SUSTAINABILITY WHITEPAPER

AMMONIA AS MARINE FUEL

OCTOBER 2020

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OVERVIEW

INTRODUCTION AND OBJECTIVE

The maritime industry faces challenges in adopting new technologies and/or operational practices to comply with increasingly strict international, national, and local regulations aimed at reducing Sulfur Oxides (SOx), Nitrogen Oxides (NOx), Particulate Matter (PM), Carbon and Greenhouse Gas (GHG) emissions from ships. The regulations introduced by the International Maritime Organization (IMO), the European Union, the United States Environmental Protection Agency, the California Air Resources Board, and others are designed to reduce these emissions from ships.

Many technologies are being considered to reduce carbon emissions in shipping. The American Bureau of Shipping (ABS) publication *Setting the Course to Low Carbon Shipping: Pathways to Sustainable Future*, referred to as 'Outlook II' in this document, has categorized the available maritime fuel options for decarbonization. Among them, ammonia (NH_3) was identified as a zero-carbon fuel that can enter the global market relatively quickly and help meet the GHG reduction target for 2050 set by the IMO. Ammonia offers ship owners and operators a zero-carbon tank-to-wake emissions profile, regardless of the source of the fuel.

Despite its toxicity and stringent handling requirements, ammonia engines have been developed in the past and marine engines are currently being developed by applying existing dual fuel (DF) engine technologies to ammonia. Designs for ammonia-fueled feeder ships have also been unveiled by consortia that include designers, classification societies and shipyards. Ammonia has greater prescriptive requirements for containment and equipment than most of the other alternative fuels under consideration, is a globally traded commodity and there currently exist many smaller gas carriers that may be suitable as bunkering vessels. However, for ammonia to become a commercially-viable long-term fuel option, comprehensive supply-side infrastructure would need to be built and stringent new safety regulations be developed and implemented. This also applies to all alternative fuels under consideration.

Through a series of sustainability whitepaper publications, ABS will focus on individually detailing certain carbon emission reduction technologies. This whitepaper provides information for the consideration of ammonia as a marine fuel option in both the near-term and long-term. It is to be noted that the information provided in this document is generic. For specific guidance on ammonia as marine fuel, contact your local ABS office.

ADDITIONAL RESOURCES

For more information on the options available to achieve your decarbonization goals, please refer to these publications from ABS.

Setting the Course to Low Carbon Shipping - 2030 Outlook, 2050 Vision (2019)

Setting the Course to Low Carbon Shipping - Pathways to Sustainable Shipping (2020)

Sustainability Whitepaper: LNG as Marine Fuel

IMO GOAL AND STRATEGY

The adoption of the *Initial International Maritime Organization Strategy on Reduction of Greenhouse Gas Emissions from Ships* by IMO Marine Environment Protection Committee (MEPC) Resolution MEPC.304(72) in April 2018 demonstrates IMO's commitment to support the Paris Agreement.

The IMO strategy includes initial targets to reduce the average carbon dioxide (CO_2) emissions per transport work from 2008 levels by at least 40 percent by 2030, and 70 percent by 2050. These targets also seek to reduce the total annual GHG emissions from shipping by at least 50 percent by 2050. Technical approaches, operational approaches and alternative fuels may be used to achieve these goals. The near-term regulatory changes and the future impact of the IMO's greenhouse gas targets for 2030 and 2050 should be considered when making decisions on fuel selection.

AMMONIA AS FUEL FOR REDUCTION OF GREENHOUSE GAS

LIFE CYCLE EMISSIONS

'Tank-to-wake' only considers the emissions from burning or using an energy source, not the process of sourcing the fuel or getting it to the ship. To measure net carbon impact, 'well-to-wake' emissions should be considered for alternative fuels because the concept encompasses the life cycle of a fuel, including production, transportation and use.

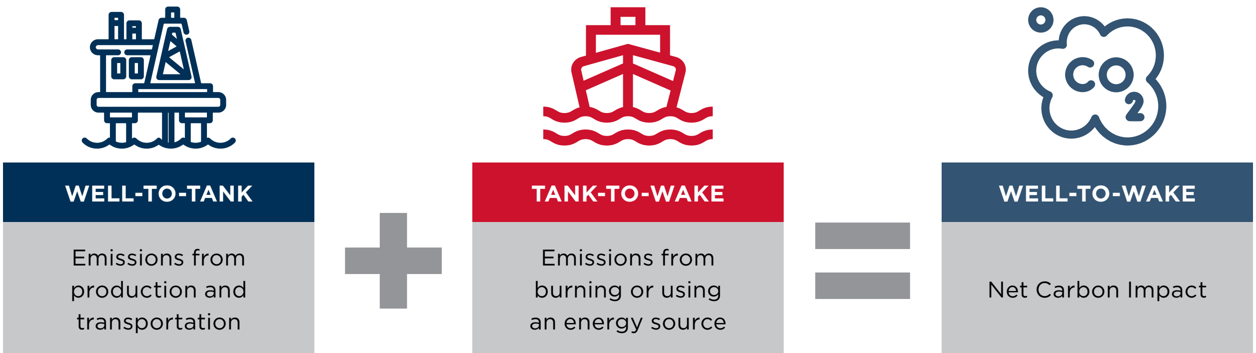

Figure 1: Life cycle emissions

When used as a fuel, hydrogen is zero carbon at point of use (tank-to-wake). However, if it is produced from non-renewable feedstock, such as nonrenewable natural gas through a process using energy not from renewable source, the process (well-to-tank) could produce significant emissions. Alternatively, it can be produced by electrolysis of water with renewable energy to eliminate the emissions from feedstock and the production process.

Ammonia is typically created by combining nitrogen with hydrogen. Therefore, the emissions from producing hydrogen as feedstock and the emissions arising from the synthesis of ammonia should be considered as part of the life cycle emissions of ammonia fuel. Table 1 shows the well-to-tank emissions for ammonia production, transmission, and distribution. The production emissions include those associated with electricity generation for production of NH_3. The transmission and distribution emissions were calculated using the Greenhouse Gases, Regulated Emissions, and Energy use in Transportation (GREET) model.

Electricity Source	Production Emissions (g CO_2e/MJ)	Transmission and Distribution Emissions (g CO_2e/MJ)	Total Emissions (g CO_2e/MJ)
Municipal Waste	18.31	0.42	18.73
Hydropower	20.46	0.42	20.88
Nuclear Power	45.23	0.42	45.65
Biomass	45.77	0.42	46.19

Table 1: Well to tank emissions for ammonia by energy source for the production process. Source: ABS Outlook II

AMMONIA AS HYDROGEN CARRIER (REFORMATION/CRACKING)

Hydrogen offers a high energy content per mass, high diffusivity, and high flame speed. Hydrogen as a fuel has been demonstrated in internal combustion (IC) engines, gas turbines, and fuel cells. However, it requires cryogenic storage (-253 °C or lower) and dedicated fuel supply systems for containment. Significant technical advances are needed before hydrogen can be considered a viable, large scale, commercial fuel option, particularly for marine applications where energy content on a volumetric basis is low for hydrogen (9.93 GJ/m^3) and application would therefore significantly impact ship design. Energy loss during storage and boil off gas generation are also challenges for application.

Compared to hydrogen, ammonia storage is more practical due to its energy density and liquefaction temperature (see Table 2). However, ammonia is toxic. Ammonia has been handled as cargo and reductant in Selective Catalytic Reduction (SCR) systems for many years. Therefore, ammonia handling in ships is sufficiently feasible. Ammonia as fuel for IC engines is under development. A challenge inherent in its combustion is the large percentage of pilot fuel required for ignition.

Interest is growing in the use of ammonia as a feeder to hydrogen-fed fuel cells by owners operating Liquefied Petroleum Gas (LPG) carriers carrying ammonia as cargo. Other ship owners also seek to reduce GHG emissions using ammonia. Operators of power barges supplying green electricity to ships during port stay, power plants on remote islands, backup power supplies on land and grid emergency generator operators are also displaying an interest in ammonia.

Once cracked, the hydrogen from ammonia can be an abundant resource for fuel cells to generate electric power. That said, ammonia's advantages should be weighed against the energy losses and additional equipment required for conversion to hydrogen before it is used in fuel cells. Certain fuel cell types can internally reform the fuel to run on ammonia directly, eliminating the need to separate the hydrogen and nitrogen before input. An issue with using ammonia as a fuel is the undissociated ammonia concentration in the product gas. Although the concentration may be less than 50 parts per million (ppm), this is still enough to damage fuel cells with acid electrolytes, so an acid scrubber is needed to remove the final traces of ammonia gas from the cracker.

Storage of liquid hydrogen requires at least five times more volume compared to petroleum-based fuels while ammonia requires about 2.4 times more volume. Therefore, as a long-term solution, zero carbon fuels would require new vessel designs and optimization of operational factors to avoid compromising travel distance, refueling needs, or cargo volume. Even so, the widespread use of ammonia in industrial and agricultural processes makes it a logistically attractive and affordable fuel that can be distributed using existing infrastructure.

AMMONIA PRODUCTION AND STORAGE

According to the United States Geological Survey, worldwide production of ammonia in 2019 was about 150 million metric tons. The average ammonia price for the year 2019 was estimated to be $230 USD per short ton. Global ammonia capacity is expected to increase by a total of 4% during the next 4 years.

Ammonia is carbon-free and its synthesis from renewable power sources is a carbon-free process. Like hydrogen, it can be produced from fossil fuels using "green" methods such as carbon capture and storage or renewable energy, both of which may influence its cost competitiveness.

Currently, ammonia is produced in large scale from hydrocarbon fuels that are used to produce hydrogen by reforming methane with steam. The nitrogen required for production is extracted from the air after liquefaction. Renewable energy sources can be used to produce hydrogen from the electrolysis of water and later synthesized to ammonia. In this case, ammonia has zero carbon intensity during production or use. If sufficient quantities can be produced using carbon-neutral technology, ammonia has a significant potential to help meet IMO's 2050 GHG reduction targets.

Ammonia has a higher volumetric energy density than liquefied hydrogen, closer to that of methanol, which reduces the need for larger tanks. The volume of NH_3 storage tanks will be significantly less than of those for liquid hydrogen for the same energy requirement — even more so considering the volume of insulation required. The fuel characteristics of ammonia enable the use of Type C or prismatic tanks and require significantly lower re-liquefaction energy compared to hydrogen or LNG.

Industrial scale ammonia storage is typically at -33.6 °C or lower as this costs less than pressurization. The energy required to store it can be generated from green sources to reduce the total carbon footprint. Ammonia can be stored in liquid form at 8.6 bar and at ambient temperature (20 °C) on board the vessel. Ammonia can be used directly as a liquid fuel in engines more feasibly than as a hydrogen carrier.

AMMONIA SAFETY

Ammonia Property	Value
Energy density (MJ/L)	12.7
Latent heat of vaporization (MJ/kg)	188
Heat of vaporization (kJ/kg)	1371
Autoignition temperature (°C)	651
Minimum ignition energy (mJ)	680
Liquid density (kg/m³)	600
Adiabatic flame temperature at 1 bar (°C)	1800
Molecular weight (g/mol)	17.031
Melting point (°C)	-77.7
Boiling point at 1 bar (°C)	-33.6
Critical temperature (°C)	132.25
Critical pressure (bar)	113
Flammable range in dry air (%)	15.15 to 27.35
Cetane number	0
Octane number	~130

Table 2: Properties of Ammonia

CHARACTERISTICS OF AMMONIA

Ammonia is a compound of nitrogen and hydrogen and at atmospheric pressure and normal temperatures is a colorless gas with a characteristic pungent smell. At higher pressures ammonia becomes a liquid, making it easier to transport and store. The typical heating value for ammonia is similar to methanol. As with most alternative fuels, it has a lower energy density than fuel oils, so producing the same energy content would require about 2.4 times more volume as compared to petroleum-based fuels. The properties of ammonia are listed in Table 2.

NH_3 also has a relatively narrow flammability range compared to some other fuels being considered, and is toxic and very reactive. Hence, the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code) specifies strict requirements on the materials that can be used to contain ammonia and on the design features a plant needs to minimize the risk of exposing personnel to NH_3 poisoning. It also lists any required personal protective equipment necessary to safely manage the fuel.

TOXICITY

Ammonia is a widely used and commercially available chemical. Ammonia is found in nature and toxic in concentrated form. It is classified as a hazardous substance and is subject to strict reporting requirements by facilities that produce, store or use it in significant quantities. The odor threshold for ammonia is very low, ranging from 0.037 to 1.0 ppm, meaning it can be detected by most people at low concentrations that do not constitute a health risk.

Ammonia is toxic to humans. Exposure to ammonia must be limited to permissible limits for the safety of personnel on the vessel. Human permissible exposure limits of ammonia using different methodologies are shown in Table 3.

In low concentrations, ammonia can be irritating to the eyes, lungs, and skin and at high concentrations or through direct contact it is immediately life threatening. Symptoms include difficulty breathing, chest pain, bronchospasms, and at its worst, pulmonary edema, where fluid fills the lungs and can result in respiratory failure. Skin contact with high concentrations of anhydrous ammonia may cause severe chemical burns. Exposure to the eyes can cause pain and excessive tearing, in addition to injury to the corneas. Acute exposure to anhydrous ammonia in its liquid form can cause redness, swelling, ulcers on the skin, and frostbite. If it comes in contact with the eyes it can cause pain, redness, swelling of the conjunctiva, damage to the iris and cornea, glaucoma, and cataracts.

Guideline*	10 min	30 min	1 hour	4 hour	8 hour
AEGL-1[a,b]	30 ppm	30 ppm	30 ppm	30 ppm	30 ppm
AEGL-2[c]	220 ppm	220 ppm	160 ppm	110 ppm	110 ppm
AEGL-3[d]	2,700 ppm	1,600 ppm	1,100 ppm	550 ppm	390 ppm
ERPG-1 (AIHA)[e]	—	—	25 ppm	—	—
ERPG-2 (AIHA)[e]	—	—	150 ppm	—	—
ERPG-3 (AIHA)[e]	—	—	750 ppm	—	—
EEGL (NRC)[f]	—	—	100 ppm	—	100 ppm (24 hour)
PEL-TWA (OSHA)[g]	—	—	—	—	50 ppm
IDLH (NIOSH)[h]	—	300 ppm	—	—	—
REL-TWA (NIOSH)[i]	—	—	—	—	25 ppm
REL-STEL (NIOSH)[j]	35 ppm (15 min)	—	—	—	—
TLV-TWA (ACGIH)[k]	—	—	—	—	25 ppm
TLV-STEL (ACGIH)[l]	35 ppm (15 min)	—	—	—	—
MAK (Germany)[m,n]	—	—	—	—	20 ppm
OELV (Sweden)[o] (Dutch)	50 ppm (15 min)	—	—	—	25 ppm
SMAC[p]	—	—	20 ppm	—	14 ppm (24 hour)
OSHA[q]	—	—	—	—	50 ppm

Table 3: Ammonia Acute Exposure Guideline Levels – Standards and Guidelines

Source: National Research Council (US) Committee on Acute Exposure Guideline Levels. Acute Exposure Guideline Levels for Selected Airborne Chemicals: Volume 6. Washington (DC): National Academies Press (US); 2008. 2, Ammonia Acute Exposure Guideline Levels. Available from: https://www.ncbi.nlm.nih.gov/books/NBK207883/

For footnotes of this table, see Appendix III

FIRE SAFETY

Ammonia is a flammable gas with narrow flammability range. Its flammable range in dry air is between 15.15% and 27.35%. It has an auto ignition temperature of 651 °C. The risk of an ammonia fire is lower compared to other fuels due to its narrow flammability range, relatively high ignition energy (2-3 orders of magnitude higher than common hydrocarbons) and low laminar burning rate (more than four times less than methane [< 0.010 m/s]). However, there is potential for ammonia fires in the right conditions and safety principles require ammonia to be isolated from any ignition sources. The fire risks of ammonia when mixed with other fuels and lubricating oils is to be investigated in addition to pure ammonia combustion. Such fuel mixtures may have a much broader explosive range.

Ammonia can react with halogens, interhalogens and oxidizers and may cause violent reactions or explosions. Therefore, ammonia should be stored in a cool, well-ventilated location, away from sources of ignition, and separate from other chemicals, particularly oxidizing gases (chlorine, bromine, and iodine) and acids. Dilution systems may be utilized to avoid the flammability range of ammonia. The United States National Center for Biotechnology Information recommends that small fires involving ammonia can be extinguished with dry chemicals or CO_2 and large ammonia fires can be extinguished through water spray, fog, or foam but care needs to be taken to prevent environmental contamination from diluted water/runoff.

CORROSION

Ammonia is incompatible with various industrial materials, and in the presence of moisture reacts with and corrodes copper, brass, zinc and various alloys forming a greenish/blue color. Ammonia is an alkaline reducing agent and reacts with acids, halogens and oxidizing agents. Materials are to be carefully selected when ammonia is used onboard a vessel. Iron, steel and specific non-ferrous alloys resistant to ammonia should be used for tanks, pipelines and structural components where ammonia is used.

Stress corrosion cracking is induced and proceeds rapidly at high temperatures in steel when oxygen levels of more than a few ppm in liquid ammonia are introduced. The IGC Code outlines the requirements for piping components, cargo tanks and equipment in contact with ammonia liquid or vapor.

REGULATORY COMPLIANCE CONSIDERATIONS

IMO REGULATIONS

The IGC Code Section 16.9 addresses alternative fuels and technologies. It states that if acceptable to the administration, other cargo gases may be used as fuel, providing that the same level of safety as natural gas in the IGC Code is ensured. However, the use of cargoes identified as toxic products are not permitted. Ammonia is considered a toxic product and is currently not permitted for use under this code, which in the long-term will require amendment to align with what is already permitted under the International Code of Safety for Ships Using Gases or other Low-Flashpoint Fuels (IGF Code), and in the short-term will require discussions with the Flag Administration.

The IGF Code applies to ships to which Part G of International Convention for the Safety of Life at Sea, 1974, as amended (SOLAS) Chapter II-1 applies. The IGF Code has been developed on a prescriptive basis for the burning of natural gas. Other low flashpoint fuels may also be used as marine fuels, provided they meet the intent of the goals and functional requirements of the IGF Code and provide an equivalent level of safety.

THE IGF CODE ALTERNATIVE DESIGN PROVISION

The IGF Code currently does not provide prescriptive requirements to cover low flash point fuels such as NH_3. It does provide, the mechanism to approve alternative technical design arrangements for the use of low flash point fuels, pending acceptance by the Flag state.

Section 2.3 of the IGF code details the mechanism for approval of alternative technical design arrangements. The first step in this process is a preliminary Hazard Identification (HAZID) study at the preliminary design phase of the project to identify high level risk. This HAZID supports the Alternative Design process and follows established risk assessment methodologies to satisfy the IGF Code (ammonia as fuel) risk assessment requirements detailed under 4.2.1 and 4.2.3 of the IGF Code.

The risk assessment is to be performed to confirm that the risks from the use of the low flashpoint fuel affecting persons on board, the environment, and the structural strength or the integrity of the ship are addressed. The IGF Code requires that consideration be given to the hazards associated with physical layout, operation and maintenance following any reasonably foreseeable failure. The risk assessment should consider, as a minimum, loss of function, component damage, fire, explosion and electric shock.

The objective of the risk assessment as required by the IGF code is to help eliminate/mitigate any adverse effect to the person on board, the environment or the ship. Its scope in general covers:

- Equipment installed on board to receive, store, condition as necessary and transfer fuel to engines, boilers or other fuel consumers
- Equipment to control the operation
- Equipment to detect, alarm and initiate safety actions
- Equipment to vent, contain or handle operations outside of process norms
- Fire-fighting appliances and arrangements to protect surfaces from fire, fuel contact and escalation of fire
- Equipment to purge and inert fuel lines
- Structures to house equipment

Further guidance on the risk assessment requirements of the IGF Code are given in *International Association of Classification Societies* (IACS) Recommendation No.146 "Risk assessment as required by the IGF Code". For a fully developed design, the referenced SOLAS Regulation II-I/55 requires the submission of an engineering analysis to the Flag Administration based on the IMO Guidelines contained in MSC.1/Circ.1212. IMO has also provided further guidelines for the approval of alternative and equivalent designs required by various IMO instruments in MSC.1/Circ.1455.

Ultimately this formal documentation will be required to be submitted to the flag state for consideration, and subsequent communication to IMO through the Global Integrated Shipping Information System (GISIS) database. In this process flag state will be engaged with all stakeholders (designers, shipyard, owner, etc.) from an early stage to ensure all necessary processes are followed and documentation made available – see Figure 2 for the stakeholder involvement map from MSC.1/Circ.1455 and Figure 3 for an outline of the alternative design and approval process from MSC.1/Circ.1455.

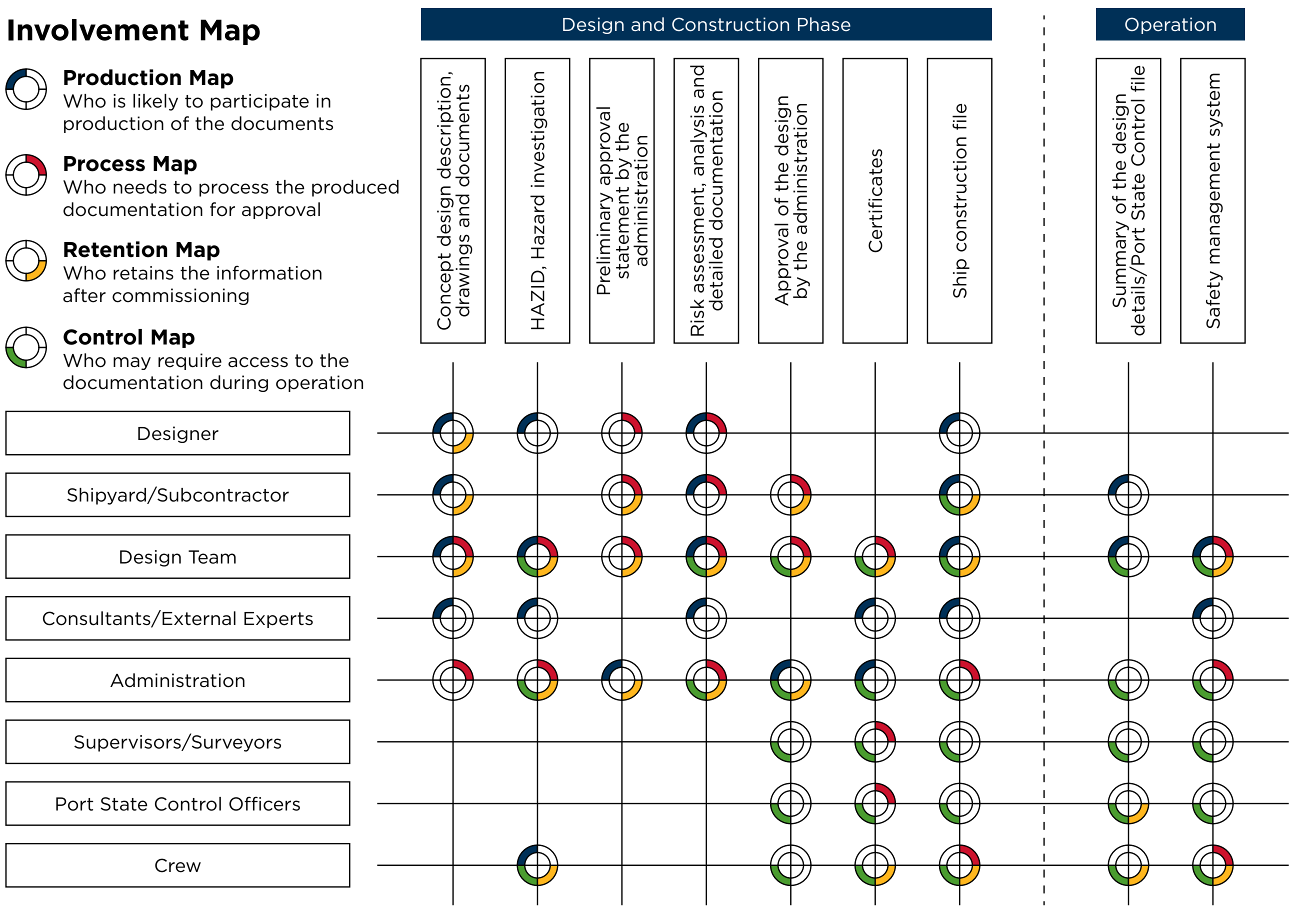

Figure 2: MSC.1/Circ.1455 Involvement Map

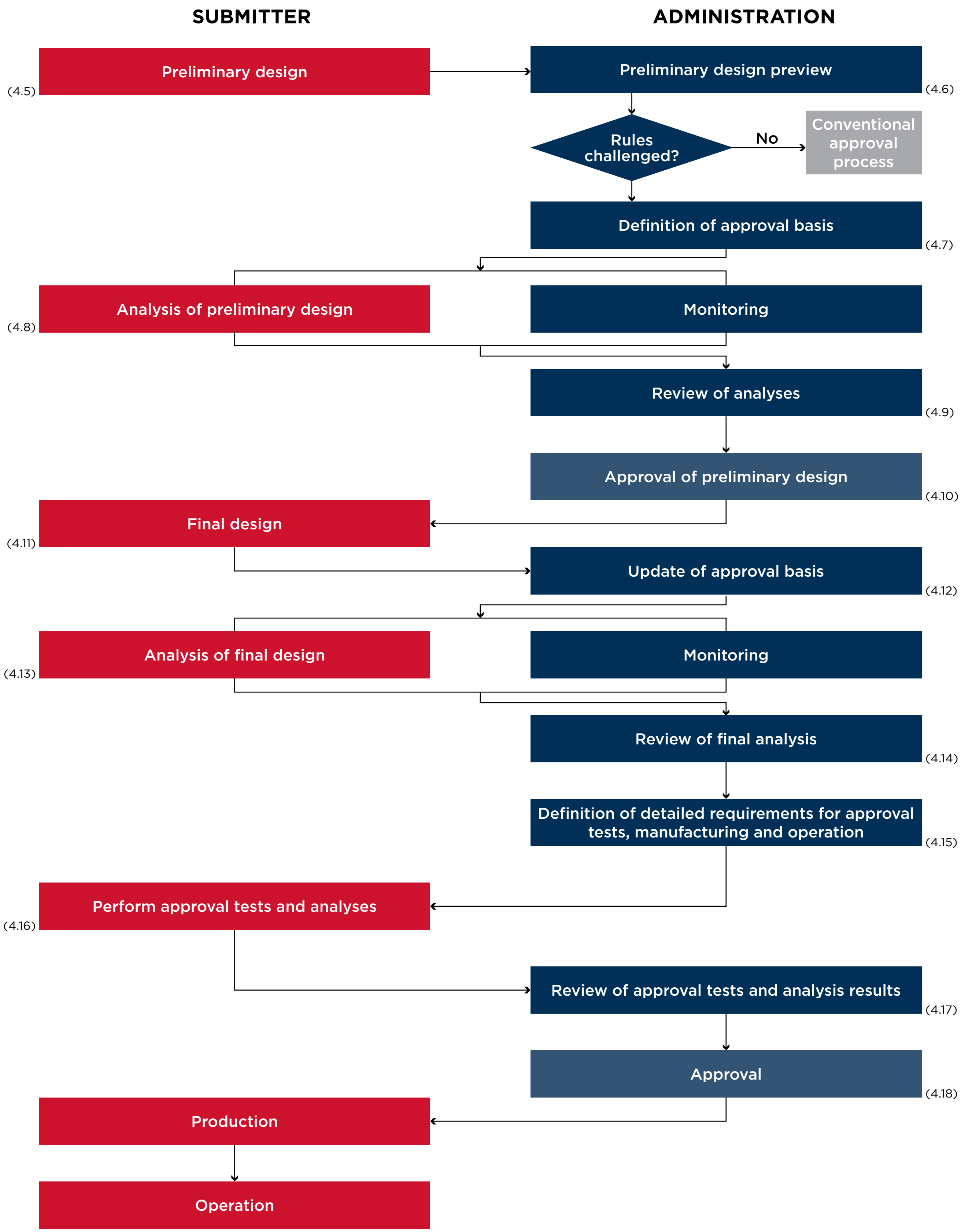

Figure 3: MSC.1/Circ.1455 Design and Approval Process

EXISTING ABS RULES FOR AMMONIA

Through the ABS *Guide for Gas and Other Low-Flashpoint Fuel Ready Vessels*, ABS offers Alternative Fuel Ready notations including the 'Ammonia Fuel Ready' notation. This Guide is to be applied to both new construction and existing vessel conversions utilizing gases or other low flashpoint fuels, including ammonia, regardless of size. The guide also applies to vessels burning conventional fuels but having design features suitable to permit conversion at a future date to a particular gas or other low flashpoint fuel burning concept based on existing Class requirements. Recognition and notations of this Guide will be offered to ships complying with the scope of the IGC Code on a case-by-case basis, provided such proposals are arranged in accordance with the requirements of the IGC Code and 5C-8 of the Marine Vessel Rules and with agreement of the Flag Administration.

The Rules for Vessels Using Gases or other Low-Flashpoint Fuels including Alternative Low Flashpoint Fueled Ship are covered under ABS Marine Vessel Rules (MVR) 5C-13-1/1.2 under the notation LFFS (Low Flashpoint Fueled Ship). The LFFS notation may be assigned where a vessel is arranged to burn a low flashpoint fuel other than natural gas for propulsion or auxiliary purposes and is designed, constructed and tested in accordance with the requirements of MVR 5C-13. The equivalence of the design is to be demonstrated by application of the Alternative Design criteria detailed under MVR 5C-13-2/3.

Other sections of the rules cover ammonia in different contexts like refrigeration (ABS MVR 5C-18-6, MVR 6-2-11 and MVR 7-9-1/1.1.2). These rules may be used as guiding principles when establishing design requirements including ventilation, emergency ventilation, deluge systems, dispersion study, storage, materials, personal protective equipment, vapor detection and alarm system etc.

To download the latest ABS Rules and Guides visit our Rules and Guides Database on www.eagle.org.

LAND-BASED USE REGULATIONS

Ammonia is the second most widely used chemical, supporting the production of fertilizers, pharmaceuticals, and many other chemical applications. It can be produced from fossil fuels such as natural gas as feedstock, or with renewables.

The United States Environmental Protection Agency issued a Chemical Safety Alert titled 'Hazards of Ammonia Releases at Ammonia Refrigeration Facilities' in August 2001. Lessons learned from this can be adapted to marine use. Hazard reduction strategies in that document (such as training programs, maintenance procedures, inspection procedures and ventilation procedures) may be adopted to marine systems, as applicable.

DESIGN CONSIDERATIONS

CONCEPT EVALUATION

Ammonia as a fuel has additional challenges before being commercially available for the non-gas carrier fleet. Although there are historical references for using ammonia as a fuel in IC engines, ammonia is in the early stages of development for marine propulsion. Ammonia-fueled engines are under development, and ammonia use is also being explored in fuel cells. Ammonia can be a zero-carbon fuel and provide solutions for decarbonization of the global fleet. Nevertheless, the cost of producing ammonia-based fuels and making them safe for marine use is being explored. Apart from the cost of adapting infrastructure, ammonia is toxic to humans and aquatic life. Thereby, considerable safety measures must be taken.

When used as fuel in IC engines, ammonia combustion predominantly produces water and nitrogen. Unburnt ammonia must be closely controlled and guidance on acceptable limits to avoid plume formation or human health hazards (see Table 3) can be drawn from other regulatory requirements, where limits of 2-10 ppm may be applied. IMO NOx limits would also be applicable upon combustion of ammonia.

Fuel containment, distribution and supply systems can be based on existing technologies and prescriptive requirements. In a liquid state, ammonia is not flammable and cannot ignite. However, it vaporizes rapidly, and the vapor has a narrow flammable range. The main concern is toxicity and additional measures are needed to control normal and abnormal discharges.

Understanding the requirements of ammonia gas including low-temperature service, pressurized storage tanks, flammable gases, and working with corrosive and toxic materials is key to addressing the safety hazards of using ammonia as a marine fuel. Some of the considerations when using ammonia as fuel on a vessel are listed below:

- Corrosion
- Design
- Equipment failure
- Cascading failures
- Safety management plan
- Personnel training to reduce human error

Ammonia tanks need to be designed for temperature and/or pressure control if ammonia is stored in a refrigerated condition, as ammonia continuously evaporates and generates boil-off gas due to heat gain, which increases pressure in tanks if not managed. Alternatively, ammonia can be stored in Type C tanks. Typical new fuel challenges apply to ammonia when used as a marine fuel. This includes crew training, bunkering availability, port discharge limit compliance, tank venting and planning for human exposure beyond permissible limits. These challenges need to be addressed during the Hazard Identification study when designing the vessel.

Advantages	Challenges
• Carbon free - no CO_2 or soot • Low flammability risk – 15.15% to 27.35% in air • Can be produced from electrical energy – renewable • Easily reformed to hydrogen and nitrogen • Can be stored and transported as a liquid at a practical pressure and temperature • Established commercial product	• Toxicity • Fuel infrastructure • Lack of regulations • Engine development at design stage • Cost • Corrosiveness to certain materials • Poor combustion characteristics for IC engine application • Possible need for high percentage of pilot fuel • Possible increased NOx emission • Possible ammonia slip

Table 4: Advantages and challenges of using ammonia as marine fuel

VESSEL ARRANGEMENTS

Future tankers, bulk carriers and container vessels will require holistic designs based on the selected fuels and power generation and propulsion systems. Novel power generation systems such as fuel cells may also change the architecture of the current engine room.

As ammonia has low energy content it will require larger tanks for storage and their location on board will be a critical design factor. When ammonia is used as a fuel, the changes in vessel arrangement are dependent on the location and type of ammonia tank/containment system. Cargo capacity also is expected to decrease based on the use of ammonia combustion engine or ammonia fuel cell arrangement employed. The additional space for fuel, due to lower energy density, may require larger vessels sizes, decreased cargo space or more frequent bunkering.

For ammonia fueled vessels, the specific vessel arrangements will vary depending on the actual fuel pressure and temperature settings of the fuel. The prime mover selected and fuel storage conditions will also affect vessel design. The link between the fuel storage, fuel preparation and fuel consumer is much more interdependent than with conventional fuels. It is critical that equipment and system design decisions consider this interdependence.

For ammonia fueled ships, the main systems the require different or additional concepts in ship designs are the ammonia fuel containment system, associated ammonia bunker station and transfer piping, a fuel supply system, boil-off gas handling, reliquefication, gas valve unit/train, nitrogen generating plant, vent piping systems and masts, and for some ammonia tank types, additional equipment for managing tank temperatures and pressure. Deluge systems, personal protective equipment, independent ventilation for ammonia spaces, emergency extraction ventilation and closed fuel systems may also be required.

A practical ammonia tank location that does not compromise safety or cargo capacity and operations is a challenge. Potential designs for ammonia vessels can be found in the ABS Outlook II publication.

VENTING AND GAS DISPERSION

Effective mechanical ventilation of the spaces where ammonia is used and stored is necessary. The ABS MVR 5C-18-6/3.3.3 may be used for initial guidance when conceptualizing the design. The ABS rules provide guidance on the independence of the ventilation system, manning, air changes, stopping of ventilation fans, closing the ventilation openings, air inlet positioning, exhaust duct positioning, etc.

The vent mast location can be a separate challenge because of the requirements for hazardous area zones around the vent mast exit and the physical location criteria for the ammonia tank pressure relief valve vents. These need to be at least 10 m from air intake openings, opening to accommodation, service and control spaces or other non-hazardous area and any exhaust system outlet.

When exhaust duct outlets cannot be positioned at least 10 m from the air intake openings, openings to accommodation spaces and other enclosed spaces, and at least 2 m (6.5 ft) above the open deck, the Rules allow the distance to be reduced to 3m provided a water deluge system and emergency response plan are provided and an approved gas dispersion study is conducted. See MVR 5C-18-6/3.3.6(vi).

Emergency ventilation rules are listed in MVR 5C-18-6/3.3.4 and may be used for preliminary guidance. However, a hazard identification study will need to be completed and only this can effectively assess all the risks pertaining to the vessel.

FUEL STORAGE

Ammonia maintains a liquid state either at -33.6 °C and 1 bar or 8.6 bar and 20 °C. Industrial scale storage uses low temperatures, which requires energy to maintain. This option may have a lower capital cost than pressurization in some cases, due to the lower storage design pressures. However, pressurized storage in Type C tanks (approximately 18 bar) may be a convenient marine solution and would eliminate the need for additional re-liquefaction equipment to be installed onboard.

Ammonia requires about 2.4 times more tank volume than Heavy Fuel Oil (HFO) to generate the same energy. Ammonia tanks need to comply with the requirements of the IGC and IGF Codes on minimum distances from the hull's shell, accommodation space, design and safety requirements, etc. However, as highlighted page 7, this is part of the risk assessment route to approval. The IGC Code contains specific material requirements for ammonia fuel containment under Section 17.12 and these would be expected to be applied, as applicable, for marine fuel storage tanks.

FUEL SUPPLY

The purpose of the fuel supply system (FSS) is to deliver fuel at the correct temperature and pressure to the engine. The use of low flashpoint fuels and gases introduces complexity to the fuel supply and consumer systems and creates a greater interdependence between the key systems over conventional fuel systems. For fuels using cryogenic/ pressurized liquefied storage, such as ammonia, the fuel can be pumped or pressure fed, directly in liquid form.

The FSS can be one of the more complex and expensive systems required for gas fueled applications. The FSS needs to ramp fuel supply quantities depending on the engine fuel demand. This transient fuel demand can be a challenge, particularly when maintaining fuel supply readiness in times of high demand or zero demand, without causing a shutdown of the FSS. It may also not be part of the engine Original Equipment Manufacturer (OEM) supply, but solely designed to comply with the engine OEM's specifications.

Liquid fuel systems can be simpler than gas systems. However, this not only depends on the properties of the fuel being used but also the prime mover technology.

PRIME MOVERS AND COMBUSTION

Ammonia can be burned either in an IC engine (compression ignition with pilot fuel/spark ignition) or used in fuel cells. Historically, ammonia was first demonstrated as a fuel for IC engines in 1822 in a locomotive. Later, during World War II, it was used in Belgium to fuel buses for public transportation.

Ammonia has a high auto-ignition temperature, a high heat of vaporization and a narrow flammability range. Due to these characteristics, ammonia typically requires a pilot fuel injection in two-stroke diesel cycle engines. High pressure injection systems can help to minimize ammonia slip, an important consideration given its toxicity.

When ammonia is combusted in compression ignition engines, significant amounts of NOx are generated due to the high temperatures and pressures involved. Nitrous oxide (N_2O) is a potent GHG with a greenhouse warming potential about 298 times greater than CO_2 for a 100-year period. Therefore, the ammonia fueled engine research and development needs to deliver an appropriate combustion technology and also evaluate the exhaust emissions to ensure NOx compliance with the regulatory limits, investigate possible issues with N_2O and control unburnt ammonia to levels acceptable in land based IC engines fitted SCR systems.

The use of ammonia in fuel cells is still relatively experimental. However, the current pace of development is accelerating, with large stationary plants currently under development. To use NH_3 in fuel cells, the hydrogen contained in the molecule must be separated out. Although it is possible to achieve this through an external reformer so that the hydrogen can be used in low temperature fuel cells such as a polymer electrolyte membrane (PEM), using ammonia directly in high-temperature fuel cells such as a solid oxide fuel cell (SOFC) can be a more efficient solution.

There are also other advantages of using ammonia in SOFC, such as high electrical efficiency, the absence of NOx production and the lack of vibration. Fuel cell development is not as mature as IC engines and typically has a higher cost. These factors are expected to show gradual improvement as research continues. An additional shortcoming of SOFC compared to PEM is the sensitivity of the solid oxide ceramic materials used to heat gradients, which requires relatively long and careful start up and shut down procedures and often lasts for hours. Ideally, SOFC plants should be run continuously to minimize the risk of permanent damage. This would typically require the use of batteries for energy storage to accommodate fluctuations in load demand.

Slow flame velocity, ignition temperature, narrow flammability range and lower heat of combustion are issues for ammonia ignition. Engine control strategies by engine manufacturers can address these issues. The advent of electronic engine controls and existing DF technologies, including the Diesel process used by MAN Energy Solution's ME-LGI engine shows promise in addressing these issues in the near future.

Ammonia has high heat of vaporization (1,371 kJ/kg), which results in considerable evaporative cooling of the mixture after injection and reduces the cylinder temperature at the start of combustion, helping to control NOx formation.

However, any benefit may be offset by the fuel-bound nitrogen, which may increase NOx formation, and the levels of N_2O that may be present as a result of combustion remain to be confirmed by engine research.

Burning ammonia in IC engines produces water, nitrogen, unburnt ammonia, and possible additional NOx. Even though the compound itself along with the combustion is carbon-free, these ammonia and NOx by-products need to be managed. The NOx produced may need to be treated with an after-treatment process. These engine and aftertreatment solutions would therefore need to meet existing NOx emissions limits and regulations.

BUNKERING

Bunkering is an indispensable operation, supplying fuel to a ship for use by the ship's machinery. Conventionally, any kind of fuel/oil used for this purpose is called a bunker fuel or bunker oil. Currently in the marine industry, ammonia is a bulk commodity frequently loaded/unloaded from gas terminals to ships and ships to gas terminals. The operation is similar to bunkering — the difference is that ammonia is transferred to a dedicated storage tank instead of a fuel tank.

As a new bunker fuel, ammonia will necessitate a complete establishment of provisions and guidelines for a successful start-up. It is foreseen that the previous experience from the fertilizer and chemical industry, and the recent development from LPG/LNG bunkering will help to inform the process. It is necessary to find gaps between established industry and marine bunkering context and solutions to align operations using technical and operational measures. Ammonia can be stored at liquid form pressurized, semi-refrigerated or fully refrigerated depending on the needed volume for safe storage, varying from small pressurized 1,000-gallon nurse tanks up to liquefied 30,000-ton storage tanks at distribution terminals.

During transfer from one tank to another, either "cold inbound" or "warm inbound" is chosen as a result of the transferred volume and re-refrigeration process. The capacity of an onshore full pressure non-refrigerated tank is usually limited. The overall handling can be energy intensive. Lessons learned have identified high risk areas such as leakage when handling and toxicity. Measures need to be taken to avoid leakage, handle toxicity and maintain equipment in good working condition through regular inspection.

The use of anhydrous ammonia in fertilizers, SCR reagents and refrigerants has provided enormous knowledge and experience in handling and transporting ammonia. This extensive established chemical/process industry infrastructure can be leveraged and extended to marine terminals and ports.

Due to the similar physical properties, operational experiences on LPG bunkering will provide additional useful guidance in creating ammonia bunkering procedures. Three modes of future ammonia bunkering via truck, tank or ship are envisaged. However, being chemically far from LPG, the safety aspect of ammonia will deserve a separate study that may benefit from the established chemical industry, where safety precautions, material compatibility and machinery are meticulously addressed.

ONGOING RESEARCH

PRIME MOVERS

WÄRTSILÄ FOUR-STROKE AMMONIA ENGINE

Wärtsilä in cooperation with Knutsen OAS Shipping AS and Repsol and the Sustainable Energy Catapult Centre is testing a full-scale ammonia fueled marine four-stroke combustion engine. The testing project will commence in the Sustainable Energy Catapult Centre's testing facilities at Stord, Norway during the first quarter of 2021.

MAN TWO-STROKE GREEN-AMMONIA ENGINE

MAN is collaborating with a Japanese university to assess the combustion and heat release characteristics of ammonia. MAN has introduced the ME-LGIM engine designed to operate on a DF combustion mode with methanol using diesel pilot fuel and has already accumulated thousands of hours of operation burning methanol on a number of methanol carriers. The ME-LGIP engine, which is designed to operate on LPG and closest to the expected configuration for burning ammonia, is also entering service for burning LPG on LPG carriers. The ME-LGIP engine can be used with ammonia with slight modifications to the fuel-delivery system to supply ammonia at approximately 70 bar and inject it into the cylinder at 600–700 bar. Ammonia slip will need to be carefully controlled. The high-pressure direct-injection systems used in DF engines, such as the MAN ME-LGIM and ME-LGIP, can inject fuel at optimum levels and timing to avoid ammonia slip. NOx emissions can be further reduced by using exhaust gas recirculation, or SCR aftertreatment for the exhaust gas. For more information on these prime movers refer to the ABS *Advisory on Gas and Other Low Flashpoint Fuels.*

To discover more about guidance on available technologies, regulatory requirements and installation and operational considerations for adopting gas or other low flash point fuels, download the *Advisory on Gas and Other Low Flashpoint Fuels*.

INDUSTRY PILOT PROJECTS

SHIPFC PROJECT TO CONVERT OFFSHORE VESSEL TO RUN ON AMMONIA POWERED FUEL CELL

The ShipFC project is being run by a consortium of 14 European companies and institutions has been awarded funding from the European Union's Research and Innovation program Horizon 2020 under its Fuel Cells and Hydrogen Joint Undertaking. The project will see Viking Energy, an offshore vessel, retrofitted with a 2MW ammonia fuel cell, allowing it to sail completely on clean fuel for up to 3,000 hours annually. It is a proof of concept project for long-range zero-emission large ship voyages. The ammonia fuel cell system will be installed in late 2023. Yara International is contracted to supply green ammonia produced by electrolysis. This will be delivered to Viking Energy in containers for easy and safe refueling. The project also tests the viability of sustainability sourced ammonia in a solid oxide fuel cell system for a commercial ship.

NIPPON YUSEN KAISHA LINE (NYK) EXAMINES CONCEPT OF USING AMMONIA AS MARINE FUEL

In January 2020, NYK presented its approach of using ammonia as marine fuel for zero-emission ships. NYK is also participating in the Japan's Green Ammonia Consortium established in April 2019 to consider not only the maritime transport of ammonia as a power generation fuel used by electric power companies but also the use of ammonia as marine fuel, one of the possible solutions for decarbonization. NYK made a presentation introducing ammonia as marine fuel from both the technical and operational side.

JAPAN'S ROADMAP TO ZERO EMISSIONS FROM INTERNATIONAL SHIPPING

The Japanese Ministry of Land, Infrastructure, Transport and Tourism formulated a roadmap for zero emissions of international shipping. This was done in cooperation with maritime industries including shipping, shipbuilding, research institutes and public institutions. International rule development, technological development, demonstrations and promotions would be conducted. They aim to commercialize a zero-emission ship by 2028. Two scenarios are detailed in this document. The first scenario is a fuel shift from LNG to carbon-recycled methane; in this case hydrogen/ammonia has a 10% share in contributing to a path to zero-emissions. In the second scenario there is an expansion of hydrogen and/or ammonia, which is expected to have a 45% share in the path to zero-emissions.


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MEMORANDUM OF UNDERSTANDING TO STUDY AMMONIA MARINE FUEL SUPPLY CHAIN IN SINGAPORE

ITOCHU ENEX, ITOCHU Corporation and Vopak Terminals Singapore Pte Ltd signed a memorandum of understanding to jointly study the feasibility of developing an infrastructure to support the use of ammonia as an additional source of marine fuel for vessels in Singapore. The project includes development of a zero-emission ship by ITOCHU and ITOCHU ENEX with other partners wherein:

- ITOCHU ENEX will promote the development of ammonia fuel supply chain
- ITOCHU will promote the development of offshore facility with ITOCHU ENEX and other partners.
- VOPAK will support ITOCHU in the feasibility study and promote development of an independent, onshore facility for the storage and handling of ammonia with loading/un-loading facilities.

PROJECTED ROLE OF AMMONIA AS MARINE FUEL

Zero carbon fuels such as ammonia and hydrogen have great potential to lower the carbon footprint of shipping: particularly when using the tank-to-wake criteria. However, one of the challenges of alternative fuels being considered, is their lower energy content compared to conventional fuel oils such as HFO. This is particularly a challenge for hydrogen; however with ammonia being a more volumetric efficient hydrogen carrier, it offers a potential practical zero carbon solution for shipping. The use of ammonia as a fuel is expected to grow due to its zero-carbon content, easier distribution, storage and bunkering compared to hydrogen, and its suitability with existing and emerging technologies for propulsion and power generation. The Figure 4 shows the projected marine fuel use until 2050 as the industry strives to meet the GHG emissions-reduction targets mandated by the IMO and is reprinted from the ABS Outlook II publication.

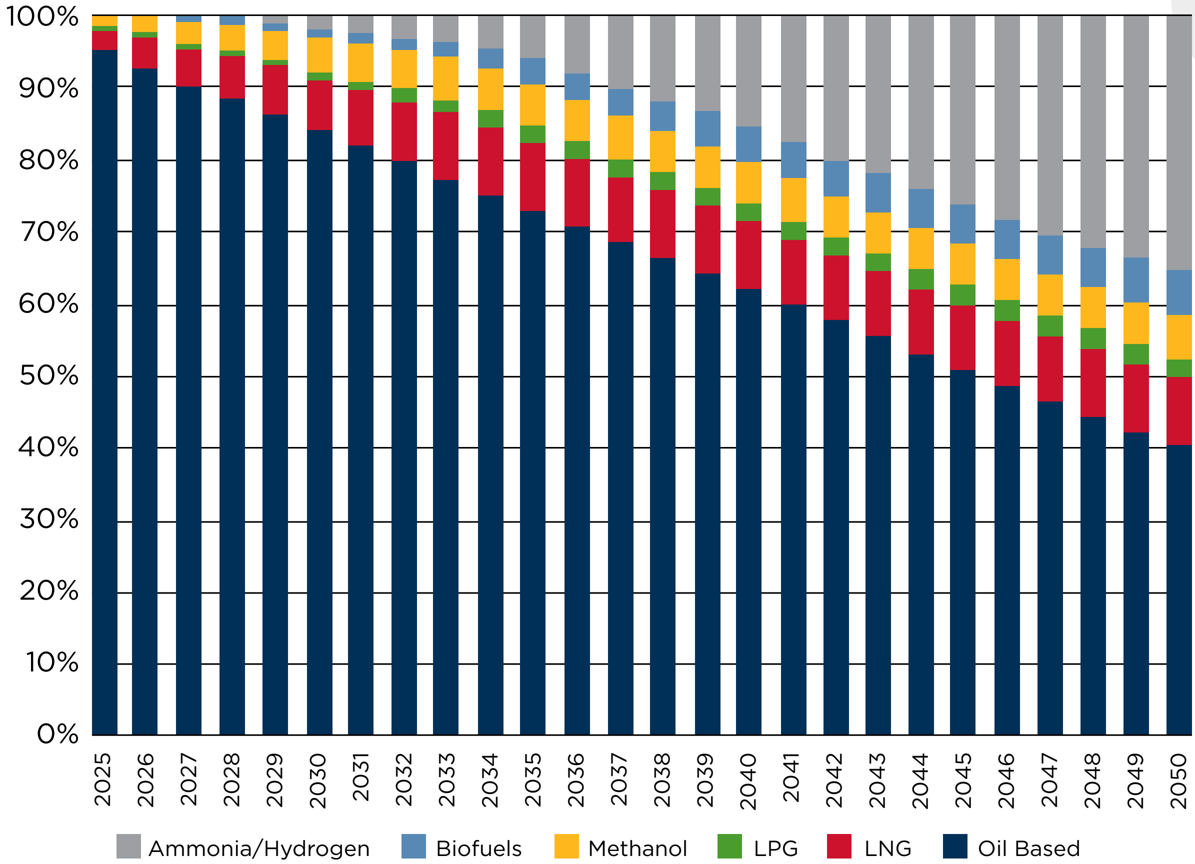

Figure 4 – Projected marine fuel use to 2050

PRELIMINARY STUDY ON ALTERNATIVE SHIP PROPULSION SYSTEM FUELED BY AMMONIA: ENVIRONMENTAL AND ECONOMIC ASSESSMENTS

A study entitled "*A Preliminary Study on an Alternative Ship Propulsion System Fueled by Ammonia: Environmental and Economic Assessments*" was published in March 2020 by Kim et.al. in the Journal of Marine Science and Engineering where four possible propulsion systems fueled by ammonia were proposed and compared. The study focused on fuel consumption, and economic and environmental aspects for a 2,500 TEU container feeder ship. Results showed that the ammonia-based ship would require more volume (1.6-2.3 times) and weight (1.4-1.6 times) than a conventional HFO-based ship, and cost 3.5-5.2 times more from a total lifecycle perspective. However, the NH_3-fueled ship could reduce GHG emissions by approximately 83.7-92.1%, depending on the propulsion type and the fuel production method used.

THE POTENTIAL ROLE OF AMMONIA AS MARINE FUEL—BASED ON ENERGY SYSTEMS MODELING AND MULTI-CRITERIA DECISION ANALYSIS

A special issue article titled "*The Potential Role of Ammonia as Marine Fuel–Based on Energy Systems Modeling and Multi-Criteria Decision Analysis*" was published in April 2020 by Hansson et.al. in the Sustainability Journal. The paper assessed ammonia's prospects as a marine fuel. Energy systems modeling including cost-effectiveness of ammonia as marine fuel as compared to other fuels in inching towards global targets were analyzed. The multi-criteria decision analysis methodologies used also considered fuel performance. The article concluded ammonia may to some extent be a marine fuel option.

ABS SUPPORT

LIST OF SERVICES OFFERED BY ABS

ABS can assist owners, operators, shipbuilders and original equipment manufacturers as they consider the practical implications of the use of ammonia as fuel. Services offered include:

- Risk assessment
- Regulatory and statutory compliance
- New technology qualifications
- Life cycle and cost analysis of ammonia fueled vessels
- Vessel/fleet benchmarking and identification of improvement options
- NOx emission reduction options
- EEDI verification and identification of improvement options
- Optimum voyage planning
- Alternative fuel adoption strategy
- Technoeconomic studies
- Cyber safety notations and assessments
- Contingency arrangement planning and investigations

APPENDIX I - BIBLIOGRAPHY

ABS PUBLICATIONS:

ABS. Advisory on Gas and Other Low Flashpoint Fuels.

ABS. Guide for Gas and Other Low-Flashpoint Fuel Ready Vessels, July 2020.

ABS. Guidance Notes on Gas Dispersion Studies of Gas Fueled Vessels, November 2019.

ABS. Marine Vessel Rules, July 2020.

ABS. Setting the Course to Low Carbon Shipping – 2030 Outlook/2050 Vision, June 2019.

ABS. Setting the Course to Low Carbon Shipping – Pathways to Sustainable Shipping, April 2020.

ABS. Bunkering of Liquefied Natural Gas-Fueled Marine Vessels in North America. 2nd Edition.

IACS DOCUMENTS:

IACS Recommendation No.146. Risk Assessment as Required by the IGF Code. August 2016.

IACS Unified Interpretation GF8. Control and maintenance of pressure and temperature of liquefied gas fuel tanks after the activation of the safety system. Dec 2017.

IMO DOCUMENTS:

IMO MARPOL Annex VI. Regulations for the Prevention of Air Pollution from Ships. Adopted by the Protocol of 1997, 15 to 26 September 1997.

IMO Resolution MEPC.251(66). Amendments to the Annex of the Protocol of 1997 to Amend the International Convention for the Prevention of Pollution from Ships, 1973, as Modified by the Protocol of 1978 Relating Thereto. Amendments to MARPOL Annex VI and the NOx Technical Code. (Amendments to Regulations 2, 13, 19, 20 and 21 and the Supplement to the IAPP Certificate under MARPOL Annex VI and certification of dual-fuel engines under the NOx Technical Code 2008). Adopted 4 April 2014.

IMO Resolution MSC.391(95) – Adoption of the International Code of Safety for Ships Using Gases or other Low-Flashpoint Fuels (IGF Code). Adopted 11 June 2015.

IMO MEPC 75/7/15. Reduction of GHG Emissions from Ships, Fourth IMO GHG Study 2020 – Final report. Dated 29 July 2020.

IMO CCC 7/INF.8. Forecasting the alternative marine fuel: Ammonia. Dated 10 July 2020.

IMO Circular MSC.1/Circ. 1558. Unified Interpretations of the IGF Code. Dated 28 November 2016.

IMO Circular MSC.1/Circ.1591. Unified Interpretations of the IGF Code. Dated 11 June 2018.

IMO Circular MSC.1/Circ. 1455. Guidelines for the Approval of Alternatives and Equivalents as Provided for in Various IMO Instruments. Dated 24 June 2013.

IMO Circular MSC.1/Circ.1212. Guidelines on Alternative Design and Arrangements for SOLAS Chapters II-1 and III. Dated 15 December 2006.

REGIONAL REQUIREMENTS:

USCG CG-521 Policy Letter No. 01-12. Equivalency Determination – Design Criteria for Natural Gas Fuel Systems. Dated 19 April 2012.

USCG CG-521 Policy Letter No. 01-12, CH-1. Equivalency Determination – Design Criteria for Natural Gas Fuel Systems (Change 1). Dated 12 July 2017.

United States Federal Register 78 FR 52192, Final Aquatic Life Ambient Water Quality Criteria For Ammonia - Freshwater 2013

INDUSTRY GUIDANCE:

STANDARDS

ISO 14040:2006. Environmental management – Life cycle assessment – principles and framework

ISO 14044:2006. Environmental management – Life cycle assessment – requirements and guidelines

PUBLICATIONS

National Institute of Standards and Technology. NIST Handbook 135. 1995. Life-Cycle Costing Manual

International Energy Agency, The Future of Hydrogen, 2019

International Renewable Energy Agency, Global Renewables Outlook, April 2020

Ammonfuel - An industrial view of ammonia as a marine fuel by Alfa Laval, Hafnia, Haldor Topsoe, Vestas, Siemens Gamesa. Dated August 2020.

Khan, A S, Kelley, R D, Chapman, K S, & Fenton, D L. Flammability limits of ammonia-air mixtures, United States Department of Energy Office of Scientific and Technical Information.

Japanese Ministry of Land, Infrastructure, Transport and Tourism, Roadmap to Zero Emission from International Shipping, March 2020, can be found online at https://www.mlit.go.jp/common/001354314.pdf

MAN Energy Solutions, Engineering the future two-stroke green-ammonia engine, can be found online at https://man-es.com/docs/default-source/marine/tools/engineering-the-future-two-stroke-green-ammonia-engine.pdf?sfvrsn=2b4d9d8a_10

Roadmap to decarbonizing European Shipping, a study by Transport & Environment, November 2018, can be found online at https://www.transportenvironment.org/publications/roadmap-decarbonising-european-shipping

Davenne, Tristan & Greenwood, Simeon & Wood, Thomas & David, Bill & Makepeace, Joshua. (2020). Feasibility Study, Ammonia to Green Hydrogen Project, can be found online at https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/880826/HS420_-_Ecuity_-_Ammonia_to_Green_Hydrogen.pdf

Bossel U. and Eliasson B., "Energy and the Hydrogen Economy", can be found online at https://afdc.energy.gov/files/pdfs/hyd_economy_bossel_eliasson.pdf

Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D.W., Haywood, J., Lean, J., Lowe, D.C., Myhre, G., Nganga, J., Prinn, R., Raga, G., Schulz, M., & Van Dorland, R. Miller, H.L. (Ed.). (2007). Changes in Atmospheric Constituents and in Radiative Forcing Chapter 2. United Kingdom: Cambridge University Press.

National Research Council (US) Committee on Acute Exposure Guideline Levels. Acute Exposure Guideline Levels for Selected Airborne Chemicals: Volume 6. Washington (DC): National Academies Press (US); 2008. 2, Ammonia Acute Exposure Guideline Levels, can be found online at https://www.ncbi.nlm.nih.gov/books/NBK207883/

United States National Center for Biotechnology Information (2020). PubChem Compound Summary for CID 222, Ammonia. Retrieved September 2, 2020, can be found online at https://pubchem.ncbi.nlm.nih.gov/compound/Ammonia

United States Geological Survey, National Minerals Information Center, Mineral Commodity Summaries, Nitrogen (Fixed)-Ammonia, January 2020, can be found online at https://pubs.usgs.gov/periodicals/mcs2020/mcs2020-nitrogen.pdf

United States National Institute for Occupational Safety and Health (NIOSH), Immediately Dangerous To Life or Health (IDLH) Values – Ammonia, can be found online at https://www.cdc.gov/niosh/idlh/7664417.html

United States Energy Information Administration, Few transportation fuels surpass the energy densities of gasoline and diesel, Dated January 03, 2014 can be found online at https://www.eia.gov/todayinenergy/detail.php?id=14451

United States Environmental Protection Agency, Chemical Safety Alert: Hazards of Ammonia Releases at Ammonia Refrigeration Facilities. Dated August 2001, can be found online at https://www.epa.gov/sites/production/files/2013-11/documents/ammonia.pdf

JOURNAL ARTICLES

Hansson, J.; Brynolf, S.; Fridell, E.; Lehtveer, M. The Potential Role of Ammonia as Marine Fuel—Based on Energy Systems Modeling and Multi-Criteria Decision Analysis. Sustainability 2020, 12, 3265.

Kim, K.; Roh, G.; Kim, W.; Chun, K. A Preliminary Study on an Alternative Ship Propulsion System Fueled by Ammonia: Environmental and Economic Assessments. J. Mar. Sci. Eng. 2020, 8, 183.

Pavlos Dimitriou, Rahat Javaid; A review of ammonia as a compression ignition engine fuel, International Journal of Hydro Energy 45 (2020) 7098-7118

Armijo, Julien & Philibert, Cédric. (2019). Flexible production of green hydrogen and ammonia from variable solar and wind energy. Case study of Chile and Argentina. 10.1016/j.ijhydene.2019.11.028.

Acar, Canan & Dincer, Ibrahim. (2013). Comparative assessment of hydrogen production methods from renewable and non-renewable sources. International Journal of Hydrogen Energy. 39. 1-12. 10.1016/j.ijhydene.2013.10.060.

Kobayashi, Hideaki & Hayakawa, Akihiro & Somarathne, Kunkuma & Okafor, Ekenechukwu. (2018). Science and technology of ammonia combustion. Proceedings of the Combustion Institute. 37. 10.1016/j.proci.2018.09.029.

A Valera-Medina, H Xiao, M Owen-Jones, W.I.F. David, P.J. Bowen, Ammonia for power, Progress in Energy and Combustion Science, Volume 69, 2018, Pages 63-102, ISSN 0360-1285, https://doi.org/10.1016/j.pecs.2018.07.001.

PRESENTATIONS

R. Hattenbach, Transportation & Delivery of Anhydrous Ammonia by Ray Hattenbach Chemical Marketing Services, Inc., Transportation (Amst)., 2005.

D. Webb, Large Scale Ammonia Storage and Handling, pp. 1–37, 2008.

Masterclass Ammonia Safety Webinar Presentation, Ammonia Energy Association. Dated 28 May 2020

Department of Mechanical Engineering, Iowa State University, Characteristics of an SI Engine Using Direct Ammonia Injection, can be found online at https://nh3fuelassociation.org/wp-content/uploads/2013/10/nh3fcx-song-charng-kong.pdf

Marine Fuels Webinar Week Presentation on Ammonia. Riviera Maritime Media. Dated 1 July 2020, can be found online at https://www.rivieramm.com/webinar-library/marine-fuel/ammonia-fuels-webinar-1

How to Handle Anhydrous Ammonia, Accessed April 09, 2020, can be found online at https://www.wikihow.com/Handle-Anhydrous-Ammonia

THESIS

Niels de Vries, Master’s Thesis at C-Job Naval Architects and TU Delft, Safe and effective application of ammonia as a marine fuel, can be found online at http://resolver.tudelft.nl/uuid:be8cbe0a-28ec-4bd9-8ad0-648de04649b8

Emtiaz Ali Brohi, Chalmers University of Technology, “Ammonia as fuel for internal combustion engines?” Applied Mechanics, Master’s Thesis 2014:55

PRESS ARTICLES

Press release article, June 12, 2020, ITOCHU group and Vopak Singapore to sign Memorandum of Understanding to study ammonia marine fuel supply chain in Singapore, can be found online at https://www.itochu.co.jp/en/news/press/2020/200612.html

Press release article, January 30, 2020, Nippon Yusen Kaisha Line, NYK Examines Concept of Using Ammonia as Marine Fuel, can be found online at https://www.nyk.com/english/news/2020/20200130_02.html

Press release article, January 23, 2020, Fuel Cells and Hydrogen Joint Undertaking, Major project to convert offshore vessel to run on ammonia-powered fuel cell, can be found online at https://www.fch.europa.eu/press-releases/major-project-convert-offshore-vessel-run-ammonia-powered-fuel-cell

Press release article, June 30, 2020, Wärtsilä, World’s first full scale ammonia engine test - an important step towards carbon free shipping, can be found online at https://www.wartsila.com/media/news/30-06-2020-world-s-first-full-scale-ammonia-engine-test---an-important-step-towards-carbon-free-shipping-2737809

Press article by Marcus Hand at Seatrade Maritime News, Dec 04, 2019, can be found online at https://www.seatrade-maritime.com/shipbuilding/lr-man-and-dsic-cooperate-ammonia-fuelled-ultra-large-containership-design

Newsletter, Hofstrand, D. Ammonia as a Transportation Fuel, 2009, can be found online at https://www.agmrc.org/renewable-energy/renewable-energy-climate-change-report/renewable-energy-climate-change-report/may-2009-newsletter/ammonia-as-a-transportation-fuel

Online article, Hinokuma, S. New catalyst turns ammonia into an innovative clean fuel, April 2018, can be found online at https://phys.org/news/2018-04-catalyst-ammonia-fuel.html

Online article, B. Wheeler, Safe handling of anhydrous ammonia, Power Eng. (Barrington, Illinois), vol. 114, no. 6, pp. 44–46, 2010.

APPENDIX II - LIST OF ACRONYMS AND ABBREVIATIONS

ABS	American Bureau of Shipping
CO_2	Carbon dioxide
DF	Dual Fuel
FSS	Fuel Supply System
GHG	Green House Gas
GISIS	Global Integrated Shipping Information System
GREET	Greenhouse gases, Regulated Emissions and Energy use in Transportation
GV	Gas Valve Unit
HAZID	Hazard Identification
HFO	Heavy Fuel Oil
IACS	International Association of Classification Societies
IC	Internal Combustion
IDLH	Immediately Dangerous to Life or Health
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
IMO	International Maritime Organization
ISO	International Organization for Standardization
LFFS	Low Flashpoint Fueled Ship
LNG	Liquified Natural Gas
LPG	Liquified Petroleum Gas
MAN	MAN Energy Solutions
MARPOL	The International Convention for the Prevention of Pollution from Ships
ME-GI	MAN engine identifier – M series Electronic Gas Injection
MEPC	Marine Environment Protection Committee (IMO)
MSC	Maritime Safety Committee (IMO)
MVR	Marine Vessel Rules
NH_3	Ammonia
NIOSH	National Institute for Occupational Safety and Health
NIST	National Institute of Standards and Technology
N_2O	Nitrous Oxide
NOx	Nitrogen Oxides
NYK	Nippon Yusen Kaisha
OEM	Original Equipment Manufacturer
Outlook I	ABS publication on *"Setting the Course to Low Carbon Shipping: 2030 Outlook/2050 Vision"*
Outlook II	ABS publication on *"Setting the Course to Low Carbon Shipping: Pathways to Sustainable Future"*
PEM	Polymer Electrolyte Membrane
PM	Particulate Matter
ppm	parts per million
SCR	Selective Catalytic Reduction
SOFC	Solid Oxide Fuel Cell
SOLAS	International Convention for the Safety of Life at Sea, 1974, as amended
SOx	Sulfur Oxides
STS	Ship to Ship
TEU	Twenty-foot Equivalent Unit
USCG	United States Coast Guard

APPENDIX III - FOOTNOTES OF TABLE 3

AMMONIA ACUTE EXPOSURE GUIDELINE LEVELS - STANDARDS AND GUIDELINES - FOOTNOTES

a. Under the authority of the United States Federal Advisory Committee Act (P.L. 92-463) of 1972, the National Advisory Committee for Acute Exposure Guideline Levels (AEGL) for Hazardous Substances has been established to identify, review, and interpret relevant toxicological and other scientific data and develop acute exposure guideline levels (AEGLs) for high-priority, acutely toxic chemicals. AEGLs represent threshold exposure limits for the general public.

b. AEGL-1 is the airborne concentration (expressed as parts per million [ppm] or milligrams per cubic meter [mg/m^3]) of a substance above which it is predicted that the general population, including susceptible individuals, could experience notable discomfort, irritation, or certain asymptomatic non-sensory effects. However, the effects are not disabling and are transient and reversible upon cessation of exposure.

c. AEGL-2 is the airborne concentration (expressed as ppm or mg/m^3) of a substance above which it is predicted that the general population, including susceptible individuals, could experience irreversible or other serious, long-lasting adverse health effects or an impaired ability to escape.

d. AEGL-3 is the airborne concentration (expressed as ppm or mg/m^3) of a substance above which it is predicted that the general population, including susceptible individuals, could experience life-threatening health effects or death.

e. ERPG (emergency response planning guideline, American Industrial Hygiene Association) (AIHA 2000). The ERPG-1 is the maximum airborne concentration below which it is believed nearly all individuals could be exposed for up to 1 h without experiencing other than mild, transient adverse health effects or without perceiving a clearly defined objectionable odor. The ERPG-1 for ammonia is based on a concentration associated with a mild odor perception or mild irritation. The ERPG-2 is the maximum airborne concentration below which it is believed nearly all individuals could be exposed for up to 1 h without experiencing or developing irreversible or other serious health effects or symptoms that could impair an individual's ability to take protective action. At the ERPG-2 level, ammonia will likely have a strong odor and cause some eye and upper respiratory irritation in susceptible populations, but serious effects are unlikely. The ERPG-3 is the maximum airborne concentration below which it is believed nearly all individuals could be exposed for up to 1 h without experiencing or developing life-threatening health effects. The ERPG-3 for ammonia is based on the median lethal concentrations of 7,340-16,600 ppm for rats and 4,230-4,840 ppm in mice. This concentration may cause respiratory distress and severe eye and nasal irritation.

f. EEGL (Emergency exposure guidance level, National Research Council) (NRC 1987). The EEGL is the concentration of contaminants that can cause discomfort or other evidence of irritation or intoxication in or around the workplace but avoids death, other severe acute effects, and long-term or chronic injury. The EEGL for ammonia is based on effects experienced by subjects exposed to it at 140 ppm for up to 2 h.

g. PEL-TWA (permissible exposure limit-time-weighted average, Occupational Health and Safety Administration) (OSHA 1999) is defined analogous to the ACGIH TLV-TWA but is for exposures of no more than 10 hours per day, 40 hours per week.

h. IDLH (immediately dangerous to life and health, National Institute of Occupational Safety and Health) (NIOSH 1997) represents the maximum concentration from which one could escape within 30 min without any escape-impairing symptoms or any irreversible health effects. The IDLH for ammonia is based on acute toxicity data in humans.

i. REL-TWA (recommended exposure limit-time-weighted average, National Institute of Occupational Safety and Health) (NIOSH 1997) is defined analogous to the ACGIH TLV-TWA. NIOSH recommendations are not enforceable.

j. REL-STEL (recommended exposure limit-short-term exposure limit) (NIOSH 1997) is defined analogous to the ACGIH TLV-STEL. NIOSH recommendations are not enforceable.

k. TLV-TWA (American Conference of Governmental Industrial Hygienists, Threshold Limit Value-time-weighted average) (ACGIH 2001) is the time-weighted average concentration for a normal 8 hour workday and a 40 hour workweek, to which nearly all workers may be repeatedly exposed, day after day, without adverse effect.

l. TLV-STEL (Threshold Limit Value-short-term exposure limit) (ACGIH 2001) is defined as a 15-min TWA exposure, which should not be exceeded at any time during the workday even if the 8 hour TWA is within the TLV-TWA. Exposures above the TLV-TWA up to the STEL should not be longer than 15 min and should not occur more than four times per day. There should be at least 60 minutes between successive exposures in this range.

m. MAK (maximale arbeitsplatzkonzentration [maximum workplace concentration]) (Deutsche Forschungsgemeinschaft [German Research Association] 2000) is defined analogous to the ACGIH TLV-TWA.

n. MAC (maximaal aanvaarde concentratie [maximal accepted concentration]) (SDU Uitgevers [under the auspices of the Ministry of Social Affairs and Employment], The Hague, The Netherlands 2000) is defined analogous to the ACGIH TLV-TWA.

o. OELV (occupational exposure limit value) (Swedish National Board of Occupational Safety and Health 1996) is the maximum acceptable average concentration (time-weighted average) of an air contaminant in respiratory air. An occupational exposure limit value is either a level limit value (one working day) or a ceiling limit value (15 min or some other reference time period).

p. SMACs (spacecraft maximum allowable concentrations) (NRC 2000) provide guidance on chemical exposures during normal operations of spacecraft as well as emergency situations. Short-term (1-24 hours) SMACs refer to concentrations of airborne substances (such as a gas, vapor, or aerosol) that will not compromise the performance of specific tasks by astronauts during emergency conditions or cause serious or permanent toxic effects. Such exposures may cause reversible effects such as mild skin or eye irritation but are not expected to impair judgment or interfere with proper responses to emergencies. The 1- and 24-hour SMACs are based on concentrations that would cause only slight mucosal irritation (Wong 1995).

q. United States Occupational Safety and Health Administration. This is the standard that must be met in every workplace in the United States. The OSHA Permissible Exposure Limit (PEL) for Anhydrous Ammonia is based on a full shift, 8 hour time weighted average (TWA) exposure.

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