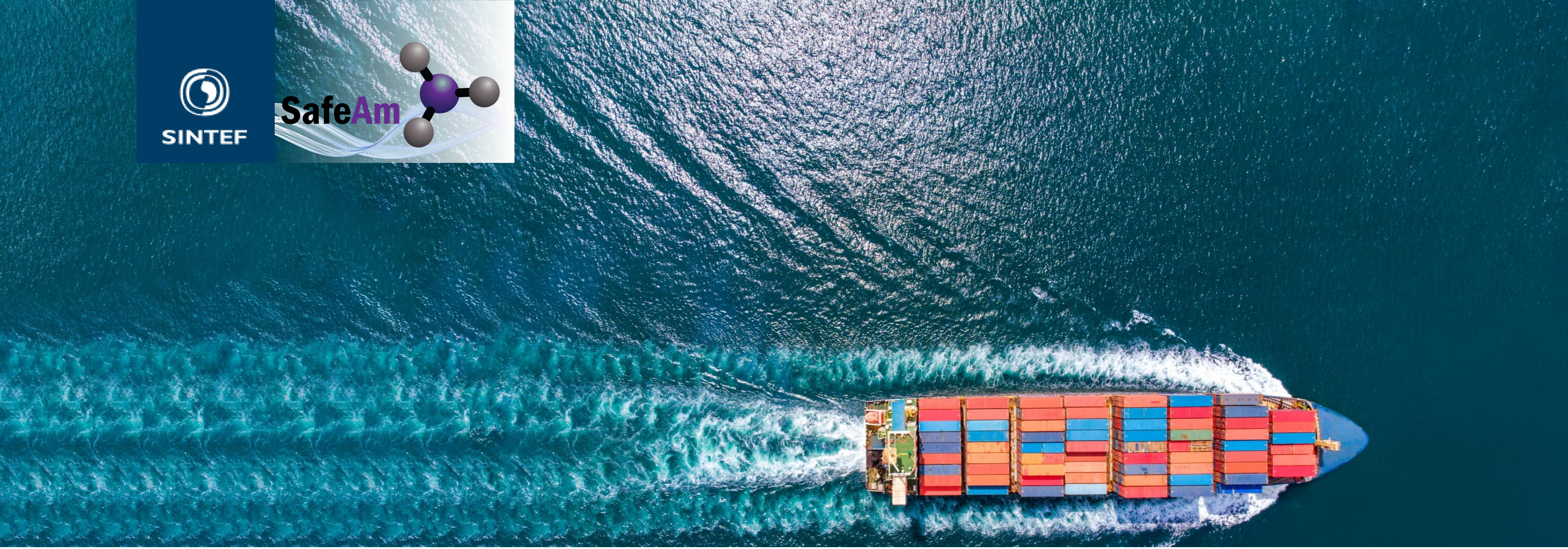

Safety Risk Management for ammonia fuelled ships

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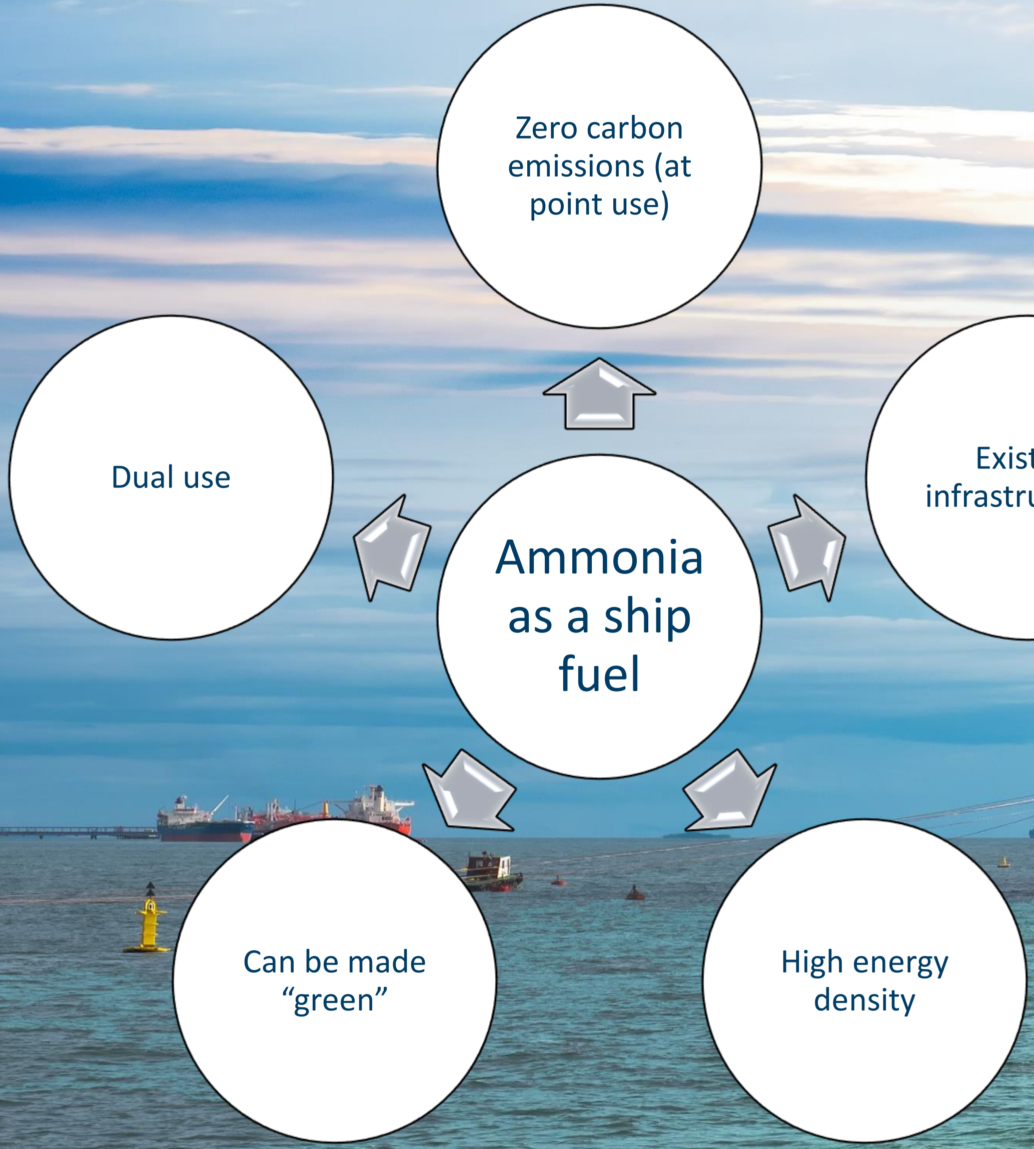
- **Over 90% of global trade** moves by sea.
- The sector emits **CO_2, NO_x, SO_x, and particulate matter (PM)**.

- Maritime emissions are **hard to decarbonize** due to long voyage distances, fuel weight, and limited refuelling infrastructure.
- **2–3% of global CO_2 emissions**—similar to a major country like Germany


Alternative fuels
CCS on board
Energy efficiency
Reducing emissions in shipping
Cold ironing
Operational measures
Teknologi for et bedre samfunn

Ammonia as alternative fuel for shipping and offshore power generation

Ammonia as hydrogen carrier



Fuel	Energy density (MJ/L)
Ammonia	12.7
Hydrogen (gas)	5.6
LNG	21
HFO	35

Ammonia challenges and risks

Challenge/Risk	Comment
Toxicity	Ammonia is highly toxic to humans and marine life (+ soluble in water). Releases could be dangerous and potentially life-threatening.
Flammability and Combustion	High ignition temperature, slow flame speed Laminar burning velocity: 0.07 m/s – vs. CH_4: 0.37 m/s
N_2O emissions	Incomplete combustion of ammonia can release nitrous oxide, a potent GHG
Corrosivity	Corrosive to certain materials
Bunkering readiness	Most ports are not equipped to refuel ammonia ships

Effect	Concentration
Immediately dangerous to life or health concentration (IDLH)	300 ppm (ref. NIOSH)
Fatal for humans	5000 – 10 000 ppm (ref. NIOSH)
Threat to marine life	Above 1700 mg/L (pH above 11, ref. ECHA)
Fatal for fish (*)	0.75 – 3.4 mg/L (ref. Thurston and Russo, 1983)

Methods

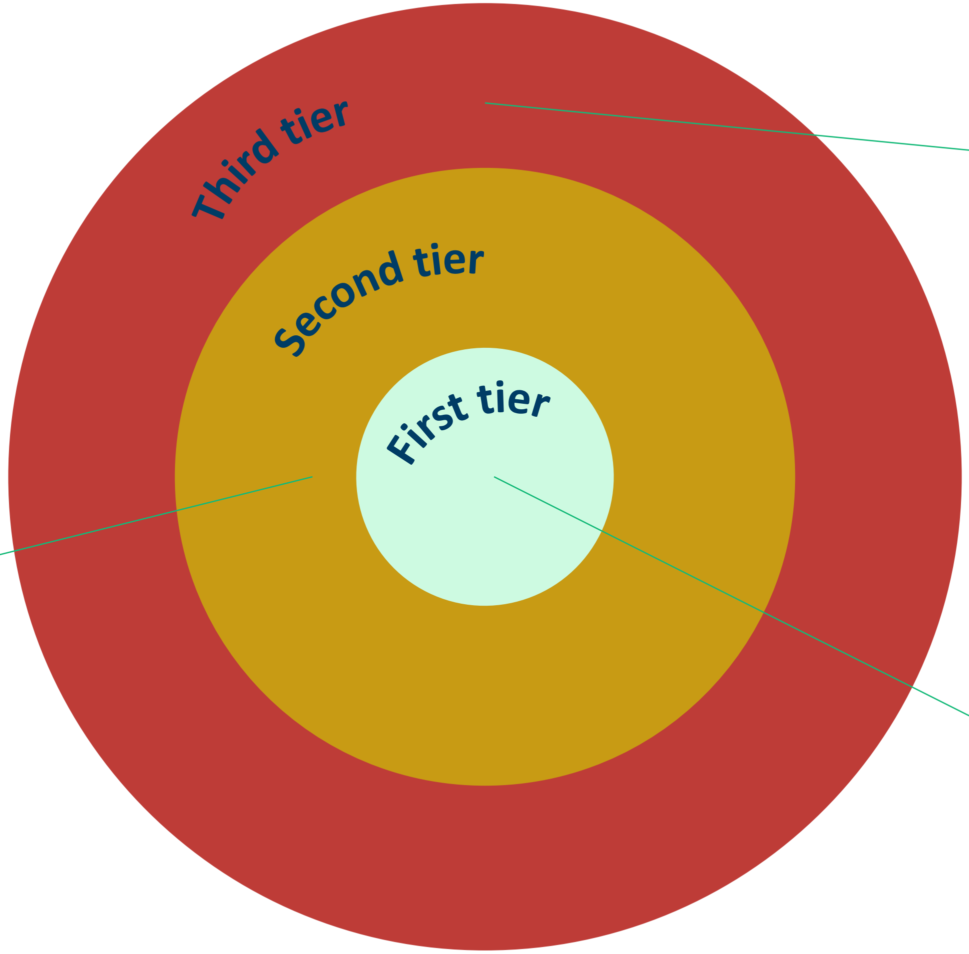
- Bibliographic literature review of past accidents involving **refrigerated liquid ammonia**.
- Both storage and transfer operations were considered.
- Different industrial domains, such as fertilizer industry, process industry and food industry, including also fishing vessels which use ammonia as a refrigerant are included in the investigation.
- The study focuses on storage conditions and operations that can provide valuable insight into the use of ammonia as ship fuel.

Two main challenges

Bunkering guidelines

Operational experience

Ammonia releases at sea



Third tier incidents

Catastrophic releases resulting in overboard leaks, including hose rupture

Second tier incidents

Medium and large releases of ammonia, potentially spreading beyond operational area and activating the emergency release system that might cause overboard spillage

First tier incidents

Flanges, connections

Contained within a specific area, *onboard*

Key safety aspect 1 – Material selection

- Ammonia is corrosive to certain materials
- Stainless steel (316SS) is usually considered suitable for use in presence of ammonia, as well as polypropylene (PP), polyethylene (PE) and Teflon (PTFE)
- Polycarbonate (PC) and nylon degrade fast
- Should be addressed for both new built and retrofit
- Effects that need investigation are:
  - Stress corrosion cracking
  - Corrosion under insulation

CHEMICAL COMPATIBILITY

CHEMICALS	METALS					PLASTICS, ELASTOMERS & LEATHER																			
A: Excellent, B: Good, C: Fair to Poor, D: Not recommended - No Data	Aluminum	Carbon Steel	Cast/Ductile Iron	304 Stainless Steel	316 Stainless Steel	Acetal	Buna	CSM (Hypalon)	EPR, EPDM	Fluorocarbon	Fluoroelastomer (FKM)	Geolast (Buna & Polypropylene)	Hastelloy C	TPE	Leather	Nitrile (TS)	Nitrile (TPE)	Nylon	Polychloroprene	Polypropylene	PTFE	PVDF	Santoprene (EPDM & Polypropylene)	UHMWPE	Urethane
Aluminum Chloride 20%	D	D	D	D	C	C	A	B	A	-	A	-	A	-	-	-	-	D	A	A	A	A	-	-	-
Aluminum Chlorohydroxide	D	D	D	D	-	-	-	-	-	-	-	-	-	-	-	-	-	A	-	-	A	-	-	-	-
Aluminum Fluoride	B	D	D	D	D	D	A	A	B	A	A	A	B	-	-	A	B	B	A	A	A	A	A	A	C
Aluminum Hydroxide	B	A	D	B	C	A	B	A	A	C	A	A	B	D	-	A	A	B	A	A	A	A	A	A	B
Aluminum Nitrate	D	-	D	A	A	B	A	A	A	A	A	A	B	-	-	A	A	B	A	A	A	A	A	A	C
Aluminum Phosphate	-	-	-	A	A	A	A	-	A	A	A	-	-	-	-	A	A	-	A	A	A	A	A	-	D
Aluminum Potassium Sulfate	C	D	D	D	B	C	A	A	A	A	A	A	C	D	-	A	A	D	A	A	A	A	A	A	D
Aluminum Potassium Sulfate 10%	C	D	D	A	A	C	A	A	A	-	A	-	C	-	-	-	-	D	A	A	A	B	-	-	-
Aluminum Sodium Sulfate (Soda Alum)	-	-	-	-	-	-	A	-	A	A	-	-	-	-	-	-	-	-	A	-	A	-	-	-	-
Aluminum Sulfate	C	D	D	B	B	B	A	A	A	A	A	A	B	B	A	A	A	A	A	A	A	A	A	A	B
Alums	A	D	D	-	A	-	A	-	A	-	D	A	B	D	-	-	-	A	B	A	A	A	-	-	-
Amines	B	D	D	A	A	D	D	D	C	D	D	D	B	D	D	D	D	D	D	B	A	-	A	A	D
Aminoethanol	-	-	-	-	-	D	-	-	-	-	-	-	-	-	-	-	-	A	-	A	A	C	-	-	-
Ammonia 10%	A	A	A	A	A	D	A	D	A	-	D	A	A	-	-	-	-	A	A	A	A	A	-	-	-
Ammonia Anhydrous	A	A	A	A	A	D	B	-	A	D	D	-	A	D	D	-	-	B	B	A	A	A	A	A	-
Ammonia Aqueous	-	-	-	-	-	B	-	-	-	-	-	-	-	-	-	-	-	B	-	A	A	A	-	A	-
Ammonia Gas — Cold	-	-	-	-	-	-	A	-	-	A	-	-	-	-	-	-	-	-	A	-	A	-	A	A	-
Ammonia Gas — Hot	-	-	-	-	-	-	C	-	-	D	-	-	-	-	-	-	-	-	B	-	A	-	A	A	-
Ammonia Liquids	D	-	A	A	-	D	-	-	A	-	D	-	B	-	-	B	B	-	A	A	A	A	A	D	B
Ammonia Liquors	A	-	A	A	-	-	-	-	-	D	-	-	-	-	-	-	-	-	A	-	A	-	A	-	-
Ammonia Nitrate	C	A	A	A	A	C	C	D	A	-	D	D	B	-	-	A	A	D	C	A	A	A	A	-	B
Ammonia, anhydrous	B	A	D	B	A	D	C	D	A	-	D	D	B	D	-	B	B	B	A	A	A	D	A	A	-
Ammonia, Gas (Cold)	-	-	-	-	-	A	A	-	A	-	D	-	-	D	-	A	B	-	A	B	A	D	A	-	B
Ammonia, Gas (Hot)	-	-	-	-	-	-	C	-	-	-	D	-	-	-	-	-	-	-	B	-	A	-	-	-	-
Ammonia, Liquids	D	-	A	-	A	-	B	-	-	-	D	-	B	-	-	-	-	B	A	A	A	A	-	-	-
Ammonia, Water	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Ammonium Acetate	B	-	A	B	A	C	B	-	A	A	A	B	-	D	-	A	A	A	A	A	A	-	A	A	D
Ammonium Bicarbonate	B	-	B	-	-	-	A	-	B	A	D	-	-	-	-	A	B	-	A	-	A	-	B	A	C
Ammonium Bifluoride	D	D	D	D	B	D	B	-	A	-	A	B	B	-	-	A	A	-	D	A	A	A	A	-	D
Ammonium Carbonate	C	B	C	B	B	D	D	-	B	A	B	D	B	-	A	B	C	A	B	A	A	A	A	A	A
Ammonium Casenite	-	-	-	A	A	D	-	-	-	-	-	-	-	-	-	-	-	-	A	-	A	-	A	-	-
Ammonium Chloride	D	D	D	C	C	D	B	A	A	A	A	B	D	A	-	-	-	C	B	A	A	A	A	A	-
Ammonium Chloride 1%	C	-	D	C	-	A	-	-	A	-	A	-	A	A	-	B	A	-	A	A	A	A	A	A	B
Ammonium Cupric Sulfate	-	-	-	-	-	-	A	-	-	A	-	-	-	-	-	-	-	-	-	-	A	-	-	-	-

Key safety aspect 2 – Equipment integrity & Maintenance

- Ammonia has been handled as a chemical for decades
- Inspection and maintenance to detect and assess potential stress corrosion cracking and/or corrosion under insulation
- Risk based maintenance and inspection
- Protocols, procedure and training for maintenance to ensure both integrity and to limit exposure to ammonia gas during inspection
- Cold spill protection
- Efficient and reliable leakage detection system

Key safety aspect 3 – Gas detection

- Ammonia detection is crucial for safety
- The gas detection system should be part of the leakage detection system coupled with low temperature measurements and other operational monitoring tools (T, P)
- **Fixed gas detectors** for emergency ventilation control and machine shut down
  - **Electrochemical sensors**
  - **Infrared and catalytic sensors** more accurate to detect ammonia gas
- **Portable gas monitors** (handheld by the crew) for maintenance and emergency response
- Sensors should be placed and calibrated to ensure safety

Key safety aspect 4 – Storage location

- The fate of ammonia upon release depends on the location of the storage tank
- Hull-located tanks are **less prone** to catastrophic release scenarios upon collision than deck-mounted tanks (Masia et all, 2024)

Key safety aspect 5 – Effect distances

- Consideration should be given to whether the ammonia release will impact trained and equipped operators or third parties and members of the **public**.
- Several stakeholders may be involved in the case of refuelling operations at ports. Risk analysis and quantification can support the identification of access-controlled zones.

Hazardous zones	Areas where ammonia leaks could occur, requiring gas detection systems and emergency response plans
Bunkering zones	Specific locations for ammonia transfer in maritime applications, with strict operational guidelines
Ventilation and dispersion areas	Proper airflow management is crucial to prevent ammonia accumulation and ensure safe working conditions

Key safety aspect 6 – PPE

- Different PPE should be planned for operations, maintenance and emergency response, based on the type and amount of potential exposure to ammonia.
- Consideration should be given to toxic inhalation protection, thermal protection (cold spills and fire) and protection from corrosive burns

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Key safety aspect 7 – Emergency preparedness

- Emergency Response Plans needs to be adequate for response to ammonia due to its toxicity
- Containment and spill response to prevent spread of vapours
- Ensure proper handling and reporting of accidents
- First aid measures to mitigate and control immediate exposure of first responders and public
- Evacuation procedures with clear evacuation routes and assembly points to ensure personnel and public safety
- Training

Key safety aspect 8 – Regulations and certifications

International Convention for the Safety of Life at Sea (SOLAS)

- •Regulations regarding fuel oils are prescriptive and based on decades of experiences
- •Low Flashpoint fuels (flash point below 60 degC) has been prohibited to prevent tank explosion and fires
- •SOLAS convention was amended to allow the use of gases or low flashpoint fuels for ships complying with IGF Code

IGF Code - International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels

- •The IGF Code requires that the safety, reliability, and dependability of the systems shall be equivalent to that achieved by new and comparable conventional oil-fueled main and auxiliary machinery.
- •It is emphasized that operational procedures shall not replace safety barriers through the ship design.
- •Specifies a set of functional requirements applicable for all fuel types covered by the Code, but only contains specific design requirements to LNG.
- •Until fuel specific regulations are in place, approval of ship is based on alternative design approach

IGC Code

- •Standard for safe carriage in bulk of liquefied gases by ships
- •Includes a chapter on use of cargo as a fuel but does not include ammonia (or other toxic products)
- •The IGC requirements cad provide useful guidance to the design of fuel storage systems for ammonia (since ammonia is transported in large quantities in gas carriers)

Class Rules

- •Set of rules for the use of a fuel not included in IGF code
- •Ammonia class rules exists from 2021 but are at different detail level and not proven

Key safety aspect 9 – Environmental damage

- Ammonia effects to fish and marine life should be understood:
  - Immediate effect
  - Accumulation and bioaccumulation
  - Reduced biodiversity
- From ARIA, around **10%** of accidents recorded from the 1950s to 2020s resulted in environmental damage

Simon Gant's contribution to this work was funded by the Health and Safety Executive (HSE). The contents of this presentation, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE policy

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