Shipping of Ammonia: What is new ?

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ABSTRACT

The decarbonization of the World will need many paradigm changes. Among others, in the Green Hydrogen economy, the trading of Ammonia by ships will grow significantly.

The objective of this paper is to address the safety aspects of this trend to come and how to address them.

First, the problematic will be analyzed. Indeed Ammonia is not new: its toxicity is well known and there is about 40 years of experience in Ammonia shipping. So how this relevant experience can be used to address safely – at concept level – the order of magnitude increase to come in volume and frequency of large Ammonia cargo transfer between the onshore storages and carrier vessels. Instead of being mitigated, should the risk of a toxic cloud be eliminated and kept away from populated areas, such as busy ports ? How can this be done ?

Other types of cargo have similar safety constraints. To create new ports or jetties dedicated for large scale Ammonia trading would be unduly CAPEX intensive, requiring long permitting process. This paper will review the various technologies available for fluid cargo transfer from onshore storage to gas carriers in open sea, in other words, without the need of new harbor nor expensive jetty.

To adapt a proven solution, Imodco will complete - by end of 2023 - the qualification for Ammonia application of Single Point Mooring (SPM) terminals, used for fluid cargo transfer in open sea, validated by over 470 systems delivered since 1958 for fluid transfer in open sea.

Finally, the safety records with jetty-less systems are good and guaranteed by the well documented regulations and guideline/recommendations for oil transfer (e.g. OCIMF). Gas Carriers are regulated by other codes (SIGTTO and IGC code), the paper will conclude on recommendations for good practices for transfer of Ammonia in open sea, using SPM terminals.

INTRODUCTION

Enhanced by the current crisis, the Energy Industry has many challenges to overcome, often summarized as an Energy Transition. Within the various Hydrogen Carrier molecules, Ammonia is one of the most affordable and has one the highest energy density. This makes Ammonia a good candidate for long haul transport of green fuels.

The presented work focus on shipping of Ammonia, first looking what will change between the past 30yr and the coming next 30 yr: from the economic and then technical standpoints with safety as the redline as ultimately the larger use of ammonia is for the sake of better world: safer & less carbonated. The technical focus will be centered on the transfer of Ammonia from/to the carrier to/from the onshore storage. Organized in four chapters, this paper ambitions to consolidate input from the various stakeholders of the Ammonia value chain.

1. The economical aspect: various uses and traded volumes, focusing on the part shipped by various types of gas carriers.
2. The technical aspect: various technologies for Ammonia transfer.
3. The safety discussions reviewing the main risks and their elimination or mitigations.
4. The overall picture from insurer's perspective which aims at a wise balancing between investment and return on investment addressing safety dimensions.

The overarching conclusion is given as summary of all these elements illustrating the main point: Ammonia SPM terminals transfer systems will a key contributor to the Hydrogen Economy & Strategy by enabling safe and cost-effective infrastructure for ammonia transfer in open sea. As an opening for further work, a status is given on recommendations for good practices and regulations for transfer of Ammonia in open sea, using SPM terminals.

1. Shipping of Ammonia: “over the last 30yr” versus “in the next 30yr”

The shipping of Ammonia is not new. Over the last 30 years, some Ammonia have been transiting as maritime cargo. Most of these shipments were onboard LPG carriers of relatively small cargo capacity (say less than 25,000 t – 38,000 m3) able to carry Ammonia at -33 deg. C and close to ambient pressure (ie. Onboard the so-called refrigerated cargo gas carrier). Ammonia shipping represents today 15-20 MTPA of the 180-200 MTPA world wide ammonia production/use, as most of today ammonia is produced and used locally.

The production/use of ammonia will grow drastically in the coming 30 years, by probably a factor 3 as illustrated in Figure 1.

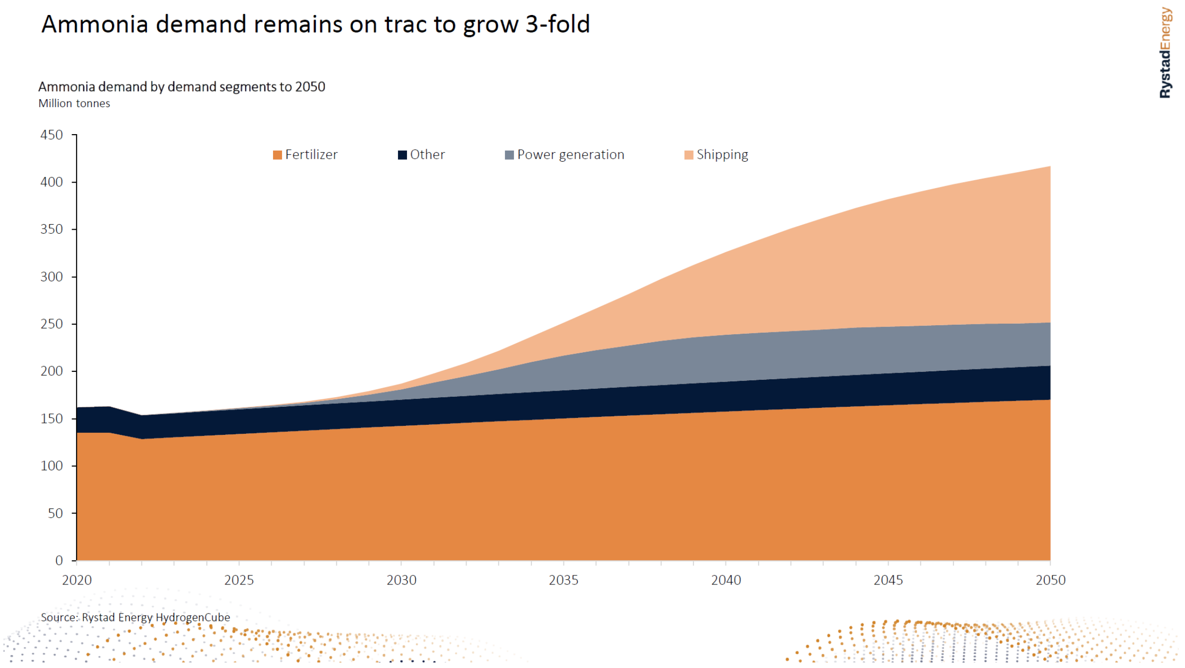


Figure 1: extract from Rystad Energy's presentation at World Hydrogen Summit, Rotterdam May-23

As illustrated in Figure 2, most of the new Ammonia production will mainly come from the most economical hydrogen production hubs such as Australia, Chile and Arabian Gulf (as other areas well exposed to sun and wind are unfortuantely less stable politically or less conveniently located) and will be exported to importing areas such as Asia and Europe.

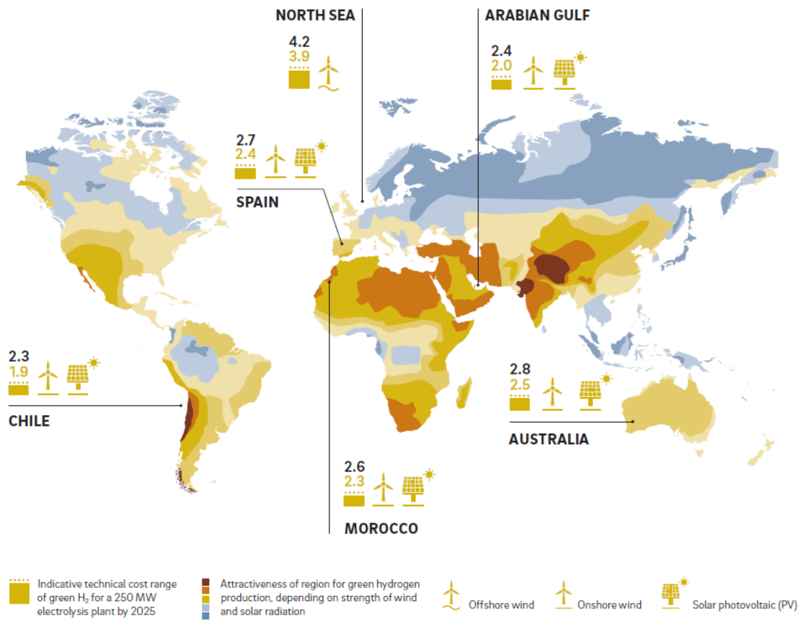


Figure 2: Cost competitive renewable electicity and green hydrogen production hubs are typically located distant from demand centers (Eur/kg) – source: roland_berger_hydrogen_transport.pdf

So most of the new ammonia production will be transported over long haul distances therefore by ships. For transport by ship, the Ammonia is liquid, typically at or close to -33 degrees Celcius when transported on carriers with refrigirated tanks. Indeed for large cargo volumes, it is more cost effective and safer to transport the ammonia close to atmospheric pressure. At that pressure, ammonia is liquid at -33deg C.

As most of new production and new consumption will be at long haul distances from each other, it results that Ammonia shipping will increase in volume and/or in frequencies by at least an order of magnitude. Depending on the sources (summarized as low and high bound estimates), the ratio is close to a factor 20, as explained in Figure 3.

Ammonia volumes	today (low)	2050 (low)	increase Ratio (low)	today (high)	2050 (high)	increase Ratio (high)
Overall production - MTPA	150	450	3	200	600	3
Local consumption in MTPA	135	150	1.11	180	200	1.11
Ammonia shipping in MTPA	15	300	**20**	20	400	**20**
Typical cargo size in kT	10	80	8	25	80	3.2

Figure 3: Ammonia Shipping increase by factor 20 between today and 2050 projections

The next section presents the various technologies available for ammonia cargo transfer from onshore storages to gas carriers. The third section will reflect from a safety standpoint on the increase by more than order of magnitude in volume and/or frequencies.

2. Ammonia cargo transfer – from/to carrier to/from shore

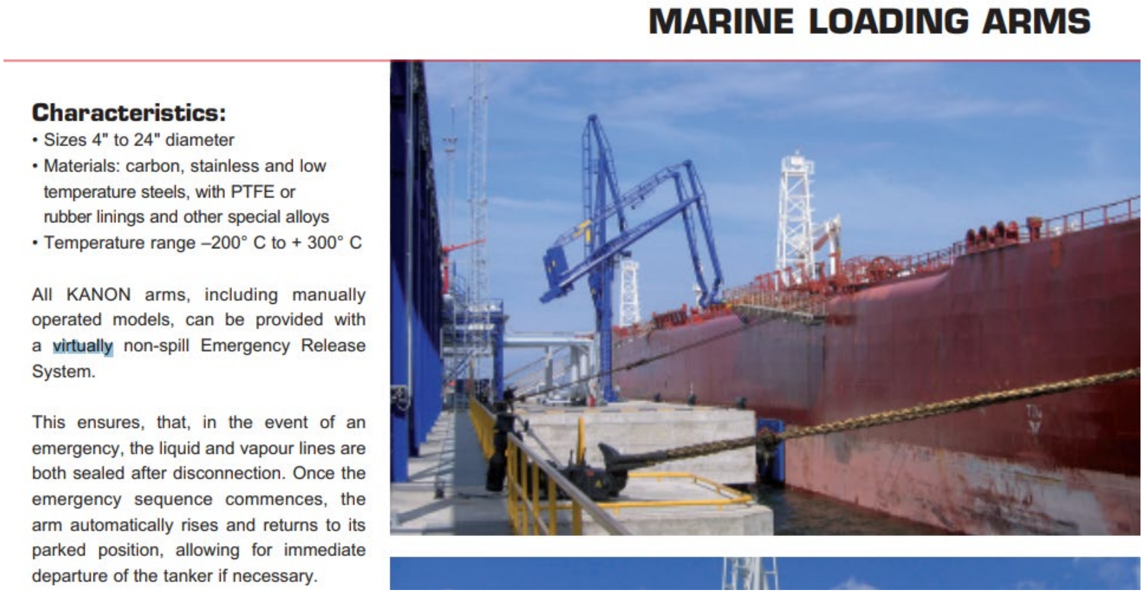
Over the last 30 yr, Ammonia cargo transfer has almost exclusively been performed in habors, at quay side, with the carrier hardly moving relatively to the fixed ground/quay: the motions are slow ("quasi-static", in opposition to "dynamic" resulting from large waves) either due to tidal variations or some residual swell diffracting within the port.

Source: https://newsroom.portofantwerpbruges.com/storage-of-ammonium-nitrate-under-very-strict-safety-conditions-in-port-of-antwerp

Figure 4: Ammonia Carrier at quay side

The fluid transfer used is either loading arms or flexible hoses – as further detailed below:

- Similar to LNG loading arms – the loading arm is an articulated piping (see Figure 5 extract from Kanon loading arm brochure) designed to accommodate a pre-defined maximum envelop of relative positions.



MARINE LOADING ARMS

Characteristics:

- Sizes 4" to 24" diameter
- Materials: carbon, stainless and low temperature steels, with PTFE or rubber linings and other special alloys
- Temperature range –200° C to + 300° C

All KANON arms, including manually operated models, can be provided with a virtually non-spill Emergency Release System.

This ensures, that, in the event of an emergency, the liquid and vapour lines are both sealed after disconnection. Once the emergency sequence commences, the arm automatically rises and returns to its parked position, allowing for immediate departure of the tanker if necessary.

Source: https://kanon.nl/wp-content/uploads/2021/06/Kanon-Loading-Equipment-brochure-en.pdf

Figure 5: typical loading arm

- Similar to bonded hoses used for dead crude oil transfer, the bonded hoses are steel wire reinforced rubber structures (comparable to car tyre technology). For the Ammonia, the focus on chemical compatibility leads to the use of different grades of rubber.

In both cases, the system has typically 3 levels of positions: allowable positions for safe fluid transfer, warning mode positions where the fluid transfer must be stopped to prepare for disconnection and extreme positions beyond which there is a risk of damage. If the position monitoring system reaches that latter level, the loading arm disconnects by activating its (Powered) Emergency Release Coupler. The Emergency Release system when using hoses, it is either designed to release beyond a given load level or also actively disconnected triggered by a position monitoring system similar to the one used for loading arms (see Figure 6).

Source: https://www.continental-industry.com/en/solutions/fluid-handling/renewable-energy-solutions/ammonia-hoses-for-bunkering

Source: https://www.trelleborg.com/en/fluidhandling/products-and-solutions/industrial-hoses/oil-petroleum/gutteling-lpg-white

Figure 6: typical current use of ammonia hoses in quasi-static application

Jetty-less systems:

In process of qualification, few Jetty-less solutions requiring longer and more dynamic ammonia hoses (being qualified by Trelleborg and Continental Industry/Contitech) will be available in 2024, both for:

- **Protected Sites**: as further explained below there are two sub-segments (1 & 2 as function of the distance from shore) in protected or/and directional environment.
- **Open Sea Sites**: which are the best, safety wise, as further away from populated areas: the ammonia cargo transfer being performed in open sea.

Such open sea offloading systems, called SPM terminals (for Single Point Mooring – allowing carrier vessels to weathervane during the fluid transfer) have been invented over 60 years ago mainly for large oil tankers which would not fit in the existing harbours or which would need to load or offload oil (or oil derivative) from a refinery away from existing infrastructures. For some large development projects, heavy and long term investments were made into large jetty systems to receive these large vessels. Over the years, the experience of these large projects indicates that Jetty systems typically are not only expensive but also have long delivery schedule. This is mainly due to the nature of jetty systems, especially those with breakwater, requiring many studies of the impact on the environment and the consequently time consuming associated permitting process. Jetty-less systems have a more straight forward permitting process and shorter overall schedule, as the simplicity of the overall system enables a virtuous spiral of simplification and cost efficiency: Jetty-less systems are conceived from day one with a view of minimum impact on the environment, including possible site reinstatement. This eases the permitting process, reduces the number of required impact studies, finally a shorter schedule and simpler system have combined and significant positive effect on the overall CAPEX.

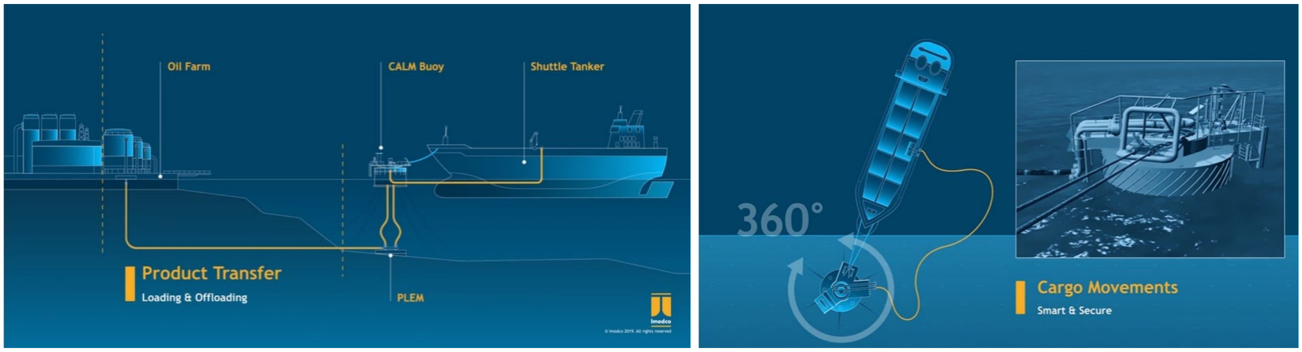


Figure 7: Typical architecture of CALM terminal (Single Point Mooring – SPM)

As illustrated in Figure 7, the carrier vessel heading can be adjusted any time to site conditions to ensure a safe approach, berthing, loading, disconnection and sail away, leveraging on over 60 years of operating experience of SPM terminals illustrated in this video [Catenary Anchor Leg Mooring (CALM) Terminal (vimeo.com)](https://vimeo.com).

Part of the experience gathered over these many years of SPM operations, the safety distance to account for safe maneuvering of the approaching vessel. As per ABS rules, the terminal (SPM or fixed heading) location should be at least three times the vessel length from the bathymetry line of minimum allowable water depth for the largest vessels planned to use this terminal.

The safety records with SPM systems are good and guarantied when adhering to the well documented regulations and guideline/recommendations (e.g. OCIMF). For most products that are in liquid form at ambient temperatures, the captains of carrier vessels are generally used to berth, load/offload, unberth from jetty-less systems. This is a testament to the fact that jetty-less systems are widely used for simple reasons: it works and it is cost effective (best Net Present Value for all scale projects), as summarized in below Figure 8.

Figure 8: Summary of 60 yr experience with Jetty-less solutions

Once far enough from populated areas (main selection criteria), the choice of jetty-less solution depends on the flow rate, the ability to manage Boiled-Off Gas (BOG), traffic related risks and other parameters (pressure drop, …).

So, as illustrated in Figure 9, from a descriptive view point:

- Segment 1: Protected Sites - allowing <u>fixed heading jetty-less solutions</u> - using <u>only floating flexible hoses</u>. When feasible & operationally safe & good uptime, this is the simplest solution.

- Segment 2: Protected Sites - allowing <u>fixed heading jetty-less solutions</u> - using <u>subsea pipeline</u>. When required (i.e. segment 1 solutions not working), this could be considered but once the pipeline cost is absorbed, the remain delta cost between segment 2 and segment 3 is relatively small.

- Segment 3: **Open Sea** Sites - requiring weathervaning jetty-less solutions (SPM for Single Point Mooring). For the Liquid Ammonia, Methanol and LOHC, two types of SPM systems are available:

  - CALM terminals (Catenary Anchor Leg Mooring buoy), by default, unless not enough water depth for a submarine hose configuration or too harsh operational environment.

  - TLU Terminals (Tower Loading Unit) for more challenging projects where the CALM concept does not meet the project requirements (either harsh survival environment, safety or uptime).

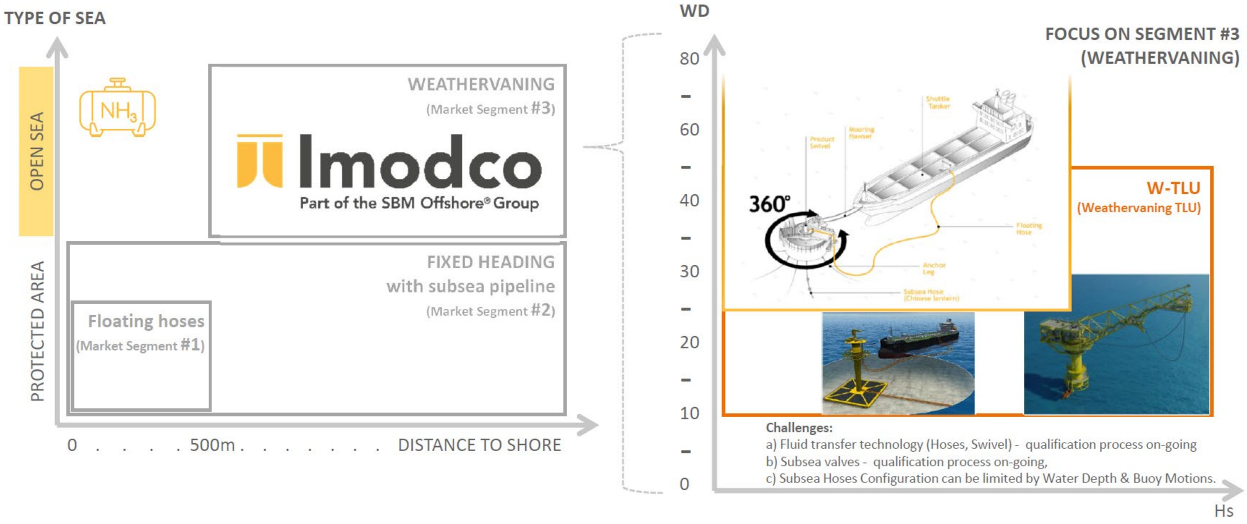


Figure 9 : Technical Segmentation for Ammonia Jetty-less solutions

3. Safety discussion: mitigations vs elimination of the main risks

As we saw in the previous section, the connection of the Ammonia transfer system to the carrier vessel necessarily has an Emergency Release Coupling (ERC) system that is either designed to release beyond a given load level (passive ERC) or also actively disconnected (powered ERC) triggered by a position monitoring system similar. See next page for explanatory images gathered under Figure 10.

The purpose of such ERC is two folds: prevent from escalation of an unplanned event by protecting the asset (avoid tearing off the fluid transfer system by a controlled disconnection/weak point) and minimize the release of the inventory contained in the fluid transfer system. In unplanned disconnections, there is a release of Ammonia which has to be managed somehow.

As ammonia is highly toxic at high concentration, for ammonia transfer the key subjects are :

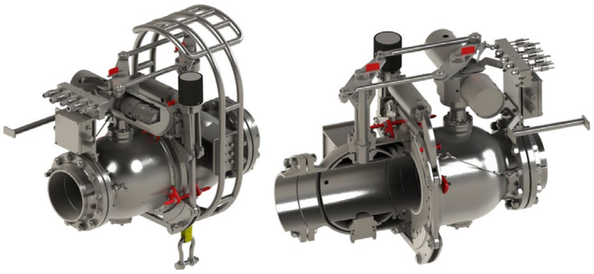
1) How much liquid is released in such an un-planned (and rare) event ?
2) Where this released liquid ammonia and associated vapor go ?

Indeed in populated areas, a small cloud of high ammonia concentration could either kill or severily harm people within an area in order of a few hundred meters – dependings on the released amount, the weather (humidity, temperature, wind,…). Over the last 30 yr, no such catastrophic event has happened, but it is important to analyze what is behind this good track record in order to re-validate whether this will remain applicable for the coming 30 yr where the volume and/or frequency of ammonia transfer will be multiplied by at least a factor 10.

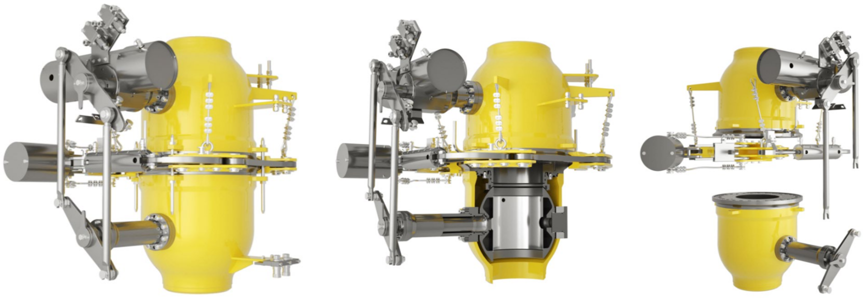
Figure 10: typical Emergency Release Couplers (ERC) – (here Powered version so PERC)

Below images are MIB courtesy: https://www.mibitaliana.com/product-emergency-release-system/

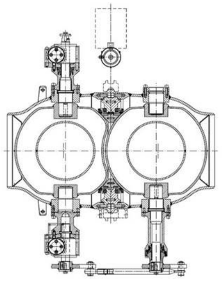
MIB®



Powered Emergency Release Coupler (PERC) for cryogenic gas



Key principles of PERC: synchronized closure of ball valves (to isolate inventory) before parting



MIB (P)ERC design minimizing released volume for a given diameter

<u>Mitigations against creation of toxic cloud</u>:

- Minimize the released volume : in case of emergency (i.e. when no time for an automatic purge of the piping to a safe location) typically the volume contained between the two ball valves that are automatically closed during the release – this is proportional to the square of the valve diamter. MIB have developped a (P)ERC design that minimizes this volume. (bottom image in previous page)
- Water spray: to mix the liquid ammonia with water this minimize the formation of toxic cloud. The resulting water is drained to avoid dumping it into the habor water.
- Exclusion zone during ammonia transfer: stop all activities with a safety/exclusion zone (dependent on project conditions) of several hundreds of meter. In busy ports, this operational mitigation can be a severe constraint for the surrounding businesses.

As illustrated in Figure 11, the principle of inherently safer design is to first try to eliminate the identified risk before to mitigate it. This principle also applies in the project definition, as illustrated in Figure 12, the operational safety performance is drastically impacted by the concept selection and further project definition: despite best operational efforts, a sub-optimal concept cannot lead to the best safety performance of the optimum concept selection.

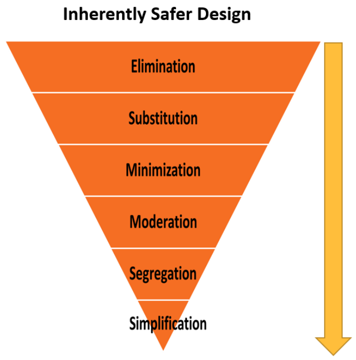


Figure 11 : Principles of Safety in Design

Figure 12 illustrates the relative safety performance of the same project with 4 scenarios splitted in two cases:

- the blue curve: the main risks are only mitigated as concept level.
- the green curve: the main risks are eliminated as concept level.

For instance, the risk of a toxic cloud in populated area can be minimized using the above proposed mitigations (the blue curve in Figure 12) or eliminated using a SPM terminal in open sea (the green curve in Figure 12).

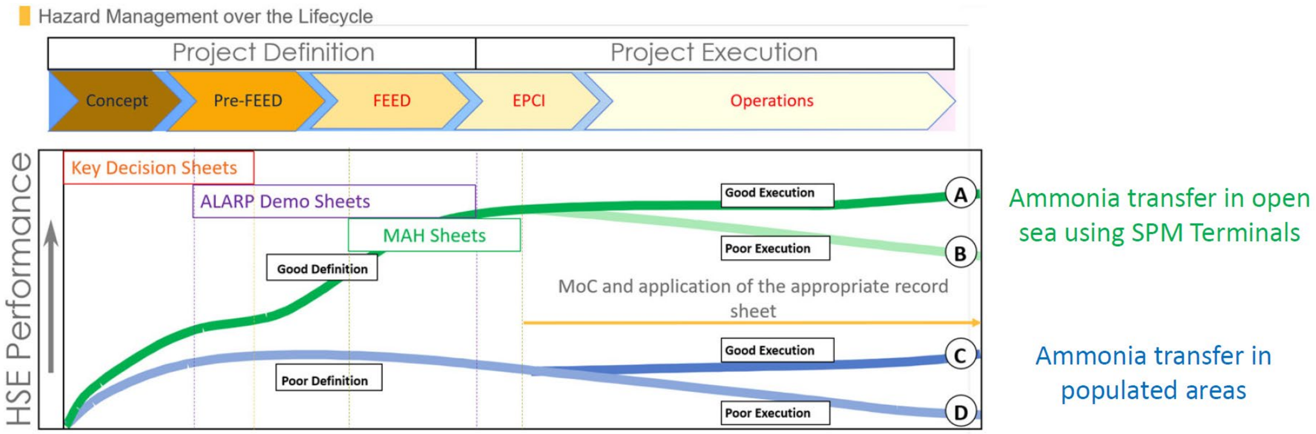


Figure 12: Safety in Design applied over project life from concept to delivery – impact on operations

For large and frequent ammonia transfers, therefore with a higher likelihood of an unplanned disconnection and therefore release of ammonia, it is recommended to make at concept selection the decision to eliminate (instead of minimizing) the risk of a toxic cloud in populated area by moving offshore – in open sea - the operations of connecting to and disconnecting the carrier to the fluid transfer system. Also, a contribution factor is the wider forum of personels & crews involved in Ammonia transfers among which the proper training level may no longer be as uniformly high enough as it used to be over the last 30 years without accidents: this is typically the possible degradation from good to poor execution, as illustrated in Figure 12.

4. Overall picture - insurer's perspective - a wise balancing between investment and return on investment addressing safety dimensions

The section lists the key subjects/questions to address when making the concept decision for projects which will eventually rely on large and frequent ammonia export for their economics.

Project Economics: **how important is the Ammonia export revenue stream ?** if it had to stop along the project life, what would be the impacts ? Below we only address the reasons of why the Ammonia export could be either stopped or at least significantly less than planned, assuming the "blue curve" scenario of Figure 12 (the main risks are only mitigated instead of eliminated). A few scenarios are considered:

a) The main mitigation is at SIMOPS level: all activities within the design/original safety/exclusion zone are stopped during an Ammonia transfer operation. Either the *port activities are picking up* and this constraint becomes so large that the arbitration turns in favor of reducing the frequency and/or duration of the Ammonia exports, hence overall a significant reduction of the associated revenue.

b) The main mitigation is at SIMOPS level: all activities within the design/original safety/exclusion zone are stopped during an Ammonia transfer operation. Unfortunately, for some reasons, there has been an event where the release of Ammonia was larger/longer than assumed in the definition of the safety/exclusion zone. As a consequence,

    - at the best, there was no victime, but the safety/exclusion zone has been increased impacting more activites, and similarly to above scenario a), the arbitration results in significant reduction of the ammonia revenue for the project.
    - at the worse case, there has been victimes, in addition to above the project is now facing majors legal and financial issues.

If the project economics requires the highest protection of the ammonia export revenues, then such a project should make the choice at concept selection to eliminate the risks associated with ammonia tranfer in populated area: shift away that risk offshore, in open sea, using SPM terminals (the "green curve" scenario of Figure 12).

Public perception and future of ammonia as green fuel: in case of major problem on one project consequence on other projects may lead be:

- Increase of insurance premium

- Longer permitting process (or worse: permit not granted) due to NIMBY (Not In My Back Yard) push-back.

Impact on environment: while it is clear that going offshore eliminate the risk to a toxic cloud in populated area, one could ask whether this would increase the overall risk to the environment:

- Ammonia release within "closed" water of a port: while the release amount can be probably better reduced (e.g. shorter flexible hoses) the dilution will be less effective.
- Ammonia release in open sea: while lacking of scientific data so far, it is known ammonia dilutes well in water therefore the relative concentration will quickly reduce to level below long term severe impact. According to EDF study comparing to oil (for which there is 60 yr of SPM operational experience and which ammonia would attempt to progressively replace as a fuel), the impact on environment is globally similar to Marine Gas Oil but it is lower in "deep sea" in other words in "open sea" - see Figure 13.

  Source: [Environmental Defense Fund (EDF), LR, and Ricardo launch report examining ecological impact of ammonia as a shipping fuel across diverse habitats and receptors | Environmental Defense Fund (edf.org)]

  << A joint study released by Environmental Defense Fund (EDF), Lloyd's Register (LR) and Ricardo PLC, examines the potential marine environmental impacts of ammonia spills during its use as a shipping fuel. Ammonia generated from renewable energy is considered a sustainable alternative to fossil fuels as the shipping industry decarbonises.>>

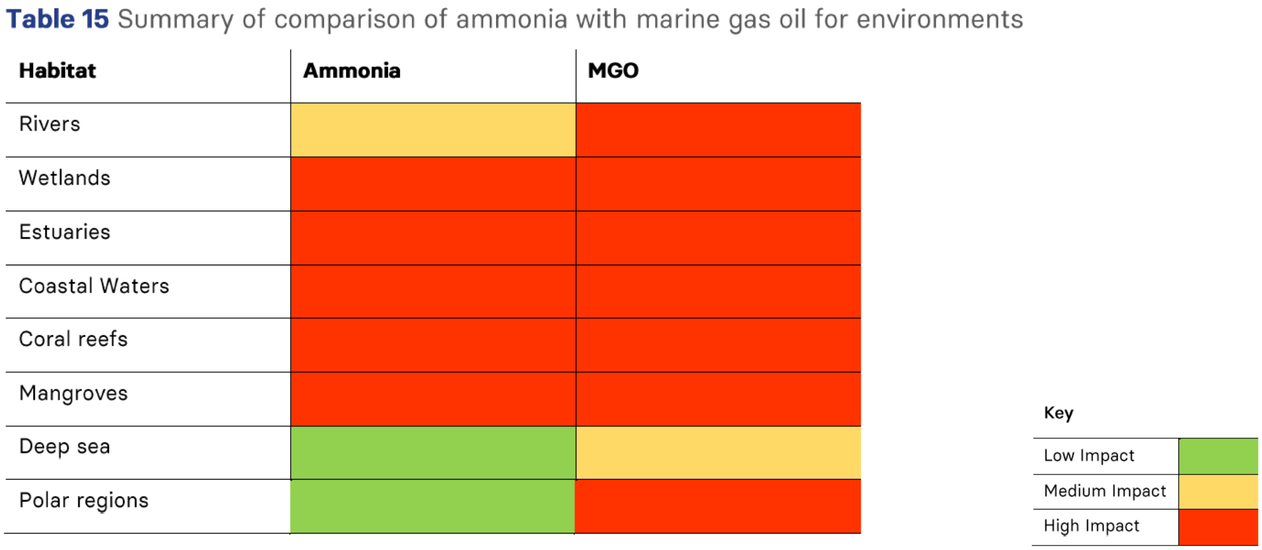


Table 15 Summary of comparison of ammonia with marine gas oil for environments

Habitat	Ammonia	MGO
Rivers	🟨	🟥
Wetlands	🟥	🟥
Estuaries	🟥	🟥
Coastal Waters	🟥	🟥
Coral reefs	🟥	🟥
Mangroves	🟥	🟥
Deep sea	🟩	🟨
Polar regions	🟩	🟥

Key

Low Impact	🟩
Medium Impact	🟨
High Impact	🟥

Figure 13: extract from EDF report comparing impact of Ammonia vs Marine Gas Oil

Summary and Conclusions

The pitch of this paper is to look at the overall Health, Safety, Security and Environment (HSSE) impacts of Ammonia transfers from/to carrier vessels.

Organized in four chapters, this paper has consolidated input from various stakeholders of the Ammonia value chain to make the following conclusions:

1. The economical aspect: the traded volumes of shipped Ammonia will at least grow by factor 10 or more in the coming 30 years.
2. The technical aspect: various technologies for Ammonia transfer are well known, the key subject is "where is the transfer performed ?":
    a. Within populated areas such as ports – mitigating the risks related to high toxicity of Ammonia.
    Or
    b. Offshore – using SPM terminals – being qualified for Ammonia application – eliminating the risks, shifting them away from populated areas
3. The safety discussions reviewing the main risks and their elimination vs mitigations. The order of magnitude change in volume and frequency of Ammonia transfers calls for changing paradigm from risk mitigation to risk elimination.
4. The overall picture from insurer's perspective - which aims at a wise balancing between investment and return on investment addressing safety dimensions – confirms and gives business back-up to this strong recommendation – for large Ammonia export projects - to use SPM terminals enabling Ammonia transfers offshore away from populated areas.

The overarching conclusion: in a similar way than for Oil shipping, the Ammonia SPM terminals transfer systems will be a key contributor to the Hydrogen Economy & Strategy by enabling safe and cost effective infrastructure for ammonia transfer in open sea. Consequently, further work has started to adapt and recommend good practices and regulations for transfer of Ammonia in open sea, using SPM terminals, which will be relevant to many of the future exporting Green Hydrogen projects.

ACKNOWLEDGEMENTS

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