Ammonia as Marine Fuel and Its Mitigation Strategy

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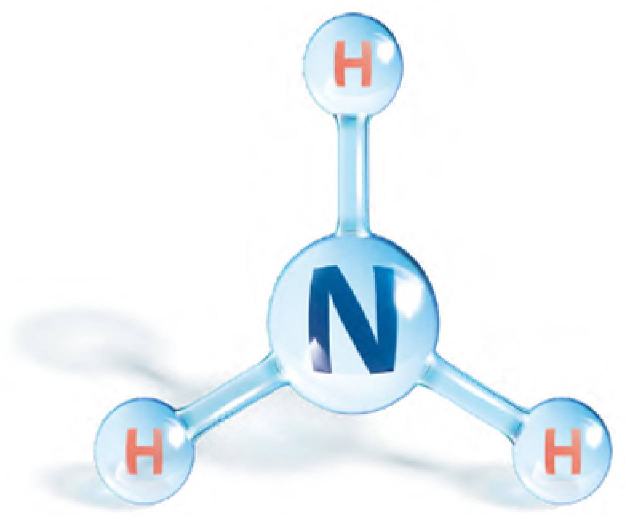
MESD Seminar 2025
24 Nov 2025

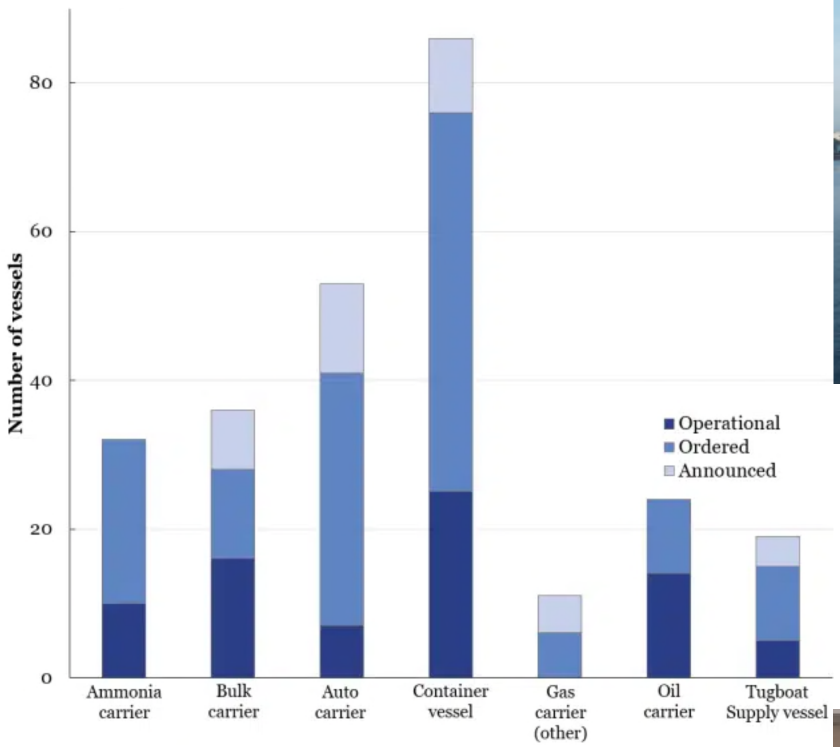
Outline

1. Ammonia as Future Bunker Fuel
2. Safety Aspects of Ammonia
3. Ammonia Loss of Containment Onboard
4. Mitigating Ammonia LOC
5. Field Experiment
6. MESD Innovations
7. Key Insights



Ammonia as Future Bunker Fuel

- Carbon-free fuel with reasonable energy density & mature supply chain.
- **>450 ammonia-ready vessels** have been in order and announced (Sept ’25).
- **Three bunkering trials** have been performed: Green Pioneer in Singapore (Early 2024), GCMD trial in West Australia (Late 2024), Rotterdam (April 2025)



Source: Ammonia Energy Association

Source: Fortescue

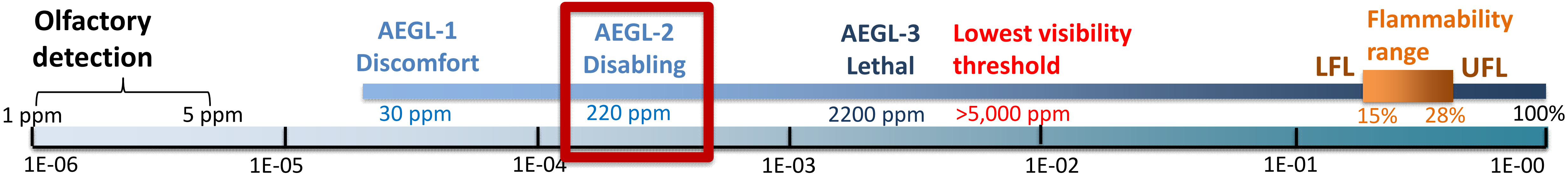
Source: BunkerMarket.com

Source: YARA Clean Ammonia

- **Safety** remains one of gaps to be fully addressed:
  - How ***ammonia disperse*** under realistic release conditions
  - ***Mitigations*** and ***Strategy of Mitigation***

Safety Aspects of Ammonia

- Ammonia is hazardous primarily due to its **low toxicity threshold**.
- Ammonia vaporization entails **volume expansion** ~800 times of its liquid form, even during discharge phase → propensity of forming relatively **fast-moving two-phase cloud**.



Example of **'cold' ammonia release** (ammonia pipeline damage in Donbass Region, Ukraine, Oct '25)

Source: Ministry of Defense, Russian Federation

"The ammonia residues dissolve very quickly in the air — ammonia is a very light gas. This pipeline no longer transports ammonia directly; there are only traces left from many years ago. They will dissipate into the air — people may briefly notice a slight unpleasant odor, but that would occur only at the moment of the leak. The farther from the rupture site, the lower the ammonia concentration," the professor explained.

Note that dense ammonia two-phase cloud is **heavier than air** and can be **persistent**

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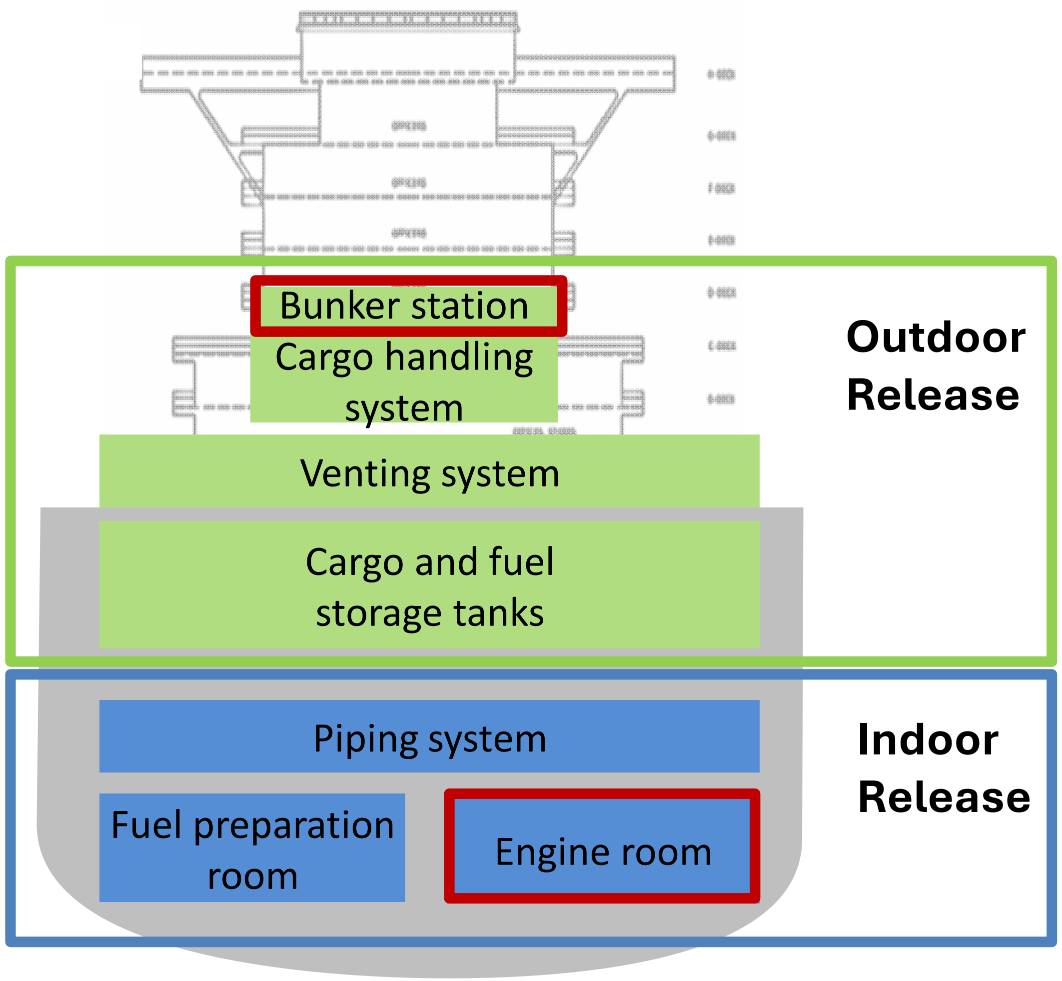
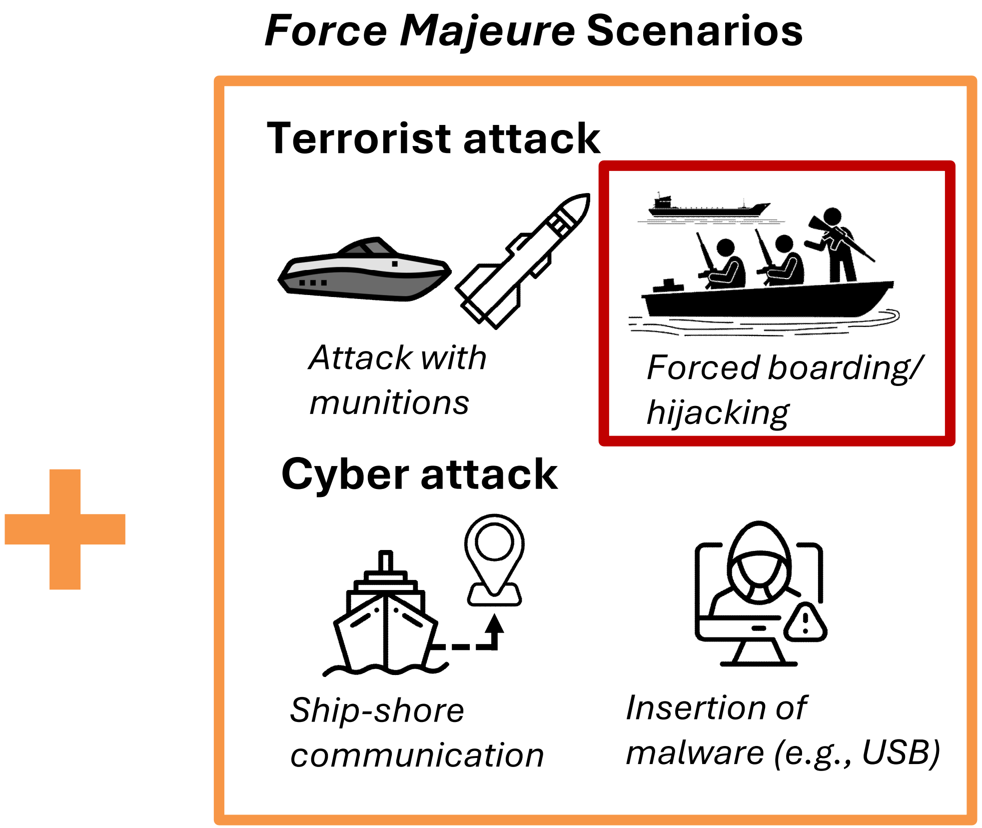
Loss of containment (LOC) of ammonia onboard

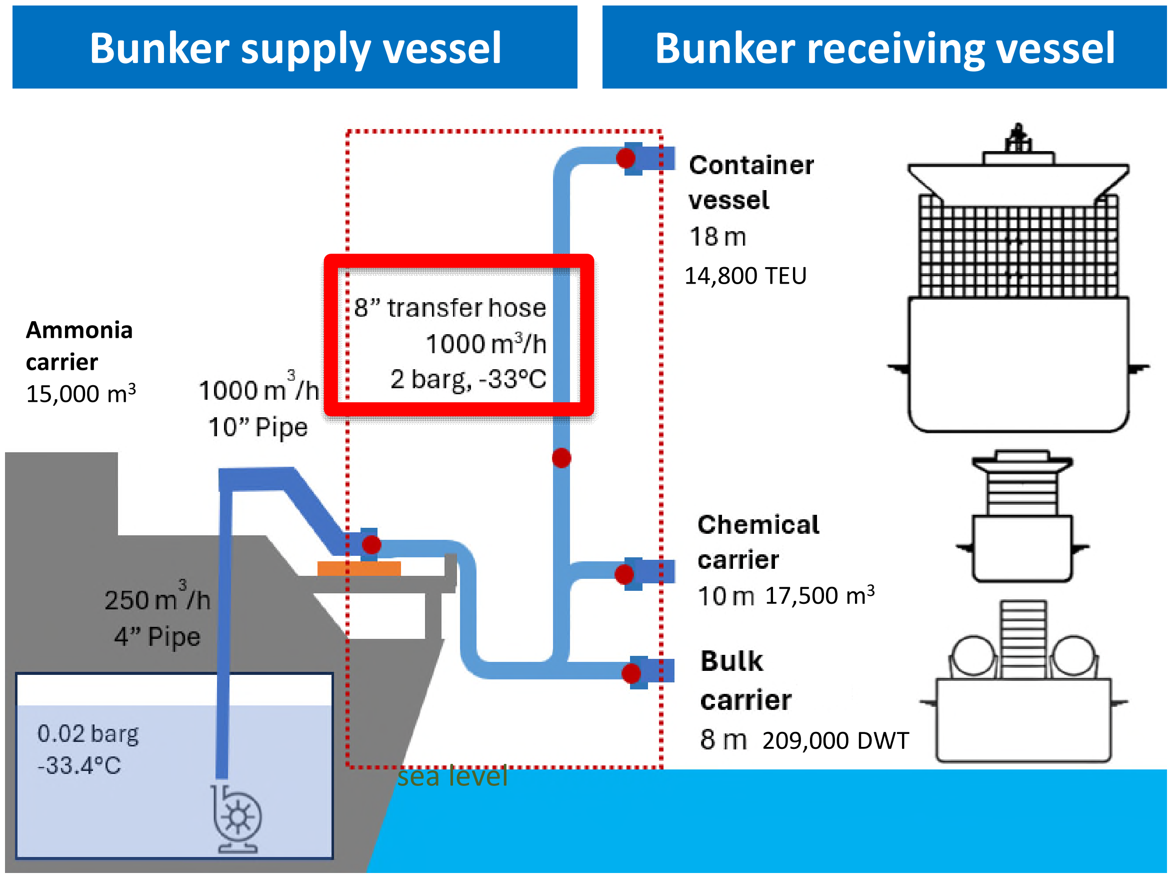
Understanding of accidental ammonia release occurring onboard ammonia fueled/carrying ships is **indispensable**





- Ammonia dispersion strongly depends on its **condition in containment (pressure & temperature)**.
- Due to diversity of ammonia phase in containment onboard, each case poses different risk levels.

LOC Scenario 1: Outdoor - Bunker station

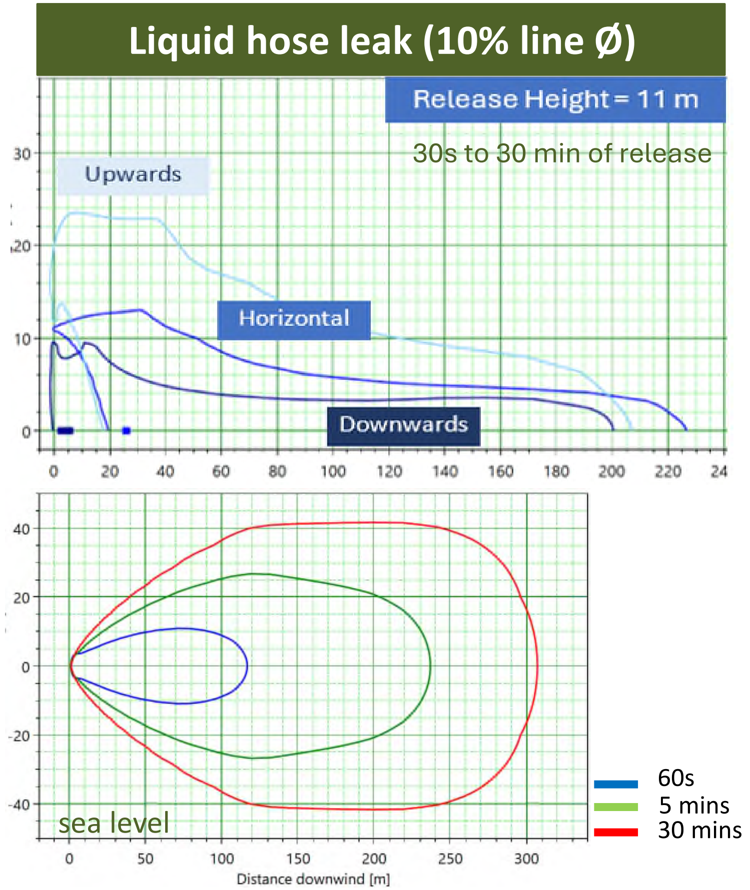


Ammonia bunkering is performed at **refrigerated-subcooled condition**

220 ppm cloud side view

3% lethality footprint top view
Direction: ↓
Height: 11 m

Lethality footprints increases with release duration

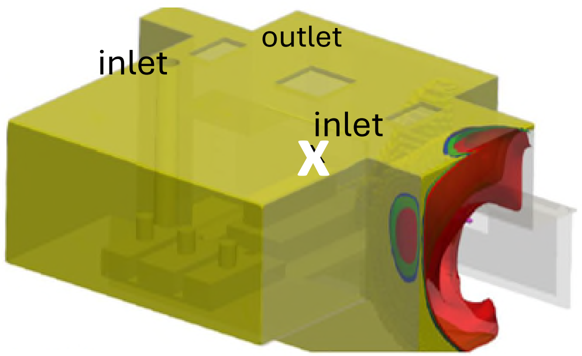


- Heavy cloud immediately onto surface level
- Cloud below 220 ppm: < 10 min after release ends.
- Rainout pool > 3m from release point, fully depleted in 1-2 mins
- Lethality footprint on sea surface: < 350m

LOC Scenario 2: Indoor – Engine Room

Bunker Vessel (4-stroke), Main Fuel Line

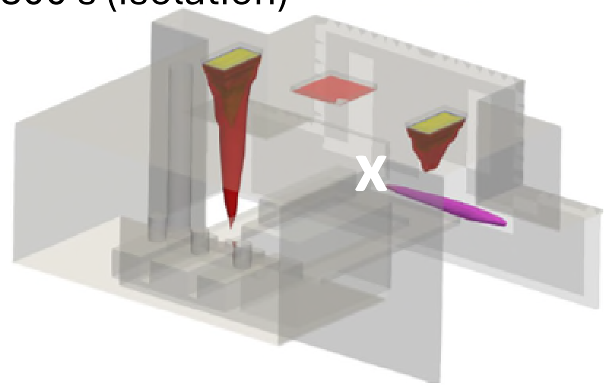
10 s



Superheated vapor, 45 °C, 6 barg, flow rate in pipe ~0.6 kg/s

Ventilation rate 30 ACH

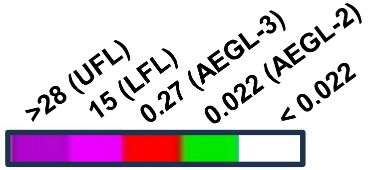
300 s (isolation)



Time for cloud to decrease below AEGL-2: 20-30 min

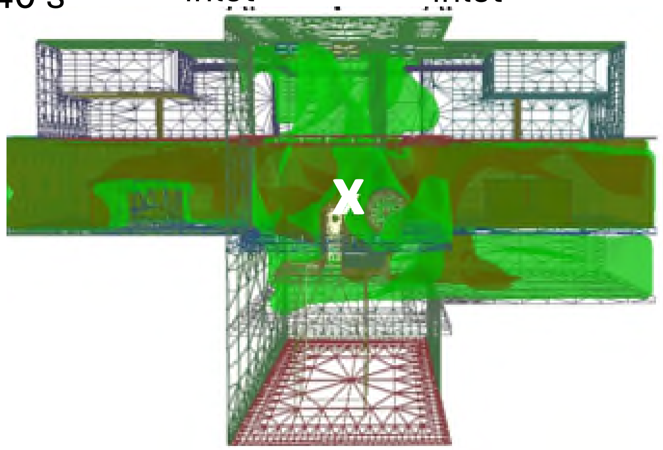
Very rapid propagation, but **'quick' dissipation**

3D drawing generated from vessel general arrangement provided by PaxOcean



Container Ship (2-stroke), Main Fuel Line

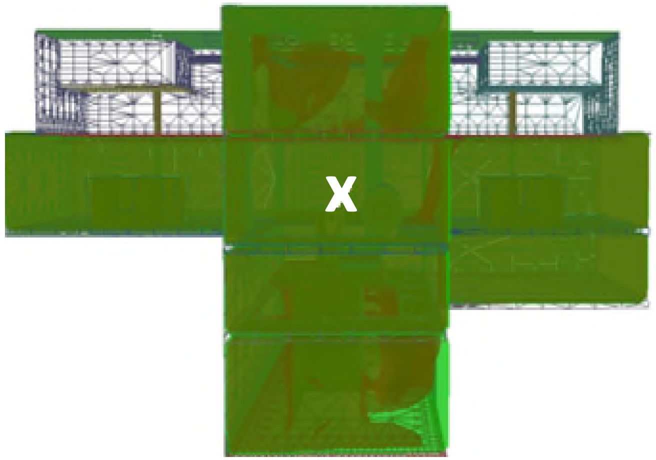
40 s



Subcooled liquid, 30°C, 80 barg, flow rate in pipe 7.6 kg/s (before injection)

Ventilation rate 30 ACH, drip tray no drainage

300 s (isolation)



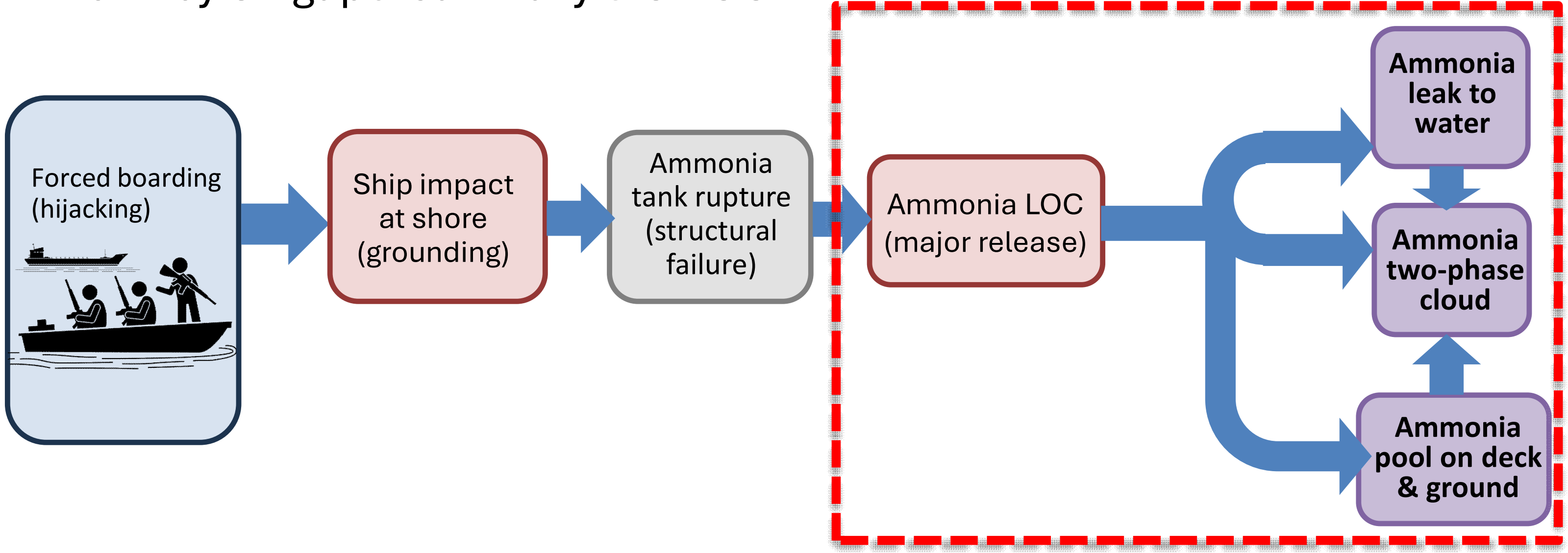
Time for cloud to decrease below AEGL-2: >1 hr

Rapid propagation, but **very lengthy dissipation**

LOC Scenario 3: Terrorist Attack

Scenario is based on **Operation Highcrest** in 2021 by Singaporean Navy & SMCC

Source: Ministry of Defense, SG



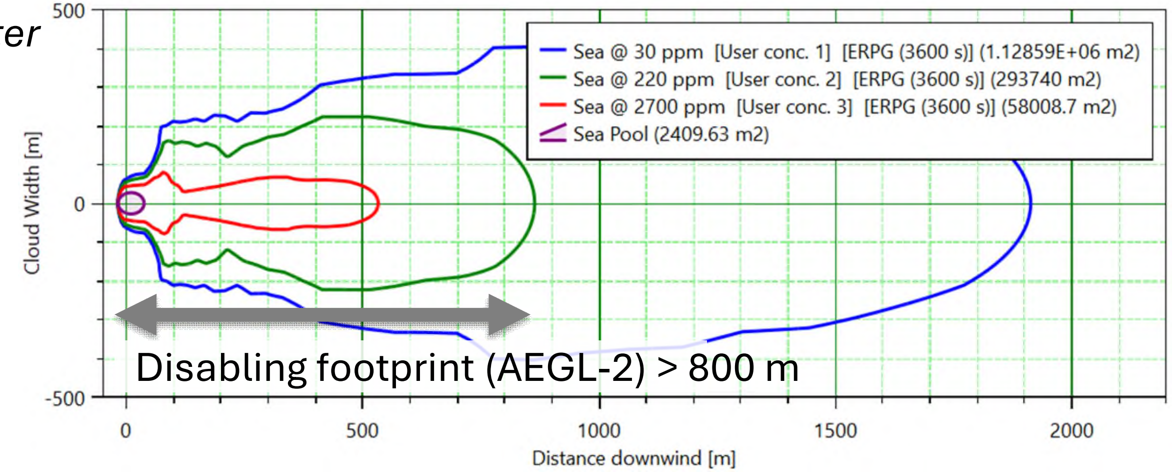
Consequences from forced grounding of Ammonia Carrier (capacity: 15,000 m^3)

Refrigerated ammonia spill in seawater

Source: Manifold News

Ammonia cloud from interaction w/ water

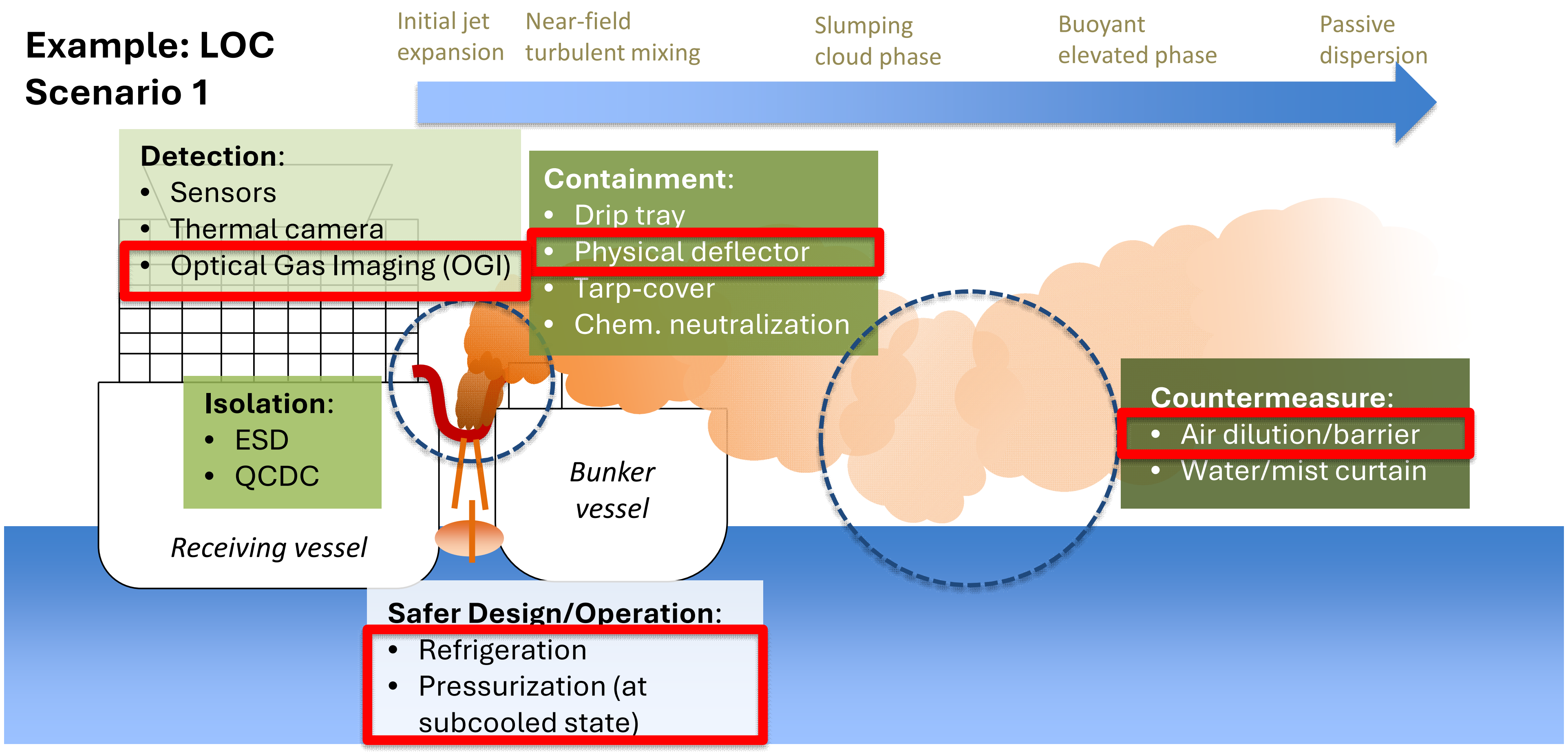
Mejillones Port, Chile (2016)



Mitigating Ammonia LOC

- “Mitigation” encompasses aspects from LOC prevention, to avoidance of ammonia cloud from reaching sensitive receptors.
- Keys: **(1) Reduce incidence, (2) Reduce airborne cloud quantity, (3) Increase lighter-than-air vapor proportion**
- Due to this complexity, **no single “silver bullet”** that can work as the only mitigation measure.

Inherently safer design/operation
↓
Release detection
↓
Release Isolation
↓
Containment (within release proximity)
↓
Countermeasure (beyond release proximity)



Mitigations highlighted are chosen for experimental testing

Ammonia release field experiment @Fort Ord, USA

Aim: (1) To understand **ammonia cloud dispersion behaviour** under realistic ammonia containment conditions and LOC
(2) Testing **mitigation measures** against the released ammonia cloud.

Ammonia release field experiment in Oct 2024 at Military Operations on Urban Terrain (MOUT) site, California, USA.

Release on land
Incl. state of pressurization

Release in water

Release on water surface

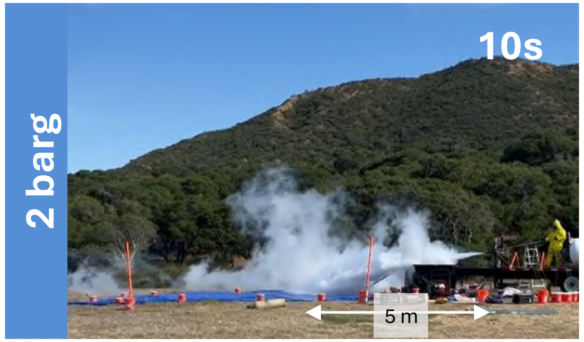
Mitigation measures:

High-powered fan

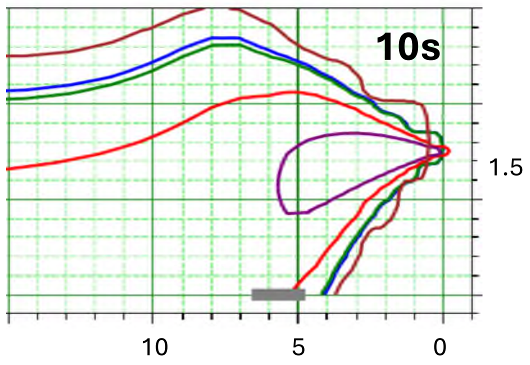
Physical deflector

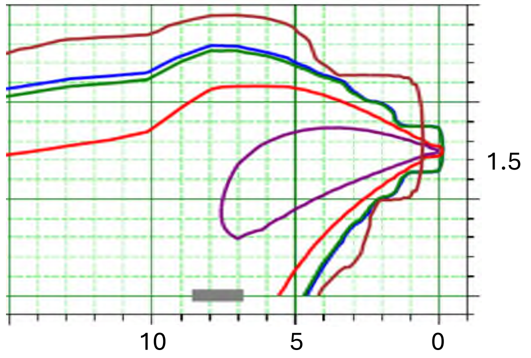
Results of release field experiment

Visible light

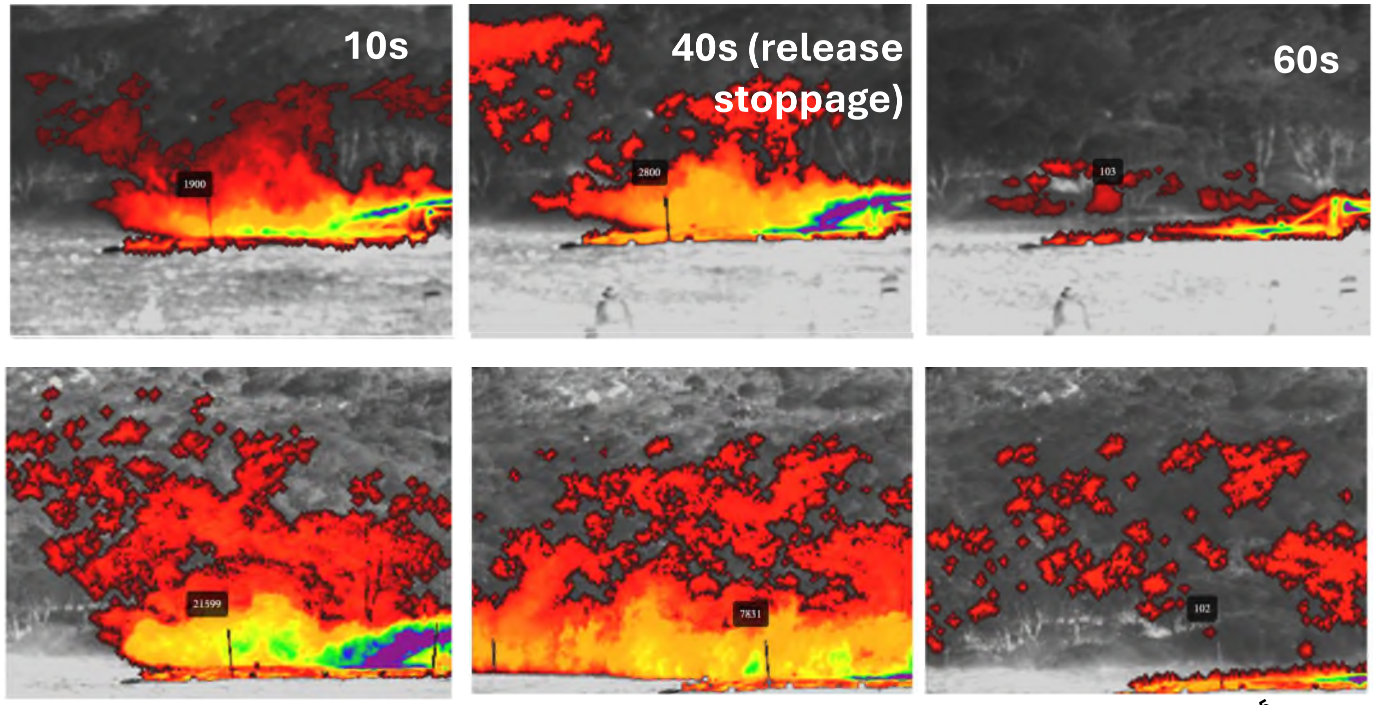


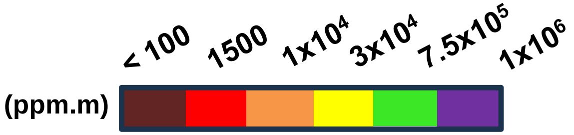
Simulation (PHAST)





Optical Gas Imaging (OGI)





- Model prediction of ammonia rainout pool agrees well with experimental results.
- Column concentration 2700ppm.m does not extend beyond 20m. Concentration falls quickly once release ends.
- **Higher release pressure projects the cloud further forward**.
- **Larger, denser cloud formed at higher pressure**.
- **Lesson learned:** sufficient ammonia release scale ensures cloud to be more measurable (longer duration in air).

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Results of release field experiment

- Water body can be protective layer against ammonia cloud release.
- **Inherently safer design – storing & bunkering ammonia below water surface**.
- Proposed concepts have been put forward in literature e.g., LNG storage.
- Safety evaluation: will ammonia still emerge at water surface in LOC?

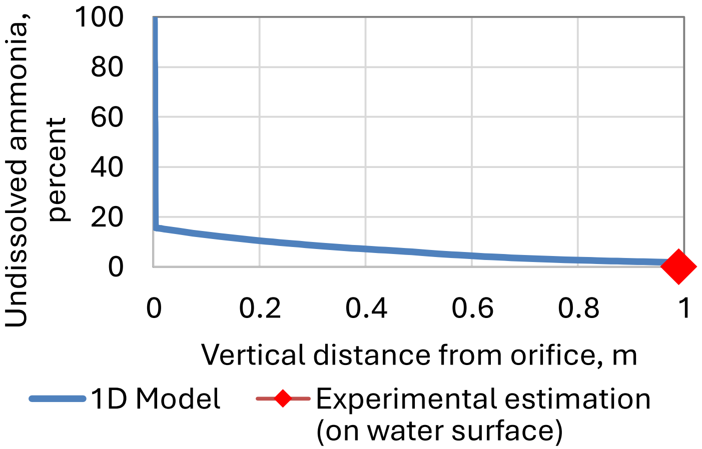
NOV takes to the floor for subsea storage

Large-scale testing planned for SSU technology that could replace floating production vessels

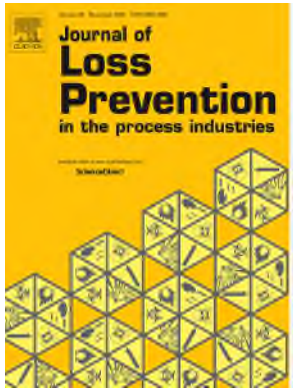
5 June 2019 12:29 GMT UPDATED 7 June 2019 12:15 GMT

By Beate Schjolberg in Kjeller

Model vs experimental result



- Almost all ammonia released (**>99%**) is dissolved, even at shallow depth. Model agrees with experiment result.
- **More tests at close to realistic bunkering conditions** are to be performed in upcoming live field releases.



doi.org/10.1016/j.jlp.2025.105818

Scan to check the paper

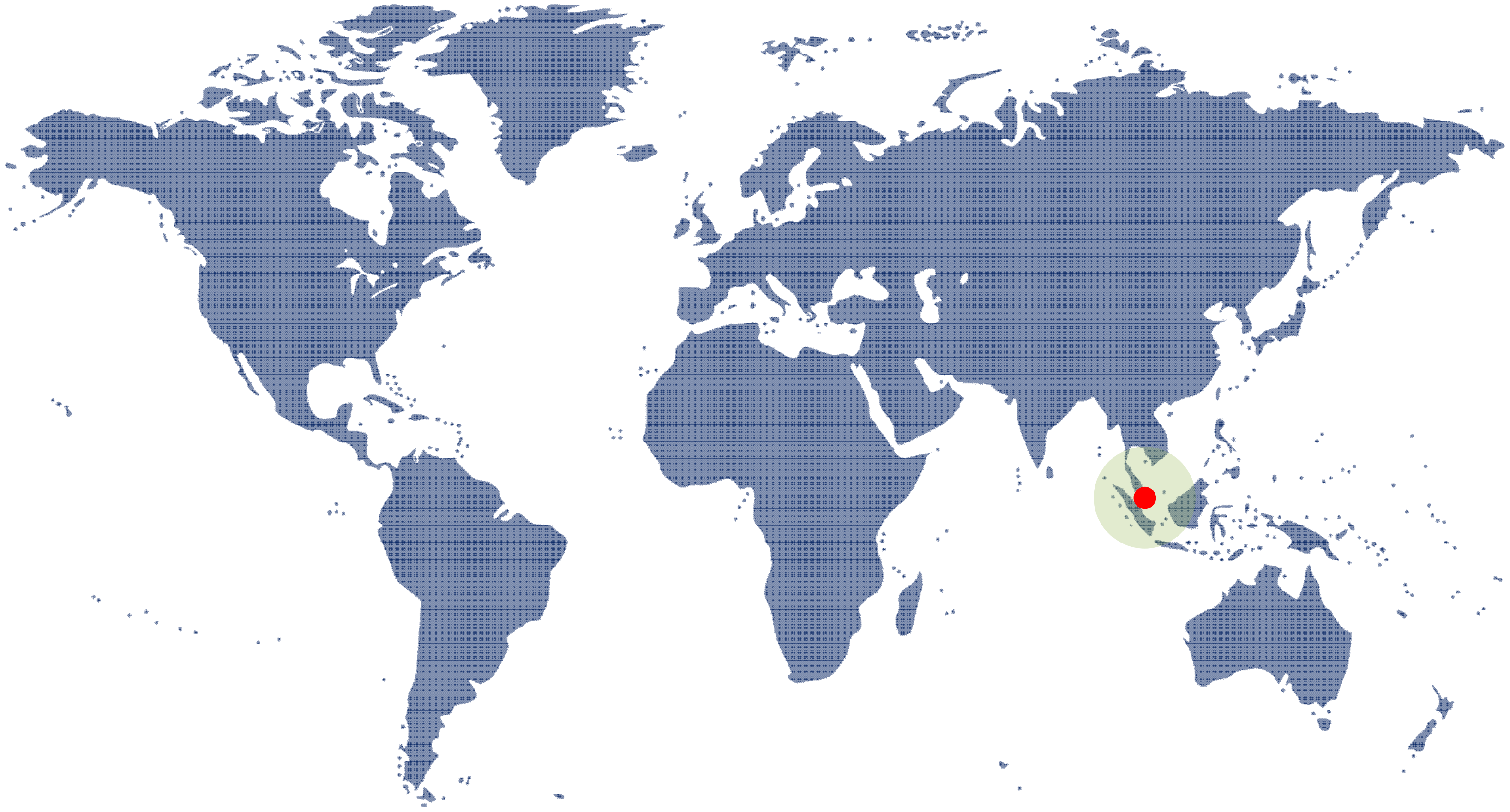
Key Insights

- **Unique challenges:** Liquid expands rapidly upon release, forming dense cloud. Ammonia state in containment (esp. pressurization) strongly affects dispersion behavior.
- **Field experiment:** prepare well – particularly on release scale and duration.
- **The Best Strategy:** prevention is always better than mitigation.
- **No single “silver bullet”: Multiple pre- and post-release mitigation measures** to complement one another to managed the risks effectively.
- **Do not panic:** When release does occur, follow ERP e.g., keep the release small, induce rainout and/or vaporize existing cloud into light vapor.

- **Studies in the pipeline:**
  - Experimental release with realistic scale onto water surface.
  - Study on water curtain against ammonia cloud.
  - Detailed study on novel ammonia engine room safety.

Public Report on Ammonia Mitigation and Release Experiment will be released in 2026. Stay tuned!

MESD Ammonia Bunkering Report Phase 1 (2023)



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