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**TNO report**

**TNO 2023 R10677**

# MENENS | Qualitative risk assessment of the storage, bunker and fuel distribution systems

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# Summary

The maritime sector is looking for sustainable pathways to achieve their emission reduction targets. An option that can currently count on a lot of support in the international maritime sector is methanol, because of its wide applicability and the potential for significant $CO_2$ reduction potential at an acceptable price. This work package focuses on the safety of the methanol fuel system, which needs to be equivalent that of a marine gasoil system.

A qualitative risk assessment is the basis for validating the safety of the storage, bunkering and fuel distribution of a methanol powered ship. Hazards with a high associated risk, without adequate mitigation measures, need to be examined in more detail. This document distils the research questions that need to be answered to properly understand the implications associated with a methanol powered ship.

# Contents

# 1 Introduction

The maritime sector is looking for sustainable pathways to achieve their emission reduction targets. However, it is still unclear how these targets can be achieved in the most effective and safe way.

An option that can currently count on a lot of support in the international maritime sector is methanol, because of its wide applicability (different usage profiles) and the potential for significant $CO_2$ reduction potential at an acceptable price. In addition, existing ships can be made suitable for sailing on methanol by means of retrofit, so that the energy transition can be initiated more quickly.

At the same time, industry should become ready to adopt alternative future fuel options that enable completely $CO_2$-free sailing, such as hydrogen and ammonia. Although in the short-term methanol systems already make an essential contribution to $CO_2$ reduction in shipping, it is of great importance that the maritime sector also bears in mind the longer-term perspective in which other zero-emission options can (will) play a greater role. Future-proof solutions are needed that are 'forward compatible', so that the sector can switch (and/or switch up) to future clean propulsion systems such as hydrogen in the most efficient and safe way.

A qualitative risk assessment is the basis for validating the safety of the storage, bunkering and fuel distribution of a methanol powered ship. Hazards with a high associated risk, without adequate mitigation measures, need to be examined in more detail. This document distils the research questions that need to be answered to properly understand the implications associated with a methanol powered ship.

The fuel distribution system is divided into discrete parts to equipment function and location, described in chapter 2. The definition of the qualitative risk assessment is given in chapter 3. Whereafter the hazards with a high associated risk are formulated in question for further research (chapter 4).

# 2 Inventory components methanol per compartment

The components present in a methanol powered vessel are described in this chapter. The description of components is grouped in the compartments where they are located, see Figure 1 for a schematic representation. The piping and instrumentation diagram for the Hunteborg is used as the base case, see reference [4]. The components used in this diagram are deemed characteristic and scalable for vessels powered on methanol.

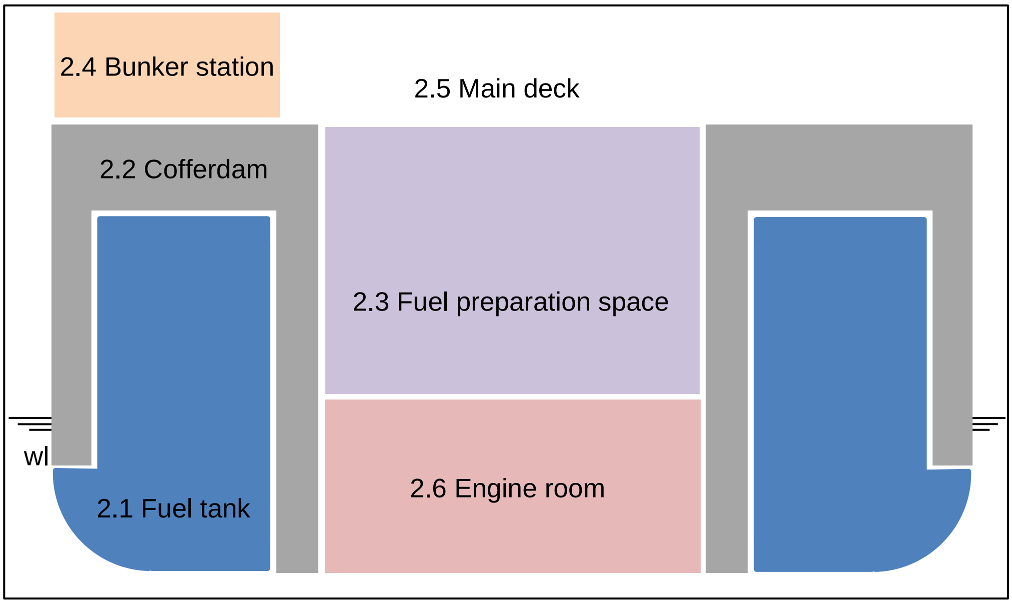



Figure 1 Compartmentalisation of the Hunteborg design, with reference to the subsections. Figure not to scale.

## 2.1 Fuel tank

### 2.1.1 *Tank*

Methanol is stored in liquid form and atmospheric pressure, since it is in liquid phase between -93°C to +65°C at atmospheric pressure. Due to its density and lower heating value (19.5 MJ/kg), methanol requires approximately 2.5 times larger fuel tanks than marine gas oil per energy unit, and similar or smaller fuel tanks than LNG – if factoring in volume inefficiencies of C-type LNG tanks, reference [1]. The methanol fluid is extracted from the bottom of the fuel tank for use in the power unit, see Figure 2.

The flash point of methanol is around 11 to 12 °C. In a fuel tank, when the temperature is equal to or above the flash point, this liquid gives off vapours in a quantity such as to be capable of forming an ignitable vapor to air mixture. By inerting the empty space in the fuel tank, it prevents the methanol from forming a flammable concentration of 6.7 - 36% in air. The wide range of flammability limits indicates that the fuel is flammable under several condition and therefore the additional safety measure of inerting the tanks is required.

Pressure sensors transmitters at the bottom of the tank determine the fuel filling level. The pressure reading is an important quantity in the methanol driven ship.

The bunker operation depends on this value not to overfill the tank and determine the distribution between the multiple tanks. The valves in the pump room, supplying methanol to the power unit, are also operated based on the readings of the filling levels for the starboard and port side tank.

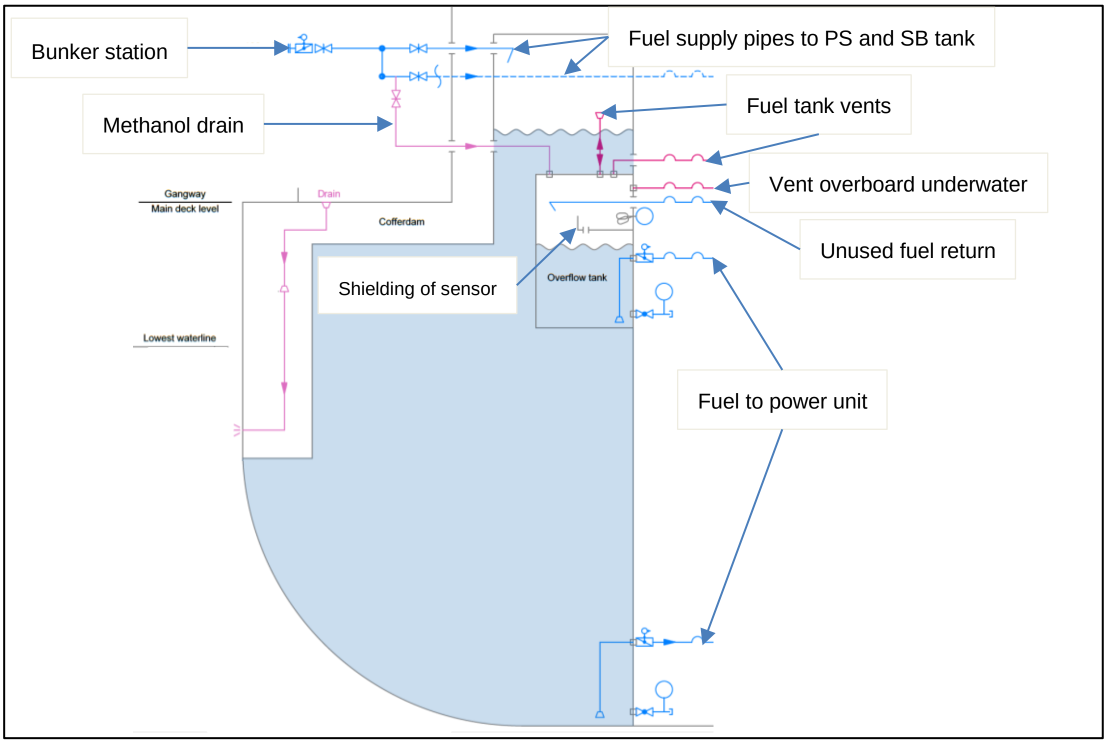



Figure 2 Example methanol fuel tank piping and instrumentation diagram, reference [4]. Port side fuel tank is shown in this figure. The venting of the starboard tanks is routed to the overflow tank located inside the port side tank.

### 2.1.2 *Piping*

Valves in the piping system divide the fuel of both tanks. The fuel supply line to each fuel tank ends at the top of the fuel tank. In this diagram it is possible to redistribute the methanol between the fuel tanks. While filling the tanks, the overpressure gas mixture is directed via the overflow tank to an underwater vent. In case there is no vapour retour line, the maximum flow of 100 m$^3$/h is vented.

### 2.1.3 *Overflow tank*

The vents of the fuel tanks are in direct contact with the overflow tank. The overflow tank, and thus the fuel tanks, are under a slight overpressure supplied by the inerting system (40 mbar). The inerting system should be able to provide the necessary volume to fill all methanol fuel tanks at the maximum consumption rate of the power unit. If the pressure increases to 50 mbar, the gas mixture is vented overboard under the waterline.

Unused methanol from the power unit or leak discharges from the high-pressure pump are also directed into the overflow tank. A methanol drain, which is used for flushing the methanol bunker lines, is directed to the overflow tank.

Pressure is measured to determine the filling of the overflow tank. At the critical filing level of the overflow tank, a level sensor is triggered, and the main alarm is activated. This is a mechanical sensor activated when the floater arm is lifted by the buoyancy from methanol. The sensor is shielded from tank sloshing, as shown in Figure 2. The overflow tank is drained when methanol is requested by the pumping circuit of the power unit or in case of a high-level alarm pumped to a fuel tank.

## 2.2 Cofferdam

The fuel tank is surrounded by a cofferdam, except for side shell below the lowest waterline. The cofferdams act as an isolating space of the fuel tank and ensure that methanol is not leaked into other parts of the vessel. The cofferdam is an empty space inerted by nitrogen. Sensors are present in the cofferdam to warn if the cofferdam has begun to fill with methanol liquid or gas. A bilge pump is used to pump liquid overboard and a mechanical ventilation system is present to exchange the air. The minimum horizontal distance between the fuel tank side and the ship's shell shall be at least 600 mm and insulated when adjacent to a hot space. A hatch from main deck provides access for inspection and maintenance. The cofferdam is made gas-free by filling them with water, after which the tanks are drained. The liquid or gas mixture can dissolve in water and safe to pump overboard.

## 2.3 Fuel preparation space

The fuel preparation space houses the equipment to condition the methanol for use by the power unit. The preparation space is divided into the subsystems described in the subsections below.

### *2.3.1 Pumps*

The pumps are used for distributing the methanol through the ship. The pump circuit receives the fuel from three sources: two main fuel tanks and the overflow tank, see Figure 3. The output of the pump P&ID is the input to the high-pressure pump.

Two pumps are situated in the ring line, which can be completely closed off by valves on either side of the pumps. Valves in the parallel input line (tag numbers 113 to 115) determine the source of the input fuel. The valves with tag numbers 108 to 110 are usually closed and only open when a redistribution of methanol over the fuel tanks is needed.

The pump provides a constant flow of methanol, of which the supplied flow of methanol is higher than the demand by the power unit. The overcapacity in flow is send through the bypass loop, where the inline heat exchanger is present. The bypass loop is activated with an increased pressure and opens the spring-loaded non-return valve.

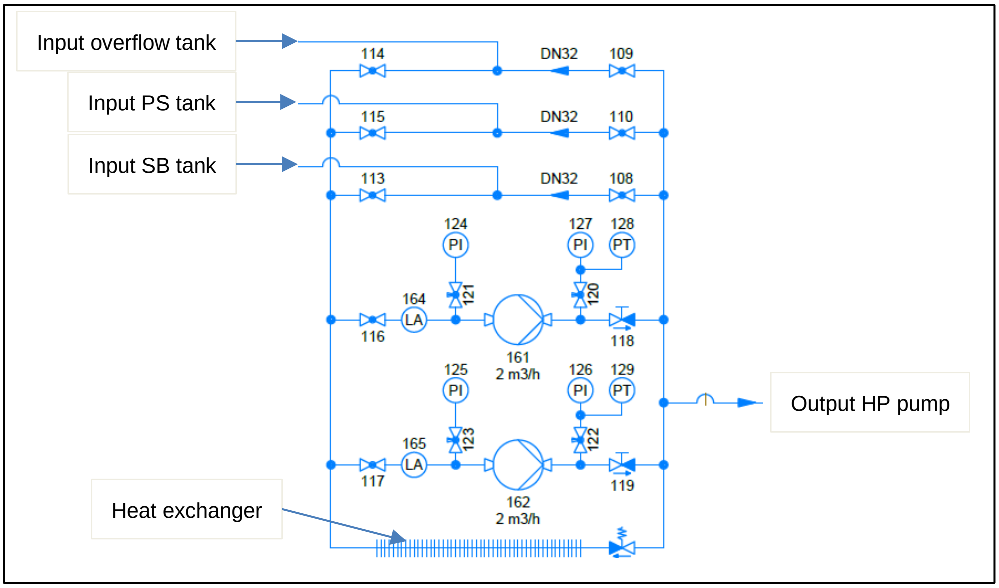


Figure 3 Pump P&ID for bringing the fuel to the fuel preparation space

### 2.3.2 *Heat exchanger*

The passive liquid to air inline heat exchanger, as shown in Figure 3, dissipates heat from the circulating fluid in the closed loop. The supply from the main fuel tanks provides cooling to the pumps in normal operation. The boiling point of the methanol fluid is 64.7 °C at atmospheric conditions. Heat due to de-pressurizing the compressed fuel inside the flow loop is extracted by the heat exchanger.

### 2.3.3 *Fuel filter*

Duplex fuel filters are present on the suction side of the high-pressure pump, see Figure 4.

### 2.3.4 *Expansion vessel*

On the suction side of the high pressure pump an expansion vessel is present to stabilize the input pressure. The cavity behind the membrane, inside the expansion vessel, is filled with nitrogen.

### 2.3.5 *High-pressure pump*

The high-pressure pump supply methanol to the power unit, as shown in Figure 4. Due to the lower heating value of methanol compared to marine gas oil, a higher injection volume for a similar power output is required. If the methanol is combusted in the power unit, the liquid needs to be pressurized to ~450 bar (called high pressure). If the vessel is powered solely on methanol, redundancy in the supply of high-pressure methanol should be present. The master gas valve determines the flow rate to the power unit.

The fluid leaked from the high-pressure pump is send back to the overflow tank and needs a manual shut off valve for maintenance reasons.

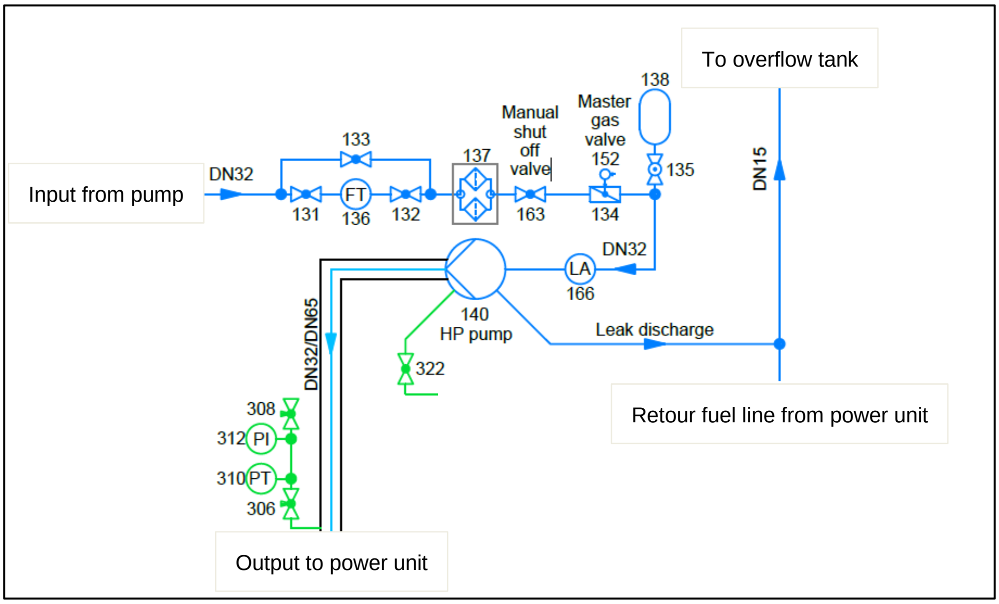



Figure 4 High pressure pump

## 2.3.6 *Piping*

The piping in the fuel preparation space is single walled pipe. For the definition of pipework, see Figure 5. Pipework that needs to enter the engine room, makes the transition between single to double walled piping in the fuel preparation space.

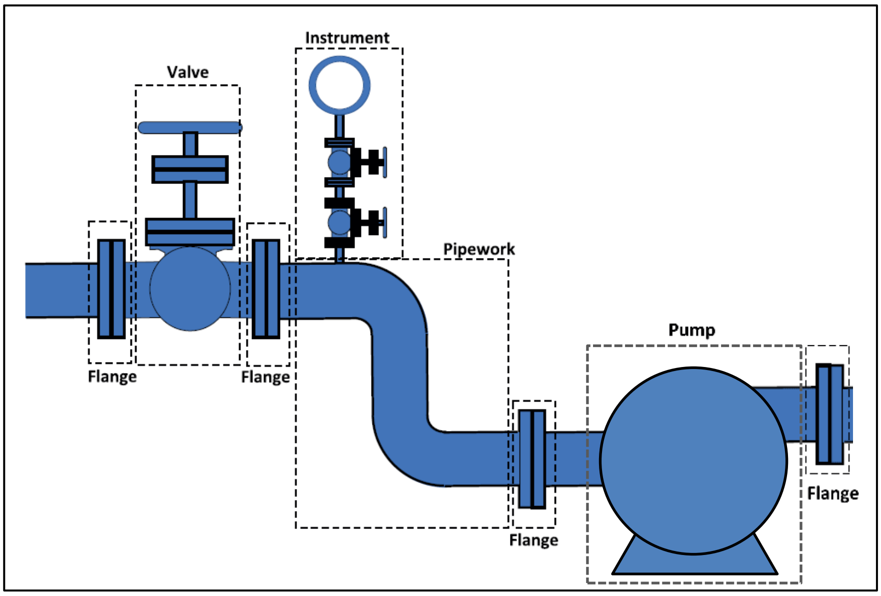



Figure 5 Boundaries of equipment types, Reference [3] .

## 2.3.7 *Flanges*

Piping components can be bolted together between flanges. Flanges are used to connect pipes with each other, to valves, to fittings, and to specialty items such as fuel filters and pressure vessels. Flanges are joined by bolting, and sealing is often completed with the use of gaskets. In the presented P&ID diagram, the flanges are not drawn, but are abundantly present in the system.

## 2.4 Bunker station

For the bunker operation, the following lines are connected to the vessel:
- Hose for the transfer of methanol. The coupling from the bunker facility to the vessel is made with a bolted flange with gasket. The hose can be equipped with an ERS (Emergency Release System) and/or a QCDC (Quick Connect Disconnect Coupler). The vapor can be retoured to the supplier side.
- Break away wire, to monitor if the ship is adrift. Pneumatic operated valves close automatically in case of a break away. The location of the failure of the hose is predefined by the placement of a snap link.
- Grounding wire.

The bunker station is shown in Figure 6. The bunker lines are first connected on the bunker supply side and then on the vessel side. The handling of the hose is done by crane. The air in the hose is flushed out with nitrogen gas. After this operation, the transfer of methanol starts. Figure 6 shows that an operator on the vessel manually opens valve 103 and 104 to distribute the fuel between the portside and starboard fuel tanks.

When the transfer of fuel is complete, the methanol is flushed out of the lines into the overflow tank, by opening valve 105.

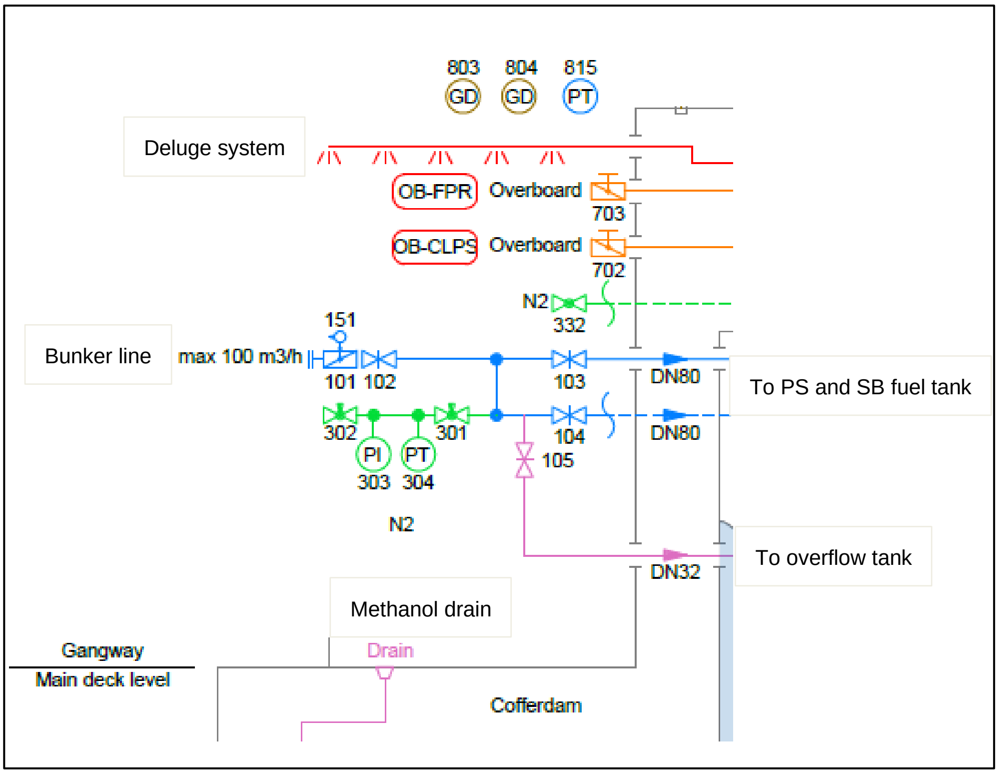



Figure 6 Bunker station layout

Typical LNG bunkering emergency release couplings, quick connection and disconnection couplings, separation systems and the power source for the emergency release system are shown in Figure 7 to Figure 10.

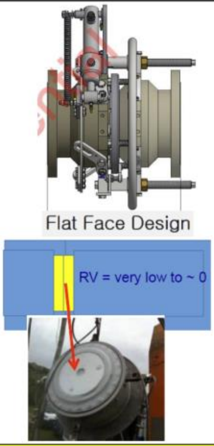
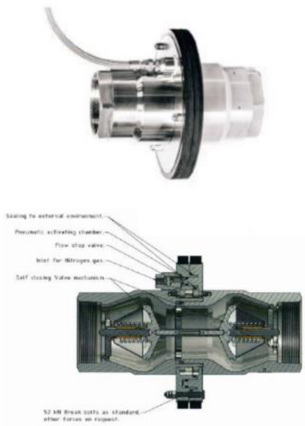
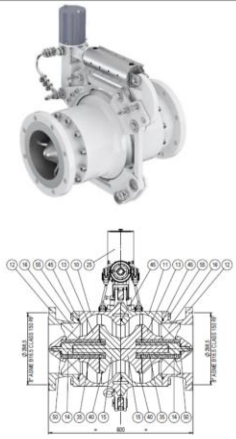
| ARTA | MannTek | MIB |
|---|---|---|
|  |  |  |
| Separate clamp using hydraulic cylinder | Break breaking bolt using nitrogen gas | Separate clamp using hydraulic cylinder |

Figure 7 Emergency release couplings

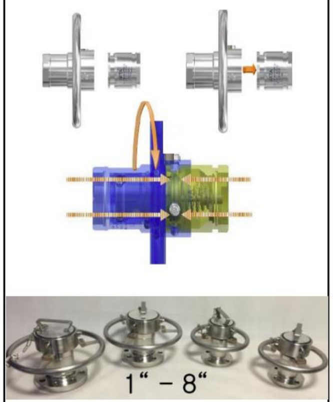
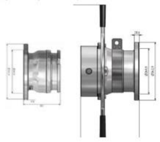
| ARTA | MannTek | MIB |
|---|---|---|
|  | <br>**TECHNICAL INFORMATION**<br>**Sizes:**<br>1" (DN 25) to 6" (DN 150)<br> | <br>**AVAILABILITY**<br>Sizes: 3" to 20"<br>Pressure rating: ASME B16.5 class 150, 300 DIN 2632 PN10, DIN 2633 PN16, DIN2634 PN25, DIN2635 PN40<br>Temperatures: -196 °C to +85 °C<br>Fluids: LNG, Ethylene, LPG, Crude Oil, Refined oils and Petrochemicals |
| 6", 8" OK | | |

Figure 8 Quick connection and disconnection couplings

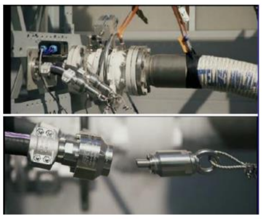
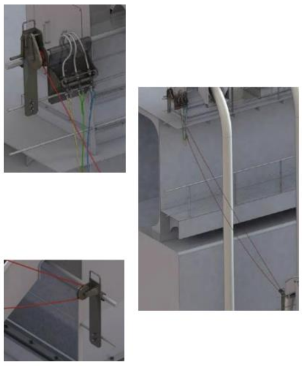
| ARTA | MannTek | MIB |
|---|---|---|
|  |  |  |

Figure 9 Separation system

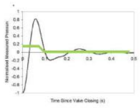
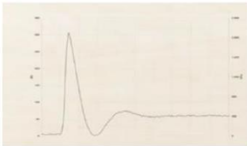
| ARTA | MannTek | MIB |
| --- | --- | --- |
| Multi Functional Triggering available<br>Cable Trigger – Pneumatic Trigger – Hydraulic Trigger<br>HPU<br>; ATEX zone 1<br> <br>PPU<br>; 12 [barg]<br> | Nitrogen<br>; 200 [bar] (min. 150 [bar])<br><br> | Hydraulic<br>; 210 [bar] (min. 140 [bar])<br> |
| Hyd. Or pneumatic can be used over12 bar, surge pressure is not high | High pressured nitrogen gas<br>High surge pressure | Hydraulic power pack of 210 bar<br>surge pressure is not high |

Figure 10 Power source for emergency release system

## 2.5 Main deck

### *2.5.1 Pipework*

From the bunker station to the starboard fuel tank, the supply pipe is routed via the main deck. Similar, the venting of the starboard fuel tank is running over the main deck to the overflow tank located on the other side of the vessel.

### *2.5.2 Openings to fuel tank*

In order to gain access to the cofferdam and fuel tank, manhole covers are installed on the main deck. Sounding pipes with covers are usually present to manually sound the fuel tanks. Both covers provide (in)direct access to the methanol fuel.

## 2.6 Engine room

The engine room is classified as a non-hazardous area. The is assumed because the piping of methanol is double walled and the entrance of the engine room is fitted with an air Lock, making it a protected space isolated from the fuel preparation space, see Figure 11.

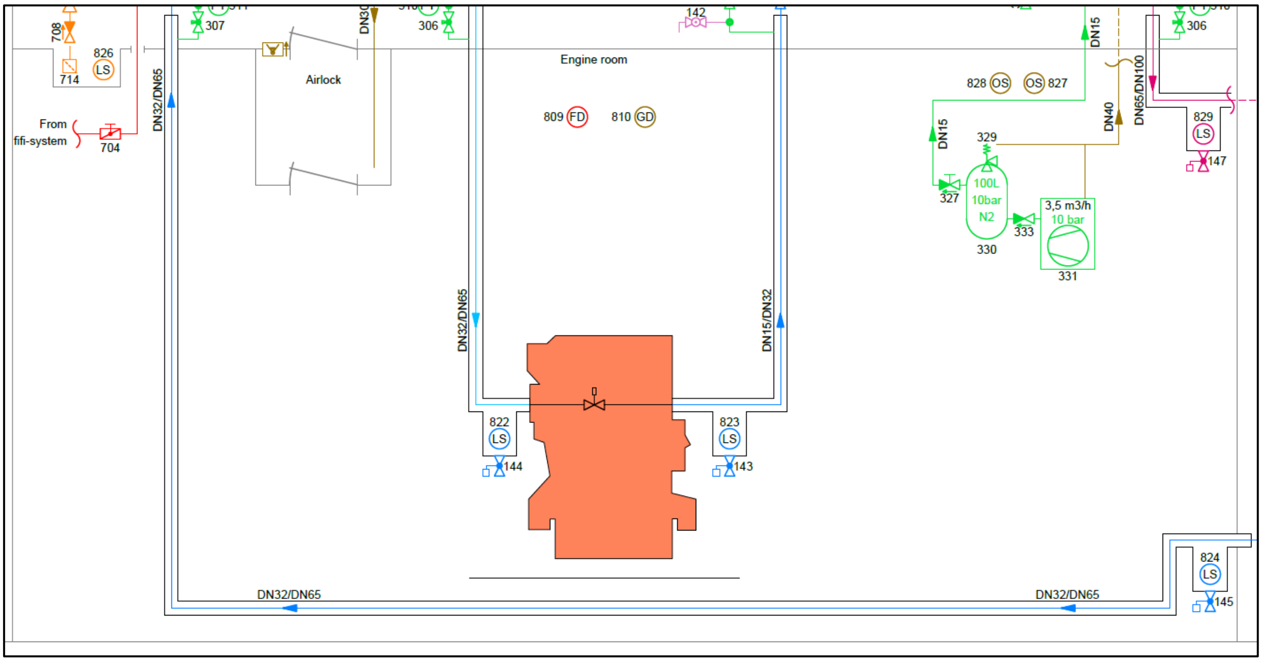



Figure 11 Diagram of the engine room compartment with airlock, double walled piping and power unit.

## 2.6.1 *Pipework*

All pipework in the engine room is double walled, creating an additional barrier against mechanical damage and pipe leaks. Both the high pressure as well as the low-pressure piping is double walled. The transition to double walled piping is started in the fuel preparation space or cofferdam.

### 2.6.1.1 *Double walled high-pressure pipe*

Double walled high pressure fuel pipe between pump room and engine, as used in the Stena Germanica (Reference [2]). The working principle is a small overpressure in the outer pipe. An increase in pressure is a leak of the inner pipe, decrease in pressure is a leak in outer pipe.

## 2.6.2 *Flanges*

For the definition of the flanges, see Section 2.3.7. Due to the presence of a heat source (the power unit) in this compartment, leakage of a flange has a higher consequence.

## 2.6.3 *Instrumentation*

The instrumentation in the engine room is coupled to the safety control system. Readings from the sensor equipment needs to be visible to the crew before entering the engine space.

## 2.6.4 *Main Engine*

There are two main options for using methanol as fuel in conventional ship engines: in a two-stroke diesel-cycle engine or in a four-stroke, lean-burn Otto-cycle engine. It is also feasible to use methanol in fuel cells.

General propulsion layouts of ships are either direct propulsion via a main engine, drive shaft and propeller, or alternatively a main engine, generator and an electric motor that drives a shaft and propeller. Electric generators are also present, especially at passenger's ships, where the electric use at the ship is large. This PI&D shows one main engine, as a black box. By neglecting the engine in this research, possible risks are not addressed: unburnt fuel in the exhaust, heat source for ignition of methanol (engine and exhaust lines), fuel lines on top of the engine, etc.

# 3 Qualitative risk assessment

A qualitative risk study is performed (Appendix A), which is a technique for the identification of significant hazards associated with the bunkering, storage and distribution of methanol fuel onboard a vessel. The purpose of this study is to review the process at an early stage with a view to ensuring that the process design accounts for the credible hazardous scenarios.

The fuel distribution system is divided into discrete parts to equipment function and location for the systematic identification of the hazards, as defined in Reference [6]. The system is divided into the following compartments, indicating which space on board or in the vicinity of the ship is being considered:

- Fuel tank;
- Cofferdam surrounding the fuel tanks;
- Fuel preparation space;
- Bunker station;
- Main deck;
- Engine room.

Equipment in the compartments is listed in the column subsystem. For the columns of the hazard matrix, see Figure 12.

To ensure that the necessary assessment of the risks is carried out, the hazards are identified in three phases:

1. **Physical layout**. How the fuel system is located in the ship;
2. **Operation**. The operation of the fuel system;
3. **Maintenance**. The maintenance of the fuel system.

To capture adverse effects on the persons on board, the environment and the ship, as defined in Reference [5].

| Compartment | Subsystem | Phase | | | Example cause resulting in unwanted event | Unwanted event | Adverse consequence | Likelihood of cause and consequence per event (1=rare, 5=(almost) certain) | Severity of consequence (1=low, 5=catastrophic) | Risk (likelihood * severity) | Anual likelihood (1=rare, 5=(almost) certain) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Physical layout | Operation | Maintenance | | | | | | | |

Figure 12 Columns of the hazard matrix

Hazard identification includes three aspects, namely identification of the hazard, its cause and effect. Each cause and adverse consequence are rated on the likelihood of the event and severity of the consequence, based on the judgement of a suitably qualified individuals. The risk associated to the hazard is the product of the likelihood and severity score. Mitigation measures may be intended to directly reduce the hazard. High risk items which lack mitigation measures are linked to research questions, answered in a later stage of the project.

# 4 Research questions

In this chapter, the high-risk items (risk ≥ 5) from the HAZID are listed and discussed. A short description of the cause resulting in the unwanted event is given followed by a couple of research questions and possible mitigation measures. If the measures effectively mitigate risks, no research question is proposed.

## 4.1 Fracture of tank shell

A fracture of the tank wall indicates that an object has penetrated the tank shell. The consequences of tank breach need to be understood to eliminate or mitigate any adverse effects to the persons on board, the environment and the ship.
The causes for an opening in the tank shell are found in Appendix A:
- Drop of suspended load or collision above the waterline;
- Collision or grounding below the waterline.

### *4.1.1 Research questions tank breach*

The risk associated with a tank breach can be quantified by answering the following questions:
- What is the likelihood of a (double) breach?
- What is the environmental effect of a methanol spill?
- Is a cofferdam surrounding the fuel tank necessary? If yes, what are the minimum physical layout requirements of the cofferdam and steel plating?
- How to contain the risk of an explosive and flammable atmosphere at the location of the tank rupture?
- When spilling the methanol into the surrounding water, is there a methanol and air mixture at the surface of the water which is flammable, considering the leaking rate and pressure drop?

## 4.2 Corrosion in fuel system due to methanol

There is a need to investigate the methanol induced corrosion effects on steel. The adverse consequence of corrosion could not be ranked in the hazard matrix since it is out of the field of expertise. The required knowledge is defined in the research question to properly identify the risk.

### *4.2.1 Research questions corrosion*

- What is the effect of methanol on the corrosion rate of steel?
- What kind of corrosion is expected, localized or uniform corrosion?
- What is the corrosion mechanism?

### *4.2.2 Mitigating measures corrosion*

Mitigating measures are defined which could reduce the risk of methanol induced corrosion: methanol specific coating for the fuel tank, inspection of the fuel tank and the conductivity of methanol allows for a tank design with anodes.

## 4.3 Pressure increase in fuel system

A pressure increase in the fuel system could result from mechanical and thermal energy added to the system. The boiling of methanol is at 64.7 degrees Celsius at atmospheric pressure. This phase change will result in high pressures in the pipework and or fuel tank. The causes for a pressure increase in the fuel system are found in Appendix A:

- No vapour return line is used in the bunker operation;
- The bunker operation overfills the fuel tanks;
- Fire in the vicinity of the methanol fuel tank or equipment;
- Insufficient heat dissipation heat exchanger in pumping circuit;
- Overheating of the high-pressure pump.

#### *4.3.1 Research questions pressure increase in fuel system*

The risk associated with a pressure increase in the fuel system can be quantified by answering the following questions:

- What is the likelihood of a failing venting system?
- How can the venting system fail?
- What are the requirements for a venting system?
- Is inerting the fuel tank and cofferdam required for a fire event?
- What is the effect of a higher pressure in the fuel tank?
- What is the consequence of reaching the boiling point in the pump circuit?
  - What temperature will damage the equipment?
  - What are the requirements for the heat exchanger?
- What is het amplitude of the pressure that can occur during overfilling the tank or evaporation of the methanol due to heat introduction?
- Is placing the vent under the waterline a good decision?
  - What is the environmental effect of a methanol spill?
  - What is the environmental effect of a nitrogen spill?
  - Is the mixture of gas at the water surface flammable?
  - What is the best position for the (underwater) vent?

#### *4.3.2 Mitigating measures pressure increase in fuel system*

Mitigating measures are defined which could reduce the risk of a pressure increase in the fuel system are: fire insulation, redundant layout of tank filling sensors and manual bypass of (redundant) venting system.

For the heat exchanger design the following items are proposed. Design the heat exchanger based on full flow in closed loop system. Inspection and maintenance of heat exchanger. Clearly mark the item to warn personnel from obstructing the air flow around the heat exchanger. Heat exchanger without moving parts.

### 4.4 Leaking methanol at a flange coupling

Cracking of the gasket or insufficient flange pressure will result in methanol spillage. Bolt creep is more likely to take place due to the presence of main engine vibrations. The autoignition temperature of methanol is 470 °C and is more than double that of diesel. A spark will ignite the methanol and oxygen mixture due to the flame point at 11°C.

#### *4.4.1 Research questions flange couplings*

- What is the likelihood of a flange coupling failure?
- What is a correct inspection procedure for checking the flange connections?
  - What is the material degradation, including gasket, to methanol exposure?
  - What is the required flange pressure (relation to section 4.3)?
- What damage does a high-pressure leakage do to people and equipment?

#### *4.4.2 Mitigation measures flange couplings*

Gas detection which will shut down the supply of methanol. Spray screens at the flange connections to shield personnel from fuel contact. Welded connections.

### 4.5 Leaking methanol at the bunker hose

A failure of the bunker hose or connection will result in spilling of methanol with adverse consequences for people on board and the environment. Causes for a methanol leak are:

- Incorrect installation of hose;
- Gasket failure due to reuse;
- Leak at the gasket due to debris or soiling;
- Lifetime of bunker hose.

#### *4.5.1 Research questions bunker hose leak*

The following research questions are defined:

- What is the likelihood of the cause and consequence for the events?
- What is the environmental effect of a methanol spill?
- What is a safe coupling for the bunker hose connection?
- Which checks are available for the correct instalment of the hose?
- What are the procedures that needs to be followed before the bunker operation can take place?

#### *4.5.2 Mitigating measures bunker hose leak*

There is knowledge in the LNG equipment, define the limits and options for the use with methanol. Pressure testing the bunker hose and connection before the start of the operation. Scheduled replacement of hose and gaskets. Life extension of the gasket and hose can be determined through testing of the used specimens. No personnel near the bunker station during the operation.

### 4.6 Machine room fire damaging the safety control system

Although the engine is not part of the equipment considered in this safety study, it is a heat source in the engine room. A machine room fire will damage the critical components to the safety control systems and or emergency backup generator. Fire will prevent access to the machine room and any gas detection indicators shown there.

#### 4.6.1 *Research question fire damaging safety control system*

- How to design the physical layout of the control system such that in case of a fire the system is not damaged?

#### 4.6.2 *Mitigation measures fire damaging safety control system*

Routing of critical safety control equipment through the cofferdam, such that parameters from inside the machine room are always visible from outside.

## 4.7 Emptying the fuel tank with secondary pumps

It is unclear how to strip the fuel tanks in case of planned maintenance or in more critical events:

- Inspection of fuel tank;
- Sensors in cofferdam indicate presence of methanol;
- Fire in the neighbourhood of the fuel tanks.

#### 4.7.1 *Research questions emptying fuel tank*

- What is the likelihood of the events?
- How to safely empty a fuel tank from methanol?
- What equipment and protective systems are intended for use in potentially explosive atmospheres?
- A purging system is expected for removing vapours. Safe for personnel to enter the fuel tank?

#### 4.7.2 *Mitigating measure emptying fuel tank*

Procedure with checklist and training of crew and the correct equipment.

## 4.8 High risk causes with effective mitigation measures

There are example causes in the hazard matrix which have a high associated risk with distinct mitigation measures. With the mitigation measures in place and with the knowledge in the industry, no new research is needed. The following subsections elaborate on the causes and the mitigation measures.

#### 4.8.1 *Fuel inlet at the top of the tank*

Static electricity due to the freefall of fuel could be the source of ignition.

**Mitigating measure**

To mitigate the risk of static electricity ignition, a revised mitigation measure involves modifying the fuel system design. Instead of having the fuel supply located at the top of the tank, an additional piping system is implemented to inlet the fuel at the bottom of the tank. This modification helps reduce the potential for static electricity build-up and discharge during the freefall of fuel.

#### 4.8.2 *Drop of suspended load on bunker station*

Fracture of pipework and connections when a suspended load drops onto the bunker station. Gas mixture of methanol and nitrogen can escape from the collision zone.

**Mitigating measure**

One effective mitigation measure for the potential fracture of pipework and connections caused by a suspended load dropping onto the bunker station is to implement a comprehensive dropped object protection system. This system should include measures such as sturdy barriers, safety nets, and adequate signage to prevent objects from falling onto critical infrastructure. Additionally, it is crucial to have a deluge system in place, which can rapidly discharge a large volume of water or fire-retardant foam onto the collision zone, minimizing the chances of a gas mixture of methanol and nitrogen escaping and reducing the risk of fire or explosion. By combining these measures, the risk of damage, injury, and gas leakage can be significantly reduced.

#### *4.8.3 Mechanical damage of methanol pipework over main deck*

The filling and venting methanol piping is routed over the main deck. This piping is susceptible to mechanical damage. Damage to the pipework would result in release of methanol and nitrogen vapor.

**Mitigating measure**

To mitigate the risk of mechanical damage to the filling and venting methanol piping located above the main deck, protective frames will be installed around the vulnerable sections of the pipework. This will provide physical protection and minimize the potential for accidental damage. Furthermore, an additional valve will be incorporated into the pipework adjacent to the fuel tank, enhancing the system's integrity and allowing for isolation in the event of damage or leaks.

#### *4.8.4 Failure of gas detector sensor and instrumentation*

Faulty gas detection instruments in the cofferdam could miss the methanol and nitrogen mixture present in this compartment. Failure of sensor measuring temperature, flow or pressure could cause incorrect actions of the control systems.

**Mitigating measure**

To mitigate the risks posed by faulty gas detection instruments in the cofferdam, a triple (redundant) sensor layout should be implemented. This involves installing multiple gas sensors in strategic locations to ensure accurate detection of the methanol and nitrogen mixture within the compartment. Additionally, the internal gas flow should be continuously monitored, and exhaust samples should be regularly analyzed. Following the guidelines set by Safety Integrity Level (SIL) and Atmosphere explosible (Atex) will help ensure the appropriate safety measures are in place.

#### *4.8.5 Failure of the high-pressure pump*

An uncontrollable vessel is the risk of the failure of the (single) high pressure pump.

**Mitigating measure**

To mitigate the risk of a single high pressure pump failure leading to an uncontrollable vessel, a measure has been implemented involving redundant high-pressure pumps. These pumps are equipped with tested control loops to ensure reliability and effectiveness. This redundancy ensures that even if one pump fails, the second pump can maintain the vessel's control with a 100% backup capacity.

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# 6 Signature

Delft, 29 juni 2023

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# Appendix A – Hazard matrix

| Compartment | Subsystem | Phase: Physical layout | Phase: Operation | Phase: Maintenance | Example cause resulting in unwanted event | Unwanted event | Adverse consequence | Likelihood of cause and consequence per event (1=rare, 5=(almost) certain) | Severity of consequence (1=low, 5=catastrophic) | Risk (likelihood * severity) | Anual likelihood (1=rare, 5=(almost) certain) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Fuel tank** | Tank | x | | | Drop of suspended load or collision | Mechanical damage above waterline | Permanent deformation | 4 | 1 | 4 | 4 |
| | | x | | | Drop of suspended load or collision | Mechanical damage above waterline | Fracture main deck | 2 | 3 | 6 | 3 |
| | | x | | | Drop of suspended load or collision | Mechanical damage above waterline | Fracture tank wall | 1 | 5 | 5 | 2 |
| | | x | | | Collision below waterline | Mechanical damage below waterline | Permanent deformation | 4 | 1 | 4 | 4 |
| | | x | | | Collision/grounding below waterline | Mechanical damage below waterline | Hull/fuel tank rupture | 1 | 4 | 4 | 3 |
| | | x | | | Leak in tank wall due to fatigue | Vibrations | Fatigue load cracking | 1 | 2 | 2 | 2 |
| | | x | | | Corrosion of tank wall due to methanol | Methanol and steel contact | Corrosion | ? | ? | ? | ? |
| | | | x | | Fuel levels exceed maximum | Pressure increase | ? | ? | ? | ? | ? |
| | | | x | | Fire near the fuel tank | Pressure/temperature increase | ? | ? | ? | ? | ? |
| | | x | x | | Flammable mixture air/methanol incorrect inerting | Flammable mixture not measured | Fire/explosion | 1 | 5 | 5 | 2 |
| | | x | x | | Venting of total gas volume when bunkering | Toxic/flammable atmosphere | Toxicity level | 5 | 2? | ? | 5 |
| | | | | x | Person inside fuel tank | Toxic atmosphere | Toxicity level human | 1 | 5 | 5 | |
| | | | | x | Person inside fuel tank | Flammable mixture | Explosion | 1 | 5 | 5 | |
| | | | | x | Emptying fuel tank, entrapment of methanol (fluid and gas) | Flammable mixture | Fire/explosion | 1 | 5 | 5 | |
| | Piping | x | | | Fuel inlet at top of tank | Static electricity free fall of fuel | Ignition source | 1 | 5 | 5 | |
| **Cofferdam surrounding the fuel tanks** | Instrumentation | x | | | Leak of methanol in cofferdam due to leak fuel pressure sensor | Material damage | Fracture | 2 | 2 | 4 | 3 |
| | | | | x | Dropped objects onto sensor arrangement | Material damage | Fracture | 1 | 3 | 3 | 2 |
| | | | x | x | Failure of gas detector sensor | Faulty gas detection instrument | Water impact or high gas exposure | 2 | 4 | 8 | 2 |
| | Pipe openings | x | | | Leak in cofferdam at the pipe openings | Vibrations | Fatigue load cracking | 2 | 2 | 4 | 3 |
| | Piping | x | | | Leak of piping | Material damage | Fracture | 2 | 2 | 4 | 2 |
| | Access to cofferdam | x | x | | Air leak of manhole cofferdam to main deck | Leakage of methanol | Toxicity, explosion | 3 | 1 | 3 | 3 |
| | | x | x | | Air leak of manhole fuel tank to cofferdam | Leakage of methanol | Toxicity, explosion | 2 | 2 | 4 | 2 |
| **el preparation spa** | Pumps | | x | | Flow of pumps higher than demand | Temperature increase | Ignition source | 2 | 2 | 4 | 2 |
| | | | x | | No circulation of fluid (incorrect operation of valve) | Pump and fluid temperature/pressure increase | ignition source/burst | 1 | 3 | 3 | 1 |
| | | | x | | Air bubble at pump (incorrect bleeding of the system) | Pump temperature increase | Ignition source | 1 | 1 | 1 | 1 |
| | | | x | | Failure of one pump | Decrease in flow | Lower power output of engine | 3 | 1 | 3 | 3 |
| | | | x | | Vibration source to piping and fixtures | Vibrations | Fatigue load cracking | 2 | 2 | 4 | 2 |
| | | | | x | Pump replacement | Release of methanol fluid/gas | Toxicity, flammable | 1 | 2 | 2 | 2 |
| | Heat exchanger | | x | | Closed loop flow, insufficient heat dissipation heat exchanger. | Boiling point exceeded | Pipe burst | 3 | 5 | 15 | 3 |
| | Fuel filter | | | x | Fuel filter replacement | Release of methanol fluid/gas | Toxicity, flammable | 1 | 2 | 2 | 2 |
| | Expansion vessel | x | | | Leak frequency expansion vessel | Material damage | Fracture | 2 | 3 | 6 | 2 |
| | High pressure pump | | x | | Failure of one pump | No supply of fuel to the power unit | No propulsion of vessel | 3 | 5 | 15 | 3 |
| | | | x | | Overheating of the HP pump | Boiling point exceeded | Pipe burst | 2 | 5 | 10 | 2 |
| | | | x | | Vibration source to piping | Vibrations | Fatigue load cracking | 2 | 2 | 4 | 2 |
| | | | x | | Pump leaks | Leakage of methanol | Toxicity, flammable | 1 | 4 | 4 | 1 |
| | Piping | x | | | Leak frequency piping | Material damage | Fracture | 2 | 2 | 4 | 2 |
| | | x | | | High pressure pipe leak | Material damage | Fracture | 2 | 1 | 2 | 2 |
| | | | x | x | Mechanical damage of high pressure piping | Mechanical damage | Fracture | 1 | 3 | 3 | 1 |
| | Instrumentation | | x | | Instrumentation fails | Incorrect sensor values | Incorrect control parameters | 2 | 2 | 4 | 2 |
| | Flanges | x | | | Gasket leaks at flange connections | Material degradation, bolt creep | Cracking, insufficient flange pressure | 3 | 3 | 9 | 3 |
| **Bunker station** | | | x | | Incorrect manual operation of distributing the fuel between tanks | See Fuel storage: Fuel levels exceed maximum | | | | | |
| | | | x | | Drain valve open to overflow tank: filling the wrong tank | See Fuel storage: Fuel levels exceed maximum | | | | | |
| | | x | | | Drop of suspended load or collision (bridge) on open bunker station | Mechanical damage above waterline | Fracture of piping and connections or deck | 2 | 3 | 6 | 3 |
| | | | x | | Incorrect installation of hose | Toxic and Explosive atmosphere | Toxicity level / explosion | 3 | 4 | 12 | 3 |
| | | | x | | Failure of hose, unknown lifetime | People or environment exposed to methanol | Toxicity level | 2 | 4 | 8 | 2 |
| | | | x | | Vessel adrift / travel between hose couplings too large | Mechanical damage connection / hose | Fracture | 2 | 4 | 8 | 2 |
| | | | x | | Methanol fluid or gas mixture present when disconnecting the hose | Toxic and Explosive atmosphere | Toxicity level / explosion | 2 | 4 | 8 | 2 |
| | | | | x | No maintenance of gaskets: leakage of fluid | Toxic and Explosive atmosphere | Toxicity level /explosion | 2 | 5 | 10 | 2 |
| **Main deck** | Piping | x | | | Damage to piping: bunker station to fuel tank over main deck | Mechanical damage pipe open deck | Fracture | 3 | 2 | 6 | 3 |
| | Tank sounding holes | x | | x | Improper closure of sounding hole | Leakage of methanol | Toxicity level / explosion | 1 | 4 | 4 | 1 |
| **Engine room** | Piping | x | | | High pressure pipe leak | Material damage | Fracture | 2 | 1 | 2 | 2 |
| | | | x | x | Mechanical damage of high pressure piping | Mechanical damage | Fracture | 1 | 4 | 4 | 1 |
| | Flanges | x | | | Cracking, insufficient flange pressure | Material degradation / vibrations | Fracture | 4 | 3 | 12 | 4 |
| | Instrumentation | x | | | Gas detection damaged or display not accessible due to machine room fire (see cor | Fire in engineroom | Oxcidation | 2 | 5 | 10 | 2 |

| Mitigation measures | Research questions | Reference to section report | General questions |
|---|---|---|---|
| | | | |
| | | | |
| | Fracture of tank shell | 4.1 | |
| | | | |
| Pump fluid to other tank to minimise the spill of methanol? | Fracture of tank shell. Is there a methanol and air mixture at the surface of the water which is flammable, considerin | 4.1 | |
| Regular inspection | | | |
| Coating. Inspection. | Corrosion in fuel system due to methanol | 4.2 | No Subject Matter Experts; no score |
| Level sensors redundant - Venting of overpressure redundant - Overflow tank | Likelihood failing venting system? Consequence of high tank pressure? Pressure bunker station? | 4.3 | |
| Fire insulation | Consequence of reaching the boiling point of methanol in the fuel tank | 4.3 | |
| Measure oxygen level in fuel tank? | | | |
| Vapour retour line to bunker vessel or to second tank if available | Is placing the vent under the waterline a good decision? | 4.3 | |
| Fill with fresh water before inspection? Gas detector, make sure normal air is supplied during emptying. | Emptying the fuel tank with secondary pumps | 4.7 | |
| Fill with fresh water before inspection? | | 4.7 | |
| Fill with fresh water before inspection? | | 4.7 | |
| Design fuel outlet at bottom of fuel tank | Fuel inlet at top of tank | 4.8.1 | |
| Gas detection sensor. Increase in pressure cofferdam (level sensor) | | | |
| Personal gas detector when entering the cofferdam. Equipment with tether to person. | | | |
| Triple sensor layout; two sensors vote for the faulty sensor. | | | |
| Decrease of overpressure in cofferdam | | | |
| Gas detection sensor. Level sensor | | | |
| Gas sensor in cofferdam. Overpressure of N2 in combination with pressure sensor. Purging | | | How to empty fuel tank? |
| Gas sensor in cofferdam. Overpressure of N2 in combination with pressure sensor. | Emptying the fuel tank with secondary pumps | 4.7 | |
| Heat exchanger in circuit, designed on 100% pump speed of both pumps. | Pressure increase in fuel system | 4.3 | |
| Monitor delta digital pressure sensor suction and discharge side? Shut off of pump. Measure temperatures. | Pressure increase in fuel system | 4.3 | |
| Measure temperature at the pump. Tripping of pump. | | | |
| Redundant pumps | | | |
| Inspection & replacement program in place | | | |
| Operational: close valves around pump and inert that section, needs procedures. Full attention. PPE. | | | Can the isolated pump be inerted? |
| Measure temperature. Boiling point methanol | Pressure increase in fuel system | 4.3 | |
| Extractor of gasses in place | | | |
| Gas detection of methanol vapour and automatic shutdown of pumps plus visual inspection and replacement schedule. | | | |
| Redundant pumps. Cumulative: assuming redundancy in pumps. Uncontrollable vessel:risk. Backup fuel system | | | |
| Measure temperature at the pump. Anti cavitation design. | Pressure increase in fuel system | 4.3 | |
| Visual inspection plus gas detection | | | |
| Gas detection sensor. Inspection schedule | | | |
| Gas detection sensor. Visual inspection schedule. Fuel prep space - personnel needs to be aware. | | | |
| Assumption: Double walled pipe | | | |
| Automatic shutdown of flow when pressure drops at the consumer side | | | |
| Safety control system in place | | | |
| Regular inspection, gas detection. Welded connections | Leaking methanol at a flange coupling | 4.4 | |
| Feedback loop filling grade | | | How is this communicated. Need for a control system? |
| | | | |
| Barriers in place (e.g. protecting frame around and above bunker station). No suspended load over bunker station. | Drop of suspended load on bunker station | 4.8.2 | Depends on design of bunker system, is the bunker station |
| Visual aids? Consider bolted connection | Leaking methanol at the bunker hose | 4.5 | |
| | Leaking methanol at the bunker hose | 4.5 | |
| Safety system and possibly a breakaway coupling. QCDC connectors with clear visual aids. Dry Release couplings. | Leaking methanol at the bunker hose | 4.5 | |
| Sensors? And Procedures which include sensor readings. | Leaking methanol at the bunker hose | 4.5 | How to determine the hose is empty? |
| Regular inspection, gas detection. Procedure: pressure test the system with N2 before bunkering. | Leaking methanol at the bunker hose | 4.5 | |
| Valve near deck. Protective frames in vulnerable locations. | Mechanical damage of methanol pipework | 4.8.3 | |
| Clear visual inspection aids. Detect loss of overpressure in fuel tank. | | | Do fuel tanks have sounding holes or similar? |
| Double wall piping with sensor | | | |
| Double wall piping with sensor | | | |
| Regular inspection of flange and bolt torque. Gas detection. Spray screens at flange connections. | Leaking mthanol at a flange coupling | 4.4 | |
| Proper design Engine room fire: No damage of critical (control) systems. | Machine room fire damaging the safety control system | 4.6 | |