# The use of methanol as a fuel: the impact on operational safety onboard

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# Preface:

As a student of the Antwerp Maritime Academy, I was able to attend various courses that dealt with safety and some technical systems used in the maritime field. When the time came to choose a topic for my thesis, my promoters told me that methanol was being developed as a potential fuel for engine conversion. As soon as I heard this, I was motivated to learn more about this subject. I saw an opportunity to explore the intersection of safety concepts with the unique properties and challenges associated with methanol.

Having a comprehensive understanding of the various aspects related to operational safety when using methanol as a fuel can greatly benefit my future profession in the maritime industry. As I will be exposed to new and different safety systems on a daily basis, having knowledge and expertise in methanol safety will allow me to effectively adapt to these evolving technologies. Therefore, I decided to develop my thesis on exploring the impact of methanol on operational safety aboard vessels. To delve deeper into this subject, I conducted insightful interviews with individuals who are actively involved in this field of research.

I would like to thank all the following people who helped me in any way in the writing of this thesis. In particular Mr. Potters and Mrs. Verstraelen, my supervisors who guided me in my research. I had the opportunity to interview Patrik Molander, a naval architect at ScandiNAOS ship design company, who provided me valuable insights into the different regulations and their implications. Mr. Decrop, a highly experienced chief engineer, helped me to understand various safety systems. Mr. Pennman, a naval architect involved in conversion of engine to methanol fuel, shared interesting details based on the experience of Stena Bulk company. Mr. Jonkers from Methanex and Mr. Beernaert from De Wit bunkering, explained the transportation chain from production facilities to the methanol cargo tank on board vessels in a clear and comprehensive manner.

# Résumé :

Ce document de recherche examine l'impact du méthanol en tant que carburant sur la sécurité opérationnelle à bord des navires. Alors que la demande de carburants plus propres et durables dans le secteur maritime augmente, le méthanol émerge comme une alternative prometteuse en raison de ses avantages environnementaux et de sa compatibilité avec les moteurs existants. Cependant, l'adoption du méthanol soulève des questions sur la sécurité opérationnelle et nécessite une évaluation approfondie des mesures de sécurité requises pour son utilisation efficace.

La recherche aborde plusieurs aspects liés à l'impact du méthanol sur la sécurité à bord des navires en examinant les réglementations et les normes en vigueur pour son utilisation, ainsi que la complexité liée à son intégration dans les opérations maritimes. Les différents systèmes de sécurité, les procédures de gestion des risques et les formations requises pour les équipages sont également analysés. Des études de cas et des expériences de professionnels impliqués dans la transition vers des opérations maritimes utilisant le méthanol sont développées.

L'analyse de l'impact du méthanol sur la sécurité opérationnelle révèle que des systèmes de sécurité et des règles ont été développés pour permettre une utilisation sécurisée du méthanol comme carburant à bord des navires.

# Abstract:

This research document analyses the impact of methanol as a fuel on operational safety on board ships. As the demand for cleaner and more sustainable fuels in the maritime sector increases, methanol is emerging as a promising alternative due to its environmental benefits and compatibility with existing marine engines. However, the adoption of methanol raises questions about operational safety and requires a thorough assessment of the safety measures required for its effective use.

The research develops several aspects of the impact of methanol fuel on the safety onboard vessels by examining the regulations and provisions in place for its use, as well as the complexities involved in integrating it into maritime operations. The various safety systems, risk management procedures and training required for crews are also analyzed. Case studies and experiences of professionals involved in the transition to maritime operations using methanol are developed.

The analysis of the impact of methanol on operational safety reveals that safety systems and rules have been developed to enable the safe use of methanol as a fuel on board ships.

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# List des acronyms and abbreviations:

- ADH: alcohol dehydrogenase
- BLEVE: Boiling Liquid Expanding Vapor Explosion
- CSS: carbon capture and storage
- DMFCs: direct methanol fuel cells
- DME: dimethyl ether
- EGR: exhaust gas recirculation
- ESD: emergency shutdown
- GHG: greenhouse gases
- HAZID: Hazard Identification
- HFO: heavy fuel oil
- ICE: internal combustion engine
- LEL: lower explosive limit
- MAWP: maximum allowable working pressure
- MMO: methane monooxygenases
- MTBE: methyl tert-butyl ether
- MMT: million metric ton
- $NO_{x:}$ nitrogen oxides
- PIC : person in charge
- PM: particles matte

- PPE: personal protective equipment
- PSA: pressure swing adsorption
- P/V valves: pressure vacuum valves
- SCC: stress corrosion cracking
- SCR: selective catalytic reduction
- SMR: steam methane reformation
- SOEC: solid oxide electrolysis cells
- SOFC: solid oxide fuel cells
- $SO_x$: sulphur oxides
- SSL: ship shore link
- VLSFO: very low sulphur fuel oil

# 1. Introduction

The shipping industry predominantly relies on non-renewable fossil fuels, which have a substantial environmental impact. However, a shift towards alternative fuels presents a potential solution for rapidly reducing emissions. Methanol has emerged as a promising solution for utilizing renewable fuel sources in the shipping industry (Svanberg et al., 2018). With its potential to be derived from sustainable feedstocks such as biomass, methanol offers a clean pathway of production to significantly reduce carbon emissions at its production. Moreover, methanol combustion produces lower emissions of particulate matter and sulphur oxides compared to conventional fossil fuels.

A comprehensive overview of the different ways to produce methanol with their related ecological impact is provided, as well as an in-depth exploration of the sustainability aspects of methanol. The chapter explains also the use of methanol as a fuel in engines and the resulting emissions. At the end of the chapter, the weaknesses of methanol are thoroughly discussed, shedding light on the reasons behind the implementation of various safety systems for its use as a fuel. These main weaknesses include its toxicity, its corrosive behaviour, its lower energy density, is flammability.

The previous chapter provides the various properties and weaknesses of methanol. However, the remaining challenge lies in the adaptation and implementation of methanol onboard vessels. Given the weaknesses associated with methanol, its use onboard represents a significant challenge that necessitates careful attention to ensure safety. The objective of this thesis is to examine the impact of methanol on operational adaptation and safety aboard methanol-powered vessels. Addressing this issue requires a comprehensive understanding of the operational aspects and safety implications of using methanol as a fuel.

Key areas of this research focus on the development and implementation of safety guidelines, the adoption of appropriate safety system and training programs for crew members to facilitate the safe handling of methanol.

Various safety aspects related to the utilization of methanol as a fuel are examined. The rules governing the utilization of methanol as a fuel onboard ship, such as the interim guidelines provided by the IMO, are elucidated through the insights of individuals who have hands-on experience in this field. The approach adopted by ship design companies when converting vessels to methanol fuel, is provided with valuable insights into the process. The associated challenges in implementing the regulations governing the use of methanol as a fuel are developed. The experiences and opinions of individuals actively involved in the development of methanol as a fuel are given. Technical considerations, alternatives safety solutions, and operational adjustments are proposed. Practical examples of successful vessel conversions to methanol fuel are explained.

By examining the impact of methanol on operational adaptation and safety onboard vessels, this thesis aims to provide valuable information concerning the challenges associated with using methanol as a fuel. This research with the integration of technical knowledges, regulatory insights, and real-world experiences provides suitable solutions to use safely methanol as a fuel on board vessels.

# 2. Methanol

In this chapter, various aspects of methanol, including its production methods, emissions, use as a fuel, and the associated drawbacks when used as a fuel source.

Methanol ($CH_3OH$) is also known as methyl alcohol, or wood alcohol because methanol can be made from wood matter. It is a light flammable liquid with a distinctive smell (Dalena et al., 2018). Methanol is readily biodegradable in both aerobic and aquatic environments (Plevrakis, 2021). At ambient conditions, methanol remains in liquid form with a medium vapor pressure and can be used as an organic solvent (Ott et al., 2012). One of its advantages is its liquid state at ambient temperature (Bos et al., 2020). Methanol has a density of 792 kg/m$^3$ and its boiling point is about 65°C (Ott et al., 2012).

## 2.1 Production

Methanol synthesis is the process of producing the different types of methanol (Cui et al., 2022). There are different concepts of methanol synthesis but there are all based on principle of the conversion of $H_2$, CO and $CO_2$ to methanol in contact with a catalyst. The choice of the $H_2$ source, the catalyst type and the operating pressure will define the synthesis process used (Mannan, 2012). In any case, the synthesis consists of the reaction between $CO_2$ and $H_2$ to produce methanol. The $CO_2$ used can be provided from the Carbon Capture and storage technology and $H_2$ can be taken from renewable way of producing as the water electrolysis.

In order to know the production process more easily, the industry introduced a color-coding scheme to distinguish the different energies and processes used for producing methanol. By using this colour-coding, it will be easier to recognise the type of methanol that is involved in the research.

The main types of methanol production are listed below (Mamalis et al., 2021):

- *GREEN:* refers to methanol produced with renewable energies.
- *E-METHANOL:* refers to methanol produced from renewable electricity
- *BLUE*: represents the methanol produced from fossil sources using emissions-control technologies, such as carbon capture and storage.
- *GREY*: represents to the methanol produced from fossil sources without emissions-control technologies.
- *ORANGE*: refers to a blend of blue, grey or green methanol.
- *BLACK/BROWN:* refers to methanol produced from coal sources (Marchant, 2021).

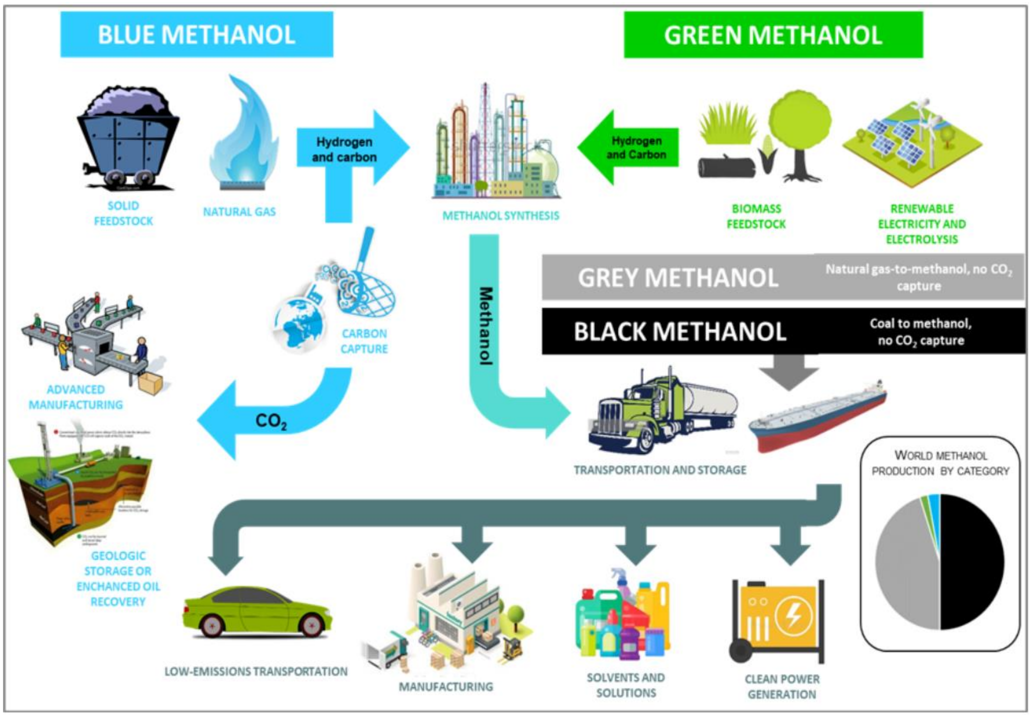


*Figure 1 Different production methods of methanol*

*Source: (Blue Methanol, 2021)*

**Green methanol**, also called bio-methanol, is produced with a feedstock composed of biomass matter such as wood, sewage sludge, municipal solid waste (Plevrakis, 2021). Biomass is a term that includes a range of different feedstocks suitable for biofuel production processes (Roode-Gutzmer et al., 2019).

Bio-methane (CH4) coming from the biodegradation of the biomass is put in the reaction Equation 1 to produce bio-methanol. Other elements as dioxygen and hydrogen are also engaged in the production reaction Equation 1 of green methanol. The origin of the hydrogen can be from water electrolysis.

$$CH_4 + O_2 + 2e^- + 2H^+ \rightarrow (MMO)\ CH_3OH + H_2O \qquad \textit{(Equation 1)}$$

where the reaction is catalysed by a methane monooxygenase (MMO), the only enzyme known to catalyse biological methane conversions (Lawton & Rosenzweig, 2016). A catalyst material is used to speed up the chemical reaction by lowering the activation energy (Richardson, 2013). Thus, methanol and water are obtained.

**E-methanol** is produced from renewable electricity (from wind or solar power) and $CO_2$ captured from the atmosphere combined with water. E-methanol is considered a sustainable fuel solution because it uses a renewable energy source and does not contribute to increased $CO_2$ emissions into the atmosphere.

The chemical equation Equation 2 for the production of e-methanol depends on the process used, but here is a general equation:

$$CO_2 + 2H_2O + \text{electricity} \rightarrow CH_3OH + 3/2\ O_2 \qquad \textit{(Equation 2)}$$

In simple terms, carbon dioxide and water are converted to methanol and oxygen using electricity (Siemens Energy, 2022). This process is also known as electrochemical carbon dioxide reduction (Schlager et al., 2016). The main difference between e-methanol and bio-methanol is the energy source used to produce methanol. E-methanol uses renewable electricity while bio-methanol uses renewable feedstocks. Both are considered sustainable alternatives to methanol produced from fossil sources. For example, the production of 250t of e-methanol can be achieved with 350t of $CO_2$ and 48t of hydrogen (Kang S. et al., 2021).

**Blue methanol** production uses methane from natural gases (fossil source) and from which the $CO_2$ is removed for reuse and recovery. The gases are so separated from their $CO_2$ via the process of carbon capture and storage (CCS).

Basically, there are three ways of CCS (Tian et al., 2022):

1) *Pre-combustion*:

Fossil fuels are gasified with oxygen at high pressure to produce syngas mainly composed of CO, $CO_2$ and $H_2$. Once syngas is combined with steam, it passes through a catalyst-filled bed in which CO is converted to $CO_2$ by a water-gas shift reaction. The water-gas shift is an exothermic chemical reaction which can be assisted by a catalyst, and in this case is a reaction of steam with carbon monoxide to produce carbon dioxide (Pal et al., 2018). At last, $CO_2$ is separated from $H_2$ to be stored, while the resulting $H_2$ is kept for further use as fuel or to be sent to gas or steam turbines for combined cycle power. Nonetheless, this process is poorly compatible with existing equipment, which limits equipment transition (Tian et al., 2022). The energy consumption of this process is half of that required by the post-combustion technique (Roode-Gutzmer et al., 2019).

2) *Oxy-fuel combustion*:

A combustion of fuel in a high concentration of $O_2$ originated from water occurs, and $CO_2$ content after cooling is about 80-98% (Tian et al., 2022). Mostly, a cryogenic air separation unit is used to make a high-purity oxygen available for the combustion. Cryogenic separation is a physical method to separate $CO_2$ from the fuel mixture by cryogenic condensation process, when the pressure is higher than the critical pressure and temperature is lower than the critical temperature. A part of the flue gas circulates again in the combustion chamber. The use of specific blend of $O_2$ and $CO_2$ allows to control the flame temperature. The more $O_2$ is present, the higher the flame temperature is (Tian et al., 2022).

3) *Post-combustion*:

The post-combustion capture consists of the capture of $CO_2$ from flue gas after the combustion process. Power plants use air for combustion and release flue gas under atmospheric pressure. An issue to this process is concerning the strong chemical solvents which are used to capture low-concentration $CO_2$, these solvents need to be regenerated but it requires a lot of energy. When this solvent contains the $CO_2$, it goes through a heat exchanger to be steam-stripped to generate pure $CO_2$ (Roode-Gutzmer et al., 2019).

Once the methane has been released from its $CO_2$, the rest of the process is the same as for the green methanol production.

**Grey methanol** is produced from fossil sources involving a process known as steam reforming, which uses high-temperature steam to react with the natural gas to produce a mixture of hydrogen, carbon monoxide and carbon dioxide (McNeil et al., 1989). This mixture is then converted into methanol using a catalytic process known as the methanol synthesis reaction (Wainwright, 1988).

The chemical equation for the methanol synthesis reaction is:

$$CO + 2H_2 \rightarrow CH_3OH \qquad \textit{(Equation 3)}$$

In the Equation 3, carbon monoxide reacts with hydrogen to form methanol (Cheng, W. & Kung, H.H., 1994). The reaction is exothermic, meaning that it releases heat. The reaction is usually carried out at pressures of around 50-100 bar and temperature of 200-300°C, depending on the specific catalyst and process conditions used (Valera & Agarwal, 2019). The most common catalysts used in the methanol synthesis reaction are copper-based catalysts, typically supported on a zinc oxide (Wang et al., 2022). These catalysts can help to speed up the reaction and increase the yield of methanol. However, the reaction can also reduce unwanted by-products, such as methane, water, and higher alcohols, which can reduce the efficiency of the process (Pashchenko et al., 2021). Therefore, optimizing the catalyst and process conditions is important for maximizing the yield and purity of methanol. The production of grey methanol from fossil sources has several environmental concerns, including greenhouse gas emissions, air pollution, and resource depletion.

**Black methanol** is made from coal and uses also the steam reforming to produce methanol. Firstly, the coal gasification takes place, and its chemical reaction is (IRENA, 2021):

$$C + H_2O + 0_2 \rightarrow CO + H_2 \quad \textit{(Equation 4)}$$

This coal gasification Equation 4 represents the initial stage of black methanol production, in which coal enters in reaction with steam and oxygen to produce a mixture of carbon monoxide and hydrogen (Wagner et al., 2008). Then once this mixture is obtained, the next stage to obtain methanol consists out of the methanol synthesis Equation 3.

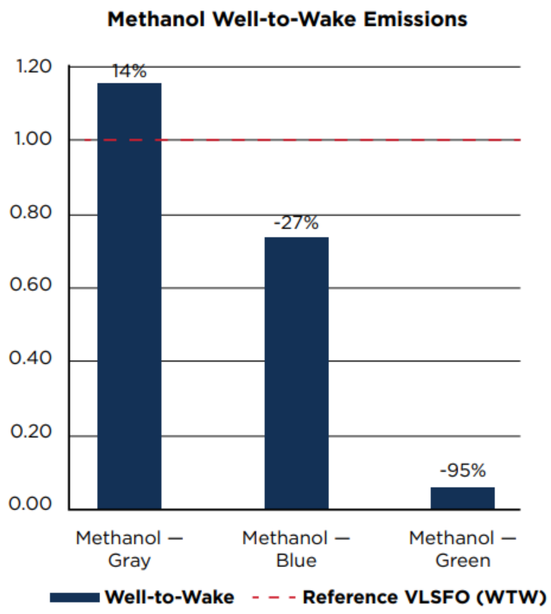


*Figure 2  Normalized well-to- wake CO2 emissions comparisons for methanol*

*Source: (Mamalis et al., 2021)*

As shown on the Figure 2  Normalized well-to- wake CO2 emissions comparisons for methanol,  green methanol is not reaching a carbon neutrality. In fact, green methanol still emits a low amount of $CO_2$ emissions since it is combined with some pilot fuel for the combustion, what is explained in detail in chapter 2.7.5. However, the progress by using green methanol is up to a decrease of 95% compared to the reference level of VLSFO (Mamalis et al., 2021). Blue methanol can achieve a 27% reduction compared to the reference, as illustrated on the Figure 2.

Anyway, the amount of carbon emitted using methanol strongly depend on the method of production. Methanol fuel produced from renewable energy can possibly reduce the GHG emitted from the shipping industry. Unfortunately, as described by the pie chart in the lower right of the Figure 1, the main types of methanol produced in the world are the black and the grey.

## 2.2 Methanol as a fuel

There are different ways to use methanol as a fuel: in a blend with diesel (as alternative fuel for maritime industry), as methyl tert-butyl ether (MTBE) or as dimethyl ether (DME). These 3 options of using methanol represents 31% of its total consumption, the rest of total methanol consumption is used as a product in the chemical industry as explained in chapter 2.3 (Kang S. et al., 2021). MTBE is an oxygenated anti-knock fuel additive in gasoline, which when added to non-oxygenated gasoline will increases its octane number (Mack et al., 2014). Therefore, octane number reflects resistance for engine knock (Mack et al., 2014) and a higher-octane number will lead to a higher compression ratio, resulting in a more efficient use of energy in an appropriate engine (Kang S. et al., 2021). Because of its high-octane rating, methanol can be used as an additive or substitute for gasoline in engines. DME is a liquefied gas at moderate pressure, which can easily replace LPG where it was used as heating or cooking, with no or very limited modifications. The use of DME in engines can be accomplished in compression ignition engine when the fuel system has been adapted for DME (Merkouri et al., 2022). Another way of using methanol is the direct methanol fuel cells (DMFCs) that convert its chemical energy directly into electrical power at ambient temperature (Kang S. et al., 2021).

The methanol presents itself as an alternative competitor fuel to crude oil which is currently the most used worldwide because it generates less pollution if it is produced in a renewable way. China is the country that has shown to have the most expectation with methanol, several vehicles (cars, trucks) run on methanol in China (Methanol Institute, 2021). These methanol-powered vehicles are using GEM fuels (gasoline/ethanol/methanol), these mixtures can be -found with different percentages like for example: M85 (85% methanol and 15% gasoline) (Verhelst et al., 2019). Nowadays, there are more than 210,000 vehicles running on methanol in China (Zhao et al., 2021). In 2019, the total consumption of M100 and M85 in China reached 507 000 metric tons of methanol (Methanol Institute, 2021).

## 2.3 Volume produced

In 2019, 98 million tons of methanol were produced with the majority of this production being made in China from fossil fuels (Kang S. et al., 2021). China delivers 57% of the world’s production (International energy agency, 2022). China is therefore the world’s largest consumer and producer, with a production capacity of 69.9 million metric tons and a consumption of 80 million metric tons in 2019 (Methanol Institute, 2021). In that year, more than 60% of the production was used for synthesizing basic chemicals to produce different products used in daily life (Kang S. et al., 2021). Daily consumer products such as building materials, paints, plastics, and pharmaceutical products are few examples of the wide range of products that incorporate methanol in their composition (Methanol Institute, 2019). LEGO®, the kids toys company, is actively exploring the utilization of e-methanol in certain types of its building bricks (Rattan, 2023). LEGO® company is committed to develop new prototype bricks, incorporating e-methanol as an innovative component (P. Jonkers, personal communication, 26 May 2023).

Although production has already doubled in the last decade, the International Renewable Energy Agency (IRENA) predicts that production could rise to 500 million metric tons per year by 2050 (Kang S. et al., 2021). This expected production should be composed 250 MMT of e-methanol, 135 MMT of bio-methanol and 115 MMT of methanol produced from fossil fuels (John Snyder, 2021). Currently, the global production of grey methanol outweighs all other types. Renewable methanol, commonly referred to green methanol, constitutes less than 0.2% of the total methanol production worldwide. Methanex was the first company to introduce green methanol in the European market. Methanex is the world largest single product producer of methanol. Methanex closest production site to Europe is in Egypt from where ports as Antwerp or Rotterdam are delivered in methanol. Today, methanol production is not sufficient to deliver all the potential consumers(P. Jonkers, personal communication, 26 May 2023).

Coal is a mean of producing methanol rapidly on a large scale and at low prices, that is why coal is used to produce plastics. Coal represents 36% of process energy to produce primary chemical in 2021 (International energy agency, 2022).

To achieve cleaner emissions, with fewer GHG and other pollutants (such as $NO_x$, CO, $SO_x$), the use of better fuels is required. A fuel would be better if fewer emissions were emitted into the air, considering the emissions from its production to its consumption. (Kang S. et al., 2021). Generally, scientists speak about a cradle-to-grave analysis, which is an entire life cycle analysis of a fuel (from its beginning to its end). In any case, if the aim is to reduce or even stop all emissions, it is time to use fuel made from renewable feedstocks, green methanol made from biomass and renewable $CO_2$. If only methanol produced from biomass (green methanol) is used, then carbon neutrality can be considered (Kang S. et al., 2021). Methanol fuel is biodegradable and disperses easily in the water, making it virtually impossible to recover if it is accidentally discharged overboard (P. Jonkers, personal communication, 26 May 2023). Methanol is produced naturally by phytoplankton and consumed by bacteria microbes, it is the reason why if methanol leaks in small quantity, it will not have an environmental impact (Koutsourakis, P., 2021). The fact that these fuels degrade quickly makes them attractive as marine fuels (Verhelst et al., 2019).

## 2.4 Combustion

There are 2 types of combustion with methanol:

1) Combustion of methanol alone

The reaction for methanol combustion is composed of 2 molecules of methanol and 3 molecules of dioxygen, that will be burned as follows:

$$2\ CH_3OH + 3\ O_2 \rightarrow 2\ CO_2 + 4\ H_20 \qquad \textit{(Equation 5)}$$

This chemical reaction produces 2 molecules of carbon dioxide and 4 molecules of water (chemistNATE, 2019). Methanol is used as a fuel in internal direct injection engines (also known as direct injection spark ignition engines) in which the fuel is directly injected into the combustion chamber. The combustion process is similar to that of gasoline, but methanol combustion produces less carbon monoxide and nitrogen oxides than gasoline combustion, making it a cleaner alternative.

2) combustion of methanol and diesel fuel

The combustion of a blend of methanol and diesel can be represented by the following chemical equation:

$$CH_3OH + C_{12}H_{23} + 37/2\ O_2 \rightarrow 13\ C0_2 + 12\ H_2O \qquad \text{(Equation 6)}$$

The combustion of methanol and diesel combined with oxygen produces carbon dioxide and water (Yao et al., 2008). The combustion of methanol and diesel fuel can be used to reduce emissions and improve fuel efficiency in diesel engines. Methanol has a higher oxygen content than diesel fuel, which can lead to more complete combustion and fewer emissions of particulate matter and other pollutants (Yusaf et al., 2013).

## 2.5 Emissions

As we can notice the burning of the methanol with oxygen does not produce any sulphur oxides ($SO_x$), any nitrogen oxides ($NO_x$). So, the pollutant that need to be treated is again the carbon dioxide emitted after the combustion due to the use of pilot fuel to ignite the methanol in the combustion chamber. Ideally to make it renewable by doing a closed-loop process, the $CO_2$ is kept onboard to be sent later to the shoreside methanol production process (Mamalis et al., 2021). Until now, the capture of $CO_2$ after the combustion has not been implemented on any vessel (P. Decrop, personal communication, 25 May 2023).

Regardless of the type of methanol used in engine combustion, the amount of $CO_2$ produced will remain the same. What will vary is the amount of $CO_2$ emitted during the production process. Currently, the global production of green methanol is not sufficient to significantly reduce the $CO_2$ impact at the production stage, as explain in chapter 2.3 (P. Jonkers, personal communication, 26 May 2023).

## 2.6 Comparison of chemical properties

Under normal conditions of use, methanol is a chemically stable product. It has the general properties of primary alcohols (INRS, 2018).

*Table 1 Comparison table of fuel characteristics*

*Source: adapted from (Valera & Agarwal, 2019) and (Methanol, 2016) and (INRS, 2018)*

| Fuels | Methanol | Diesel |
|---|---|---|
| Chemical formula | $CH_3OH$ | $C_{12}H_{23}$ |
| Molar mass | 32 kg/kmol | 183 kg/kmol |
| Density at 15°C | 792 (kg/m$^3$) | 840(kg/m$^3$) |
| Carbon/Hydrogen/Oxygen | 37,5/12,5/49,9 % | 83/11/0 % |
| Boiling point | 65°C | 180-360°C |
| Freezing point | -98°C | -15°C |
| Auto-ignition T° | 464°C | 250-450°C |
| Pour point | -97°C | -10°C |
| Flash Point | 11°C | 52°C |
| Critical pressure | 81 bars | 30 bars |
| Critical temperature | 239°C | 435°C |
| Octane number | 109 | 15-25 |
| Heat of vaporization (at 1 bar) | 1089 kj/kg | 250 kj/kg |
| Heat of combustion | 22,7 Mj/kg | 42,5 Mj/kg |
| Flammability limits | 6-36% | 0,5-7,5% |
| Sulphur content | < 0,5 ppm | < 15 ppm |

The flash point is the lowest temperature at which a liquid fuel gives off enough vapor to form an ignitable mixture with air and is a critical safety parameter as it indicates the temperature at which the fuel is most likely to ignite (Raj, 2016). As shown by Table 1, methanol flashpoint is around 11°C, which is a temperature that can often be found at room temperature. That is the reason why inert gas is used to be filled in the tank when storing methanol, explained in chapter 5.2.6. The auto-ignition temperature, which is the minimum temperature at which the fuel will spontaneously ignite without an external ignition and is around 464°C for methanol as found in Table 1.

# 2.7 The down sides of using methanol as a fuel

Although methanol has some advantages over traditional fuels as HFO, diesel and gasoline, but there are still points that make methanol hazardous in certain situations. In this chapter, the various downsides which are encountered when methanol is used as a fuel, are developed.

## 2.7.1 Toxicity

One problem of methanol is its toxicity, as it can enter the body through four primary routes: ingestion, skin contact, eye contact, and inhalation (Methanol Institute, 2019). Although it is easily metabolised in small quantities by the human body, because it is naturally present in fruit and vegetables and is therefore not released by the body as a foreign substance, methanol toxicity results from overloading the body (Dorokhov et al., 2015). Methanol can be absorbed into human body via the respiratory, oral and dermal routes (Richter, 2014). It is eliminated through the urine and respiratory tract.

The fatal dose of methanol when left untreated is between 1 and 2 ml per kg of body mass, which is between 6-24 cl for the average body weight (Verhelst et al., 2019). However, the process extends from 10 to 48 hours after ingestion and the treatment is well known, consisting of intravenous administration of ethanol, which the body metabolizes preferentially, while methanol is rejected (INRS, 2018). The administration of ethanol, which reduces the oxidation of methanol, causes a marked increase in methanoluria, which is the presence of methanol in the urine. In the body, ethanol is metabolized in the liver similarly to methanol by the enzyme ADH (alcohol dehydrogenase). However, ethanol has about 7-10 times greater affinity for the ADH enzyme than methanol (Vu Hoang Huy, n.d.). Thus, if methanol and ethanol are present in the bloodstream at the same time, it is ethanol that will be metabolised first, while methanol is waiting its dialysis and measures to be eliminated (Korabathina, K., 2018).

Symptoms of acute methanol poisoning by direct ingestion includes dizziness, nausea, breathing problems, coma and eventually death. As acute toxicity, methanol causes neurological disorders in high doses (excitation, convulsion, paralysis). It is slightly irritating for the ocular and respiratory mucous membranes (Wimer et al., 1983). With repeated exposure, headaches and visual disturbances could take place. Respiratory intoxication is the most common in industry. Irritation of the nasal and ocular mucous membranes, in case of massive and prolonged exposure, may develop into tracheitis or bronchitis (INRS, 2018).

Epidemiological studies carried out on workers exposed to methanol vapours on a chronic basis show that (American Conference of Governmental Industrial Hygienists, 1991):

- concentrations of 1200 to 1800 ppm may cause visual disorders similar to those of acute intoxication (target organs: optic nerve and retina)
- concentrations of 200 to 300 ppm can cause persistent and recurrent headaches
- concentration of 25 ppm is without effect.

As chronic toxicity, repeated exposure causes signs of central nervous system depression and degenerative liver damage (INRS, 2018). Methanol induces also birth defects in the presence of only low maternal toxicity, prenatal exposure to methanol vapours of 2000 ppm or more is sufficient (INRS, 2018).

Various measures exist to prevent direct exposure to methanol, including the use of personal protective equipment (PPE). When working in situations with low risk of vapor and low volume of splash exposure, PPE such as gloves, safety glasses, and boots should be worn. In high-risk scenarios with a significant vapor and splash area, a full chemical suit, gloves, breathing apparatus, and boots are necessary components of the PPE (Methanol Institute, 2019).

## 2.7.2 Corrosion

Methanol's polarity may be a problem in terms of material compatibility, because engines fuel systems may be adapted for methanol use and methanol is a conductive polar solvent (Methanol Institute, 2020). Metals and elastomers (soft components used for seals and fuel lines) can be damaged by methanol, if they are in contact. In general, light alcohols are more corrosive on both ferreous and non-ferrous metals than gasoline (Verhelst et al., 2019). Dry corrosion is caused by the polarity of methanol and ethanol, but this corrosion is increased by the presence of ionic impurities such as chloride ions in the fuel, what should be avoided when methanol fuel is used (Brown, 2011). Methanol is an electrical conductor and its corrosion behaviours such as electrochemical and galvanic corrosion, can be enhanced by an increase in the electrical conductivity of alcoholic fuel due to the absorption of water and contaminants (Brown, 2011). If incompatible materials are placed in electrical contact with one another, galvanic corrosion may be incurred (Methanol Institute, 2020). Alcohol fuels can be extremely aggressive toward magnesium, aluminium and copper (P. Jonkers, personal communication, 26 May 2023). The growth of corrosion is very sensitive to temperature (Turner, 2012). Austenitic stainless steel and other metals coated with a zinc or nickel alloy are commonly used for frequent contact with methanol. Alcohol-rich fuels can result in shrinkage, swelling, hardening or softening of elastomers in the fuel system (Brown, 2011). When comparing methanol and diesel fuel, there is more potential for corrosion to take into account for methanol. Being a non-acidic substance, methanol exhibits lower corrosiveness in comparison to certain chemicals frequently encountered in the chemical industry. From a material perspective, using approved stainless steel is suitable for mitigating corrosion concerns when handling methanol. The use of additives and engine oils leads to a reduced corrosion impact in low level blends. The material typical for M85 applications can be used with any blend composed of methanol because none of the blends indicated more swelling than M85 (Verhelst et al., 2019). Cathodic protection or appropriate coatings are vitally important for material protection against corrosion failure (Methanol Institute, 2020).

Methanol is hygroscopic and extracts moisture from ambient air that enters tanks because of its affinity to form mixtures with water (Methanol Institute, 2020). If the liquid in the tank passes through large volumes at frequent intervals, moisture laden ambient air can be sucked into the tank. This can be particularly harmful in a coastal environment where the moisture-laden air carries dissolved chloride salts. If the facility is located in an area of typically high relative humidity, methanol will dry out the air in the vapour space remaining in the tank, resulting in self-contamination of the methanol (Methanol Institute, 2020). In pure methanol, a small amount of water does not systematically increase the rate of general corrosion. However, due to the relatively high conductivity of liquid methanol, corrosion failures of steel tanks have been reported (Boruń & Wypych-Stasiewicz, 2021).

If a methanol-water mixture forms within a gasoline-methanol tank, and the mixture is separated from the tank content, it is possible that localized corrosion happens (Soetens & Bopp, 2015). If the methanol-water separation phase contains chlorides salts due to the proximity of the coastal environment, this will increase corrosion. This high chloride concentration causes stress corrosion cracking (SCC) in high carbon and heat affected areas (Guo et al., 2018).

Carbon steel is more likely to corrode than stainless steel, particularly in the presence of moist air or water. The use of padding tank freeboard space with dry inert gas such as nitrogen can help to mitigate the corrosion (Flessas, 1999).

A 300 series stainless steel alloys are recommended as well as welding procedures to prevent heat-affected zone are the recommended solutions to follow to avoid corrosion (Methanol Institute, 2020). Galvanized steel is not suitable for methanol service.

As purity is an important consideration not only for methanol quality but also for risk reduction, therefore the right compatible materials has to be chosen (Methanol Institute, 2020). Ensuring the purity of methanol is crucial, which means that the fuel received onboard must always be of high quality (P. Molander, personal communication, 19 May 2023). Consequently, the use of purifiers and separators commonly employed on ships to obtain high-quality heavy fuel oil (HFO) is avoided in the case of methanol. This presents a significant advantage as it eliminates the need for separators, which are known to be cumbersome, prone to blockages, and require full cleaning every five weeks. Eliminating separators from the process simplifies the tasks of engineers and reduces the potential maintenance and operational challenges they may face (P. Decrop, personal communication, 25 May 2023).

### 2.7.3 Cold start

A fuel-air mixture is required at spark timing and the combusted mixture needs to generate enough work to keep the engine running (Verhelst et al., 2019). These conditions are required to start a cold engine, but they are not easily reached due to methanol characteristics (Verhelst et al., 2019):

- More mass needs to evaporate due to lower energy density of methanol with its heat of combustion at 22,7 Mj/kg.
- More energy is needed to evaporate the fuel due to its high heat of vaporization at 1089 Kj/kg
- Short circuiting between the spark electrodes can be caused if not all fuel has evaporated due to the conductivity of methanol

Methanol is considered as a light alcohol due to its low molecular weight of 32g/mol (in Table 1). Light alcohols as methanol form an ignitable mixture in ambient temperature and pressure because of the above reasons. Solutions have been developed for starting a cold engine with light alcohol fuels, they are either focusing on adapting some parts of the engine or using some additives in the fuel. For example, methanol is mixed with 5% of a polyethylene glycol derived additive, designed for alcohol fuels (Cordtz et al., 2021).

The engine modifications can be done on different parts as (Verhelst et al., 2019):

- Engine block where the intake would be electrically heated
- Injectors which would be heated to obtain a higher fuel temperature
- Valves that should work with a better valve timing
- Ignition timing which should be improved by using multiple sparks

### 2.7.4 Low energy density

Methanol has a lower energy density than diesel as shown by Table 1, which means that it does not provide as much power per unit of volume. Methanol has a heat of combustion of about 22,7 Mj/kg, which is about half the heat of combustion of diesel, which has a heat of combustion of 42,5 Mj/kg. Engines designed to run on methanol often require more fuel to produce the same amount of power as an engine designed to run on diesel because of methanol lower energy density. Therefore, more volume of methanol will have to be stored onboard to obtain the same amount of stored energy (An inside Look at Methanol as Fuel, 2023). In order to have the same energy content onboard, methanol requires about 2,5 times more storage volume than the size of HFO tanks, making less attractive to have methanol fuel on smaller ships (Koutsourakis, P., 2021). Consequently, if methanol is compared to a conventional fuel as diesel, methanol is then considered as a low energy density fuel. But when methanol is compared with fuels that are promising as alternative fuels for the future like ammonia with 18 Mj/kg as heat of combustion, methanol has a greater energy density (Kobayashi et al., 2019). To say that methanol has a low energy density depends on the other fuels methanol is compared to (P. Molander, personal communication, 19 May 2023).

### 2.7.5 Poor ignition

In the combustion process of methanol, one challenge is its inherent difficulty to ignite and burn efficiently. Unlike diesel fuel, which has a well-defined ignition point and combustion process, methanol ignition is less defined. To overcome this, diesel is often used as a pilot injection to ignite the methanol fuel. In this configuration, the diesel fuel acts as a reliable ignition source. Diesel is injected into the combustion chamber as a flame. The resulting flame and high temperatures of diesel helps to initiate the combustion of methanol. It provides the necessary heat and energy to kickstart the reaction and ensure reliable and efficient burning of the methanol fuel. By combining the fuels, the combustion process becomes more controlled and consistent. As a rough estimate, at full RPM, approximately 5% of the total fuel consumed will be diesel, while the remaining 95% will be methanol. The pilot injection, which accounts for approximately 5% of the total fuel consumed, represents the lowest quantity of diesel fuel that can be used in the combustion process, because a minimum quantity of diesel is required to maintain the combustion of methanol (L. Pennman, personal communication, 2 June 2023).

Using a spark plug as an ignition source is a feasible solution for small engines like cars engines, it may not be suitable for larger ship engines (Singh et al., 2022). The reason is that big ship engines require higher temperatures to ignite the methanol efficiently. Diesel flames, with their high temperatures, are capable of achieving this ignition. Spark plugs generate a spark that ignites the air-fuel mixture in gasoline engines. However, in the case of methanol, which is less easily ignited than gasoline, achieving reliable ignition solely through a spark plug in engine of big size is no feasible (L. Pennman, personal communication, 2 June 2023).

### 2.7.6 Fire protection

Methanol flames are practically invisible in sunlight that can lead to hazardous situations, but it can be changed by putting it with additives or, adding a blend of gasoline. The use of water will remove heat and dilute the methanol to the point where most fires become extinguishable but foam is more commonly used on board to extinguish fire (L. Pennman, personal communication, 2 June 2023). The fire protection against methanol fire will be further developed in chapter 5.2.14.

# 3. Methanol impact on operational safety

After presenting methanol as a new alternative fuel by describing its production, emissions, and addressing the associated disadvantages, the compelling reasons for choosing methanol as a future fuel have been explained. From P. Jonkers's point of view (pers. comm.), methanol is not an alternative fuel, because it is already on the market as a fuel. Chapter 2 also delves into the negative aspects that could potentially impose constraints on its operation.

In the upcoming chapters, technical aspects related to the construction and regulations concerning the implementation of new systems to maintain safe methanol operations will be discussed. The regulations and operational constraints will be further addressed in the following chapters. One important aspect that will be detailed, is the impact of methanol fuel on shipping operations.

In chapter 4, the approach of ship design companies towards the conversion of vessels to methanol fuel is discussed. The process and the construction of a general safety system are explained chronologically.

In chapter 5, the regulations for the use of methanol as a fuel and the challenges associated with its implementation are discussed. This includes the insights and experiences of different individuals involved in the development of methanol.

In chapter 6, the conversion to methanol of certain existing vessels is explained.

In chapter Table 3, a table summarizing the advantages and disadvantages of using methanol is detailed.

Chapter 8 serves as a conclusion, summarizing the impact of methanol on onboard operational safety.

# 4. How a safety system is created in practice?

Chapter 4 provides some explanations of the process involved in developing a comprehensive safety system for methanol usage. The chapter discusses the key elements of a general safety system, by outlining the step-by-step approach to design it. The importance of collaboration between ship design companies and classification societies in the creation of a safety system is described.

The insights for this chapter were partly based upon an interview with Patrik Molander from ScandiNAOS, which is a ship design company based in Gothenburg. ScandiNAOS is focusing on the design of complete marine ships, they aim to develop solutions that promote sustainability and reduce the ecological impact of marine transportation (*ScandiNAOS AB*, n.d.). One of the solutions developed at their company is methanol fuel, ScandiNAOS is one of the leading designer companies which has already the experience of building methanol fuelled vessels. Since 2009, Patrik Molander has been a naval architect involved in the progress of methanol fuel by developing design, rules, safety and mechanical parts of methanol fuelled ship (P. Molander, personal communication, 19 May 2023).

In order to put things into perspective, ScandiNAOS has already built their first methanol design in 2011, but at that time the interim guidelines regulations were not yet created (IMO, 2020a). They built the design purely based on work analysis and risks assessment because there were no regulations in place for the methanol design (P. Molander, personal communication, 19 May 2023). At that time, naval architects had to argue and prove to the flag state, classification societies and ship owners that every step of the design was safe. For example, they proved that if a spill is developing at one place, an alarm is activated to avoid a fire development. Once the design is approved to be safe by the flag state and the classification society, an approval is delivered which is the evidence for having the allowance to sail for the ship (P. Molander, personal communication, 19 May 2023). In general, classification societies is a third part inspection not legally binding and they are checking dimensions for all systems until every single detail, while flag state has more an overview over the project to verify the compliance of the vessel with the regulations (EMSA, n.d.). Nowadays, classification societies and flag states have a set of quite similar rules which is mainly inspired by the interim guidelines rules from the IMO (IMO, 2020a). Classification societies including American Bureau of shipping, Bureau Veritas, DNV, Lloyd's register have developed their own rules focusing on the use of methanol as fuel (P. Molander, personal communication, 19 May 2023).

From the outsell, ScandiNAOS developed design and arguments to gain the approval to build ships propelled by methanol, only by making a work analysis. A work analysis, in this case, involves gathering information and knowledge about the safety before making the test on the engine part or safety system in question. Since the introduction of interim guidelines, classification societies often use them as a reference to justify their position when evaluating alternative designs. P. Molander (pers. comm.) believes that these guidelines are particularly valuable for those who do not have the background knowledge of methanol when it comes to designing and constructing vessels. However, classification societies tend to require strict adherence to these established rules without considering the possibility that alternative designs could be equally safe. This approach eliminates much of the discussion and analysis required for designs based purely on risk assessment. With the rules already in place, approximately 90% of the design is automatically compliant, reducing the need for extensive deliberation (P. Molander, personal communication, 19 May 2023).

To build a good general safety system, the following elements should be considered (Weekes, 2017):

1) Hazard identification
2) Risk assessment
3) Procedures
4) Crew training
5) Personal protective equipment (PPE)
6) Safety inspections
7) Incident investigation
8) Continuous improvement
9) Leadership and accountability

1) A hazard is a condition, object, activity or event with the potential of causing injuries to personnel, damage to equipment, loss of material (Maragakis et al., 2009). Hazard identification (HAZID) is the act of recognizing the failure conditions or threats, which could lead to undesirable events and defining the characteristics of these undesirable events in terms of their potential safety outcomes (Maragakis et al., 2009). HAZID follows structured approach that relies on documents and drawings for identifying risks and hazards associated with the operation of the system (Bureau Veritas, 2023). In fact, using the hazard identification database to implement risk assessment and management is crucial (Hao & Nie, 2022).
2) A risk assessment of a safety system is an evaluation of the potential hazards and risks associated with a particular safety system (Andales, 2023). The assessment involves identifying potential hazards occurring, and evaluating the consequences of those hazards if they were to occur. After prioritizing the risks by determining the likelihood of risk occurrence, the risk assessment develop the risk management strategy to eliminate the identified risk (Glossop, 2021). When a client or a ship owner is contacting the ship design company with its request (building or retrofit), a risk assessment takes place. From P. Molander's experience (pers. comm.), risk assessment generally involves the following progress.

First of all, naval architects think about where the tank, fuel pipes can be placed, they always try to find a design solution with safety in mind. In this step, consideration is being given to the location of the big pieces of the system. Then, a discussion with the client takes place to check that the design fulfills their expectations (example: tank is big enough to do what they expect to do with the ship). Once the client is happy with the first ideas of the design, the classification society is invited to make a HAZID study analyzing the design system. After the HAZID analysis, the design is developed in detail, the sizes of the different components are decided together with the classification society (size of the pipe, size of the pump, how many pipes). The purpose is to ensure that the design is safe by answering some questions like: “what would happen if…” and demonstrate that there are solutions to mitigate potential risks (Together in safety, n.d.). When the classification society and customer are satisfied with the detailed drawings and all the dimensions in the system, then classification society approve and stamp the design. Once the vessel has been built or retrofitted, classification society's inspectors come in the shipyard to compare that all the systems comply with the drawings and calculations. As confirmation, the inspectors sign and stamp again the design for the final stage. This step must be carried out because certain modifications may be applied to the original design plan for specific reasons while the operation in the shipyard is underway and these modifications must be approved.

3) The procedures of a safety system are designed to ensure that it is functioning correctly and effectively to mitigate potential hazard. Checklist is one element of all the procedures and is a pre-organized document used during safety inspections for the identification of potential hazards (Ubongeh, 2022a).
4) The purpose of crew training is to ensure that the crew members are familiar with the operation of the safety system in a safe and effective manner. Crew training for safety systems is critical in preventing accidents and ensuring the safety of the crew (Pradeep, 2016). In order to prove the crew's familiarisation, some drills on simulated scenarios should be experienced (P. Decrop, personal communication, 25 May 2023).
5) PPE refers to equipment designed to protect workers from injury or accidents caused by workplace or product (Tarlengco, 2023). By implementing a comprehensive safety system that includes PPE, crew can help prevent workplace injuries and promote crew safety (Methanol Institute, 2019).
6) Safety inspections involve a systematic review of a workplace, facility or equipment to identify potential hazards and assess the effectiveness of existing safety measures. By conducting regular safety inspections, organization can help to ensure the safety, the well-being of the worker and environment. The aim of inspection is also to prove that the safety system complies with the regulations and standards (Ubongeh, 2022b).
7) Incident investigation involves a systematic process of gathering, analysing information to determine the factors that contributed to an incident and develop corrective actions to prevent them from happening again (Paradies & Hughes, 2019).

8) The aim of continuous improvement of a safety system is to enhance the effectiveness of the safety program by continually identifying opportunities for improvement and implementing corrective actions to prevent accidents. (Mlean, 2022).
9) Leadership is a critical component of a safety system, as it sets the tone for the entire organization and provides direction for the safety program. Effective safety leadership involves establishing a culture of safety, demonstrating a commitment to safety and providing the necessary resources to ensure the safety program is successful (Ward, 2017).

The IMO has put into place the international safety management code (ISM) for safe management, operation of ships and prevention of pollution (IMO, 2023). The code establishes safety-management objectives and requires a safety management system (SMS) to be established by the user which is supposed to operate the system or products (Crutchfield & Roughton, 2014).

# 5. Safety

This chapter explores the different facets of methanol safety by illustrating the regulations that govern the utilization of methanol as a fuel on ships, with insights from individuals responsible for interpreting and implementing these regulations.

## 5.1 Rules history created for the use of methanol fuel

When a liquid with a flashpoint of 60°C or higher is spilled on a surface with a temperature exceeding 60°C, the liquid will rapidly evaporate, creating an ignitable mixture of gases. Conversely, if the ambient temperature is lower than 60°C, the evaporation of the liquid will be minimal, making ignition of the gases unlikely. Therefore, the atmosphere is considered safe when the ambient temperature remains below 60°C in the presence of a liquid with a flashpoint of 60°C. Diesel fuel has a flashpoint higher than 60° and is deemed safe for use in ship's engine rooms, where temperatures typically range below 60°C (mainly  around 45°) due to ventilation (Wartsila, n.d.-a).

On the other hand, methanol, with a flashpoint of 11°C, poses greater risk than diesel. If methanol is spilled on a surface with a temperature above 11°C, rapid evaporation occurs, creating an explosive atmosphere. Methanol, like LNG, is categorized as a low flash point fuel due to its flashpoint below 60°C. LNG, with a flash point fuel of -163°C, becomes ignitable if the ambient temperature rises above its flashpoint.

Comparing the flashpoints, LNG has a flash point fuel of -163°C, methanol has a flashpoint of 11°C, and diesel has a higher flashpoint. However, there is a significant difference in margin between methanol and LNG compared to methanol and diesel. Initially, both LNG and methanol fell under the regulations for low flash point fuels, but since 2020, methanol has specific rules for its use. The interim guidelines for the safety of ships using methanol as fuel were made in 2020 and were derived from the previous regulations for low flash point fuels, including LNG (IMO, 2020a).

P. Molander (pers. comm.) suggests that a better approach would have been to start with the existing safety regulations for diesel use and subsequently incorporate the necessary safety requirements specific to methanol. He believes that the safety requirements imposed by the regulations to use methanol as a fuel are extensive, because these rules originated partly from the rules for low flash points fuels. For instance, some aspects of the rules are not suitable for the use of methanol due to the significant differences in properties compared with the LNG, as their flashpoints.

Mr. Molander (pers. comm.) emphasizes the importance of recognizing this historical context of the interim guidelines, highlighting the need to avoid blind adherence and instead question their relevance and effectiveness. This critical approach prevents the possibility of adopting suboptimal or unsuitable designs or encouraging the exploration of alternative solutions that offer equivalent safety standards. According to P. Molander's point of view (pers. comm.), the advantage lies in the flexibility to adapt to alternative designs that offer an equivalent level of safety. However, it is important to note that this process may require more time for development and obtaining approval through risk assessment, in contrast to the straightforward adherence to the existing rules. In general, ScandiNAOS strives to adhere to the rules as closely as possible, they comply with the rules 95% of the time. However, in certain situations where they find the rules to be overly extensive, they explore alternative design options. The rules often include sections that acknowledge the possibility of achieving equivalent safety. (P. Molander, personal communication, 19 May 2023).

## 5.2 Safety requirements and provisions for methanol fuel

Originally, the application of the IGF code was limited to the use of natural gas, the Maritime Safety Committee added some requirements to the Code about the use of low-flashpoint fuels (IMO, 2015). The purpose for the Committee was to provide international standards for using methyl alcohol as fuel. Therefore, interim guidelines have been created to make functional requirements for the installation, equipment and systems using methanol to improve the safety (IMO, 2020a). A risk assessment should be carried out for controlling the risks arising from the use of methanol fuels affecting persons on board, the environment, structural soundness, or the integrity of the ship (Dasgupta, 2019). Risks should be analysed using recognised risk analysis techniques. The analysis purpose is to eliminate operational risks where possible in order to improve the safety of the workplace (Andales, 2023). Risks which cannot be eliminated should be mitigated where necessary.

## 5.2.1 Methanol fuel tanks requirements

Due to the different physical and chemical properties of methanol compared to other standards fuels, some considerations of tank storage are unique to methanol. Therefore, some precautions, explained in the chapter 5, must be taken about tank storage of methanol, focusing on cathodic protection, electrical grounding, in-tank vapor control, vapor space fire suppression (Methanol Institute, 2020). Methanol tanks can be constructed of either carbon steel or 300 series austenitic stainless steel (Methanol Institute, 2020). Austenitic refers to a type of metallic alloy that is characterized by the face-centered cubic crystal structure of austenite (P. Decrop, personal communication, 25 May 2023). This structure is commonly found in stainless steels, which are composed primarily of iron, chromium, and nickel (Bergsen, 2019). Austenitic alloys provides good properties such as good formability, high strength, and resistance to corrosion (Bell, 2019).

These followings functional requirement are general provisions for all the different type of tanks containing methanol. There are 3 different type of tanks which can be used (IMO, 2020a):

- independent tank which are self-supporting tank and are not part of ship's hull. Tank is constructed and then transported to the shipyard, where it is either welded or bolted onto the ship's structure. This type of tank is specifically designed for smaller vessels like pilot boat with a tank capacity of 2 or 3 $m^3$ (P. Molander, personal communication, 19 May 2023). One advantage of this approach is that the tank can be prepared in advance before the ship arrives at the shipyard. The area around independent fuel tanks must be wide enough to allow safe evacuation and rescue operations (IMO, 2020a).

- portable tank which are independent tank able to be removed from ship and be installed again onboard. Due to the potential hazards associated with deck leaks, this type of tank is less commonly used (P. Molander, personal communication, 19 May 2023). Fuel tanks laying on open decks must be protected against mechanical damage by means of coamings (IMO, 2022). The use of portable tanks requires some considerations about the use of flexible hoses, leakage of fuel, the connexion to a fixed venting system and the integration of a monitoring system in ship's control (IMO, 2020a).
- integral tank which are part of the ship's hull and are stressed by the same loads which stress the ship's hull (IMO, 2016). These tanks are used for bigger boats, as tug boat with larger tank capacity. For tank capacities exceeding 3 $m^3$, the use of integral tank is recommended (P. Molander, personal communication, 19 May 2023). Integral fuel tanks are surrounded by protective cofferdams to keep the methanol fuel inside the tank segregated (IMO, 2022).

Tanks containing fuel should not be located within accommodation or machinery space of category A (IACS, 2007). Machinery spaces of category A are spaces and trunks which contains (IMO, 2006):

- internal combustion machinery used for main propulsion
- internal combustion machinery used for purposes other than main propulsion where such machinery has in the aggregate a total power of not less than 375 kW
- any oil-fired boiler or fuel oil unit

The fuel containment system should be abaft of the collision bulkhead and forward of the aft peak bulkhead (IMO, 2022). After recognizing that certain ships do not use their full ballast water capacity, Mr. Molander conducted a risk analysis to demonstrate the safety of repurposing these ballast tanks for use as methanol fuel tanks. This simplifies the process as it eliminates the need for additional tank installation or redesigning the ship's stability to accommodate a new tank in different location (P. Molander, personal communication, 19 May 2023).

## 5.2.2 Provisions for holding tank & drip trays

Drip trays must be installed where leakage and spill are expected to occur, especially where pipes and their connections are not double walled. Drip trays serve the purpose of identifying the origin of leaks and collecting the substances being discharged. For instance, drip trays are found mainly underneath valves, filters, each connection and at the connexion at the manifold to collect droplets that are dripping out (P. Molander, personal communication, 19 May 2023). To prevent fuel spillage while bunkering, a large drip tray is installed beneath the manifold connection to collect any fuel. The collected fuel is then transferred to a slop tank for disposal or burning. Methanol fuel requires high-quality standards to be considered suitable for use. Once the fuel has been almost in contact with the deck in the drip trays, it is considered contaminated. Such dirty fuel cannot be reused as a fuel and necessitates appropriate disposal (P. Decrop, personal communication, 25 May 2023).


*Figure 3 Drip tray underneath the manifold*

*Source: (Baer, 2021)*

Each tray drip must have sufficient capacity to ensure that the maximum amount of spillage found by the risk assessment can be manageable. Drip trays for leakage of less than 10 litres shall be emptied manually (Indian Register of shipping, 2021). Drip tray system for leakage and some water spray system for cooling must be installed on open decks (IMO, 2022). Each drip tray should be able to drain the spillage in order to transfer it to the holding tank and shall be equipped with a system that prevents the backflow from this holding tank. Some holding tank for collecting drainage or leakage of methanol should be installed to ease the transfer of liquids containing methanol to the shore (IMO, 2020a). The holding tank should be equipped with a level indicator combined with an alarm and should be inerted at all times (Indian Register of shipping, 2021).

### 5.2.3 Spill containment

Spill containment is a process of keeping spillage or leakage of a liquid or hazardous material within a barrier (PACTEC, 2021). Tank storage of methanol requires enforced provisions to prevent over filling or tank overflow. Tank maximum allowable working volume must always allow additional volume for liquid expansion (IMO, 2014). The volumetric coefficient of thermal expansion for methanol is 0.0001124/°C (National Institute of Standards and Technology, 2023). A general rule of thumb is to allow 20% of tank working volume for liquid expansion (Methanol Institute, 2020). General guidance for liquid hydrocarbon (gasoline, diesel, and methanol) spill containment is to size the containment volume to at least 110% of the working volume of the largest tank (Pettitt & Waite, 2003). Therefore, this volume is able to accommodate a worst-case volume. Spill containment must allow extra capacity for the substantial volume of fire water (greater than 5 parts water to 1 part methanol) necessary to dilute methanol to a non-flammable concentration (Methanol Institute, 2020). As methanol is highly soluble in water, and the flammability of its mixture with water is persistent to high proportions of water, it is suggested that the containment volume for methanol tank spills be enlarged accordingly if water is to be used as an extinguishing way (PubChem, 2018). If alcohol resistant foam is used, then less volume is required for spill containment (Methanol Institute, 2020). A bilge system should be installed specifically for methanol and should be separated from the spaces where methanol cannot be present (IMO, 2020a).

### 5.2.4 Fuel preparation room

All pump-related equipment in the fuel preparation room is installed, allowing for remote control to prevent unnecessary access to the room during normal operations. Normally, access to this room is only granted for maintenance or repairs, and appropriate safety measures must be taken before entering (Port of Antwerp, 2021). For instance, the fuel preparation room has been installed in the fuel tank 9 and the upper void in the Methatug retrofit project and the room was isolated from the engine room with A-60 insulation. Due to the presence of fuel-containing pipes leading to the pump, where fuel sampling can take place, as well as valves connecting to the engine, the room is classified as a 'Hazardous Area Class 1', which is explained in details in paragraph 5.2.14 (Port of Antwerp, 2021). In ships which sails on heavy fuel oil, the fuel preparation room is equivalent to the purifier room, which contains heaters and filters. However, for methanol, these components are not necessary. Methanol does not require heating before use as a fuel, and it is already of high quality, eliminating the need for additional filtration (P. Decrop, personal communication, 25 May 2023).

### 5.2.5 Provisions for openings in enclosed spaces

If there is a direct access for operational reasons from a non-hazardous area to a hazardous area, the openings should be built with an airlock which is a space enclosed by gastight bulkheads with two gastight doors spaced of minimum 1.5 m and not more than 2.5 m apart (Indian Register of shipping, 2021). For example, there are always two doors between a smoking area and the accommodation (P. Decrop, personal communication, 25 May 2023). Airlocks should have a mechanical ventilation at an overpressure relative to the adjacent hazardous area (IMO, 2020a). An audible and visual alarm system to give a warning on both sides of the airlock should be installed in order to know if more than one door is open (Indian Register of shipping, 2021). Fuel preparation spaces should have independent access direct from open deck. Therefore, when an access from open deck is not practicable, an airlock entrance should be installed. Fuel tanks and surrounding cofferdams should have suitable access from the open deck, where practicable, for gas freeing, cleaning, maintenance and inspection (Indian Register of shipping, 2021). In practice, entry into the fuel tank for inspection with the classification society is typically conducted once every five years, provided that no issues have been experienced with the system inside the tank. Entering a methanol fuel tank is easier compared to entering in a heavy fuel tank, as it tends to have fewer residues and sediments present(P. Decrop, personal communication, 25 May 2023).

Without direct access to open deck, an entry space to fuel tanks or surrounding cofferdams should be provided and comply with the following (IMO, 2020a):

1) be fitted with an independent mechanical extraction ventilation system, providing a minimum of six air changes per hour. A low oxygen alarm and a gas detection alarm should be fitted.
2) have sufficient open area around the fuel tank hatch for efficient evacuation and rescue operation
3) not be an accommodation space, service space, control station or machinery space of category A
4) a cargo space may be accepted as an entry space, depending upon the type of cargo, if the area is cleared of cargo and no cargo operation is undertaken during entry to the space.

## 5.2.6 Fuel tanks venting, gas freeing, inerting and atmospheric control

**Tank vents** play a crucial role in maintaining the integrity of a vessel during fluid transfer. Without tank vents, the vessel's structural integrity would be compromised (Drennen, 2019). When filling a vessel, it is essential to allow air or vapor to escape, preventing the vessel from bursting. Conversely, when emptying a vessel, air needs to be allowed to enter to prevent implosion. This process of air escape and entry is commonly referred to as "breathing" (P. Decrop, personal communication, 25 May 2023). A controlled tank venting system must be installed in the fuel tanks with independent ventilation system from all others venting system of the ship (Indian Register of shipping, 2021).

The control venting system in the fuel tank used for the relief of excess pressure and/or vacuum shall have a back-up system. Pressure sensors installed in each fuel tank shall be connected to an alarm system, which may be accepted in lieu of the secondary redundancy requirement for pressure relief (IMO, 2020a). PRVs should vent to a safe location on open deck and should be of a type which allows an easy checking of the valve (Phillips, 2016). The venting system should be connected to the highest point of each fuel tank and vent lines should be self-draining under all normal operating conditions (Indian Register of shipping, 2021).

A fixed piping system should be designed to enable each fuel tank to be safely **gas freed**, and to be safely filled with fuel from a gas-free condition. The formation of gas pockets as remaining air during the gas freeing operation should be avoided by taking into account the location of gas freeing inlets and outlets and the tank structure (Indian Register of shipping, 2021). Pressure and vacuum relief valves should be fitted to each fuel tank to minimise the pressure or vacuum. If these valves are installed at the end of the vent pipes, they should be of the high velocity type and accompanied with a flame arrestor at the outlet (IMO, 2020a).

Shut-off valves should not be arranged either upstream or downstream of the PRVs (pressure relief valve), instead bypass valves may be provided. Pressure bypass valves serve to control pressure in a system by diverting a portion of the flow, they supplement the performance of reducing the pressure (TLV, 2022). For temporary tank segregation purposes (maintenance), shut-off valves may be accepted on common vent lines if an additional protection against pressure fluctuations is provided to all tanks (Indian Register of shipping, 2021).

The arrangements for gas freeing and ventilation of fuel tanks should be arranged in a way to minimize the hazards by taking into account the flammable vapours going to the atmosphere and the flammable gas mixture laying in the tanks (IMO, 2022). The ventilation system for fuel tanks is installed mainly for ventilating and gas freeing purposes. Gas freeing operations should be carried out such that vapour is initially discharged in one of the 3 following ways (Indian Register of shipping, 2021):

- through outlets at least 3 m above the deck level with a vertical flow velocity of at least 30 m/s maintained during the gas freeing operation
- through outlets at least 3 m above the deck level with a vertical flow velocity of at least 20 m/s which are protected by suitable devices to prevent the passage of flame
- through outlets underwater

During bunkering operation, an initial step involves introducing **inert gas**, creating a layer of inert gas above the fuel level. The higher density of the inert gas compared to air allows it to function as a barrier or separation layer between the fuel and the incoming air. This arrangement ensures that there is no direct contact between the air and the methanol fuel inside the tank (P. Decrop, personal communication, 25 May 2023). During normal operation, maintaining all fuel tanks filled with inert gas is required. When there is an overpressure in the tank, the pressure/vacuum (P/V) valves will open to release the excess pressure. In that case, the inert gas, being heavier than air, will escape first through the P/V valves. Its opening releases the overpressure in the tank to allow the escape of a mixture of inert gas with a small percentage of methanol vapour. The inert gas acts as a barrier, preventing the pure methanol vapour from escaping the tank (L. Pennman, personal communication, 2 June 2023). The presence of nitrogen on board serves the crucial purpose of displacing oxygen within the tank, effectively reducing the potential risk of explosions (P. Molander, personal communication, 19 May 2023). During any atmosphere change operation, gas freeing or inerting, a flammable mixture atmosphere should never be developed in fuel tank.

Blanking arrangements should be fitted in the inert gas supply line to individual tanks. Blanking arrangement refers to a configuration that involves the installation of blanking plates or devices to seal off specific passages in a system, to block the flow of fluids, gases, or other substances through pipes (P. Decrop, personal communication, 25 May 2023). According to regulations, blanking should be performed using removable spool pieces that can be operated manually (IMO, 2020a). However, in practice, these spool pieces are often left in place permanently, they are used to isolate or control the flow of substances during maintenance or repairs (P. Decrop, personal communication, 25 May 2023).
To prevent the flow of flammable liquid and vapor back into the inert gas system, two shut-off valves in series with a venting valve in between (known as double block and bleed valves) installed on the inert gas supply lines. Additionally, a closable non-return valve is commonly installed between the double block and bleed setup and the fuel system (P. Molander, personal communication, 19 May 2023).

Sufficient inert gas must be available on board at all times in order that at least one voyage can be made with the maximum expected consumption of fuel and the tanks can be kept inerted for 2 weeks in port with minimum consumption (IMO, 2016). A production plant or adequate storage capacities must be used to have inert gas on board.

Pieter Decrop (pers. comm.) has been on small chemical tankers where nitrogen is stored in cylinders on the deck. He suggests that having a nitrogen generator onboard is ideal because it increases the likelihood of having clean and uncontaminated nitrogen, which is crucial for maintaining the quality of methanol. Since the inert gas will come in contact with the fuel, it is essential to ensure that the inert gas does not contain any moisture or impurities (P. Decrop, personal communication, 25 May 2023).

The inert gas system must ensure that the percentage of oxygen in the volume produced is never more than 5%. A permanent oxygen level control and a 5% alarm must be installed on the inert gas supply lines. In the event that the gas contains more than 5%, the inert gas must be automatically vented to the atmosphere. The system shall be capable of maintaining an atmosphere with an oxygen level not exceeding 8% of the volume in the fuel tank (IMO, 2015). According to P. Molander's perspective, while using nitrogen as an inert gas to take away oxygen eliminates one risk, it introduces another risk due to the fact that nitrogen is not breathable (Juillion, 2019). Therefore, introducing pure nitrogen in the tank adds safety by limiting the risk of explosion but it also makes the atmosphere in the tank not breathable which can be hazardous for the crew (P. Molander, personal communication, 19 May 2023).

For this reason, ScandiNAOS has explored the two following alternative system design solutions in order to minimize these safety risks:

- ScandiNAOS has obtained approvals for specific designs of smaller ships that do not require the use of nitrogen. As there are no personnel present in the machinery room in these smaller vessels, they argue that nitrogen would impose unnecessary maintenance requirements. They have developed another solution to replace nitrogen to limit the risk of explosion, focusing on the tank. To ensure the structural integrity of the tanks in the event of an explosion, they have conducted rigorous explosion tests to determine the maximum pressure that can be generated during a methanol explosion. The results have shown that the tanks can withstand pressures below 10 bars, allowing for the creation of methanol fuel tanks capable of resisting such pressure (P. Molander, personal communication, 19 May 2023).
- ScandiNAOS has implemented another safety alternative measure by installing flame arresters. Sparks cannot enter the tank due to the efficient function of the flame arresters, even if someone is smoking outside near the tank. Extensive demonstrations and testing have proven the effectiveness and safety of this approach, enabling the use of nitrogen to be dispensed with. This alternative solution brings numerous advantages, including cost reduction, decreased maintenance requirements, and reduced weight of

equipment on board. The flame arresters effectively prevent a flame to enter the tank, further enhancing safety. While initially implemented for smaller vessels such as pilot boats with smaller tanks, this approach has shown great potential for wider application (P. Molander, personal communication, 19 May 2023).

Fuel tank vent outlets should be located not less than 3 m above the deck or gangway, if located within 4 m from such gangways. The vent outlets are also to be situated at a distance of at least 10 m from the nearest air intake or opening to accommodation and service spaces and ignition sources. Connection between fuel tank and fuel preparation space ventilation should be avoided. The vapour discharge must be directed vertically in the form of jets without being obstructed (Indian Register of shipping, 2021).

Cofferdams should be able to be either purged or filled of water by means of a non-permanent connection. Emptying the cofferdams should be done by a separate drainage system (IMO, 2020a)

### 5.2.7 Material

There are two different options as materials solutions commonly used for fuel tank (P. Molander, personal communication, 19 May 2023):

- carbon steel tanks, also known as "black steel tanks". During the conversion of this type of tank for use in methanol fuel, a crucial step involves blasting and cleaning the tanks thoroughly prior to the application of a protective coating. This protective layer prevents direct contact between the fuel and steel, as a plastic separation layer.
  This coated tank solution is suitable for larger ships with integrated tanks made of black steel. Black steel can pose a problem when exposed to even small amounts of water, as it becomes highly corrosive in such conditions. While pure and clean methanol may not cause any issues, the presence of water in methanol renders it

corrosive to black steel. Since water is highly soluble in methanol, determining the presence of water in methanol becomes impossible.

- stainless steel tanks, which are more expensive and may not require additional treatment. Due to its higher cost, stainless steel is commonly used in smaller ships, particularly vessels with independent stainless-steel tanks that are encased by aluminium or steel hulls.

All materials used must be suitable for the fuel under the maximum working pressure and temperature (IMO, 2020a). The design pressure for any section of the fuel piping system is the highest set pressure to which the system may be subjected in service (Indian Register of shipping, 2021). Pipes composed of materials other than steel should possess an allowable stress level equivalent to that accepted for steel materials (P. Molander, personal communication, 19 May 2023).

High pressure fuel piping systems are constructed with sufficient constructive and fatigue strength, which can be verified through stress analysis. This test should consider various factors such as the weight of the piping system, acceleration loads, internal pressure, and loads resulting from hogging and sagging bending moment of the ship (IMO, 2020a). To prevent electrostatic discharge, all fuel piping and independent fuel tanks must be electrically bonded to the ship's hull and electrical conductivity must be maintained across all joints and fittings. Electrical resistance between piping and the hull must be maximum $10^6$ Ohm (IMO, 2020a). To prevent the creation of potential ignition sources, non-fuel supply piping and cabling may be arranged within double-wall piping or ducts in which only piping and cabling necessary for operational purposes are installed. Filling lines connected to fuel tanks must be configured to reduce the potential for static electricity such as by minimizing the free fall into the fuel tank (Indian Register of shipping, 2021). When loading from the top of the tank, the liquid being delivered can break up into small droplets and splash, potentially creating a charged mist which can lead to an increase in the concentration of static electricity (International Chamber of Shipping & Oil Companies International Marine Forum, 2006).

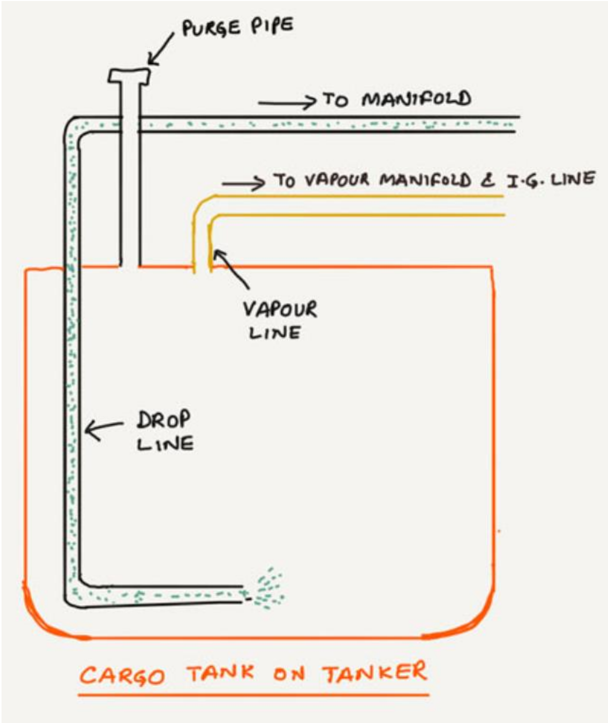


*Figure 4 Drop Line*

*Source: (Rajeev, 2018)*

A drop line is a vertically extended straight line that reaches the bottom of a tank. It is used to mitigate the risk of static electricity during the transfer process. By utilizing a drop line, the potential for static electricity is significantly reduced compared to an open pipe where static electricity can accumulate to higher levels (P. Decrop, personal communication, 25 May 2023). The arrangement and installation of fuel piping should be sufficiently flexible to maintain the integrity of the piping system under normal service conditions, with potential for fatigue taken into account. Expansion bellows is used for steam and fresh water pipes, while dresser coupling is used for fuel and cargo pipes (P. Decrop, personal communication, 25 May 2023).

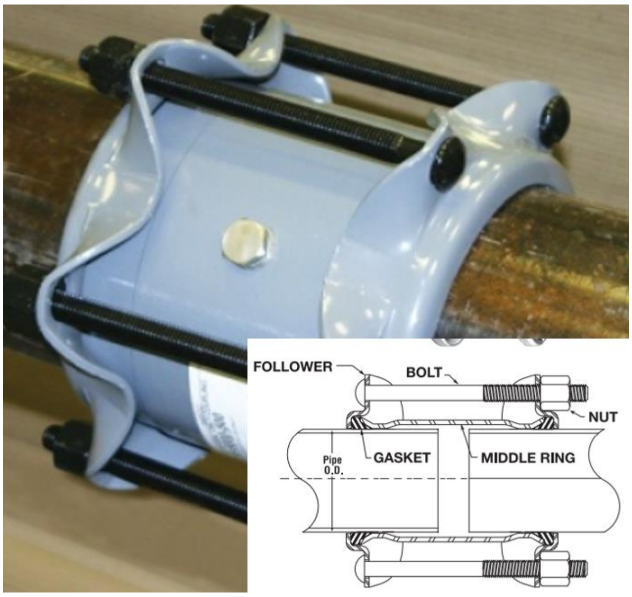


*Figure 5 Dresser coupling*

*Source: adapted from (Knoji, 2018) and (Dresser Pipeline Solutions, 2021)*

Dresser coupling is a 360 degree leak-proof seal (Dresser Pipeline Solutions, 2021).

### 5.2.8 Piping and joining

For sections of piping that require a protective duct, a full penetration butt-welding, and full radiography are required. Flange connections should be only allowed in tank connection space and fuel preparation areas (IMO, 2020a). During fuel piping use, all doors, ports and other openings on the corresponding superstructure or deckhouse side should normally remain closed (IMO, 2020a). The annular space in the double walled fuel piping must be isolated at the engine-room bulkhead, meaning there should be no common ducting between the engine-room and other areas (Indian Register of shipping, 2021). To ensure the separation of the inner pipe from the enclosed space, the fuel piping system must be enclosed in a manner that guarantees its gas and liquid tightness (IMO, 2020a). Fuel pipes should not be located less than 80 cm from ship's side (IMO, 2020a). All fuel pipes should be able to self-drain in normal condition of trim and list of the ship.

To connect fuel piping, welding should be used unless approved connections to shut- off valve and expansion joints are in place (IMO, 2020a).

The following direct connections of pipe length without flanges may be considered (Indian Register of shipping, 2021):

- butt-welded joints with complete penetrations at the root
- slip-on welded joints with sleeves and related welding that follow established standards for pipes with an external diameter of 50 mm or less (potential for corrosion must be also considered)
- screwed connections that meet recognized standards for piping with an external diameter of 25 mm or less

Butt welding should be subject to 100% non-destructive testing, while sleeve welds should be subject to at least 10% liquid penetrant testing or magnetic particle testing (IMO, 2020a). Penetrant testing is used in stainless steel cases and magnetic particle testing is used in carbon steel cases (Bale, 2022). As shown on Figure 6, sleeve weld is used to join two pieces of metal by sliding a sleeve or a tube over the joint and welding the sleeve to both pieces of metal (Futch & Wilson, 2022).

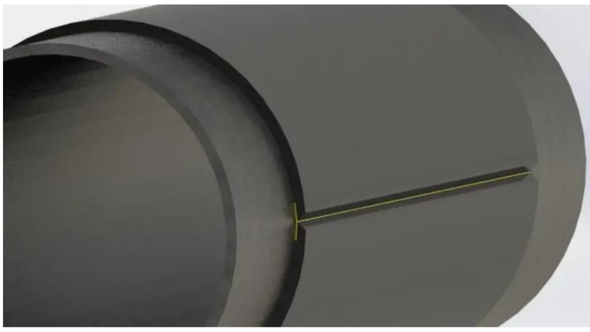

*Figure 6 sleeve welding*

*Source : (Futch & Wilson, 2022)*

Flanges, if used, must be either welded-neck or slip-on type. The weld neck flange has a tapered neck or hub that extends from the flange, which is designed to match the thickness of the pipe that is being welded to (Projectmaterials, 2017). Slip-on flange is slipped over the end of a pipe and is then welded to it, they are designed to be used with pipes that have external diameters that are smaller than the diameter of the flange (Projectmaterials, 2017).

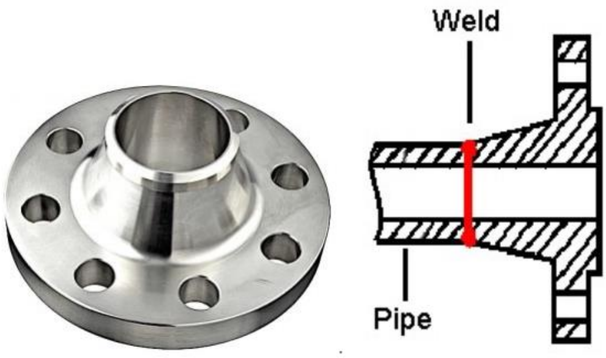


*Figure 7 Welding Neck Flange*

*Source: (Projectmaterials, 2017)*

Socket welds are prohibited in nominal sizes above 50 mm. To allow for piping expansion, expansion loops or bends should normally be provided in the fuel piping system. Slip joints should be avoided (Indian Register of shipping, 2021).

As detailed in 5.2.7, black steel material can be used also for piping, but stainless steel is more frequently used because no maintenance is required (P. Molander, personal communication, 19 May 2023).

Equipment components made of fluorinated materials like Teflon, rubber and neoprene are deemed appropriate for use in methanol service (Indian Register of shipping, 2021). These materials are known for their unique properties such as high thermal and chemical resistance, and non-stick behaviour (Liu & Grainger, 2013). Rubber hoses should have an internal coil wire for strength and ensure electrical continuity, and they should be compatible with methanol service (Indian Register of shipping, 2021). The electrical resistance of the grounding should not exceed 1 ohm per meter distance. As a chief engineer, Pieter Decrop is regularly inspecting and checking any damage on the hoses. In the event of damage, measuring the electrical resistance on the damaged piece helps to verify that it was not caused by static electricity.

All hoses must be labelled as: 'For methanol service only'. To prevent contamination during storage, hose ends must be capped or protected using suitable means (Indian Register of shipping, 2021).  For methanol-based applications, it is recommended to use stainless steel 316L grade steel. The 316L stainless steel is an austenitic stainless steel, detailed in 5.2.1, which can lead to exceptional performance in terms of corrosion, making it commonly used as material for chemical processing equipment (Ronsco, 2022).

The presence of water and inorganic salts in heat affected zones of the welds can result in corrosion, posing a risk to weld integrity. Aluminium alloys, galvanized steel, lead alloys are unsuitable for use in systems that contain methanol fuel due to their sensitivity to methanol and methanol-containing water (Indian Register of shipping, 2021). Additionally, methanol can cause stress corrosion cracking in titanium alloys (Indian Register of shipping, 2021).

In the case of a retrofit, the pipes previously used with a different fuel cannot be reused due to the impossibility of cleaning and restoring them to their original condition (P. Molander, personal communication, 19 May 2023).

### 5.2.9 Bunkering

Bunkering is the process of transferring fuel from land-based facilities or floating barge or a truck to the ship's tank (Maritime Manual, 2018). Bunkering ships with methanol is a straightforward process as methanol remains in a liquid state under atmospheric pressure, facilitating the bunkering operation (Kang S. et al., 2021). This bunkering operation is similar to other marine fuels such as heavy fuel oils, methanol bunkering necessitates minimal adjustments to existing infrastructure for bunkering conventional fuel (Kang S. et al., 2021). Methanol, when stored correctly, remains stable and has an indefinite shelf life (Kang S. et al., 2021). To ensure the safety of personnel involved and accommodate the unique properties of methanol, the bunker station is equipped with additional safety features that are discussed in this chapter.

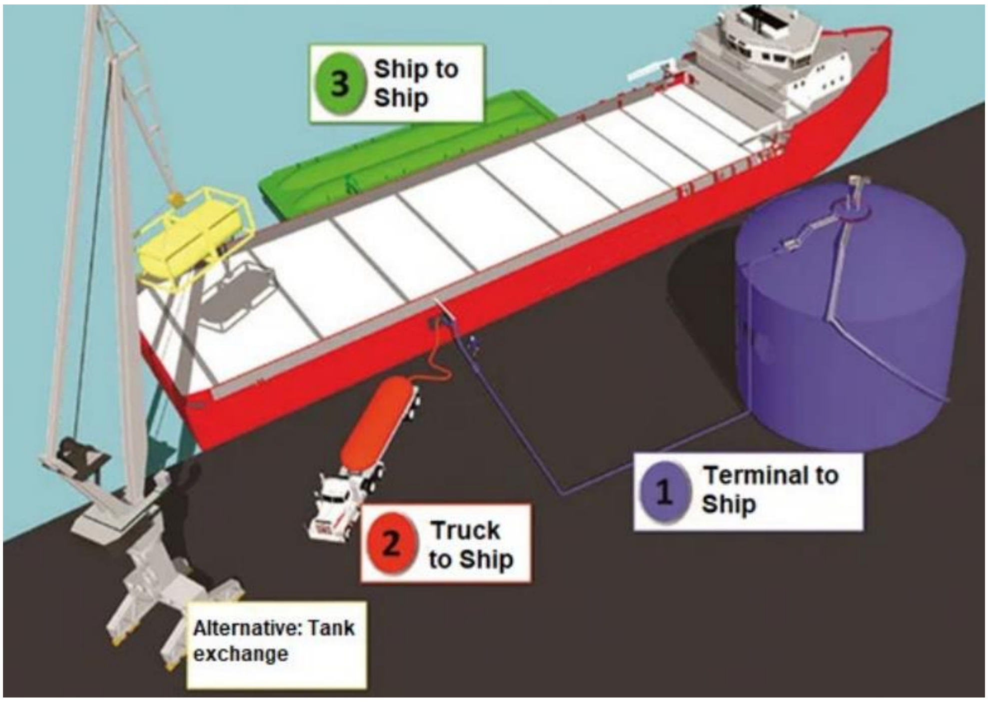


*Figure 8 Overview of the different bunkering methods*

*Source: (Port of Antwerp, 2021)*

Methanol fuel bunkered to a ship may be provided from a road tanker (truck-to-ship), a barge (ship-to-ship) or a pipe of a port facility (land storage-to-ship). In some cases, the bunkering station is equipped with two connections: one for bunkering methanol and the other for returning methanol vapours back to the supplier. The advantages of this set up are a precise pressure control within the tank during bunkering, preventing emissions through the vent mast and a reduced hazardous zone surrounding the bunker station. Therefore, this bunkering process of both liquid methanol and its vapours operates within a closed circuit (Port of Antwerp, 2021).

## Bunkering requirement:

The piping system used for bunkering must be designed to minimize the risk of harm to crew members and damage to the vessel in the event of a leak (Maritime Mutual Insurance Association, 2020). A copy of the fuel system schematic or piping and instrumentation diagram should be permanently displayed at both the bunker control station and at the ship's bunker station (IMO, 2020a). The bunkering station should not be closed to entrances, air inlets and openings to accommodation, and machinery spaces

(IACS, 2006). To prevent spills from entering enclosed spaces, closed or semi-enclosed bunkering stations should be equipped with gas and liquid-tight boundaries (IMO, 2020a). Bunkering lines are recommended to be routed outside of accommodation, control stations or service spaces (ABS, 2022). Bunkering lines passing through enclosed spaces that are not classified as hazardous are double walled or located inside gastight ducts (ABS, 2022). Appropriate measures must be in place for the safe handling of fuel spills (IMO, 2020a). Coamings and/or drip trays must be installed below the bunkering connections, along with safe means of collecting and storing spills that may occur, as detailed in 5.2.2 (IACS, 2019). This can be achieved by using a drain that leads to a designated holding tank equipped with a level indicator and alarm (IACS, 2019). In areas where accidental contact with fuel is possible, emergency showers and eye wash stations must be placed nearby (Schwarz & May 01, 2022). These emergency stations must be functional under all ambient conditions and at all time(Indian Register of shipping, 2021). For instance, on large ships such as VLCCs where there are multiple bunkering stations for different types of fuels and oils, a safety shower is installed at each station (P. Decrop, personal communication, 25 May 2023).

## Ventilation in bunkering:

To ensure adequate natural ventilation, the bunkering station are installed on open deck (P. Decrop, personal communication, 25 May 2023). When working with closed or semi-enclosed bunkering stations, mechanical ventilation should be available an all-time (IACS, 2017). To mitigate the potential risks associated with bunkering operations, two doors are required to make the separation from the accommodation area and hazardous zones, such as designated smoking areas. All ventilation systems in the ship, including those in the accommodation area, are closed from the outside to create a recirculation of air. This recirculation leads to a lower air pressure inside the accommodation. However, to prevent an under pressure situation that could affect breathing conditions, fresh air should still enter the accommodation from the aft of the ship, usually from the top of the accommodation (P. Decrop, personal communication, 25 May 2023).

## Bunker hoses:

Bunker hoses carried on board must be appropriate for methanol use and made of a suitable material. Each type of bunker hose, including end-fittings, must undergo prototype testing at a normal ambient temperature, with 200 pressure cycles ranging from zero to at least twice the specified maximum working pressure (IMO, 2020a). Once this pressure test cycle is completed, the prototype must demonstrate a bursting pressure of at least 5 times its specified maximum working pressure at both upper and lower extreme service temperatures (Indian Register of shipping, 2021). The burst pressure is the minimum pressure needed to cause irreversible damage on the pipe by bursting (Capuano, 2016). Prototype testing hoses must not be used for bunkering service (IMO, 2020a). Before being put into service, every new length of bunker hose produced should undergo hydrostatic testing at ambient temperature to a pressure not less than 1.5 times its specified maximum working pressure, but no more than two fifths of its bursting pressure (Steamship Mutual, 2008).. As part of the maintenance testing procedure, a yearly test is conducted at 100% of the maximum allowable working pressure (MAWP). Additionally, every two and a half years, a test is performed at 150% of the MAWP. These tests ensure that the system is capable of withstanding high pressures and remains in a safe operating condition (P. Decrop, personal communication, 25 May 2023). The hose should be marked with the date of testing, its specified maximum working pressure and, if used in services other than ambient temperature services, its maximum and minimum service temperature, as applicable (MEPC, 2000). The minimum allowable working pressure should be at least 10 bars (Indian Register of shipping, 2021).

*Table 2 Pressure test for bunker hoses*

*Source : own work*

| | |
|---|---|
| Prototype test | • **200** pressure cycles<br>• from **0** to **2×** ***MAWP*** |
| Bursting pressure | • minimum: **5** × ***MAWP*** |
| Hydrostatic test before being in service | • Minimum: **1,5** × ***MAWP***<br>• Maximum: ***2/5*** of bursting pressure |
| Yearly test | • At **100%** of ***MAWP*** |
| 2,5 years test | • At **150%** of ***MAWP*** |
| Minimum allowable working pressure | • Minimum 10 bars |

Provisions should be made for draining fuel from the bunkering hoses once the operation is finished (IMO, 2020a). When bunkering lines are not in use, they have to be free of gas, unless the decision of not to gas free is evaluated and approved (IACS, 2016). According to Pieter's experience, after a bunkering operation, it is common practice to blow the pipes to remove fuel residue. However, it is often challenging to completely drain the pipes. Therefore, as a precautionary measure, the pipes are subsequently filled with inert gas to minimize the risk of fire (P. Decrop, personal communication, 25 May 2023). When carrying fuel hoses on board, measures must be taken for their safe storage by either placing them on the open deck or in a dedicated storage room equipped with an independent mechanical extraction ventilation system capable of providing a minimum of six air changes per hour (Indian Register of shipping, 2021).

## Manifold:

The bunkering manifold must be designed to withstand the external loads encountered during bunkering operation (ABS, 2017). The connections at the bunkering station are of dry-disconnect technology and are equipped with an extra safety feature, such as a dry break-away coupling or a self-sealing quick release mechanism (ISO, 2019).

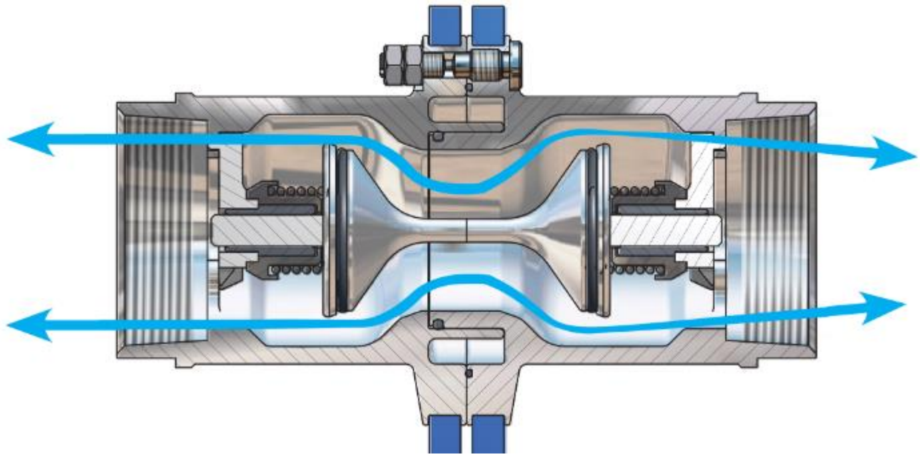

*Figure 9 Safety break-away coupling*

Source: (Guyson, 2019)

Safety break-away couplings are used to avoid accidents, protect terminal and have a breaking point which will break at a specified breaking strength while the two internal side valves will close (Tecalemit Flexibles, 2023).

The bunkering lines should be equipped with a ship-shore link (SSL) or an equivalent system that allows automatic and manual emergency shutdown (ESD) communication to the bunkering source (IMO, 2020a). SSL is a system that establishes communication between the fuel supplier and the receiving ship through a cable or hose umbilical (Stafford, 2019). SSL-ESD system is mandated to transmit an ESD signal promptly and without delay (Stafford, 2019). A manually operated stop valve operated shutdown valve must be installed in series on the bunkering line as close to the connection point as possible (Hagen, 2023). Alternatively, a combined manually operated and remote shutdown valve may be provided, which can be operated from the bunkering control station (IMO, 2020a). Suitable isolation measures must be in place for bunkering lines with a cross-over to prevent inadvertent fuel transfer to the unused ship side during bunkering (Indian Register of shipping, 2021).

## Provisions for bunkering operation:

The master of the receiving ship and the representative of the bunkering operation (persons in charge: PIC) must complete the following actions before starting any bunkering operation (Indian Register of shipping, 2021):

- agree on the transfer procedure, including the maximum transfer rates and volume to be transferred
- agree on emergency procedures
- complete and sign the bunker safety checklist

The bunker safety checklist must be completed, documenting the pre-bunkering verifications, before initiating bunkering operations (IMO, 2020a):

- ensure all communication methods are in place, including ship shore link (SSL)
- verify the fixed fire detection equipment is operational
- verify that the portable gas detection equipment is operational
- check the readiness of fixed and portable fire-fighting systems
- verify the operation of remote-controlled valves
- inspection of hoses and couplings

After bunkering operations, the ship PIC should receive and sign documentation that includes a description of the product and the quantity delivered, named as: "Bunker Delivery Note". The verification process must be documented and recorded by completing and signing the bunkering safety checklist by both PICs, indicating a successful verification (Indian Register of shipping, 2021).

## Communication while bunkering:

- Communications should be maintained between the ship PIC and the bunkering source PIC at all times. If communication is lost, bunkering should cease until it is restored.
- PICs should be able to communicate with all personnel involved in the bunkering operation.

- To ensure effective emergency shutdown (ESD), the SSL or equivalent communication system should be compatible with the ESD systems of both the receiving ship and the bunkering facility.

Bunkering control should be from a safe remote location that allows these following actions:

- Monitoring tank level
- Operation of remote-control valves
- closing of the bunkering shutdown valve from both the control location for bunkering and from another safe location
- indication of overfill alarms and automatic shutdown

If the ventilation in the ducting enclosure or annular spaces of the double walled bunkering lines stops, an audible and visual alarm must be activated at the bunkering control location. In the event of fuel leakage in ducting enclosure or the annular spaces of the double walled bunkering lines, an audible and visual alarm must be triggered, and the bunkering valve should automatically shut down.

### 5.2.10 Fuel supply to consumers

To minimize the consequences of any leakage of fuel, the methanol piping system must be kept separate from other piping systems (IMO, 2020a). When incorporating methanol in a old diesel engine, it is necessary to install new fuel supply piping and a new set of injectors on the cylinder cover segregated from the pilot fuel supply piping. This segregation is crucial to ensure that methanol is kept separate from the pilot fuel until they are blended together within the cylinder during combustion. This segregation helps to prevent any potential contamination between the methanol and pilot fuel before they enter the combustion chamber and reduce risk of hazardous situation (L. Pennman, personal communication, 2 June 2023). The fuel supply system should be designed with safe access for operation and inspection, while minimizing the consequences of any fuel release (IMO, 2020a). Additionally, the piping system for fuel transfer to the consumers must have multiple barriers to prevent leaks in the surrounding area. A reliable method for detecting potential leaks in the system is to regularly monitor the fuel tank levels. If there is a significant and abnormal change in the fuel level of a tank, it can serve as a valuable indicator of a possible leak (P. Decrop, personal communication, 25 May 2023).To further minimize the risks of injury to personnel, the fuel lines should be installed and protected  appropriately in case of any leakage (Indian Register of shipping, 2021). The space designed for fuel preparation should not be located within machinery spaces of category A and should be gas and liquid tight to surrounding enclosed spaces and vented to open air (Indian Register of shipping, 2021). The bilge system of the fuel preparation space can be used from outside the fuel preparation space (Indian Register of shipping, 2021).

### 5.2.11 Provisions for fuel distribution

The annular space between inner and outer fuel pipe must have mechanical ventilation of under pressure type with a capacity of minimum 30 air changes per hour, and the ventilation should lead to open air (IACS, 2007). Appropriate measures should be taken to detect any leaks into the annular space. The double-walled enclosure should be connected to a suitable draining tank that can collect and detect any possible leaks (Todd & Drennnen, 2019). Inerting of the annular space may be accepted as an alternative to ventilation. Suitable alarms should be installed to indicate a loss of inert gas pressure between the pipes (IACS, 2012). The outer pipe of the double walled fuel pipes must be dimensioned to withstand a design pressure equal to or greater than the maximum working pressure of the fuel pipes (IMO, 2020a). Alternatively, the calculated maximum built-up pressure in the duct, in the event of an inner pipe rupture, may be used to dimension the duct (Indian Register of shipping, 2021). Fuel tank inlet and outlet valves must be located as close to the tank as possible (IMO, 2020a). If valves must be operated during normal operation, such as when fuel is being supplied to consumers or during bunkering, they should be remotely operated if not easily accessible (teksal, 2020). Emergency shutdown means to stop all the pumps, should be provided on the escape routes from the consumer compartment, outside the fuel preparation space and at the bridge (P. Decrop, personal communication, 25 May 2023). The activation device should be a physical button that is marked and protected against inadvertent operation and is operable under emergency lighting (IMO, 2020a). When pipes penetrate the fuel tank below the top of the tank, a remotely operated shut-off valve should be installed on the fuel tank bulkhead (IMO, 2020a). If the fuel tank is adjacent to a fuel preparation space, the valve may be installed on the tank bulkhead on the fuel preparation space side (Indian Register of shipping, 2021).

## Fuel supply system:

All fuel piping should be arranged for gas freeing and inerting operation (Sustainable Ships, 2023). An automatically operated master fuel valve is installed on the main fuel supply line to each consumer or group of consumers. Its purpose is to enable a rapid shutdown of fuel flow when necessary (P. Decrop, personal communication, 25 May 2023). The master fuel valve(s) should be located outside the machinery space that contains methanol-fuelled consumers (Indian Register of shipping, 2021). A remotely operated shut-off valve must be installed on the fuel supply line for each consumer, and one manually operated shutdown valve should be installed in the fuel line to each consumer to ensure safe isolation during maintenance (Health and safety executive, 2004b). Valves should be of the fail-safe type, which is the valve's ability to prevent a hazardous condition by stopping or regulating the flow of fluid (Spence, 2016). For instance, on the tanker vessel owned by Stena Bulk, the methanol used as fuel is sourced from the cargo tank. The methanol cargo has the same safety requirements as fuel, then their quality standards are maintained at the same level. Since methanol serves as the cargo being transported on this ship, the fuel supply line is connected to the day service tank, which serves as the storage for the daily quantity of methanol consumed. The day service tank is filled with methanol sourced from the cargo tank. (L. Pennman, personal communication, 2 June 2023).

## 5.2.12 Pumps

Deepwell pumps which are submerged pumps, are installed within fuel tanks. They are powered by hydraulic systems located mainly on the deck. These pumps have a long shaft that extends down into the tank, allowing the actual pump to be submerged and operate within the fuel (P. Decrop, personal communication, 25 May 2023).

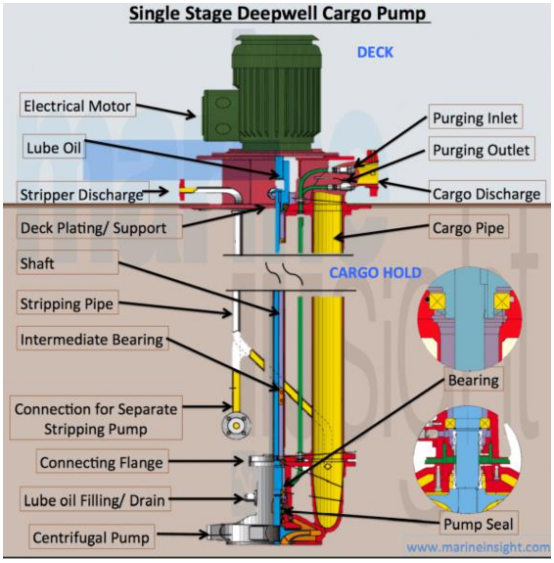


*Figure 10 Deepwell pump*

*Source : (Wiring schematica, 2022)*

Deepwell cargo pumps provide several advantages over traditional pump rooms. These include the elimination of the conventional pump room, improved pumping and stripping efficiency, enhanced flexibility in cargo segregation (Wartsila, n.d.-b). Deepwall pumps should have double barriers to prevent direct exposure of the hydraulic system to methanol. The double barrier should be equipped with a detection system and a drainage system for any potential methanol leakage (IMO, 2020a). All fuel system pumps should be protected against dry operation, meaning they should not operate in the absence of fuel or service fluid (Siemens, 2018). Relief valves should be provided for all pumps capable of developing a pressure exceeding the system's design pressure (Dey, 2020). Each relief valve should be in closed circuit, discharging back to the piping upstream of the suction side of the pump and limiting the pump discharge pressure to the design pressure of the system (Indian Register of shipping, 2021).

## 5.2.13 Power generation and other energy converters

The exhaust system must be designed to prevent the accumulation of unburned fuel, and each fuel consumer must have a dedicated exhaust system (IMO, 2020a). The thermal efficiency of the engine shows small differences between running fully on diesel or mainly on methanol. When running on diesel, the outlet temperature of the exhaust gas is around 230°C. However, when running mainly on methanol, the exhaust gas temperature is lower at around 210°C. This indicates that there is less energy left in the exhaust when using methanol fuel due to its lower sulphur content. In conventional engines, an exhaust gas boiler is used which ensures that the exhaust gas temperature at its outlet is not below 180°C to prevent the formation of sulfuric acid ($SO_x$). However, since methanol does not contain sulphur, the exhaust gas temperature can be reduced to around 160°C without the risk of $SO_x$ formation. When operating mainly on methanol without using heavy fuel oil (HFO), certain components such as purifiers and tank heating become unnecessary. In this case, if only diesel is required as a pilot fuel, the remaining heat requirements would primarily include the lubricating oil purifier and providing hot water for showers and accommodation heating. The absence of HFO simplifies the heat demand, as the focus shifts to fulfilling the specific needs related to diesel fuel usage (L. Pennman, personal communication, 2 June 2023).

The fuel system must be designed to withstand a single failure without causing an unacceptable loss of power (IACS, 2019). Engine components and systems must be designed to minimize the risks of fire and explosion. To prevent leakage of fuel into the machinery space, engine components that contain methanol fuel must be effectively sealed (IMO, 2020a).

If there is direct communication between the space below the piston and the crankcase in an engine, it is necessary to assess the potential risk of fuel gas accumulation in the crankcase. In four strokes engine, there is a direct communication between the piston connecting rod and the crankshaft, called crankcase, which could lead to accumulation of unburned fuel under the piston. In large two-stroke engines found in big ships, direct communication between the under-piston space and the crankcase is not feasible due to space constraints. The size of the piston rod and crankshaft makes it impractical to have a direct connection. Therefore, a stuffing box is employed to bridge the gap between the piston and the crankshaft. The stuffing box allows for the transfer of motion from the piston to the crankshaft while maintaining the necessary clearance and space within the engine room (P. Decrop, personal communication, 25 May 2023). Fuel gas accumulation in the crankcase can be hazardous and pose a risk of explosion or fire (Indian Register of shipping, 2021). In slow-turning two-stroke engines, the under-piston space may accumulate sludge, which can create a hazardous situation.


*Figure 11 Sludge in the underpiston space*

*Source: (P. Decrop, personal communication, 25 May 2023)*

When injectors in an engine malfunction, they may fail to inject fuel properly, resulting in a compromised spray or jet. This situation can lead to the fuel continuing to burn on top of the piston even after the combustion process. As the piston descends, the remaining flame can enter the under-piston space by the scavenging ports and mix with the incoming scavenging air. This condition is known as "scavenging air fire," where the presence of flame in the under piston space can cause undesirable effects and potentially lead to engine damage or failure (P. Decrop, personal communication, 25 May 2023). In the past, introducing $CO_2$ into that area was mitigating the hazards in the under-piston space. The intention was to displace oxygen and reduce the risk of fire or explosion. However, this approach was found to have limitations. $CO_2$, when introduced into a hot area, have a cooling effect and create thermal stress, potentially leading to thermal cracks in the engine components. In modern practice, steam is employed as a preventive measure to mitigate the risk of accumulated fuel ignition in the under-piston space. Steam is an inert substance and, being hot, it helps to avoid thermal stresses (P. Decrop, personal communication, 25 May 2023). As long as there is a burning flame of the diesel injector, methanol leakages will be avoided, as the methanol is fully combusted in the presence of the flame. To ensure safety and proper operation, sensors are installed on the fuel injection system. These sensors monitor the injection process, and if the injection of diesel fuel stops, the injection of methanol is also halted to prevent any undesired fuel flow and any potential leakage of methanol in under-piston space. The delivery of methanol injection is facilitated by a booster pump unit, which also plays a role in regulating the temperature of the methanol supply. In practice, the methanol supply temperature is maintained within the range of 25 to 50°C. These monitoring sensors are installed on both the diesel and methanol fuel injectors and play a crucial role in detecting any instances of poor combustion or misfiring (L. Pennman, personal communication, 2 June 2023). Misfiring can occur when there is inadequate in-cylinder combustion, often caused by inappropriate ignition timing or an imbalanced air-fuel ratio (Jafarian et al., 2018). If such issues are detected, continued operation may be allowed, provided that the fuel supply to the affected cylinder is shut off and that engine operation with one cylinder disabled is acceptable in terms of torsional vibrations (Indian Register of shipping, 2021).

## Dual-fuel engines:

If the methanol supply is shut off, the engines should be able to run continuously on oil fuel without interruption (IMO, 2020a). A reliable automatic system should be installed to switch from methanol to oil fuel mode with minimum engine power fluctuations (Søholt, 2021). The system's reliability should be demonstrated through testing (Dierickx et al., 2021). If the engine operates unstably on methanol, it should automatically switch to oil fuel mode, and there should be a provision for manual changeover as well. In case of an emergency or regular shutdown, the methanol fuel supply should be automatically shut off before the pilot oil fuel supply (IMO, 2020a). Shutting off the fuel supply to each cylinder or the entire engine should be done first or simultaneously before shutting off the pilot oil fuel (Indian Register of shipping, 2021).

### 5.2.14 Fire and explosion

The purpose is to provide fire protection, detection and fighting for all systems related to the use and operation of methanol as fuel (IMO, 2020a). The International Code Council (ICC) and the National Fire Protection Association (NFPA) designate methanol as a Class IB flammable liquid (Methanol Institute, 2020). Class IB liquids are characterized by a closed-cup flash points below 23°C and with a boiling point at or above 38°C (Williams, 2019). A closed cup flashpoint refers to the lowest temperature at which a liquid fuel or flammable substance, contained in a closed cup, produces enough vapours to ignite when exposed to an ignition source like a flame or spark (P. Decrop, personal communication, 25 May 2023). The vapor phase is the most hazardous physical state of methanol, its vapours are volatile, and can be easily ignited (Methanol Institute, 2020). Hazard management is especially important when the temperature of the liquid phase rises above flash point temperature (Methanol Institute, 2020). The fact that flash point temperature of methanol is low indicates substantial amounts of vapor are present rapidly above the liquid surface in the tank (Curley, 2023). Ignition may occur both within and outside the tank due to external heating and subsequent Boiling Liquid Expanding Vapor Explosion (BLEVE), which happens when pressurized methanol has reached a temperature above its boiling point (Mohit, 2021). Flash point temperature, vapor pressure, upper and lower flammability limits, autoignition temperature, and heat of combustion are important factors when assessing the ease of ignition and hazard severity of methanol (Methanol Institute, 2020).

When methanol tanks are being filled, the vapor from the methanol can escape through the tank vents into atmosphere, which can create hazardous conditions in the surrounding air due to the potential flammability and toxicity of the methanol vapor.

There are two different ways to control these hazards (Methanol Institute, 2020):

- Eliminating ignition sources and identifying potential toxicity hazards by designating the area surrounding the tank as a hazardous location
- taking out the air from tank vapor space by inerting or gas blanketing

The measures for controlling potential ignition sources in vicinity of methanol liquid storage tanks are similar to those applied for gasoline storage tanks (Methanol Institute, 2020). Inert gas blanketing is a common method used to prevent the formation of flammable or explosive atmospheres inside tanks or pipelines (Sensotec, 2016). The lower flammable limit of gasoline vapor is 1.4 % compared to 7 % for methanol (Cox et al., 1991). The relative density of gasoline vapor is 3 to 4 times heavier than air, compared to methanol which is 1.1 times heavier (Ode, 2021). Gasoline vapor will travel further along the ground without being diluted below the lower flammability limit and will ignite at much lower concentration than methanol vapor (Roberts, 2011). Generally speaking, the hazard zone for ignition of methanol vapor is less restrictive than that of gasoline (MacCarley, 2013). When defining the perimeter of hazard zones for methanol, the toxicity and the flammability of methanol must be considered (Methanol Institute, 2020).

## Provision for fire protection:

To ensure fire protection, fuel preparation spaces should be treated as machinery space of category A (IMO, 2020a). The approved non-combustible materials used to insulate from fire hazard should limit the temperature rise on the unexposed side to a maximum of 140°C above the original temperature and at any point, the temperature should not increase more than 180°C above the original temperature within the following time frames (Hoque, 2013):

- Class ’A-60’: 60 minutes
- Class ’A-30’: 30 minutes
- Class ’A-15’: 15 minutes
- Class ’A-0’: 0 minutes

The space containing methanol must be isolated from other machinery spaces of category A, accommodation, control station or cargo areas with barriers of at least A-60 fire integrity (IMO, 2020a). Any boundary of accommodation that faces fuel tanks on open deck, service spaces, control stations, machinery spaces and escape routes, must also have A-60 fire integrity. For the fuel tank boundaries, they must be separated from machinery spaces of category A and other rooms with high fire risks by a cofferdam of at least 600 mm and insulation of not less than A-60 class for fire integrity (Indian Register of shipping, 2021). Regarding bunkering stations, they should be separated by A-60 class divisions from machinery spaces of category A, accommodation, control stations and high fire risk spaces (IMO, 2020a). However, insulation standards may be reduced to class A-0 for spaces such as tanks, voids, auxiliary machinery spaces of little or no fire risk, sanitary and similar spaces (Indian Register of shipping, 2021).

Isolating valves must be installed in the fire main in order to allow isolation of damaged sections of the fire main when the fuel storage tank is situated on the open deck. Isolation of a section of fire main should not affect the water supply to the fire line ahead of the isolated section (IMO, 2020a). A flame arrester is fitted on tanks to prevent the fire outside the thank from igniting the methanol in the tank (IMO, 2020a). Aluminium can be used as a material for flame arresters, but it is susceptible to corrosion, especially when in contact with seawater (Storagetech, 2022). Corrosion compromises its effectiveness in preventing the propagation of flames. To ensure long-term reliability and durability, stainless steel is more commonly used for flame arresters on board ships. By using stainless steel, the flame arrester can maintain its effectiveness in preventing the spread of fire even when exposed to seawater (P. Decrop, personal communication, 25 May 2023).

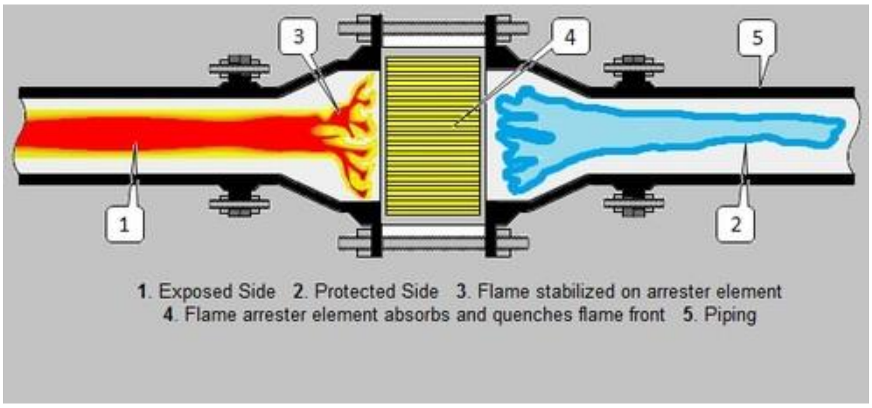


*Figure 12 Flame Arrester Working Principle*

*Source: (Host, n.d.)*

Flame arresters is comprised of screens, perforated plates, and slots that are enclosed within a frame (Crimtech, 2019). The case helps to absorb the heat of a flame and extinguish it (Nolan, 2019). The typical flame arrester features numerous small tubes that facilitate the necessary venting capacity while preventing the passage of flames (Crimtech, 2019). The principle behind its operation is that the flame's speed decreases as the pipe diameter reduces (Crimtech, 2019).

Methanol fire emits no light and create no smoke. When methanol burns in air, it produces very little visible light compared to conventional hydrocarbon fuels. This is primarily due to the absence of carbon-carbon bonds in methanol, which results in minimal soot or particulate emissions during combustion (MacCarley, 2013). Due to its clean-burning nature, methanol fires can be challenging to detect visually in the absence of contaminants. As a result, infrared flame detectors are commonly used to detect methanol fires, as they are sensitive to the unique light spectrum emitted by methanol flames, even when they are visually imperceptible by crew members (L. Pennman, personal communication, 2 June 2023).

## Provision for firefighting:

A fixed fire-fighting system of alcohol-resistant foam type, in accordance with the requirement of chapter 17 of the IBC Code and chapter 14 of the FSS Code should be installed beneath fuel tanks located on open deck (IMO, 2020a). The system should be designed to cover the area beneath the fuel tank where a fuel spill may potentially spread (IMO, 2020a). The bunker station should have a fixed fire-extinguishing system of alcohol resistant foam type and a portable dry chemical powder extinguisher or an equivalent extinguisher, which should be located near the entrance of the bunkering station (Indian Register of shipping, 2021). For fires in the engine room, where flammable liquids and fuels may be present, light foam with high expansion is used. High-expansion foam is capable of generating large volumes of foam bubbles, which helps to smother the fire and prevent the spread of flammable vapours. The foam's high expansion ratio allows it to fill the space rapidly and create a blanket over the fuel surface, suppressing the fire effectively. On the other hand, fires on the deck or open areas may require heavy foam with low expansion. Low-expansion foam is denser and has larger bubbles, making it more suitable for covering and extinguishing fires in these areas. The foam's lower expansion ratio ensures that it can provide better penetration and stability, enabling efficient firefighting on the deck (L. Pennman, personal communication, 2 June 2023). A fixed water spray system should be installed for diluting and extinguishing flames, provided that at least five parts water are added to one part of methanol, meaning that methanol concentration is diluted to less than 15% (Methanol Institute, 2020). Water-methanol solutions can become flammable at concentrations of approximately 80 volume percent of water (Methanol Institute, 2020).

The system should cover all exposed parts of the fuel tanks and be designed to cool tank walls as well. All compartments containing the methanol fuel system should have a fixed fire detection and fire alarm (IMO, 2020a). Detectors suitable for detecting methanol fires should be selected based on the fuel's fire characteristics (Evegren, 2017). Smoke detectors should be used in combination with other detectors that are more effective in detecting methanol fires. Means for detecting and recognizing methanol fires in machinery spaces should be provided for fire patrols and fire-fighting purposes, such as portable heat-detection devices (IMO, 2020a).

To protect machinery space and fuel preparation space that contain methanol-fuelled engines or fuel pumps, an approved fixed fire-extinguishing system should be installed in accordance with SOLAS regulation II-2/10 and the FSS Code (Indian Register of shipping, 2021). The fire-extinguishing medium used should be appropriate for the extinguishing methanol fires (Evegren, 2017). For machinery space category A and fuel preparation space, an approved alcohol-resistant foam system that covers the tank top and bilge area under the floor plates should be arranged (IMO, 2020a).

Fire suppression may use any of these following means (Methanol Institute, 2020):

- alcohol resistant fire-fighting, fire-extinguishing foam (AR-AFFF)
- dry chemical extinguishers (for small fires)
- $CO_2$
- Water mist spray

## Explosion:

To reduce the likelihood of explosions, several measures can be taken (IMO, 2020a):

- minimizing the number of potential sources of ignition
- decreasing the possibility of creating ignitable mixtures
- using approved electrical equipment suitable for hazardous area in case the use of such equipment is necessary

Area classification is a crucial process of identifying and classifying the areas where explosive gas atmospheres can be formed, with the aim of enabling safe operation of electrical equipment in such environments (Indian Register of shipping, 2021). To ensure the safety, all hazardous areas should be always restricted from passengers and unauthorized crew, and ventilation ducts should have the same area classification as the ventilated space (Health and safety executive, 2004a). Hazardous areas are classified into three zones, namely zone 0, zone 1 and zone 2, to aid the selection of suitable electrical equipment (IMO, 2020a).

<u>Hazardous area zone 0</u>:

This zone covers various areas, such as the insides of methanol fuel tanks, as well as any pipes and equipment that contain methanol fuel, and includes pipework used for pressure-relief or venting systems for fuel tanks (IMO, 2020a).

<u>Hazardous area zone 1:</u>

This zone covers various areas, including, but is not limited to (IMO, 2020a):

- cofferdams and other protective spaces that surround the fuel tanks
- fuel preparation spaces
- areas on open deck, or semi-enclosed spaces on deck, within 3 m of any methanol fuel tank outlet, gas or vapour outlet, bunker manifold valve, other methanol fuel valve, methanol fuel pipe flange, methanol fuel preparation space ventilation outlets

- areas on open deck or semi-enclosed spaces on deck near the fuel tank P/V outlets, within a vertical cylinder of unlimited height and 6 m radius centred upon the centre of the outlet and within a hemisphere of 6 m radius below the outlet
- areas on open deck or semi-enclosed spaces on deck, within 1.5 m of fuel preparation space entrances, fuel preparation space ventilation inlets and other openings into zone 1 spaces
- areas on the open deck within spillage coamings surrounding methanol fuel bunker manifold valves and 3 m beyond these, up to a height of 2.4 m above the deck
- enclosed or semi-enclosed spaces where pipes containing methanol fuel are located, such as ducts around methanol fuel pipes, semi-enclosed bunkering stations
- a space protected by an airlock is considered as a non-hazardous area during normal operation, but equipment to operate following a loss of differential pressure between the protected space and the hazardous area will need to be certified as suitable for zone 1.

<u>Hazardous area zone 2:</u>

This zone encompasses, but is not limited to:

- areas located 4 m beyond the cylinder and 4 m beyond the sphere, mentioned in hazardous area zone 1
- areas within 1.5 m surrounding other open or semi-enclosed spaces of zone 1
- airlocks

## 5.2.15 Fuel vapour detection system requirements

Gas detectors must be permanently fitted in all followings areas (Indian Register of shipping, 2021):

- all ventilated annular spaces of the double walled fuel pipes
- machinery spaces that contain fuel equipment
- fuel preparation spaces
- other enclosed spaces containing fuel piping or fuel equipment without ducting
- other enclosed or semi-enclosed spaces where fuel vapours may accumulate
- cofferdams and fuel storage hold spaces surrounding fuel tanks
- airlocks
- ventilation inlets to accommodation and machinery spaces, if deemed necessary, based on the risk assessment

Additional detectors are installed in the engine room below fuel supply because if there is a leak, fuel will be dropped by gravity. At methanol vapour concentration of 20% of lower explosion limit (LEL), an audible and visible alarm must be activated. With two detectors at 40% of LEL, the safety system should be activated (IMO, 2020a). The design process of the detection system should take into account toxicity concerns (Gandhi, 2015). Audible and visible alarms from the fuel vapour detection equipment must be located on the navigation bridge, continuously manned central control station, safety centre, control location for bunkering as well as locally (Indian Register of shipping, 2021). Continuous fuel vapour detection without delay is necessary (Health and safety executive, 2020). Audible and visible alarms for fire detection in machinery spaces containing methanol engines and fuel storage hold spaces should be activated at the navigation bridge, in a continuously manned central control station or safety centre, as well as locally (Indian Register of shipping, 2021).

Fuel vapor detection system must comply with the rules without any possibility of approving an alternative design through risk assessment. The system's conformity is strictly governed by regulatory requirements which is verified by the classification society (P. Molander, personal communication, 19 May 2023).

### 5.2.16 Ventilation

The objective is to ensure adequate ventilation that promotes safe working conditions for personnel and the safe operation of machinery and equipment where methanol is used as fuel (IMO, 2020a). The location of ventilation inlets and outlets for spaces requiring mechanical ventilation should be in accordance with the International Convention on Load Lines to avoid the need for closing appliances (Indian Register of shipping, 2021). Ducting used for the ventilation of hazardous spaces must be separate from that used for the ventilation of non-hazardous spaces (IACS, 1990). The ventilation system should be designed to operate under all environmental conditions and temperatures expected during ship's operation (Indian Register of shipping, 2021). Electric motors for ventilation fans should not be installed in hazardous spaces unless they are certified for the same hazard zone as the space being ventilated (Amerom, 2011).

The ventilation fans must not generate any source of vapour ignition in either the ventilated space or in the associated ventilation system. Ventilation fans and fan ducts, in way of fans only, should be constructed of non-sparking materials, defined as (Indian Register of shipping, 2021):

- impellers or housings made of non-metallic material, with static electricity elimination given due consideration
- impellers and housings made of non-ferrous metals
- impellers and housings made of austenitic stainless steel
- impellers of aluminium alloys or magnesium alloys and a ferrous (including austenitic stainless steel) housing, on which a ring of appropriate thickness of non-ferrous materials is mounted in the area of the impeller, with attention given to static electricity and corrosion between the ring and the housing
- any combination of ferrous (including austenitic stainless steel) impellers and housings with a tip design clearance of not less than 13 mm

The air gap between the impeller and the casing should never be smaller than 0.1 times the diameter of the impeller shaft where it passes through the bearing, but it should not be less than 2 mm (Indian Register of shipping, 2021). However, the gap does not need to be larger than 13 mm (IMO, 2020a).

The use of any combination of fixed or rotating component made of aluminium or magnesium alloy and a fixed or rotating component made of ferreous material is considered a risk for creating a spark and should be avoided in these areas, regardless of the tip clearance (Indian Register of shipping, 2021). To prevent any vapour build up, ventilation systems must be equipped with independent fans of adequate capacity (IGF, 2018). A mechanical exhaust type ventilation system should be used, with extraction inlets placed to prevent any accumulation of leaked methanol vapours in the space (Indian Register of shipping, 2021). To prevent the ingress of hazardous substances, air inlets for enclosed hazardous spaces should be sourced from non-hazardous areas (IMO, 2020b). For non-hazardous enclosed spaces, air inlets should originate from non-hazardous areas at a distance of least 1.5 m away from the boundaries of any hazardous area (IMO, 2020b). If the inlet duct goes through a hazardous space, the duct must be sealed tightly and pressurized to exceed the pressure of the surrounding space (IMO, 2020b).

The ventilation system should ensure that air outlets from non-hazardous spaces are situated outside hazardous areas and placed in an open area that would have the same or lower level of hazard as the ventilated space, in case the outlet is not present (IMO, 2020b). The capacity of the ventilation plant is normally determined by the total volume of the room, but in cases where the room has a complex shape, a higher ventilation capacity may be required (IMO, 2020b). When non-hazardous spaces have entry openings to a hazardous areas, an airlock should be installed, and the space should be kept at a higher pressure than the external hazardous area (IACS, 1990).

During initial start-up or after loss of overpressure ventilation, before turning on any electrical equipment not certified safe for the space in the absence of pressurization, two actions must be done (IMO, 2020b):

- purge the space (at least five air changes) or confirm by measurements that the space is non-hazardous
- pressurize the space

If the overpressure ventilation fails, the two followings preventions actions should work accordingly (Indian Register of shipping, 2021):

- an audible and visual alarm should be given at a manned location
- if overpressure cannot be immediately restored, automatic or programmed, disconnection of electrical installations according to a recognized standard must be required

Spaces such as double bottoms, cofferdams, duct keels, pipe tunnels, hold spaces where methanol fuel can be collected must have proper ventilation to provide a safe environment when entry into the spaces is necessary (IMO, 2020a). To ensure safety in fuel preparation spaces, a mechanical forced ventilation system should be installed for extraction purposes (Indian Register of shipping, 2021). The ventilation should be at least 30 air changes per hour during normal operation (IMO, 2020a). The ventilation fans should have sufficient power to ensure that the capacity is not reduced by more than 50% in case of a fan (or a group of fans) failure (Indian Register of shipping, 2021). Ventilation systems should be in operation when fuel treatment equipment or pumps are being used in handling spaces (IMO, 2020a). To prevent any released vapours during the bunkering operations from accumulating, bunkering stations that are not located on open deck should be properly ventilated (IACS, 2017). The ventilation system for double wall piping and ducts should be separate from all other ventilation systems and the inlets should always be in a non-hazardous area and away from ignition sources (Indian Register of shipping, 2021). The inlet opening should be fitted with a wire mesh guard and protected from water.

### 5.2.17 Electrical installation

Electrical equipment or wiring in hazardous areas should only be carried out if necessary for operational purposes or safety reasons (Indian Register of shipping, 2021). When installing electrical equipment in hazardous areas, the installation should adhere to IEC standards or comparable standards that are deemed acceptable by the organization, regarding the selection, installation, and maintenance of the equipment (IACS, 2015). In hazardous areas, the lighting system must be divided into at least two branch circuits (IMO, 2020a). All switches and protective devices must be capable of interrupting all poles or phases and should be positioned in an area that is free from any potential hazards (IACS, 2020). The electrical equipment installation must ensure secure bonding to the units' hull, ensuring safety (Indian Register of shipping, 2021).

## 5.2.18 Control requirements

To prevent an unacceptable power loss due to a single failure, the control and the monitoring of the safety systems of the methanol installations should be organized accordingly (Indian Register of shipping, 2021). In case of system failure or other fault conditions that may develop too quickly for manual intervention, a fuel safety system must be set up to automatically shut down the fuel supply system (IMO, 2020a). To avoid common cause failures, safety functions must be arranged in a separate fuel safety system that is independent of the fuel control system, including power supplies and input/output signals (Indian Register of shipping, 2021). The safety systems, along with the field instrumentation, should be designed to prevent unexpected shutdown (Lundteigen & Rausand, 2008). When regulations necessitate the use of two fuel supply systems, each system must be equipped with its own set of independent fuel control and safety systems (IMO, 2020a).

### Monitoring and detection:

To ensure the safe management of the entire fuel equipment, including bunkering, appropriate instrumentation devices must be installed for both local and remote readings of essential parameters (Indian Register of shipping, 2021). Liquid leakage detection systems should be placed in the protective cofferdams surrounding fuel tanks, in all ducts around fuel pipes, in fuel preparation spaces, and in other enclosed spaces that contain single walled fuel piping or other fuel equipment (Korlapati et al., 2022). The annular space in a double walled piping system must be monitored for leakages and the monitoring system should be connected to an alarm system (BRUGG Pipes, 2021). If any leakage is detected, it should trigger an automatic shutdown of the affected fuel supply line (Indian Register of shipping, 2021). For each enclosed space where an independent storage tank without a protective cofferdam is located, at least one bilge well with a level indicator must be installed and a high-level bilge alarm should be included (IMO, 2020a). For tanks not permanently installed in the vessel, a monitoring system equivalent to the one provided for permanent installed tanks should be included (Indian Register of shipping, 2021). A gas detection system, equipped with an oxygen sensor, is installed in areas where the crew is working to monitor and detect any potential nitrogen leaks from pipes (L. Pennman, personal communication, 2 June 2023).

## Bunkering and fuel tank monitoring:

Closed level gauging devices must be installed for each fuel tank, arranged to ensure that a level reading is always obtainable (Emerson, 2019). A closed gauging device is a specialized device that is designed to measure the liquid level in a tank without releasing the tank content into the atmosphere.

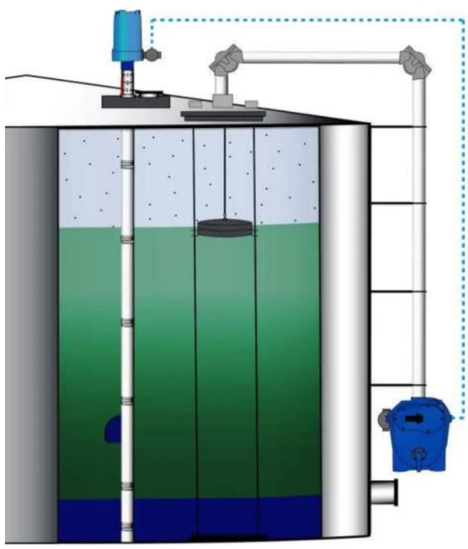

*Figure 13 Closed level gauging*

*Source : (Instrumentation tools, n.d.)*

The use of closed gauging devices is essential for maintaining safety and preventing environmental contamination when dealing with hazardous cargoes (Wartsila, n.d.-c). If maintenance is required while the fuel tank is in service, two level gauging devices must be installed (IMO, 2020a). Each fuel tank should have a visual and audible high-level alarm that can be function tested outside the tank (Indian Register of shipping, 2021). To prevent excessive liquid pressure in the bunkering line and avoid overfilling, an additional sensor (high-high-level) operating independently of the high liquid level alarm should automatically activate a shut-off valve (DNV, 2016). The high and high-high-level alarms for the fuel tanks should be visual and audible at the location where gas freeing of the fuel tanks is controlled (IMO, 2020a).

## Fuel supply system monitoring:

In addition to the instrumentation provided, indicators should be fitted on the navigation bridge, the engine control room and the manoeuvring platform for (IMO, 2020a):

- operation of methanol fuel engines
- operation and engine mode of operation in the case of dual fuel engines

In the event of an automatic valve shutting off the fuel supply, the fuel supply should not be reopened until the cause for the disconnection has been determined and necessary precautions have been taken (Indian Register of shipping, 2021). A notice outlining this procedure should be placed at the fuel shut-off valve operation station (IMO, 2020a). If a fuel leak causes a shutdown, the fuel supply should not be operated until the leak has been located and resolved. Clear instructions to this effect should be prominently displayed in the machinery space. A caution placard or signboard should be permanently affixed in the machinery space housing methanol-fuelled engines, warning against heavy lifting which could damage fuel pipes while the engine is in operation on methanol (Indian Register of shipping, 2021).

Manual remote emergency stop capability should be arranged for pumps and fuel supply from the following locations (IMO, 2020a):

- navigation bridge
- cargo control room
- onboard safety centre
- engine control room
- fire control station
- adjacent to the exit of fuel preparation spaces

### 5.2.19 Provisions for operation and maintenance

The aim of this section is to reduce the potential hazards to the crew, vessel, and surroundings by ensuring that the loading, storage, operation, maintenance and inspection of systems for methanol fuels are well-defined (Rivers, 2007). A duplicate of these guidelines and regulations found on the website of the IMO must be available on board all ships running on methanol fuel (IMO, 2020a). Maintenance procedures and information for all methanol related installations must be present at all time on board (Indian Register of shipping, 2021). The maintenance procedures are jointly developed by the ship design company and the classification society to ensure that the ship maintains a consistent level of safety throughout its service life (P. Molander, personal communication, 19 May 2023).

The fuel handling manual must cover but not be limited to the following topics (IMO, 2020a):

- the complete operation of the vessel from one dry dock to the next, which includes procedures for loading and discharging fuel, inerting and gas freeing
- the operation of inert gas systems
- procedures for firefighting and emergencies, which include operation and maintenance of fire-fighting systems and the use of extinguishing agents

- special equipment required for the safe handling of specific fuel, as well as specific fuel properties
- fixed and portable gas detection operation and maintenance of equipment
- Emergency shutdown systems
- instructions on what to do in an emergency situation such as fuel leak, fire or poisoning

Some of these procedures may originate from the ISM code and the ship should have appropriate emergency procedures in place (International Maritime Organization, 2018). Procedures for maintenance and repair must take into account the fuel containment system and its surrounding space (Indian Register of shipping, 2021). Maintenance procedures and guidelines for electrical equipment in hazardous areas must be followed, including inspection that comply with recognized standards for electrical installations in such spaces (Guy, 2019). The maintenance procedure is specific to each ship as they vary in size and configuration. Consequently, the size of the system and the frequency of maintenance will differ from one ship to another. For instance, the rule states in 5.2.6 that purging the fuel pipes with inert gas is required when the engine is shut down, on a daily basis, and after each engine stop in emergency situations. Nevertheless, the necessity of purging the fuel pipes at these different times, as the mere presence of fuel in a closed system does not immediately pose a risk of explosion. In ScandiNAOS, some architects argue that such frequent purging may not be sensible or essential. Therefore, they take time to carefully evaluate and question the necessity of applying these rules in order to effectively maintain the system while ensuring practicality and safety (P. Molander, personal communication, 19 May 2023). For instance, during situations when the engine is stopped for legitimate reasons, such as when the ship is on stand-by awaiting a pilot, the practice of purging the methanol supply line may not be necessary. This is because it is known that the engine will be restarted with methanol flowing through the pipes within approximately 30 minutes. In such cases, the decision to omit purging the methanol supply line is based on the understanding that the engine will be operational again in a relatively short period of time (L. Pennman, personal communication, 2 June 2023)

## 5.3 fuel-related training and drills for the crew

Periodical drills should include methanol fuel-related drills and exercises (IMO, 2020a). The ship must have appropriate operational procedures including a comprehensive fuel handling manual, to enable competent and trained personnel to safely operate the fuel bunkering, storage and transfer systems (IMO, 2020a). Developing a crew training procedure taking into account hazards involved by using methanol fuel is a collaborative effort between the classification society and the shipping company. Together, they strive to strike a balance between practicality in a work environment and ensuring the safety of the system. Sometimes, the ship's company may engage a third-party company that specializes in risk assessment and the development of safety exercises to ensure effective operations. The safety system for hazards and preventing accidents should be still reviewed and tested by the classification society (P. Molander, personal communication, 19 May 2023). The crew of the Stena Bulk tanker, presented in chapter 6, did not undergo significant changes in their training related to methanol usage following the retrofit. Since the tanker had been carrying methanol as cargo before the retrofit, suitable precautions and safety drills were already in place. For example, crew members of the ferry Stena Germanica, as chief engineers, were sent to the tanker to familiarize themselves by working with methanol and to become acquainted with the enhanced safety measures associated with its use (L. Pennman, personal communication, 2 June 2023).

Such exercises related to methanol fuels could include (IMO, 2020a):

- fuelling procedures based on the fuel handling manual, detailed in chapter 5.2.19
- responses to potential contingencies
- tests of equipment intended for contingency response
- assessments of assigned crew members' ability to perform their duties during fuelling, operation and contingency responses

The company must ensure that seafarers on board ships using methanol fuels have received adequate training to acquire the necessary skills for their specific duties and responsibilities. The master, officers, ratings and other personnel on ships using methanol fuels should be trained and qualified in accordance with regulation V/3 of the STCW

Convention and section A-V/3 of the STCW Code, taking into account the specific hazards of the methanol used as fuel (Indian Register of shipping, 2021).

From the supplier company, as Methanex, to the bunkering company, thorough checks are conducted to ensure compliance with the legal framework, such as the ADR (European Agreement concerning the International Carriage of Dangerous Goods by Road), which governs the transport of methanol by trucks on the road (P. Jonkers, personal communication, 26 May 2023). These regulations ensure that workers involved in the transportation are well-informed about the potential hazards they may encounter. Within the ADR code, specific procedures and provisions are outlined for the consignment, handling, and loading/unloading of methanol (UNECE, 2023b). Similarly, for barges, a specific code called ADN (European Agreement concerning the International Carriage of Dangerous Goods by Inland Waterways) exists to govern the safe transportation and handling of methanol (UNECE, 2023a). These codes provide guidelines and requirements to ensure the safety of personnel during the transfer of methanol. To enhance their responsiveness in hazardous situations while they are carrying methanol, workers of the bunkering company conduct training exercises provided by the regulations. By adhering to these codes and regulations, both the supplier and bunkering companies prioritize the safety and to prevent any potential incidents or accidents related to methanol transportation (D. Beernaert, personal communication, 27 May 2023).

# 6. Converting systems to methanol

This section will provide examples of retrofit operations and conversions carried out on systems that were previously employed in the maritime industry.
Methanol offers significant advantages due to its compatibility with existing main engines and the bunkering infrastructure in port facilities. Its seamless integration with conventional fuels allows easy blending and utilization. In terms of methanol barge-to-vessel bunkering, a notable achievement has been demonstrating to ports as Antwerp and Rotterdam with methanol storage facilities. Methanex together with Stena led the way in demonstrating to major shipping companies, including Maersk, MSC, CMA CGM and more, that efficient and safe bunkering can be successfully achieved by using existing equipment and technology (Methanex, 2023). Their pioneering efforts showcased the viability of methanol bunkering and paved the way for wider adoption within the industry. According to P. Jonkers (pers. comm.), with the bunkering technology already demonstrated by Methanex and the availability of methanol in 100 ports worldwide, the responsibility now lies with the shipping companies to initiate the conversion of their ships to methanol fuel.

When converting an engine which was running conventional fuels to a dual fuel methanol engine, several key components need to be changed or renewed to enable the use of methanol as a fuel (L. Pennman, personal communication, 2 June 2023):

- Fuel supply piping: the fuel delivery system, including the fuel supply lines, needs to be renewed. New pipes, compatible with methanol, should be installed to facilitate the connexion between the storage and the engine.
- Cylinder covers: the cylinder covers, which house the fuel injectors and other components, may need to be changed to accommodate the dual fuel system. This can involve modifications to the injector ports, installation of additional injectors for methanol, and ensuring proper sealing and compatibility with methanol fuel.
- Fuel injectors: the fuel injectors play a crucial role in delivering the fuel into the combustion chamber. When converting to a dual fuel methanol engine, a set of fuel injectors specifically designed for methanol fuel is required. For the retrofit of

recent large engines, a total of six injectors would be required, with three dedicated to methanol fuel and three dedicated to diesel fuel.

- Tanks: the fuel storage tanks may need to be coated with a suitable coating or replaced to accommodate the storage of methanol fuel. This ensures proper containment, compatibility with methanol, and sufficient capacity to meet the engine's fuel requirements.

Additionally, other supporting systems and components, such as fuel filtration systems, sensors or monitoring systems may also need to be adjusted to ensure proper operation when using methanol as a fuel.

## Ferry Stena Germanica:

In 1980, Wartsila company had an engine factory in Trieste in Italy which was doing development program for methanol engine. This initial survey was developing cylinder covers, conducing running tests and acquiring knowledge related to converting diesel engines to operate on methanol fuel. Based on their experience and knowledge gained, Wartsila used their expertise to retrofit the diesel engine of the ferry Stena Germanica with four 4 stroke engines capable of running on methanol fuel. Retrofitting involves modifying existing engines to accommodate the specific fuel requirements and ensure proper performance and efficiency. Nowadays, Stena Bulk company owns 4 tankers vessels and the ferry Stena Germanica sailing on methanol fuel (Stena Bulk, 2022).

The conversion process was relatively easier for the crew on the tanker because they were already familiar with the hazards and had been trained to handle flammable liquids in the tank. The maintenance procedures and training requirements for handling methanol are quite similar to those for other flammable substances. Therefore, the crew could leverage their existing knowledge and skills related to safety protocols, maintenance routines, and emergency procedures when transitioning to methanol. This familiarity and training facilitated a smoother conversion process and ensured that the crew was well-prepared to handle the specific requirements and risks associated with methanol as a fuel (L. Pennman, personal communication, 2 June 2023). As explained in chapter 5.2.11, bunkering operations for the tanker owned by Stena Bulk are simplified due to its unique setup of using the methanol cargo itself as fuel. Unlike traditional bunkering processes that involve going to a separate bunkering facility or receiving a dedicated methanol bunkering barge, the tanker simply needs to load its cargo at a production facility or cargo terminal. This integrated approach eliminates the need for additional bunkering procedures for this tanker vessel (L. Pennman, personal communication, 2 June 2023).

By pioneering innovative technologies for the utilization of methanol as a fuel, shipping companies like Stena Bulk and methanol suppliers such as Methanex have demonstrated the feasibility of methanol as a sustainable solution for the maritime industry's environmental needs. Their efforts have showcased that methanol can effectively serve as an alternative fuel, contributing to the cleansing of the maritime sector.

## Methatug Sleepboot 21:

The project involves the retrofit of a tug boat working for the Port of Antwerp, the conversion to a methanol fuel engine is under progress. The boat will experience its first methanol bunkering at the end of the June 2023. It is the company De Wit bunkering which will be responsible of the bunkering operation, the truck used for the operation will load its tank at the Methanex supplier storage. The driver of the truck is formed under the ADR code regulations, as explained in chapter 5.3 There is no possibility to bunker methanol fuel directly from a terminal facilities in Antwerp, it is under development (D. Beernaert, personal communication, 27 May 2023).

Sleepboot 21 is equipped with two Dual-Fuel engines, converted by ABC company, to power the Voith Schneider Propeller units. The engines will run both on methanol. The engines will always start on MGO (marine gas oil) and then switch over to Dual-Fuel mode once the operational parameters will be stabilized. When operating in Dual-Fuel mode, the fuel ratio will be approximately between 70% Methanol and 30% MGO (Port of Antwerp, 2021).

# 7. SWOT analysis of using methanol as a fuel

A SWOT analysis is a framework tool used to assess and understand the strengths, weaknesses, opportunities, and threats associated with a particular project or situation *(Peterdy, 2023)*. The Table 3, summarizes the various aspects and factors related to the use of methanol fuel on board ships in the maritime industry. The Table 3, likely provides a structured overview of the strengths, weaknesses, opportunities, and threats specific to methanol fuel usage.

*Table 3 SWOT analysis of using methanol as a fuel*

*Source: adapted from (SWOT, 2023)*

| Strengths | Weaknesses |
| --- | --- |
| • *Shipping regulations in place*<br>• *Biodegradable*<br>• *Liquid fuel at ambient temperature*<br>• *Potential for dual fuel engine*<br>• *Safe supply system* | • *Toxicity*<br>• *Limited production of green methanol*<br>• *Require pilot fuel*<br>• *Low energy density* |
| **Opportunities** | **Threats** |
| • *Engine availability*<br>• *Diverse pathways for clean production* | • *Corrosive behavior* |

Overall, this SWOT analysis, in Table 3, reveals that methanol presents significant strengths, such as its renewable nature, liquid state, and its adaptability. However, challenges related to its toxicity, energy density and its corrosive behaviour are obvious. With the support of regulations and technological advances, the opportunities for methanol, such as the availability of adaptable engines, are promising. By conducting this SWOT analysis, methanol is shown to have both positives and negatives aspects.

The positive result is that for each of the weaknesses and threats listed in table 3, there are applicable solutions or safe technologies whose effectiveness has been demonstrated in this research document. This indicates that efforts have been made to mitigate the challenges associated with methanol usage as a fuel in the maritime industry. This provides reassurance that the potential risks and limitations associated with methanol have been thoroughly considered, and steps have been taken to overcome them, ultimately contributing to the successful implementation of methanol as a sustainable and viable fuel option for ships.

# 8. Conclusion:

The utilization of methanol as a fuel onboard vessel can pose considerable challenges when it comes to adaptation and implementation. Acknowledging the weaknesses and associated risks of methanol is crucial to ensure the implementation of proper safety measures for this promising fuel option. Some of the potential downsides of methanol fuel that can lead to hazardous situations include the following elements.

Methanol is toxic and can be harmful if ingested, inhaled, or absorbed through the skin. Exposure to high concentrations of methanol vapor can cause health issues, including eye and respiratory irritation. Therefore, wearing suitable personal protective equipment (PPE) is crucial when working with methanol.

Methanol is corrosive to certain materials, what can pose challenges in terms of selecting compatible materials for fuel storage and supply systems, requiring appropriate material selection to prevent leaks and systems failure. Some solutions are commonly used in the maritime sector as the stainless steel.

Methanol has a lower energy density compared to conventional fossil fuels, which can affect the range and efficiency of vessels but adjustments to vessel design can ensure sufficient power and operational capability from methanol fuel.

Methanol's poor ignition capability can pose challenges when considering it as a standalone fuel, but its ability to mix well with other fuels opens up opportunities for its utilization in various fuel blends or as an additive.

Methanol is highly flammable, and its low flash point makes it potentially hazardous if not handled and stored properly. There are several measures and fire-fighting equipment available on ships to prevent methanol from igniting in the event of a leak and to combat fires effectively.

Despite these inherent disadvantages related to the use of methanol as a fuel, there are practical solutions available, which are developed in this research document, to effectively mitigate any risks and prevent potential hazards arising from its utilization. Ship design companies have evolved their approach to vessel conversion for methanol utilization, emphasizing the development of new safety systems. The challenges of creating safety systems to comply with regulations have been described in detail through the experiences of various individuals involved in the development of methanol. By developing technologies that allow methanol to be used safely as a fuel, different shipping companies have demonstrated that methanol can be a viable alternative for cleaning up the shipping industry. The transition to a methanol fuelled maritime industry can be facilitated by modifying the engines and technologies that are already in use. Conducting the SWOT analysis to assess the impact of methanol on operational safety reveals that methanol carries inherent risks, particularly when used aboard ships. However, this research document explores various solutions to facilitate the safe utilization of methanol. Furthermore, alternative approaches and strategies have been thoroughly examined, along with an in-depth discussion of the regulations governing methanol use.

In conclusion, methanol does have an impact on operational safety aboard ships. While methanol presents inherent risks, but it can still be used as a fuel on board vessels thanks to the implementation of new safety systems and the regulations governing its use.

# Bibliography:

ABS. (2017). *Guide for LNG Bunkering*. https://ww2.eagle.org/content/dam/eagle/rules-and-guides/current/special_service/245_Guide_for_LNG_Bunkering/LNG_Bunkering_Guide_e-Mar18.pdf

ABS. (2022). *Requirements for Fuel Cell Power Systems for Marine and Offshore Applications*. https://ww2.eagle.org/content/dam/eagle/rules-and-guides/current/other/312-requirements-for-fuel-cell-power-systems-for-marine-and-offshore-applications/312-fuel-cell-reqts-july22.pdf

American Conference of Governmental Industrial Hygienists (Ed.). (1991). *Documentation of the threshold limit values and biological exposure indices* (6th ed). American Conference of Governmental Industrial Hygienists.

Amerom, U. V. (2011). Choose the Right Electric Motors for Hazardous Locations. *Back to Basics*.

*An inside look at methanol as fuel*. (2023). Marine & Offshore. https://marine-offshore.bureauveritas.com/inside-look-methanol-fuel

Andales, J. (2023). *Risk Assessment: Process, Examples, & Tools*. SafetyCulture. https://safetyculture.com/topics/risk-assessment/

Baer, S. (2021). Upcoming Auction-Arrested Cargo-Oil. *Solution Strategists | Maritime Auctions*. https://solutionstrat.com/upcoming-auction-arrested-cargo-oil/

Bale, E. (2022, January 14). *Butt Weld Vs Socket Weld: How Are They Different?* Mewelding.Com. https://mewelding.com/butt-weld-vs-socket-weld/

Beernaert, D. (2023, May 27). *Interview of Dirk Beernaert, manager of the Methtug project for De Wit bunkering* [Teams].

Bell, T. (2019). *Characteristics of and Uses for Austenitic Stainless Steel*. ThoughtCo. https://www.thoughtco.com/metal-profile-austenitic-stainless-2340126

Bergsen. (2019, November 25). *Stainless Steel Grades and Properties*. Bergsen Metal. https://bergsen.com/stainless-steel-grades-properties/

*Blue Methanol*. (2021). Lake Charles Methanol. https://www.lakecharlesmethanol.com/domestic-oil

Boruń, A., & Wypych-Stasiewicz, A. (2021). Conductivity studies of 1:1 electrolytes in water + methanol mixtures at 298.15 K. *Journal of Molecular Liquids*, *344*, 117695. https://doi.org/10.1016/j.molliq.2021.117695

Bos, M. J., Kersten, S. R. A., & Brilman, D. W. F. (2020). Wind power to methanol: Renewable methanol production using electricity, electrolysis of water and CO2 air capture. *Applied Energy*, *264*, 114672. https://doi.org/10.1016/j.apenergy.2020.114672

Brown, A. (Ed.). (2011). *Green technologies and the mobility industry*. SAE International.

BRUGG Pipes. (2021). *Leak Monitoring Systems for double-walled piping*. https://www.bruggpipes.com/fileadmin/user_upload/downloads_en/startseite/produkte/industrieanlagen/leckueberwachung/LAZ_Technik_EN.pdf

Bureau Veritas. (2023). *Hazard identification | Identifying hazards in the workplace*. https://www.bureauveritas.co.uk/industrial-risk-management/workshop-facilitation/hazard-identification-study-hazid

Capuano, L. E. (2016). Geothermal well drilling. In *Geothermal Power Generation* (pp. 107–139). Elsevier. https://doi.org/10.1016/B978-0-08-100337-4.00005-X

chemistNATE (Director). (2019, October 18). *Complete Combustion of Methanol (CH3OH) Balanced Equation*. https://www.youtube.com/watch?v=eW547dY1qFs

Cheng, W., & Kung, H.H. (1994). *Methanol production and use* (Vol. 32). Taylor & Francis Group. http://choicereviews.org/review/10.5860/CHOICE.32-3898

Cordtz, R. F., Thomsen, T. B., Jespersen, M. C., & Schramm, J. (2021). Combustion of Methanol Blended with a Fuel Additive in a CI Engine. *MTZ Worldwide*, *82*(11), 54–59. https://doi.org/10.1007/s38313-021-0703-6

Cox, A. W., Lees, F. P., Ang, M. L., & Loughborough University of Technology (Eds.). (1991). *Classification of hazardous locations: A report of the Inter-Institutional Group on the Classification of Hazardous Locations (IIGCHL)* (Repr). Institution of Chemical Engineers.

Crimtech. (2019, March 17). *How Does a Flame Arrester Work and What are Its Uses?* Aspire Energy Resources Inc. https://www.aspireenergy.com/flame-arresters/

Crutchfield, N., & Roughton, J. (2014). Overview of Basic Safety Management Systems. In *Safety Culture* (pp. 93–107). Elsevier. https://doi.org/10.1016/B978-0-12-396496-0.00005-7

Cui, X., Kær, S. K., & Nielsen, M. P. (2022). Energy analysis and surrogate modeling for the green methanol production under dynamic operating conditions. *Fuel*, *307*, 121924. https://doi.org/10.1016/j.fuel.2021.121924

Curley, R. (2023, April 14). *Flash point | physics | Britannica*. https://www.britannica.com/science/flash-point

Dalena, F., Senatore, A., Marino, A., Gordano, A., Basile, M., & Basile, A. (2018). Chapter 1 - Methanol Production and Applications: An Overview. In A. Basile & F. Dalena (Eds.), *Methanol* (pp. 3–28). Elsevier. https://doi.org/10.1016/B978-0-444-63903-5.00001-7

Dasgupta, S. (2019, July 14). *Risk Assessment for Ships: A General Overview*. Marine Insight. https://www.marineinsight.com/marine-safety/risk-assessment-for-ships-a-general-overview/

Decrop, P. (2023, May 25). *Interview of Pieter Decrop* [Interview face to face].

Dey, A. K. (2020, April 3). *Pressure Relief Valve (PRV): Definition, Types, Working, Location, Sizing, Codes and Standards (PDF)*. What Is Piping. https://whatispiping.com/pressure-relief-valve/

Dierickx, J., Verbiest, J., Janvier, T., Peeters, J., Sileghem, L., & Verhelst, S. (2021). Retrofitting a high-speed marine engine to dual-fuel methanol-diesel operation: A comparison of multiple and single point methanol port injection. *Fuel Communications*, *7*, 100010. https://doi.org/10.1016/j.jfueco.2021.100010

DNV. (2016). *Methanol as marine fuel: Environmental benefits, technology readiness, and economic feasibility*. DNV. https://wwwcdn.imo.org/localresources/fr/OurWork/Environment/Documents/Report%20Methanol%2021.01.2016.pdf

Dorokhov, Y. L., Shindyapina, A. V., Sheshukova, E. V., & Komarova, T. V. (2015). Metabolic Methanol: Molecular Pathways and Physiological Roles. *Physiological Reviews*, *95*(2), 603–644. https://doi.org/10.1152/physrev.00034.2014

Drennen, T. W. (2019). Protect Tanks from Overpressure and Vacuum. *Back to Basics*.

Dresser Pipeline Solutions. (2021). *Dresser Engineering Data*. https://dresserutility.com/wp-content/uploads/DPS.EngineeringData.2021.pdf

Emerson. (2019). *Innovative Radar Solution Provides Accurate and Reliable Tank Level Gauging in LNG Marine Fuel Tanks*. https://www.emerson.com/documents/automation/white-paper-innovative-radar-solution-provides-accurate-reliable-level-gauging-in-lng-marine-fuel-tanks-en-6405186.pdf

EMSA. (n.d.). *Inspections of Recognised Organisations*. Retrieved 27 May 2023, from https://www.emsa.europa.eu/inspections/assessment-of-classification-societies.html

Evegren, F. (2017). *Methanol fire detection and extinguishment*. Research Institutes of Sweden.

Flessas, J. D. (1999). *Corrosion Control for Aboveground Storage Tanks: Part 1—Causes and Controls*. https://www.petrolplaza.com/knowledge/1952

Futch, D., & Wilson, J. (2022, March 17). Effect of Fit-up on Type B Steel Sleeve Life. *Allan Edwards*. https://www.allanedwards.com/white-paper/effect-of-fit-up-on-steel-sleeve-life/

Gandhi, M. (2015). *Gas Detection in Process Industry – The Practical Approach*. *160*.

Glossop, A. (2021). *What is a risk management strategy? | Ideagen*. https://www.ideagen.com/thought-leadership/blog/what-is-a-risk-management-strategy

Guo, S., Zhang, J., Wu, W., & Zhou, W. (2018). Corrosion in the molten fluoride and chloride salts and materials development for nuclear applications. *Progress in Materials Science*, *97*, 448–487. https://doi.org/10.1016/j.pmatsci.2018.05.003

Guy, B. (2019). *Hazardous Areas Explained: Part 2 – Managing Hazardous Areas*. NOF. https://www.nof.co.uk/news/2019/september/hazardous-areas-explained-part-2-managing-hazardous-areas/

Guyson (Director). (2019). *MannTek Safety Break-away Coupling*. https://www.youtube.com/watch?v=AeUHr_eWd7c

Hagen, G. (2023). *The State of Methanol as Marine Fuel 2023*. Sustainable Ships. https://www.sustainable-ships.org/stories/2023/methanol-marine-fuel

Hao, M., & Nie, Y. (2022). Hazard identification, risk assessment and management of industrial system: Process safety in mining industry. *Safety Science*, *154*, 105863. https://doi.org/10.1016/j.ssci.2022.105863

Health and safety executive. (2004a). *Hazardous Area Classification and Control of Ignition Sources*. https://www.hse.gov.uk/comah/sragtech/techmeasareaclas.htm

Health and safety executive. (2004b). *Remotely operated shutoff valves (ROSOVs) for emergency isolation of hazardous substances: Guidance on good practice—HSG244*. https://www.hse.gov.uk/pubns/books/hsg244.htm

Health and safety executive. (2020). *Failure to detect dangerous gas/vapour due to incorrect specification of sample tube*. https://www.hse.gov.uk/safetybulletins/failure-to-detect-dangerous-gas.htm

Hoque, A. (2013, May 1). Definition of: "A" Class Divisions (fire divisions). *Oil and Gas Drilling Glossary - IADCLexicon.Org*. https://iadclexicon.org/a-class-divisions/

Host, J. (n.d.). *How Does a Flame Arrester Work | Flame Arrester Diagram*. Paradox Intellectual Properties Inc. Retrieved 12 April 2023, from https://paradoxintellectual.com/how-flame-arresters-work.html

IACS. (1990). *Hazardous areas*. file:///C:/Users/dumon/Downloads/ur-d8rev2.pdf

IACS. (2006). *Access to forecastle spaces on tankers*. https://iacs.org.uk/media/3492/ui-sc120rev2.pdf

IACS. (2007). *Protection of fuel oil*. file:///C:/Users/dumon/Downloads/ui-sc211corr1%20(2).pdf

IACS. (2012). *Inert Gas Systems*.

IACS. (2015). *Hazardous area classification in respect of selection of electrical equipment, cables and wiring and positioning of openings and air intakes*. file:///C:/Users/dumon/Downloads/ui-sc274.pdf

IACS. (2016). *LNG BUNKERING GUIDELINES*. file:///C:/Users/dumon/Downloads/rec_no_142_pdf2936.pdf

IACS. (2017). *Special consideration within the risk assessment of closed or semi-enclosed bunkering stations*. file:///C:/Users/dumon/Downloads/ui-gf9.pdf

IACS. (2019). *Interpretations of the IGF Code*.

IACS. (2020). *Electrical Equipment allowed in paint stores and in the enclosed spaces leading to paint stores*. file:///C:/Users/dumon/Downloads/ur-e12rev2.pdf

IGF. (2018). *CHAPTER 5 CHIMNEYS AND VENTS, 2018 International Fuel Gas Code (IFGC) | ICC Digital Codes*. https://codes.iccsafe.org/content/IFGC2018/chapter-5-chimneys-and-vents

IMO (Ed.). (2016). *IGC Code: International code for the construction and equipment of ships carrying liquefied gases in bulk* (2016 edition, second edition). International Maritime Organization.

IMO. (2020a). *Annex—Interim Guidelines for the Safety of Ships Using Methyl/Ethyl Alcohol as Fuel*. IMO publications and doucuments. https://www.imorules.com/GUID-38B66B3F-AE5D-42C6-87C3-DFC1D2C333F5.html

IMO. (2006). *Amendments to the International Convention for the Safety of Life at Sea, 1974*. https://www.imorules.com/NSR_V2_PT1_CH3_5.html

IMO. (2014). *Chapter 15—Filling Limits for Cargo Tanks* [Concept]. https://imorules.com/GUID-977275BE-5C8B-4659-9B26-5DDEEC2AE783.html

IMO. (2015, June). *Gas and low-flashpoint fuels code adopted by IMO*. https://imopublicsite.azurewebsites.net/en/MediaCentre/PressBriefings/Pages/26-MSC-95-ENDS.aspx

IMO. (2020b). *Ventilation*. https://imorules.com/GUID-906B2DBC-7702-4167-BBCA-B7D12462A886.html

IMO. (2022). *Part A-1. Specific Requirements or Ships Using Methyl Alcohol (Methanol) or Ethyl Alcohol (Ethanol) as uel* [Topic]. https://www.imorules.com/LFPF_LRAPP1_PA1.html

IMO. (2023). *ISM Code*. IMO. https://www.imo.org/fr/OurWork/HumanElement/Pages/ISMCode.aspx

Indian Register of shipping. (2021). *Guidelines on Methanol Fueled Vessels*.

INRS. (2018). *Méthanol (FT 5). Généralités—Fiche toxicologique—INRS*. https://www.inrs.fr/publications/bdd/fichetox/fiche.html?refINRS=FICHETOX_5

Instrumentation tools. (n.d.). *Types of Tank Gauging Level Measurement Systems*. Retrieved 1 June 2023, from https://instrumentationtools.com/types-of-tank-gauging-level-measurement-systems/

International Chamber of Shipping, & Oil Companies International Marine Forum (Eds.). (2006). *ISGOTT International safety guide for oil tankers and terminals* (5. ed). Witherby's.

International energy agency. (2022). *Chemicals – Analysis*. IEA. https://www.iea.org/reports/chemicals

International Maritime Organization (Ed.). (2018). *ISM code: International Safety management code with guidelines for its implementation* (2018 edition). IMO.

IRENA. (2021). *Innovation Outlook: Renewable Methanol*. /Publications/2021/Jan/Innovation-Outlook-Renewable-Methanol. https://www.irena.org/publications/2021/Jan/Innovation-Outlook-Renewable-Methanol

ISO. (2019). *Ships and marine technology—Technical requirements for drydisconnect/connect couplings for bunkering liquefied natural gas*. https://cdn.standards.iteh.ai/samples/71167/53e1836a4fc6418cb028e43a07ebf514/ISO-21593-2019.pdf

Jafarian, K., Mobin, M., Jafari-Marandi, R., & Rabiei, E. (2018). Misfire and valve clearance faults detection in the combustion engines based on a multi-sensor vibration signal monitoring. *Measurement*, *128*, 527–536. https://doi.org/10.1016/j.measurement.2018.04.062

John Snyder. (2021). *Annual global methanol production to grow fivefold by 2050*. Riviera. https://www.rivieramm.com/news-content-hub/news-content-hub/annual-global-methanol-production-to-grow-fivefold-by-2050-64246

Jonkers, P. (2023, May 26). *Interview of Pieter Jonkers, responsible care manager of Methanex, HSSEQS: health safety security environment quality sustainability* [Teams].

Juillion, P. (2019, April 27). *What happens to nitrogen in the lungs? - Studybuff*. https://studybuff.com/what-happens-to-nitrogen-in-the-lungs/

Kang S., Boshell F., Goeppert A., & Landälv I. (2021). *Innovation Outlook: Renewable Methanol*. IRENA AND METHANOL INSTITUTE. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jan/IRENA_Innovation_Renewable_Methanol_2021.pdf?rev=ca7ec52e824041e8b20407ab2e6c7341

Knoji. (2018). *How to Repair a Leaking Pipe with a Dresser Coupling*. Knoji. https://knoji.com/article/how-to-repair-a-leaking-pipe-with-a-dresser-coupling/

Kobayashi, H., Hayakawa, A., Somarathne, K. D. K. A., & Okafor, E. C. (2019). Science and technology of ammonia combustion. *Proceedings of the Combustion Institute*, *37*(1), 109–133. https://doi.org/10.1016/j.proci.2018.09.029

Korabathina, K. (2018). *Methanol Toxicity Medication: Antidotes, Other*. Medscape. https://emedicine.medscape.com/article/1174890-medication

Korlapati, N. V. S., Khan, F., Noor, Q., Mirza, S., & Vaddiraju, S. (2022). Review and analysis of pipeline leak detection methods. *Journal of Pipeline Science and Engineering*, *2*(4), 100074. https://doi.org/10.1016/j.jpse.2022.100074

Koutsourakis, P. (2021, November 22). *Fuelling a low-carbon future with methanol as a marine fuel*. Lloyd's List. https://lloydslist.maritimeintelligence.informa.com/LL1138730/Fuelling-a-low-carbon-future-with-methanol-as-a-marine-fuel

Lawton, T. J., & Rosenzweig, A. C. (2016). Biocatalysts for methane conversion: Big progress on breaking a small substrate. *Current Opinion in Chemical Biology*, *35*, 142–149. https://doi.org/10.1016/j.cbpa.2016.10.001

Liu, F., & Grainger, D. W. (2013). Fluorinated Biomaterials. In *Biomaterials Science* (pp. 92–103). Elsevier. https://doi.org/10.1016/B978-0-08-087780-8.00011-5

Lundteigen, M. A., & Rausand, M. (2008). Spurious activation of safety instrumented systems in the oil and gas industry: Basic concepts and formulas. *Reliability Engineering & System Safety*, *93*(8), 1208–1217. https://doi.org/10.1016/j.ress.2007.07.004

MacCarley, A. (2013). *Methanol Fuel Safety—A Practical Guide*. California Polytechnic State University, San Luis Obispo,.

Mack, J. H., Rapp, V. H., Broeckelmann, M., Lee, T. S., & Dibble, R. W. (2014). Investigation of biofuels from microorganism metabolism for use as anti-knock additives. *Fuel*, *117*, 939–943. https://doi.org/10.1016/j.fuel.2013.10.024

Mamalis, S., Barcarolo, D., Polakis, M., Barling, R., & Plevrakis, G. (2021). *View of the value chain*. ABS. https://absinfo.eagle.org/acton/attachment/16130/f-c04f4eaf-a121-4560-9e15-5a56ee443f32/1/-/-/-/-/sustainability-outlook-iii-21055-web.pdf

Mannan, S. (Ed.). (2012). Chapter 11—Process Design. In *Lees' Loss Prevention in the Process Industries (Fourth Edition)* (pp. 443–508). Butterworth-Heinemann. https://doi.org/10.1016/B978-0-12-397189-0.00011-2

Maragakis, I., Clark, S., & Piers, M. (2009). *Guidance on hazards identification*. European Union Aviaton Safety Agency. https://www.easa.europa.eu/sites/default/files/dfu/ECASTSMSWG-GuidanceonHazardIdentification1.pdf

Marchant, N. (2021). *Grey, blue, green – why are there so many colours of hydrogen?* World Economic Forum. https://www.weforum.org/agenda/2021/07/clean-energy-green-hydrogen/

Maritime Manual. (2018, October 23). *What Is Bunkering In Ships? [Ultimate Guide | UPDATED 2023]*. https://www.maritimemanual.com/bunkering-in-ships/

Maritime Mutual Insurance Association. (2020). *Bunker Oil Spill Prevention and Control: Regulation and best practice*. https://maritime-mutual.com/risk-bulletins/bunker-oil-spill-prevention-and-control-regulation-and-best-practice/

McNeil, M. A., Schack, C. J., & Rinker, R. G. (1989). Methanol synthesis from hydrogen, carbon monoxide and carbon dioxide over a CuO/ZnO/Al2O3 catalyst. *Applied Catalysis*, *50*(1), 265–285. https://doi.org/10.1016/S0166-9834(00)80841-6

MEPC. (2000). *AMENDMENTS TO THE INTERNATIONAL CODE FOR THE CONSTRUCTION AND EQUIPMENT OF SHIPS CARRYING DANGEROUS CHEMICALS IN BULK (IBC CODE)*. https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/MEPCDocuments/MEPC.90(45).pdf

Merkouri, L.-P., Ahmet, H., Ramirez Reina, T., & Duyar, M. S. (2022). The direct synthesis of dimethyl ether (DME) from landfill gas: A techno-economic investigation. *Fuel*, *319*, 123741. https://doi.org/10.1016/j.fuel.2022.123741

Methanex. (2023). Methanex, Stena Line and Port of Gothenburg Achieve New Methanol Marine Fuel Milestone. *Methanex*. https://www.methanex.com/news/release/methanex-stena-line-and-port-of-gothenburg-achieve-new-methanol-marine-fuel-milestone/

*Methanol*. (2016). International Energy Agency. https://data.europa.eu/doi/10.2790/227559

Methanol Institute. (2020). *Atmospheric Above Ground Tank Storage Of Methanol*. https://www.methanol.org/wp-content/uploads/2020/04/Atmospheric-Above-Ground-Tank-Storage-Of-Methanol-Bulletin.pdf

Methanol Institute. (2021). *Methanol fuel in China 2020*. China Association of Alcohol and Ether Fuel and Automobiles (CAAEFA). https://www.methanol.org/wp-content/uploads/2020/04/China-Methanol-Fuel-Report-2020_final-1.pdf

Methanol Institute (Director). (2019, April 15). *How to Safely handle Methanol*. https://www.youtube.com/watch?v=nS3hf6zDafQ

Mlean. (2022, June 16). Continuous improvement and Safety. *Mlean®*. https://mlean.com/continuous-improvement-and-safety/

Mohit. (2021). *What is Boiling Liquid Expanding Vapour Explosion (BLEVE) on Gas Carrier Ships?* https://www.marineinsight.com/tech/what-is-boiling-liquid-expanding-vapour-explosion-bleve-on-gas-carrier-ships/

Molander, P. (2023, May 19). *Interview of Patrik Molander, a naval architect in ScandiNAOS* [Teams].

National Institute of Standards and Technology. (2023). *Methyl Alcohol*. National Institute of Standards and Technology. https://webbook.nist.gov/cgi/cbook.cgi?Name=CH3OH&Units=SI

Nolan, D. P. (2019). Fire- and Explosion-Resistant Systems. In *Handbook of Fire and Explosion Protection Engineering Principles for Oil, Gas, Chemical, and Related Facilities* (pp. 279–302). Elsevier. https://doi.org/10.1016/B978-0-12-816002-2.00016-7

Ode, M. (2021). *Calculating a Hazardous (Classified) Area: Determining air-circulation requirements for gases and vapors*. Default. https://www.ecmag.com/magazine/articles/article-detail/codes-standards-calculating-hazardous-classified-area-determining-air-circulation

Ott, J., Gronemann, V., Pontzen, F., Fiedler, E., Grossmann, G., Kersebohm, D. B., Weiss, G., & Witte, C. (2012). Methanol. In Wiley-VCH Verlag GmbH & Co. KGaA (Ed.), *Ullmann's Encyclopedia of Industrial Chemistry* (p. a16_465.pub3). Wiley-VCH Verlag GmbH & Co. KGaA. https://doi.org/10.1002/14356007.a16_465.pub3

PACTEC. (2021). *Complete Guide to Spill Containment (2021) | PacTec, Inc.* Pactec. https://www.pactecinc.com/guide-to-spill-containment/

Pal, D. B., Chand, R., Upadhyay, S. N., & Mishra, P. K. (2018). Performance of water gas shift reaction catalysts: A review. *Renewable and Sustainable Energy Reviews*, *93*, 549–565. https://doi.org/10.1016/j.rser.2018.05.003

Paradies, M., & Hughes, B. (2019, April 25). *Incident Investigation*. TapRooT® Root Cause Analysis. https://www.taproot.com/about/incident-investigation/

Pashchenko, D., Mustafin, R., & Mustafina, A. (2021). Steam methane reforming in a microchannel reformer: Experiment, CFD-modelling and numerical study. *Energy*, *237*, 121624. https://doi.org/10.1016/j.energy.2021.121624

Pennman, L. (2023, June 2). *Interview of Lars Pennman, chief engineer for 10 years and naval architect for methanol engine in Stena Bulk* [Teams].

Peterdy. (2023). *SWOT Analysis*. Corporate Finance Institute. https://corporatefinanceinstitute.com/resources/management/swot-analysis/

Pettitt, G., & Waite, P. (2003). *Bund design to prevent overtopping*. *149*.

Phillips, J. (2016, June 22). *Avoid Pressure-Relief System Pitfalls*. https://www.aiche.org/sbe/resources/publications/cep/2016/july/avoid-pressure-relief-system-pitfalls

Plevrakis, G. (2021). *Setting the course to low carbo shipping*. ABS. https://absinfo.eagle.org/acton/media/16130/sustainability-whitepaper-methanol-as-marine-fuel

Port of Antwerp. (2021). *Methanol Bunker Management Procedure for Sleepboot 21*. file:///C:/Users/dumon/OneDrive/Documents/m%C3%A9moire/Methanol%20Bunker.pdf

Pradeep, C. (2016, September 1). Crew training: The role of culture, competence and certification in safety training. *SAFETY4SEA*. https://safety4sea.com/crew-training-the-role-of-culture-competence-and-certification-in-safety-training/

Projectmaterials. (2017, September 20). *The 13 Types of Flanges for Piping Explained*. Projectmaterials. https://blog.projectmaterials.com/flanges/flange-types-piping/

PubChem. (2018). *Hazardous Substances Data Bank (HSDB): 93*. https://pubchem.ncbi.nlm.nih.gov/source/hsdb/93

Raj, P. K. (2016). A flammability (risk) index for use in transportation of flammable liquids. *Journal of Loss Prevention in the Process Industries*, *44*, 755–763. https://doi.org/10.1016/j.jlp.2016.10.001

Rajeev, J. (2018). *Inerting of Cargo Tanks: How Exactly to do it? - MySeaTime*. https://www.myseatime.com/blog/detail/inerting-on-tankers

Rattan, C. (2023, April 20). *LEGO to green plastic production with e-methanol*. Energy Central. https://energycentral.com/c/cp/novo-nordisk-lego-green-plastic-production-e-methanol

Richardson, J. T. (2013). *Principles of Catalyst Development*. Springer.

Richter, P. (2014). Methanol. In *Encyclopedia of Toxicology* (pp. 238–241). Elsevier. https://doi.org/10.1016/B978-0-12-386454-3.00748-X

Rivers, K. (2007). *Safety and environmental standards for fuel storage sites*. Buncefield Standards Task Group. https://www.icheme.org/media/10697/safety-and-environmental-standards-for-fuel-storage-sites.pdf

Roberts, R. (2011). *Using Physical and Chemical Properties To Manage Flammable Liquid Hazards*. 17.

Ronsco. (2022). *316/316L Stainless Steel Plate & Sheet Stockist In China—Ronsco*. https://www.ronscoplate.com/products/316-316l-stainless-steel-plate.html

Roode-Gutzmer, Q. I., Kaiser, D., & Bertau, M. (2019). Renewable Methanol Synthesis. *ChemBioEng Reviews*, *6*(6), 209–236. https://doi.org/10.1002/cben.201900012

*ScandiNAOS AB*. (n.d.). Retrieved 26 May 2023, from http://scandinaos.com/service.html#heading_ship_design

Schlager, S., Dumitru, L. M., Haberbauer, M., Fuchsbauer, A., Neugebauer, H., Hiemetsberger, D., Wagner, A., Portenkirchner, E., & Sariciftci, N. S. (2016). Electrochemical Reduction of Carbon Dioxide to Methanol by Direct Injection of Electrons into Immobilized Enzymes on a Modified Electrode. *ChemSusChem*, *9*(6), 631–635. https://doi.org/10.1002/cssc.201501496

Schwarz, B. J., & May 01, 2022. (2022). *An Overview of Emergency Showers and Eyewashes -*. Occupational Health & Safety. https://ohsonline.com/articles/2022/05/01/an-overview-of-emergency-showers.aspx

Sensotec. (2016, June 27). The Process of Inert Gas Blanketing. *Cambridge Sensotec*. https://www.cambridge-sensotec.co.uk/blog/2016/06/27/process-inert-gas-blanketing/

Siemens. (2018). *Protecting pumps in hazardous areas easily and reliably against dr ...* [C2_ct_press_release]. https://press.siemens.com/global/en/pressrelease/protecting-pumps-hazardous-areas-easily-and-reliably-against-dry-running

Siemens Energy. (2022). *Zero-emission fuel ramps up for shipping*. Siemens-Energy.Com Global Website. https://www.siemens-energy.com/global/en/news/magazine/2022/zero-emission-fuel-ramps-up-for-shipping.html

Singh, J., Dhar, A., & Kumar, P. (2022). Methanol Fuel in Compression Ignition Engines. In G. Di Blasio, A. K. Agarwal, G. Belgiorno, & P. C. Shukla (Eds.), *Application of Clean Fuels in Combustion Engines* (pp. 71–101). Springer Nature. https://doi.org/10.1007/978-981-16-8751-8_5

Soetens, J.-C., & Bopp, P. A. (2015). Water–Methanol Mixtures: Simulations of Mixing Properties over the Entire Range of Mole Fractions. *The Journal of Physical Chemistry B*, *119*(27), 8593–8599. https://doi.org/10.1021/acs.jpcb.5b03344

Søholt, N. (2021). *Milestone Order for World's Largest Methanol Dual-Fuel Engine*. MAN Energy Solutions. https://www.man-es.com/company/press-releases/press-details/2021/08/25/milestone-order-for-world-s-largest-methanol-dual-fuel-engine

Spence, J. (2016). *How to Choose a Fail-Safe Position for your Valves*. https://blog.craneengineering.net/how-to-choose-a-fail-safe-position-for-your-valves

Stafford, A. (2019). *The challenges of ship-to-shore links and the future of wireless ESD solutions*. Riviera. https://www.rivieramm.com/opinion/opinion/the-challenges-of-ship-to-shore-links-and-the-future-of-wireless-esd-solutions-56361

Steamship Mutual. (2008). *US Coast Guard Requirements for Hydrostatic Testing of Bunker Lines*. https://www.steamshipmutual.com/publications/articles/usbunkerlinetest0708

Stena Bulk. (2022). *Proman Stena Bulk takes delivery of fourth methanol-fuelled tanker Stena Prosperous | Stena Bulk*. https://www.stenabulk.com/press-and-news/press-releases/proman-stena-bulk-takes-delivery-fourth-methanol-fuelled-tanker-stena

Storagetech. (2022, October 18). Flame Arrestors. *Storagetech™ - World Leading Industrial Manufacturer*. https://storagetech.de/flame-arrestors/

Sustainable Ships. (2023). *The State of Methanol as Marine Fuel 2023*. Sustainable Ships. https://www.sustainable-ships.org/stories/2023/methanol-marine-fuel

Svanberg, M., Ellis, J., Lundgren, J., & Landälv, I. (2018). Renewable methanol as a fuel for the shipping industry. *Renewable and Sustainable Energy Reviews*, *94*, 1217–1228. https://doi.org/10.1016/j.rser.2018.06.058

SWOT. (2023). *The potential of low and zero emission fuels to the maritime sector*. https://www.dms.gov.cy/dms/shipping.nsf/All/42B01C3B2066465EC22589650024667C/$file/SWOT%20Event%20Report.pdf

Tarlengco, J. (2023). *Personal Protective Equipment (PPE) Safety*. SafetyCulture. https://safetyculture.com/topics/ppe-safety/

Tecalemit Flexibles. (2023). *Safety Break-away Couplings*. https://www.flexible-hose-and-coupling-tecalemit.com/en/safety-break-away-couplings

teksal. (2020, February 27). *Operating manual valves in inaccessible and hazardous locations – the case for remote valve operators*. Teksal Safety. https://www.teksal.com.au/operating-manual-valves-in-inaccessible-and-hazardous-locations-the-case-for-remote-valve-operators/

Tian, Z., Wang, Y., Zhen, X., & Liu, Z. (2022). The effect of methanol production and application in internal combustion engines on emissions in the context of carbon neutrality: A review. *Fuel*, *320*, 123902. https://doi.org/10.1016/j.fuel.2022.123902

TLV. (2022, November 7). *Bypass Valves*. TLV. https://www2.tlv.com/steam-info/steam-theory/other/bypass-valves

Todd, W., & Drennnen, P. E. (2019, November 21). *Protect Tanks from Overpressure and Vacuum*. https://www.aiche.org/resources/publications/cep/2019/december/protect-tanks-overpressure-and-vacuum

Together in safety. (n.d.). *Futur fuels- risk assessment*. https://togetherinsafety.info/wp-content/uploads/2022/06/Future-Fuels-Report.pdf

Turner, J. (2012). *Sustainable vehicle technologies: Driving the green agenda* (Department of Flow, heat and combustion mechanics, Ed.). Woodhead publ.

Ubongeh, A. (2022a, June 26). *Safety Checklist Definition; Importance, Types & Samples—HSEWatch*. https://hsewatch.com/safety-checklist/

Ubongeh, A. (2022b, July 13). *Health And Safety Audits And Inspections: Why They Are Important - HSEWatch*. https://hsewatch.com/health-and-safety-audits-and-inspections/

UNECE. (2023a). *About the ADN | UNECE*. https://unece.org/about-adn

UNECE. (2023b). *About the ADR | UNECE*. https://unece.org/about-adr

Valera, H., & Agarwal, A. K. (2019). Methanol as an Alternative Fuel for Diesel Engines. In A. K. Agarwal, A. Gautam, N. Sharma, & A. P. Singh (Eds.), *Methanol and the Alternate Fuel Economy* (pp. 9–33). Springer. https://doi.org/10.1007/978-981-13-3287-6_2

Verhelst, S., Turner, J. W., Sileghem, L., & Vancoillie, J. (2019). Methanol as a fuel for internal combustion engines. *Progress in Energy and Combustion Science*, *70*, 43–88. https://doi.org/10.1016/j.pecs.2018.10.001

Vu Hoang Huy. (n.d.). *Why use ethanol to treat methanol poisoning?* VINMEC international hospital. Retrieved 28 March 2023, from https://www.vinmec.com/en/news/health-news/general-health-check/why-use-ethanol-to-treat-methanol-poisoning/

Wagner, N. J., Coertzen, M., Matjie, R. H., & van Dyk, J. C. (2008). Coal Gasification. In *Applied Coal Petrology* (pp. 119–144). Elsevier. https://doi.org/10.1016/B978-0-08-045051-3.00005-1

Wainwright, M. S. (1988). Catalytic Processes for Methanol Synthesis – Established and Future. In *Studies in Surface Science and Catalysis* (Vol. 36, pp. 95–108). Elsevier. https://doi.org/10.1016/S0167-2991(09)60505-X

Wang, Z., Xia, S., Wang, C., Cui, C., Kang, S., Zheng, A., Zeng, K., & Zhao, Z. (2022). Sustainable production of methanol from one-pot catalytic conversion of cellulose over non-precious copper-based catalysts. *Fuel*, *322*, 123882. https://doi.org/10.1016/j.fuel.2022.123882

Ward, M. (2017, May). *Safety Leadership: Making a Culture of Safety the Foundation*. EHS Today. https://www.ehstoday.com/safety-leadership/article/21919022/safety-leadership-making-a-culture-of-safety-the-foundation

Wartsila. (n.d.-a). *Ambient conditions*. Wartsila.Com. Retrieved 28 May 2023, from https://www.wartsila.com/encyclopedia/term/ambient-conditions

Wartsila. (n.d.-b). *Deepwell cargo pumps*. Wartsila.Com. Retrieved 1 June 2023, from https://www.wartsila.com/encyclopedia/term/deepwell-cargo-pumps

Wartsila. (n.d.-c). *Gauging devices (for measuring the tank contents)*. Wartsila.Com. Retrieved 1 June 2023, from https://www.wartsila.com/encyclopedia/term/gauging-devices-(for-measuring-the-tank-contents)

Weekes, J. (2017). *6 elements of an effective safety management system | Health & Safety Handbook*. https://healthandsafetyhandbook.com.au/bulletin/6-elements-of-an-effective-safety-management-system/

Williams, B. (2019, July 30). *Flammable Liquids Classes & Categories*. Chemical Strategies, Inc. https://chemicalstrategies.com/flammable-liquids-classes-and-categories/

Wimer, W. W., Russell, J. A., & Kaplan, H. L. (1983). *Alcohols toxicology*. Noyes Data Corp.

Wiring schematica. (2022, July 16). Deep Well Pump Wiring Diagram. *Wiring Schematica*. https://wiringschematic.blogspot.com/2022/07/deep-well-pump-wiring-diagram.html

Yao, C., Cheung, C. S., Cheng, C., Wang, Y., Chan, T. L., & Lee, S. C. (2008). Effect of Diesel/methanol compound combustion on Diesel engine combustion and emissions. *Energy Conversion and Management*, *49*(6), 1696–1704. https://doi.org/10.1016/j.enconman.2007.11.007

Yusaf, T., Hamawand, I., Baker, P., & Najafi, G. (2013). The Effect of Methanol-Diesel Blended Ratio on CI Engine Performance. *International Journal of Automotive and Mechanical Engineering*, *8*, 1385–1395. https://doi.org/10.15282/ijame.8.2013.26.0114

Zhao, K., Dolan, G., & Chatterton, C. (2021). A Brief Review on Methanol-Fuelled Vehicles (MFV) in China and Implementation Policy. In A. K. Agarwal, H. Valera, M. Pexa, & J. Čedík (Eds.), *Methanol: A Sustainable Transport Fuel for SI Engines* (pp. 139–159). Springer. https://doi.org/10.1007/978-981-16-1224-4_6