

B.2 Responder Safety Considerations

Methanol presents several hazards to responders that differ significantly from cryogenic fuels such as LNG or hydrogen. The primary concerns are flammability, toxicity, and invisibility of the flame. Methanol has a wide flammable range (6 – 36.5% by volume in air) and a low flash point of 12 °C, which means it can ignite easily at ambient temperatures. Unlike some other fuels, methanol burns with a nearly invisible flame, making it difficult to identify burning areas without thermal imaging.

All ignition sources must be eliminated prior to response operations.

Personnel should operate from upwind positions and establish exclusion zones based on vapor detection readings.

Principal hazards include:

- Flammability: Methanol vapors ignite easily and can burn with little or no visible flame.
- Toxicity: Methanol is toxic by inhalation, ingestion, or skin absorption, and can cause systemic effects such as vision impairment and central nervous system depression.
- Vapor accumulation: Methanol vapors are slightly heavier than air and may accumulate in low-lying areas, increasing fire and exposure risks.

Personal Protective Equipment (PPE):

- Chemical-resistant suits and self-contained breathing apparatus (SCBA).
- Mandatory use of intrinsically safe equipment .

Responders should be trained to recognize symptoms of methanol exposure, which include headache, dizziness, nausea, and impaired vision.

B.3 Detection and Monitoring

Table B-4 shows how effective existing detection methodologies are for identifying methanol.

Table B-4. Summary of detection methodologies for methanol (Kass et al., 2021).

Visible	Radar	Infrared	Fluorescence	Chemical Analysis
No	No	No	No	Yes, but limited to spill zone

Detecting methanol releases requires equipment capable of identifying volatile organic compounds (VOCs). Photoionization detectors (PIDs) can detect methanol, but their effectiveness depends on the detector configuration. Standard 10.6 eV PID lamps may under-respond to methanol due to its relatively high ionization potential (~10.85 eV). For more accurate detection, PIDs should either be equipped with an 11.7 eV lamp (less common). While not ideal for precision measurement, PIDs are commonly used for general field screening.

Combustible gas indicators (CGIs) can help delineate flammable zones but may not capture methanol vapors. Thermal cameras are valuable tools for identifying methanol fires, which may otherwise be invisible. Fixed gas detection systems can be employed in facilities where methanol is stored or transferred.

Portable monitors should be used at multiple heights and positions to evaluate vapor distribution. Uncrewed aircraft systems (UAS) equipped with VOC sensors may assist in identifying the extent of vapor plumes over open areas or in difficult-to-access spaces. Visual observations should not be relied upon solely due to methanol's lack of color and flame visibility.

Continuous atmospheric monitoring is essential throughout the response. Detection data should inform the establishment of safe working perimeters and guide personnel movement in and out of the hazard area.

B.4 Fire Fighting

Methanol burns cleanly with little smoke and can be very difficult to see in low-light or open-water environments. Responders must verify extinguishment with thermal imaging.

Concerns/considerations:

- Firefighting operations involving methanol must account for the fuel’s low flash point and invisible flame.
- Use alcohol-resistant aqueous film-forming foam (AR-AFFF)
- Apply water spray to cool surrounding equipment/structures to reduce vapor formation but is not ideal for extinguishing the fire itself.
- Ventilation systems should be activated to disperse vapors, and all ignition sources, including electrical equipment, must be de-energized unless certified as intrinsically safe.
- Access to methanol safety data sheets (SDS) and pre-established firefighting protocols (e.g., Department of Transportation’s 2024 Emergency Response Guidebook, National Fire Protection Assocation Codes and standards) are essential for effective and safe operations.

B.5 Spill Response

Methanol is liquid at ambient temperature and spreads rapidly when spilled on water. Because of its complete solubility in water, containment and recovery are impractical. Traditional mechanical recovery methods such as absorbents, booms, and skimmers are ineffective. Response efforts must focus on hazard isolation, vapor suppression, and environmental protection.

Responders should implement exclusion zones and reroute vessel traffic. Water spray can be used to reduce vapor concentrations near the spill site. In confined areas, forced ventilation may be necessary to prevent vapor accumulation.

B.6 Environmental Impacts

Methanol is fully miscible in water and biodegrades readily under aerobic conditions. However, acute toxicity to aquatic organisms is possible at high concentrations. Spills in enclosed or low-energy marine environments can result in short-term effects on water quality and local biota.

Due to its solubility and volatility, methanol generally does not persist in the environment. It does not bioaccumulate and is not classified as a long-term environmental hazard. However, rapid dilution in open water may still lead to transient toxicity within the immediate spill zone.

Methanol has minimal impact on sediment and does not adhere to shorelines or accumulate in benthic habitats. Unlike oil spills, there is no visible residue, sheen, or physical fouling of surfaces. Remediation is typically not required once concentrations fall below environmental threshold values, but monitoring may be conducted to verify recovery.

Post-incident environmental assessments should document the affected area, concentration trends, and any observed impacts on aquatic life. Findings can be used to refine spill response protocols.

APPENDIX C. AMMONIA QUICK RESPONSE GUIDE

C.1 Overview of Spill Characteristics, Properties, Behaviors, and Hazards

Table C-1, Table C-2, and Table C-3 provide a high-level overview of ammonia spill characteristics, properties, behaviors, and hazards.

Table C-1. Ammonia spill characteristics (Kass et al., 2021).

Behavior when Spilled	Dissipation or Degradation Rate	Ecological impacts	Flammable /Explosion Risk	Toxicity	Air Displacement and Suffocation Risk to Crew	Spill Cleanup
Will partition into water forming a heated surface layer of ammonium hydroxide	Fast	No long term impacts, but marine life near the spill zone may be chemically burned and poisoned	Low	High	High	Will dissipate before cleanup can begin

Table C-2. Summary of key ammonia properties and behaviors (ITOPF, 2024a).

	Properties	Behavior
Boiling Point	-33.3 °C	At ambient conditions, ammonia is a gas.
Liquid Specific Gravity (@ -33 °C)	0.682	Ammonia is less dense than water; therefore, as a liquid, ammonia will float if spilled on water.
Vapor Specific Gravity (@ -33 °C)	>1.0	When ammonia initially vaporizes in the presence of water vapor, it will form a whiteish cloud denser than air above the ground/sea surface.
Vapor Specific Gravity (@ 20 °C)	0.597	Vapors of ammonia at ambient conditions are lighter than air (buoyant) and will easily disperse in open or well-ventilated areas.
Solubility (@ 20 °C)	529 kg/m^3	Ammonia is highly soluble in water.
Flammability Range	15.5 – 27.0 (v/v) %	Outside of this range, the ammonia/air vapor mixture is not flammable.

Table C-3. High-level overview of hazards associated with ammonia (ITOPF, 2024g).

State		Longevity in the Environment	Toxicity to Humans	Health & Safety: Main Concerns	Protracted Response to Recover Pollutant
Under Ambient Conditions	During Transport				
Gas	Liquid (pressurized and refrigerated)	Hours to days	Acutely toxic (vapors and upon direct contact)	Immediate risk in vicinity of substance, high toxicity with particular risk from vapors	Unlikely

C.2 Responder Safety Considerations

Ammonia poses a unique set of hazards due to its toxicity, corrosiveness, and ability to form hazardous vapor clouds. Unlike cryogenic fuels such as LNG or flammable liquids like methanol, ammonia is a toxic inhalation hazard and must be treated primarily as a chemical spill with both environmental and public safety implications.

Response teams should approach from upwind and remain outside the vapor cloud.

Visual indicators such as white vapor clouds and the pungent odor can assist in identifying affected areas, though odor is not a reliable exposure limit indicator.

Principal hazards include:

- Toxicity: Ammonia is highly toxic via inhalation, skin contact, and eye exposure. It can cause respiratory distress, burns, and in high concentrations, fatal pulmonary edema.
- Corrosiveness: Ammonia reacts with moisture to form ammonium hydroxide, a corrosive substance due to its basic (alkaline) nature that damages tissue and materials.
- Flammability: While less readily flammable than other fuels, ammonia can ignite in the 15.5 - 27% concentration range under specific conditions.
- Vapor hazard: Ammonia vapor is initially heavier than air but becomes buoyant with warming, spreading quickly in confined or poorly ventilated areas.

Personal Protective Equipment (PPE):

- Chemical-resistant suits and self-contained breathing apparatus (SCBA).
- Ammonia-resistant gloves.
- Mandatory use of intrinsically safe equipment.

Decontamination and medical support must be on standby due to the potential for chemical burns and respiratory injury. Response operations should prioritize evacuation, exposure limitation, and containment of further release.

C.3 Detection and Monitoring

Table C-4 shows how effective existing detection methodologies are for identifying ammonia.

Table C-4. Summary of detection methodologies for ammonia (Kass et al., 2021).

Visible	Radar	Infrared	Fluorescence	Chemical Analysis
Yes, will form a cold cloud on the water surface that will quickly dissipate	No	Potentially yes, depends on temperature reduction of ship and water surface	Unknown	Yes

Ammonia detection requires chemical-specific sensors capable of real-time air monitoring. Electrochemical detectors, portable gas monitors, and fixed sensor arrays are commonly used to identify hazardous concentrations. In the marine environment, detection efforts must be supplemented with visual observation of white clouds and deployment of personal monitors for all entry personnel.

Multi-gas meters may provide general atmospheric data but must include sensors calibrated specifically for ammonia. Photoionization detectors (PIDs) are not effective for detecting ammonia due to ammonia's high ionization potential and inorganic structure. They should not be relied upon for ammonia-specific response.

Uncrewed aircraft systems (UAS) equipped with gas detection or imaging sensors may support perimeter mapping and exclusion zone management, particularly in large or inaccessible areas.

Water monitoring is necessary in cases of aqueous release. Ammonia is highly soluble and reacts immediately with water to form a toxic, alkaline solution. pH sensors and ammonia-specific test kits can help determine concentration and spread in marine environments.

In confined areas such as storage tanks or port infrastructure, continuous monitoring and remote telemetry may be needed. All data collected should inform the establishment of hazard zones, responder positioning, and ventilation strategies.

C.4 Fire Fighting

While ammonia is not easily ignited, it can burn under specific conditions if concentrations are within the 15.5 - 27% flammable range. If a fire involving ammonia occurs, it is typically due to secondary ignition following release, as in the case of a pool fire or jet flame.

- Small ammonia fires – use dry chemical extinguishers.
- Large ammonia fires – Apply water spray to cool surrounding equipment/structures and suppress surrounding vapors.

Concerns/considerations:

- Foam is not effective.
- Water should not be applied directly to liquid ammonia spills due to increased vapor generation.
- Implement ventilation to disperse vapors in enclosed spaces. Coordination with facility operators is critical to shut down supply systems and prevent further leakage or escalation.

C.5 Spill Response

Spill response operations for ammonia focus on public safety, vapor suppression, and environmental protection. Because ammonia is highly soluble in water and toxic to aquatic organisms, immediate action is required to minimize spread and impact.

Traditional mechanical recovery methods such as absorbents, booms, and skimmers are ineffective. Instead, responders should isolate the source, implement exclusion zones, and use water spray to dilute and knock down vapors. Fixed or mobile water deluge systems can assist in vapor suppression during large-scale incidents.

In confined areas, positive-pressure ventilation may be required to maintain breathable conditions. Surface runoff must be controlled to avoid discharge into sensitive habitats, and any ammonia-contaminated water should be collected and neutralized where feasible.

Responders should notify appropriate environmental authorities and initiate water sampling protocols. Coordination with hazmat teams, port authorities, and public safety officials is necessary for effective containment and recovery planning.

C.6 Environmental Impacts

Ammonia spills in the marine environment can cause acute toxicity in aquatic life and damage to infrastructure. When released, ammonia dissolves readily in water, increasing pH and forming ammonium hydroxide, which is highly corrosive and toxic to gill-breathing organisms and plankton.

Localized fish kills and disruption of benthic ecosystems are possible in low-energy environments such as harbors and estuaries. In open water, ammonia dilutes more quickly, reducing its long-term persistence. However, the severity of immediate ecological effects depends on the volume released, metocean conditions, and temperature.

Ammonia does not bioaccumulate and is eventually assimilated into natural nitrogen cycles. Unlike oil or other hydrocarbons, it does not form persistent surface slicks or tar balls. However, infrastructure exposed to liquid ammonia or high vapor concentrations may experience material degradation due to corrosion or cryogenic damage.

Environmental monitoring should continue following containment to assess ammonia concentration, pH variation, and biological recovery. Post-spill assessments can inform future risk reduction strategies, emergency planning, and restoration activities where needed.

APPENDIX D. HYDROGEN QUICK RESPONSE GUIDE

D.1 Overview of Spill Characteristics, Properties, Behaviors, and Hazards

Table D-1, Table D-2, and Table D-3 provide a high-level overview of hydrogen spill characteristics, properties, behaviors, and hazards.

Table D-1. Hydrogen spill characteristics (Kass et al., 2021).

Behavior when Spilled	Dissipation or Degradation Rate	Ecological Impacts	Flammable / Explosion Risk	Toxicity	Air Displacement and Suffocation Risk to Crew	Spill Cleanup
Will form a cold cloud on the water surface	Fast	No long term impacts, but marine life at the water surface in the spill zone may suffocate or become chilled	High	Low	Possible	Will dissipate before cleanup can begin

Table D-2. Summary of key hydrogen properties and behaviors (ITOPF, 2024c).

	Properties	Behavior
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, liquid H_2 will float if spilled on water.
Gas Specific Gravity (@ -253 °C)	1.34	Saturated vapor is heavier than air and will remain close to the ground until the temperature rises.
Vapor Specific Gravity (@ ambient temp)	0.067	Vapors 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 (v/v) %	Hydrogen/air vapor mixture has an extremely large flammability range.

Table D-3. High-level overview of hazards associated with hydrogen (ITOPF, 2024g).

State		Longevity in the Environment	Toxicity to Humans	Health & Safety: Main Concerns	Protracted Response to Recover Pollutant
Under Ambient Conditions	During Transport				
Gas	Liquid (cryogenic), or pressurized gas	Hours	Non-toxic	Significant risks linked to flammability & explosivity	Unlikely

D.2 Responder Safety Considerations

Hydrogen, whether stored as a compressed gas or cryogenic liquid, presents hazards that require specialized response protocols. It is colorless, odorless, and burns with a nearly invisible flame, making detection and hazard recognition challenging during an incident.

Responders must conduct operations from upwind, with continuous atmospheric monitoring in place.

Responders should use flame detection systems or thermal cameras to locate active fire zones.

Principal hazards include:

- Flammability and explosion risk: Hydrogen has a very wide flammability range (4 - 75% by volume in air) and a very low ignition energy, making it prone to ignition from static discharge or minimal heat sources.
- Asphyxiation risk: High concentrations of hydrogen in enclosed or low-lying areas can displace oxygen and lead to suffocation.
- Cryogenic exposure (liquid hydrogen): Contact with liquid hydrogen or supercooled surfaces can result in severe frostbite and material embrittlement.
- Invisible flame hazard: Hydrogen flames emit little to no visible light, which may lead to accidental entry into burning zones.

Personal Protective Equipment (PPE):

- Thermal protective clothing and self-contained breathing apparatus (SCBA).
- Mandatory use of intrinsically safe equipment.

Training in hydrogen-specific hazards is essential, especially regarding safe approach techniques, early signs of cryogenic injury, and monitoring of confined spaces. First responders will need specialized training for responding to incidents involving hydrogen.

D.3 Detection and Monitoring

Table D-4 shows how effective existing detection methodologies are for identifying hydrogen.

Table D-4. Summary of detection methodologies for hydrogen (Kass et al., 2021).

Visible	Radar	Infrared	Fluorescence	Chemical Analysis
Yes, will form a cold cloud on the water surface that will quickly dissipate	No	Potentially yes, depends on temperature reduction of ship and water surface	No	Yes, but only by sampling surface airspace

Due to hydrogen's physical properties, detection relies heavily on gas-specific sensors and optical detection systems. Conventional gas detectors (e.g., catalytic bead sensors) are insufficient alone due to hydrogen's wide flammability range and low ignition threshold. Electrochemical and thermal conductivity sensors are better suited for hydrogen-specific monitoring.

Hydrogen flames are not visible in daylight and, while potentially more visible at night, may require ultraviolet/infrared (UV/IR) flame detectors or thermal imaging cameras to locate fires. Portable hydrogen detectors should be deployed at varying heights to identify accumulation zones, particularly in roof spaces or enclosures where hydrogen may rise and concentrate.

Continuous air monitoring is essential in enclosed or partially enclosed spaces. Uncrewed aircraft systems (UAS) equipped with thermal and gas sensors can support hazard zone mapping. All readings must be used to inform exclusion zones and safe approach strategies.

D.4 Fire Fighting

Hydrogen fires require both a passive and defensive approach. In most cases, the safest method is to isolate the fuel source and allow the hydrogen to burn off in a controlled manner. If the fuel flow can be stopped safely, the fire may self-extinguish.

- Small hydrogen fires – use dry chemical extinguishers.
- Large hydrogen fires – dry chemical extinguishers not typically effective. Apply water spray to cool surrounding equipment/structures but must not be directed at hydrogen leak source due to vapor cloud expansion risk.

Concerns/considerations:

- Responders must assume the flame is invisible unless confirmed extinguished via thermal imaging.
- Fire crews must maintain communication with command and use designated entry points monitored by safety officers.

D.5 Spill Response

Hydrogen spill response is primarily atmospheric in nature due to its gaseous state at ambient conditions. In the case of cryogenic hydrogen release, response must also address risks associated with extreme cold and potential for rapid phase transition.

Immediate actions include establishing exclusion zones, securing ignition sources, and conducting atmospheric monitoring to track plume movement. Since hydrogen rises rapidly, outdoor releases will typically disperse upward unless trapped under structures or within enclosed spaces.

In cases involving liquid hydrogen, responders should anticipate localized pooling and rapid vaporization upon contact with surfaces or seawater. This may generate pressure waves or physical damage due to rapid phase transitions.

Ventilation should be maximized in any structure that may trap gas. Indoor spills require immediate evacuation and atmospheric clearance verification before reentry. Emergency shutoff valves should be activated to prevent further fuel discharge.

Mechanical containment is not feasible. As hydrogen disperses quickly, response efforts should focus on risk isolation and hazard area control rather than fuel recovery.

D.6 Environmental Impacts

Hydrogen poses minimal long-term environmental impact. It is non-toxic, does not bioaccumulate, and reacts quickly in the atmosphere to form water vapor. There is no known adverse effect on aquatic ecosystems from gaseous hydrogen release.

In the event of a liquid hydrogen release into seawater, localized freezing and thermal shock may affect marine organisms, similar to the cryogenic hazards posed by LNG. However, due to the rapid vaporization and upward dispersion of hydrogen, the duration of environmental exposure is short.

The main environmental concern is the potential for fire or explosion, not chemical contamination. Infrastructure exposed to liquid hydrogen may experience structural damage due to cold embrittlement or pressure wave impacts from rapid expansion.

Environmental monitoring following an incident is generally limited to confirmation of system integrity and, if applicable, evaluation of infrastructure damage. Restoration actions are not likely to be required.

APPENDIX E. LIQUEFIED PETROLEUM GAS (LPG) QUICK RESPONSE GUIDE

E.1 Overview of Spill Characteristics, Properties, Behaviors, and Hazards

Table E-1, Table E-2, and Table E-3 and provide high-level overview of liquefied petroleum gas (LPG) spill characteristics, properties, behaviors, and hazards.

Table E-1. LPG spill characteristics.

Behavior when Spilled	Dissipation or Degradation Rate	Ecological Impacts	Flammable / Explosion Risk	Toxicity	Air Displacement and Suffocation Risk to Crew	Spill Cleanup
Will float but rapidly evaporate, forming flammable vapor cloud	Fast	No long term impacts, but aquatic life in contact with spill may be poisoned	High	Yes, but limited to spill zone	Low	Will dissipate before cleanup can begin

Table E-2. Summary of key LPG properties and behaviors (ITOPF, 2024e).

	Properties	Behavior
Chemical Composition	Primarily propane or butane, or a mixture of both. Can contain propylene of isobutane and butylenes.	LPG properties vary slightly depending on the exact composition.
Boiling Point	-42 °C	At ambient conditions, LPG is a gas.
Liquid Specific Gravity (@ -50 °C)	0.51 - 0.58	LPG has half the density of water; therefore, as a liquid, LPG will float if spilled on water.
Vapor Specific Gravity (@ -13 °C)	2.1	Vapors of LPG at low temperatures are twice the density of air and will spread above the ground/water surface when spilled.
Vapor Specific Gravity (@ ambient temp)	1.5	Vapors of LPG at ambient conditions remain denser than air and will spread above the ground/water surface when spilled.
Solubility	Insoluble	Liquid LPG will not mix with water (run-offs) or seawater.
Flammability Range	2.2 - 9.5 (v/v) %	Outside of this range, the LPG/air vapor mixture is not flammable.

Table E-3. High-level overview of hazards associated with LPG (ITOPF, 2024g).

State		Longevity in the Environment	Toxicity to Humans	Health & Safety: Main Concerns	Protracted Response to Recover Pollutant
Under Ambient Conditions	During Transport				
Gas	Liquid (pressurized and refrigerated)	Hours	Non-toxic	Significant risks linked to flammability, explosivity, asphyxiation, and extreme low temperatures	Unlikely

E.2 Responder Safety Considerations

Liquefied Petroleum Gas (LPG) typically consists of propane, butane, or a mixture of the two, stored under pressure as a liquid and vaporized upon release.

Responders must approach from upwind.

Vapor cloud behavior should be anticipated, and safe perimeters established quickly based on atmospheric monitoring and environmental conditions.

Principal hazards include:

- Flammability and explosion risk: LPG has a wide flammability range (2.2 – 9.5% by volume in air) and can form explosive vapor-air mixtures.
- Asphyxiation risk: LPG vapor is heavier than air and can accumulate in low-lying areas, displacing oxygen.
- Cryogenic exposure (when released as a refrigerated liquid): Contact can cause frostbite and material embrittlement.
- Vapor cloud formation: A dense, visible cloud can develop, spreading horizontally and posing ignition risks at a distance.

Personal Protective Equipment (PPE):

- Self-contained breathing apparatus (SCBA).
- Cryogenic-resistant gloves if cold LPG is involved.
- Mandatory use of intrinsically safe equipment.

Personnel must be trained to recognize LPG-specific hazards, particularly in enclosed or poorly ventilated areas where vapor accumulation can quickly reach explosive concentrations. Decontamination and emergency medical support should be available for cold burns and inhalation exposure.

E.3 Detection and Monitoring

Detection of LPG releases relies primarily on combustible gas indicators (CGIs) and infrared gas detectors. LPG vapors, being heavier than air, accumulate in depressions, engine rooms, and enclosed compartments, necessitating multi-level atmospheric monitoring.

Visible vapor clouds often accompany LPG releases under humid conditions. However, absence of a visible cloud should not imply safety. Portable gas detectors should be calibrated for propane or butane, depending on the specific LPG blend in use. Thermal imaging can assist in detecting cold vapor clouds, especially when visual confirmation is difficult.

Uncrewed aircraft systems (UAS) equipped with gas detectors can survey larger spills or inaccessible areas to assist in exclusion zone delineation. Continuous air monitoring during response operations is critical for responder safety and hazard management.

E.4 Fire Fighting

In the event of ignition, LPG fires are extremely intense and require careful tactical response. Unignited vapor clouds pose the highest risk and should be dispersed through controlled ventilation if safe to do so.

- Small LPG fires - use dry chemical extinguishers.
- Large LPG fires - Focus on protecting exposures and allow LPG to burn off under controlled conditions. Direct extinguishment without controlling the source may result in re-ignition or catastrophic vapor cloud explosions.

Concerns/considerations:

- Water spray may be used to cool adjacent structures and prevent escalation.
- Foam is not effective on LPG fires.
- Fire crews must remain aware of BLEVE (Boiling Liquid Expanding Vapor Explosion) potential if LPG containers are exposed to heat and should withdraw to safe distances if tank integrity cannot be assured.

E.5 Spill Response

LPG spill response focuses on vapor control, ignition prevention, and public safety. Mechanical containment of LPG liquid is generally not practical, as it rapidly vaporizes when exposed to ambient temperatures.

Exclusion zones must be established based on the predicted spread of the vapor cloud. All ignition sources within the potential flammable range must be eliminated. Portable and fixed gas detectors should be deployed to track cloud movement.

If vapor clouds are confined, controlled ventilation may assist dispersion. In open areas, natural dispersion aided by wind conditions will reduce fire and explosion risks.

E.6 Environmental Impacts

LPG releases generally pose low long-term environmental risk. As a volatile organic compound, LPG does not persist in water or soil, and evaporates quickly under most conditions.

In marine environments, spilled LPG will float on water as a cold, evaporating layer and will not dissolve well. Aquatic toxicity is considered low for short-term exposures; however, localized freezing at the water surface may cause temporary harm to marine organisms directly beneath the spill area.

Infrastructure exposed to cold LPG releases may suffer from cryogenic damage, including embrittlement of metals and concrete. Post-incident inspections should be conducted to assess structural integrity.

Long-term remediation is rarely required following an LPG release, although environmental monitoring and impact assessments may be needed to verify natural recovery.

APPENDIX F. BIOFUELS QUICK RESPONSE GUIDE

F.1 Overview of Spill Characteristics, Properties, Behaviors, and Hazards

Table F-1, Table F-2, and Table F-3 provide a high-level overview of biofuels spill characteristics, properties, behaviors, and hazards.

Table F-1. Biofuels spill characteristics (Kass et al., 2021).

Fuel Type	Behavior when Spilled	Dissipation or Degradation Rate	Ecological Impacts	Flammable / Explosion Risk	Toxicity	Air Displacement and Suffocation Risk to Crew	Spill Cleanup
Biodiesel	Will form a slick on the water surface	Moderate: Can take up to a week or more	Aquatic life may become coated	Low	Low	None	Boom containment is most optimal
HVO	Will behave as a diesel spill and rapidly spread out as a clear oily film	Moderate: Can take up to a week or more	No long term impacts are expected. Aquatic life may become coated	Low	Low	None	Boom containment is most optimal

Table F-2. Summary of key biodiesel (FAME and HVO) properties and behaviors (ITOPF, 2024b).

	FAME	HVO	Behavior
Boiling Point	182 - 338 °C	150 - 315 °C	At ambient conditions, biodiesels are liquid.
Specific Gravity (@ 15 °C)	≈0.89	0.78 - 0.79	Biodiesels are less dense than water; therefore, they will float if spilled on water.
Viscosity (@ 40 °C)	≈4.5 mm^2/sec	2.5 - 3.5 mm^2/sec	Biodiesels have a low viscosity at ambient temperatures.
Pour Point	-4 to 16 °C	-35 to -15 °C	Biodiesels, below these temperatures, will no longer be free flowing.
Solubility	Insoluble	Insoluble	Biodiesels will not dissolve in water (run-offs) or seawater.
Flash Point	>101 °C	>70 °C	Below these temperatures, biodiesels will not produce flammable vapors.

Table F-3. High-level overview of hazards associated with biofuels (ITOPF, 2024g).

State		Longevity in the Environment	Toxicity to Humans	Health & Safety: Main Concerns	Protracted Response to Recover Pollutant
Under Ambient Conditions	During Transport				
Liquid	Liquid	Weeks to months	Toxic (direct contact)	Low risk from initial exposure, toxicity poses a risk if exposed for extended periods	Likely

F.2 Responder Safety Considerations

Biofuels, specifically biodiesels such as FAME (Fatty Acid Methyl Esters) and HVO (Hydrotreated Vegetable Oil), present a different risk profile compared to cryogenic or highly flammable fuels. While they are less hazardous in many respects, they still pose important operational risks during spill incidents.

Principal hazards include:

- Flammability: Both FAME and HVO are combustible. HVO has a lower flash point, similar to conventional diesel, while FAME may have slightly higher flash points but can still ignite under the right conditions.
- Toxicity: Generally low compared to traditional petroleum fuels, but prolonged skin contact should still be avoided.
- Degradation risks: FAME in particular can degrade to produce acids and peroxides, which may complicate cleanup and increase health risks over time.

Personal Protective Equipment (PPE) will be necessary if vapors accumulate in confined spaces, especially during operations involving degraded biofuels:

- Self-contained breathing apparatus (SCBA).
- Chemical-resistant gloves and eye protection.

Decontamination procedures should be established for personnel who come into contact with spilled product. Responders must exercise caution on contaminated surfaces to prevent slips and falls.

F.3 Detection and Monitoring

Table F-4 shows how effective existing detection methodologies are for identifying biofuels.

Table F-4. Summary of detection methodologies for biofuels (Kass et al., 2021).

Fuel Type	Visible	Radar	Infrared	Fluorescence	Chemical Analysis
Biodiesel	Potentially yes	Yes	Potentially yes	Unknown	Yes
HVO	Possible if sheen is formed	No	Potentially yes	Unknown	Yes, but limited to spill zone

Detection and monitoring during a biodiesel spill are focused on identifying flammable atmospheres and assessing environmental impact. Combustible Gas Indicators (CGIs) may detect vapors if concentrations are sufficient, though biodiesel vapors are less volatile than lighter hydrocarbons.

Thermal imaging and infrared cameras are generally not required unless monitoring heated tanks or systems. Portable volatile organic compound (VOC) detectors can assist in enclosed spaces where vapor buildup could create hazardous atmospheres.

Visual inspections are essential to identify surface slicks and assess the extent of spread. Surface sampling and water quality testing may be necessary if the spill enters the marine environment, especially for detecting FAME emulsification.

Continuous air monitoring is less critical than for cryogenic fuels but should still be conducted if there is any suspicion of vapor accumulation, particularly in confined or low-ventilation spaces. The concern is lower in open-water environments.

F.4 Fire Fighting

Use same approach to fires involving biodiesel spills as conventional marine fuel fires.

Concerns/considerations:

- FAME fires:
    - Alcohol-Resistant Aqueous Film Forming Foam (AR-AFFF) is preferred due to its polar nature.
    - Can also be extinguished using standard firefighting techniques.
- HVO fires:
    - Can generally be suppressed with regular AFFF, dry chemical extinguishers, or standard firefighting techniques.
    - Water spray may be used to cool adjacent structures and suppress vapors.

F.5 Spill Response

Responders can primarily use mechanical recovery technique and strategies for biodiesel fuel spills. Absorbents, booms, and skimmers designed for oil spills are likely to be effective at containing and recovering both FAME and HVO from the water surface.

HVO behaves more predictably like a distillate fuel, floating cleanly and being more amenable to mechanical recovery using traditional oil spill response equipment. Since FAME can emulsify in water, spill responders should anticipate more challenging recovery operations compared to HVO or conventional diesel. Emulsified slicks may require skimmer modifications to improve recovery efficiency with more viscous fluids.

Exclusion zones are generally based on the extent of surface contamination rather than vapor hazard, except in confined areas where vapor monitoring should inform safe working distances.

F.6 Environmental Impacts

FAME is readily biodegradable, which can be beneficial but also cause rapid oxygen depletion in water bodies, leading to fish kills or other ecosystem impacts. Emulsification increases the surface area exposed to microbial degradation, accelerating these effects.

HVO behaves more like conventional diesel, floating on the water surface and remaining recoverable for longer periods. Its biodegradation is slower than FAME, reducing the risk of immediate oxygen depletion but increasing persistence if not promptly removed.

Both fuels have lower aquatic toxicity compared to conventional diesel. However, secondary effects from nutrient enrichment or oxygen depletion must be considered, especially in confined or low-energy environments.

Environmental monitoring following a biodiesel spill should include dissolved oxygen levels, chemical oxygen demand (COD) measurements, and tracking of visible surface contamination. Remediation is typically less intensive than for heavy oil spills but should be based on site-specific ecological sensitivity.