WIN GD
Winterthur Gas & Diesel

2-Stroke Dual-Fuel Ammonia Safety Concept

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Abbreviations

Abbreviation	Full name
ADS	Ammonia Detection System
AMS	Alarm and Monitoring System
AT	Ammonia Trip (forced switch to diesel mode)
CCU	Cylinder Control Unit
DBB	Double Block and Bleed
DENIS	Diesel Engine coNtrol & optImising Specification
DF	Dual-Fuel
DG	Design Group
Drw.	Drawing
ECR	Engine Control Room
ECS	Engine Control System
ESS	Engine Safety System
FSS	Fuel Supply System
FMEA	Failure Mode and Effect Analysis
FVU	Fuel Valve Unit
GTU	GaTeway Unit
HFO	Heavy Fuel Oil
HT	High Temperature
IGC Code	International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk
IGF Code	International code of safety for ships using gases or other low-flashpoint fuels
IMO	International Maritime Organization
LDU	Local Display Unit
LEL	Lower Explosive Limit
LO	Lubricating Oil
LT	Low Temperature
MCP	Manual Control Panel
MCU	Main Control Unit
RCS	Remote Control System
PEL	Permissible Exposure Limit
SAC	Scavenge Air Cooler
SCR	Selective Catalytic Reaction
SHD	Shutdown
SLD	Slowdown
SOV	Shut-Off Valve
TC	Turbocharger
TVM	Torsional Vibration Monitoring
WiCE	WinGD Integrated Control Electronics (ECS)
WinGD	Winterthur Gas & Diesel Ltd.

1 Introduction

The purpose of this document is to describe the engine room arrangement and safety functions of the X-DF-A engine applications. Only items that are specifically related to ammonia safety and differ from diesel engine application are handled in this document. The X-DF-A engine itself is classified. The present document contains only information that is necessary to understand the function and safety features of the X-DF-A engine.

The WinGD 2-stroke X-DF-A engine is a long-stroke crosshead engine which can be operated using either liquid ammonia or fuel oils. To enable this, the engine is equipped with an electronically controlled diesel fuel injection system and with electronically controlled ammonia fuel injection systems.

The X-DF-A engine is designed to operate on ammonia at the same safety level as when using diesel fuel. The safety concept is based on early detection of problems that could lead to a hazard, followed by immediate actions to prevent the situation from becoming dangerous. Depending on the machinery configuration and the detected problem type, the Engine Safety System (ESS) can initiate the alarm, trip to diesel mode and induce slowdown or shutdown of the X-DF-A engine.

All systems must be built in accordance with the requirements of both the IGF and IGC codes as well as the classification societies. Accordingly, the content of this document is aligned with the rules and regulations of the IGC and IGF codes and the classification society. A Failure Mode and Effect Analysis (FMEA) has been performed. The FMEA document itself is WinGD intellectual property and, therefore, cannot be disclosed to any third party.

The X-DF-A engines on board seagoing vessels use liquid ammonia as the primary fuel. The ammonia can be stored in dedicated ammonia fuel tanks or can be taken from ammonia cargo tanks. This document covers the ammonia fuel related matters, i.e., the systems that are different from or additional to a standard diesel engine. The standard diesel systems and the diesel operation safety are not described here.

The scope of the document encompasses the systems to be installed in the engine room up to the manual Shut-Off Valve (SOV) outside the engine room, which are needed to operate the X-DF-A engine in ammonia mode.

Documentation referred to in the text is listed in the Reference section at the end of this document.

The special features and safety arrangements of the X-DF-A engine installations must be included in the ship operational documentation, and the crew must be trained accordingly.

2 Description of the X-DF-A engine and related systems

The purpose of this chapter is to describe the WinGD 2-stroke X-DF-A engine general operating principle and components related to ammonia mode. Components and functions of the X-DF-A engine auxiliary systems related to ammonia mode and gas safety are also described in this chapter.

2.1 Operating principle in ammonia mode

The WinGD X-DF-A engine utilises the diesel combustion principle, ensuring emission optimised combustion. The engine is normally installed for dual-fuel operation, where the engine can operate in either ammonia or diesel mode. The operating mode can be changed while the engine is running, within certain limits (see Figure 2-4) without interruption of power generation. If the ammonia fuel supply fails, the engine automatically trips to diesel mode operation.

2.1.1 Combustion check principle

The engine is equipped with a misfiring detection system which monitors the individual cylinders in ammonia mode. This ensures that the Engine Control System (ECS) immediately trips to diesel mode in case of misfiring. The system is active when ammonia fuel is used, including transfers, and, therefore, can immediately detect a non-igniting cylinder.

2.2 Ammonia fuel system

2.2.1 General description

The ammonia fuel system consists of the bunkering station and storage tank(s), the external ammonia Fuel Supply System (FSS), the Fuel Valve Unit (FVU), the venting system, the ventilation system, the inert gas supply system as well as the engine internal ammonia fuel system. The ammonia fuel systems vary to some extent depending on the X-DF-A engine type and specific ship installation, but the main principles regarding structure, operation and safety are the same.

2.2.2 Engine internal ammonia fuel system

Because of the ignition properties of ammonia a high-pressure injection system is applied. This enables an optimum combustion process.

This system comprises:

- ammonia injectors
- servo oil system

2.2.2.1 Ammonia injection system

The injector design is based on a spring-loaded injector type for liquid ammonia injection. The injectors are placed in the cylinder head next to the main diesel fuel injectors.

2.2.2.2 Servo oil system

A dedicated servo oil system is used to build up the injection pressure in the fuel injector. The servo oil pump is mechanically driven by the engine.

2.2.2.3 Ammonia fuel supply pipes

A double-wall ammonia fuel rail distributes the ammonia fuel to the injectors.

Within the double-wall manifold, the inner pipe contains the ammonia fuel. The outer space, called the annular space, is either inerted by nitrogen or ventilated by air. For further information about the ventilation system, please see section 3.3.

Before any maintenance work is carried out, in case of ammonia leakage detection, a fire alarm or any other emergency, the system must be purged. For this purpose, the piping of the WinGD main engine and the FVU are equipped with different purging connections.

All pipes are pressure tested after assembling. Tightness of the ammonia fuel system is constantly monitored with the double-wall piping concept (where a possible ammonia fuel leakage is detected by the ammonia concentration sensors in the piping annular space).

2.2.3 External ammonia Fuel Supply System and Fuel Valve Unit

2.2.3.1 General description of external ammonia Fuel Supply System

The external ammonia Fuel Supply System (FSS) upstream of Fuel Valve Unit (FVU) consists of ammonia fuel supply piping and components, such as pumps, heat exchangers and filters. This document contains only some general information about the external ammonia fuel supply piping. For further details about the external ammonia FSS requirements, please refer to the WinGD Marine Installation Manual (MIM) and the Concept Guidance for the X-DF-A.

Ammonia fuel supply piping

The ammonia piping must be designed to minimise risks associated with any possible leakage in the system. For this reason ammonia piping must always be enclosed in a gastight secondary barrier. The annular space between the inner and outer pipe will be equipped with ammonia detectors. With underpressure detection the flow rate is monitored.

A gastight secondary barrier is not required for the ammonia fuel supply piping in the ammonia hold space (for all tanks type except C type), in tank connections space, in the fuel preparation space, in the bunkering stations, on open decks (for piping containing ammonia for short periods) as well as in case of full welded vent piping, since these areas already provide a second level of protection.

For further details about the external ammonia fuel piping system requirements, please refer to the Concept Guidance for the X-DF-A.

2.2.3.2 General description of the Fuel Valve Unit

Introduction

The Fuel Valve Unit (FVU) comprises a series of fuel control valves before the consumers and represents the interface between the engine and the ancillary systems.

Main functions of the FVU

- Safety barrier between the ammonia FSS and the engine:
  - A safety barrier is ensured by having Double Block and Bleed (DBB) valves.
- Leak test sequence:
  - The sequence is performed before the engine transfers to ammonia mode.
  - It confirms that the FVU valves are working properly and that no internal leakages are detected.
- Purging:
  - The purging sequence is included in the FVU automation. Safety is ensured during normal operation and in the event of system disturbance.
- Ammonia temperature monitoring:
  - The temperature of the ammonia fuel supplied by the FSS is monitored at the FVU inlet. If the conditions for the ammonia are outside of the operational conditions, then an Ammonia Trip (AT) is triggered.

The complete FVU functionality is controlled by the FVU control system.

Based on the signals from the control system logic, the solenoids control the valves. Additionally, a panel is mounted on the control cabinet to monitor the following parameters:

- current status of the FVU
- valve positions and readings from the sensors
- alarm history
- possible active alarms

The FVU is Factory Acceptance Tested with the control system that ensures a high quality and trouble-free commissioning.

Ammonia master fuel valve

A manually operated stop valve(s) and an automatically operated master fuel valve(s) coupled in series or a combined manually and automatically operated master fuel valve(s) must be installed on the main ammonia supply line to each consumer. The ammonia master fuel valve is open under ammonia mode condition and used to shut off the ammonia fuel supply to the engine room. These valves must be outside the machinery space.

2.2.3.3 The Fuel Valve Unit installation aspects

The FVU must be outside the machinery space. The FVU is arranged in the fuel preparation space and a FVU without housing, e.g. FVU-OD design, is currently considered for the WinGD ammonia fuel system.

2.2.3.4 Ammonia pipe purging procedure

Purging is the process of removing ammonia from the ammonia fuel piping by substituting it with an inert gas, e.g. nitrogen supplied by the inert gas supply system.

Purging of the ammonia fuel system is performed in case of ammonia leakage detection, a fire alarm or any other emergency, as well as before maintenance on the main engine or the FVU. For this purpose, the ammonia fuel system is provided with inert gas connections.

2.3 Pilot fuel oil system by means of main fuel injector

The fuel oil system is used to deliver the fuel oil to the engine during the diesel mode. For the X-DF-A engines the main FSS is also used to pilot the ammonia in ammonia mode.

2.4 Exhaust gas system

2.4.1 Exhaust gas system description

During normal operation the exhaust gas contains some unburnt ammonia due to combustion limitations. In case of a malfunction the amount of unburnt ammonia may also increase. The design of the exhaust gas system must ensure that ammonia cannot accumulate anywhere in the system. Precautions, such as explosion proofing the exhaust manifold, are in place to prevent an exhaust gas explosion causing damage to equipment and people in the close vicinity. Additionally to explosion precautions the toxicity of ammonia in the exhaust gas is carefully considered. An ammonia vapour detector is provided downstream of the Turbocharger (TC) to monitor the ammonia ppm levels. This ensures that the ammonia concentration in the exhaust gas released to the atmosphere does not present a significant health hazard at points of release. A suitable exhaust gas abatement system is required to prevent the release of emissions causing a significant health hazard.

2.4.1.1 External exhaust gas system

The external exhaust gas system consists of a compensator and piping downstream of the TC.

In the exhaust gas system design the following features must be considered:

- According to class requirements, piping and components design must ensure that ammonia cannot accumulate in the exhaust gas system, especially in the installed silencer and exhaust gas boiler.
- The exhaust gas system must be designed to withstand a potential explosion. This is achieved using explosion relief devices that enable safe discharge of explosion pressure build-up. The number and placement of these devices must be calculated, e.g. with a computer simulation. Any assumptions of the scenario simulation are to be justified. For example, for a single main engine the explosion relief devices either must include a duct leading the exhaust gas to the outside or must be made of the self-closing type.
- The explosion relief devices must be located in such a way that the hot combustion gases erupting from them do not cause a significant health hazard at the point of release. In case of eruption the gas concentration is detected by the engine room detector.
- Explosion relief devices installed within the engine room area must be of the self-closing type.
- All explosion relief devices must be equipped with flame arrestors.
- Any bellows to be used in the exhaust gas system must be approved by the classification society.
- The exhaust gas duct of the X-DF-A engine must not be connected to the exhaust gas duct of any other equipment.
- Exhaust gas emission abatement (e.g. Selective Catalytic Reaction (SCR)) can be applied to reduce the ammonia emissions.
- Ventilation arrangements of the engine exhaust gas system are already taken into account (see section 2.4.1.4).

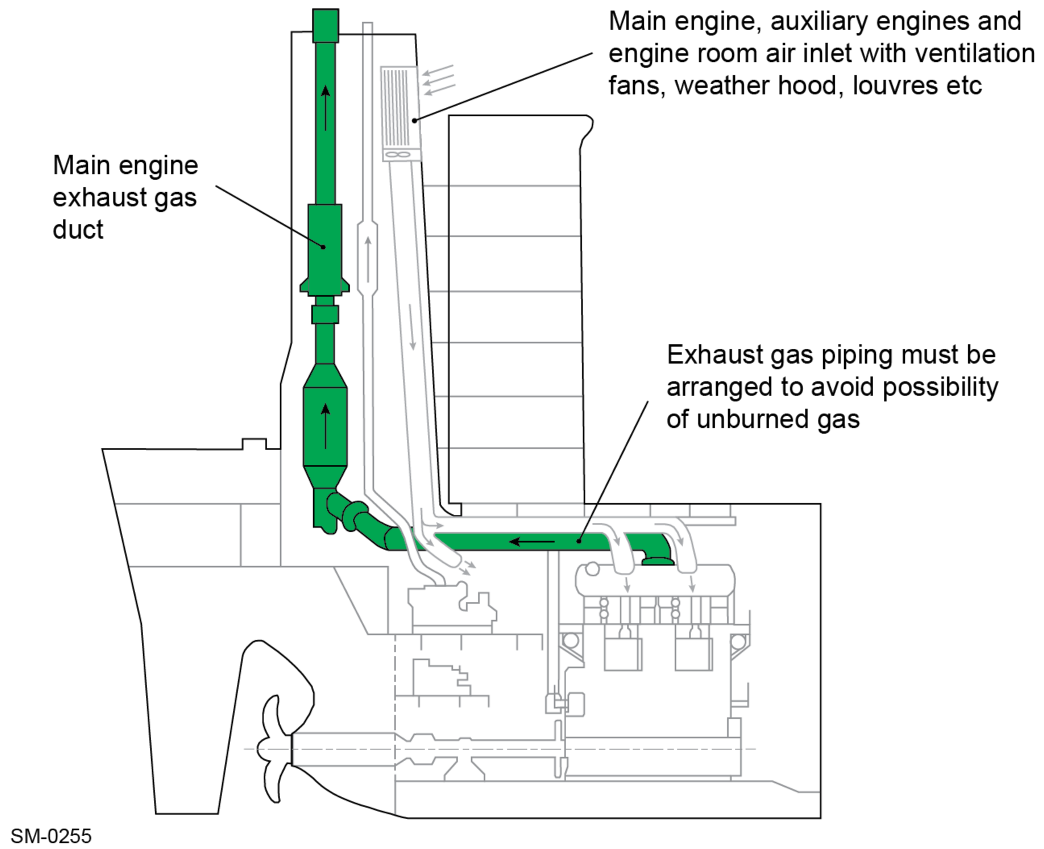

Figure 2-1: External exhaust gas system (high-pressure SCR system not shown)

2.4.1.2 Engine exhaust gas system

The engine exhaust gas system consists of pipe sections connected to the manifold with flexible bellows. These stainless-steel bellows are critical components with respect to internal overpressure in the exhaust gas system. Both the exhaust gas manifold and the flexible bellows are designed to withstand a possible explosion without bursting.

WinGD sees no reason for concerns regarding the ongoing operational functionality of a TC if an explosion has occurred in the exhaust gas system upstream of the TC. However, for specific questions about TCs, please address the TC manufacturer.

The toxicity of ammonia in the exhaust gas must be considered. This is achieved by improved sealing design of the flanges to ensure leakage-free operations.

2.4.1.3 Safety measures for preventing a potential explosion or increased ammonia concentration in the exhaust gas system

In addition to the safety measures against explosion or increased ammonia concentration in the exhaust gas system, precautions on the engine side are taken to minimise the ammonia concentration in the exhaust gas through engine internal control measures. To facilitate this, the combustion process is continuously monitored to detect misfiring and to automatically trip to diesel mode in case of such an event.

2.4.1.4 Exhaust gas ventilation procedure

- The ventilation sequence is requested automatically by the Engine Safety System (ESS) or ECS and starts after confirmation by the operator.
- The ventilation is then performed automatically by the ECS.
- The sequence can be cancelled at any time by the operator in case of an urgent need of engine start.
- The ventilation request results in a prolonged engine start.

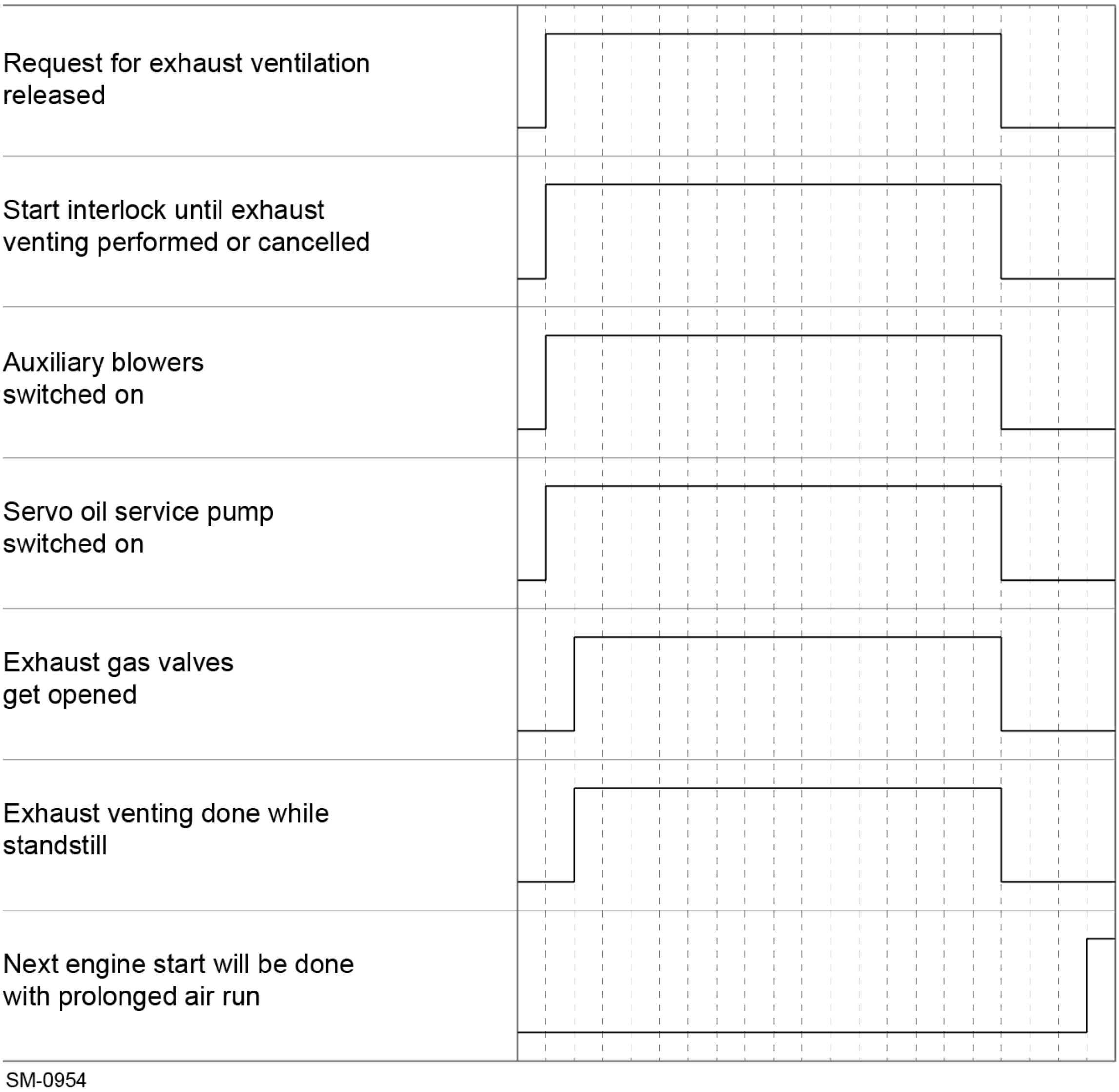

Figure 2-2: Exhaust gas ventilation procedure event sequence

2.4.1.5 Exhaust gas system with High Pressure Selective Catalytic Reduction installation

All X-DF-A engines are IMO NO_x Tier III compliant in ammonia and diesel mode with the High Pressure Selective Catalytic Reduction (HP SCR) exhaust gas aftertreatment system. The HP SCR is available as an off- or on-engine (iSCR) option.

2.5 The XDF-A engine automation architecture

The ECS provides data bus and hardwired connection to the Propulsion Control System (PCS) and the Alarm and Monitoring System (AMS). The AMS is usually provided by the shipyard. The leading suppliers of Propulsion Control Systems approved by WinGD ensure meeting the engine requirements.

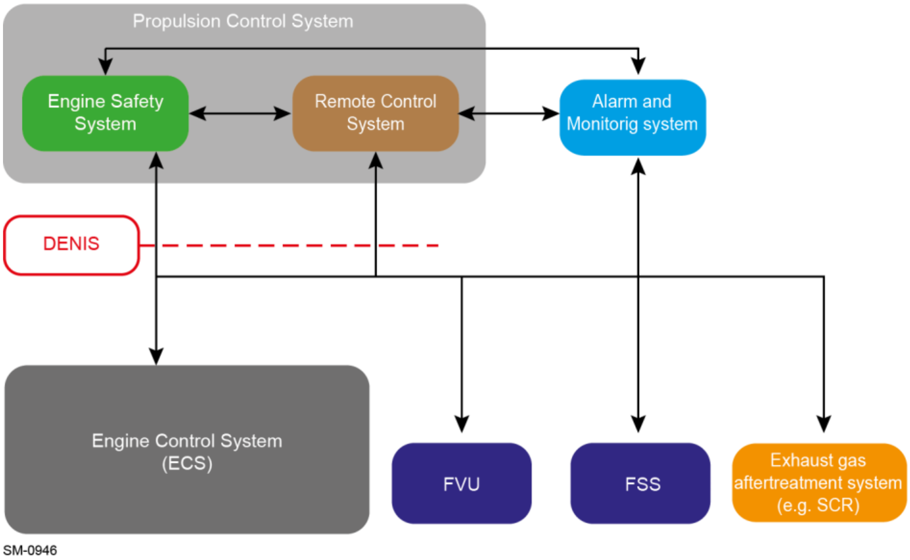

Figure 2-3: Engine automation architecture

2.5.1 Signal flow diagram between the Engine Control System and external systems

The ammonia mode related signals and the related failure actions are listed in the tables of section 8.4. Communication to external systems is described in the signal lists.

2.5.2 Fuel operating modes

The engine is designed for continuous service on ammonia fuel as well as fuel oil. Depending on the selected option, different operating modes are available within specific engine power ranges (see Figure 2-4).

The following list includes the operating modes of the X-DF-A engine:

- ammonia mode
- diesel mode

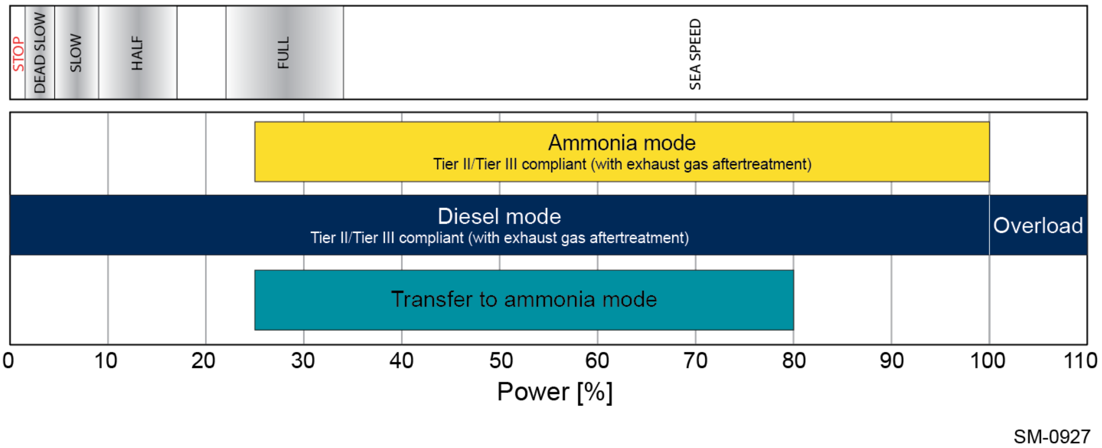

Figure 2-4: Operating modes of the X-DF-A engines

Changeover between the operating modes:

- transfer (automatically active for changeover to or between modes with ammonia operation)
- Ammonia Trip (AT) (immediate action always available while a mode with ammonia operation is selected)

The engine start and reversing are always performed in diesel mode.

2.5.3 The X-DF-A engine fuel mode transfers and trips

The changeover between operating modes can be categorised in two ways. If the changeover introduces ammonia fuel, it is called a transfer. If the changeover between operating modes stops the use of ammonia fuel, therefore, defaulting to diesel mode, then the changeover is called an Ammonia Trip (AT), or just a trip. Often an AT is associated with automatic initiation as part of a system safety procedure, but it can also be intentionally initiated by the operator. In comparison to an AT, the transfer between operating modes can only happen from operator initiation.

An AT always stops the ammonia fuel operation and results in diesel mode operation. The AT is completed within half a revolution of the engine and can occur at any engine power. This includes any point of transfer between operating modes.

While the engine runs in ammonia mode the liquid fuel backup system is always on standby with MGO or MDO. The operator can initiate an AT to diesel mode at any time. If the ECS initiates an automatic AT, it is a result of either an unacceptable operating condition, a detected failure or a command received from an external system (e.g. the ESS). If an automatically initiated AT occurs, the cause of it must be investigated. Transferring to ammonia mode is, therefore, prohibited and disabled until the problem is resolved and the alarm is reset.

The transfer from diesel mode to ammonia mode introduces the ammonia fuel. The FVU must complete a system safety test before this gradual changeover can take place.

The transfer to ammonia mode is prohibited (and, therefore, disabled) when the engine is running on HFO. Before changing to ammonia mode the engine must operate in diesel mode (Tier II) with MGO or MDO until the fuel system is fully flushed of HFO.

Like the WinGD diesel engines, changing the fuel input from HFO to either MGO or MDO and vice versa can be done at any time (assuming HFO is permitted in the operating mode) without interruption of engine operation. The fuel oil changeovers are managed by external systems.

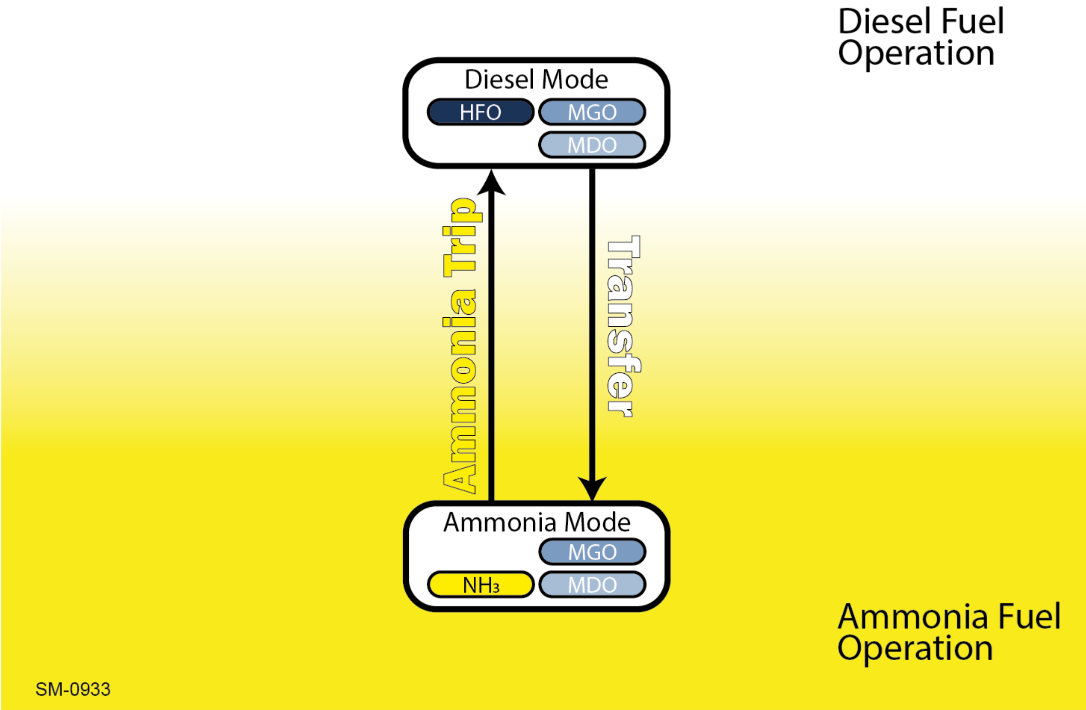

Figure 2-5: Overview of fuel transfers for the X-DF-A engines

NOTE	If an automatically initiated Ammonia Trip occurs before the operator can request a transfer back to ammonia, the cause of the Ammonia Trip must be investigated, the problem resolved and the alarm reset

2.5.4 The XDF-A engine internal operating modes

The ECS has several internal states which are called internal modes:

- start mode
- run mode
- stop mode
- slowdown mode
- emergency stop mode
- shutdown mode

The present document focuses on description of the X-DF-A engine internal modes when engine is running with ammonia fuel. Some information about internal modes in diesel mode is also shown. This information is necessary to understand the ammonia safety features, e.g. in a transfer or blackout situation.

2.5.4.1 Engine starting

Engine can only be started in diesel mode. No start block can be active to perform an engine start. Engine start can only be attempted when engine is stopped and ready for start.

Prolonged starting sequence, when the engine is turned minimum 1 revolution by air, is applied after regular stop in ammonia mode and after ventilation request. This is to ensure that all cylinders are free of ammonia fuel before the fuel injection is activated.

2.5.4.2 Engine running

Engine running in diesel mode is entered after start mode. Engine is running when speed is above a pre-set speed limit and no stop, shutdown or emergency stop is active. Ammonia mode is activated if transfer from diesel mode to ammonia mode is successfully performed.

Engine run mode can be interrupted by the following internal modes:

- stop mode
- slowdown mode
- shutdown mode
- emergency stop mode

Ammonia mode can be interrupted in case of an AT.

2.5.4.3 Engine stop from ammonia mode

In case of a normal engine stop request during the ammonia mode, the ECS changes its internal mode to engine stop mode. Immediately after the engine stop signal is activated in ammonia mode, the Shut-Off Valves (SOVs) on FSS close and FSS emptying/purging procedure is initiated. Then the SOVs on the FVU and on the cylinders close and the FVU and cylinder emptying/purging procedure is initiated. The ammonia injectors get deactivated while the main fuel injectors remain active for a while before stopping. Stop sequence is shown in Figure 2-6.

In case of a stand-by engine stop request during the ammonia mode, the ECS changes its internal mode to engine stop mode. The stand-by stop defines a temporary suspension of the ammonia supply to the engine to facilitate temporary manoeuvring operations, in a state of readiness (of the engine and FSS) to initiate the ammonia mode. The system remains pressurised in stand-by for a defined interval to allow to go back to ammonia mode in a short time. After the above defined interval, the normal engine stop procedure is initiated, if the ammonia mode is not requested.

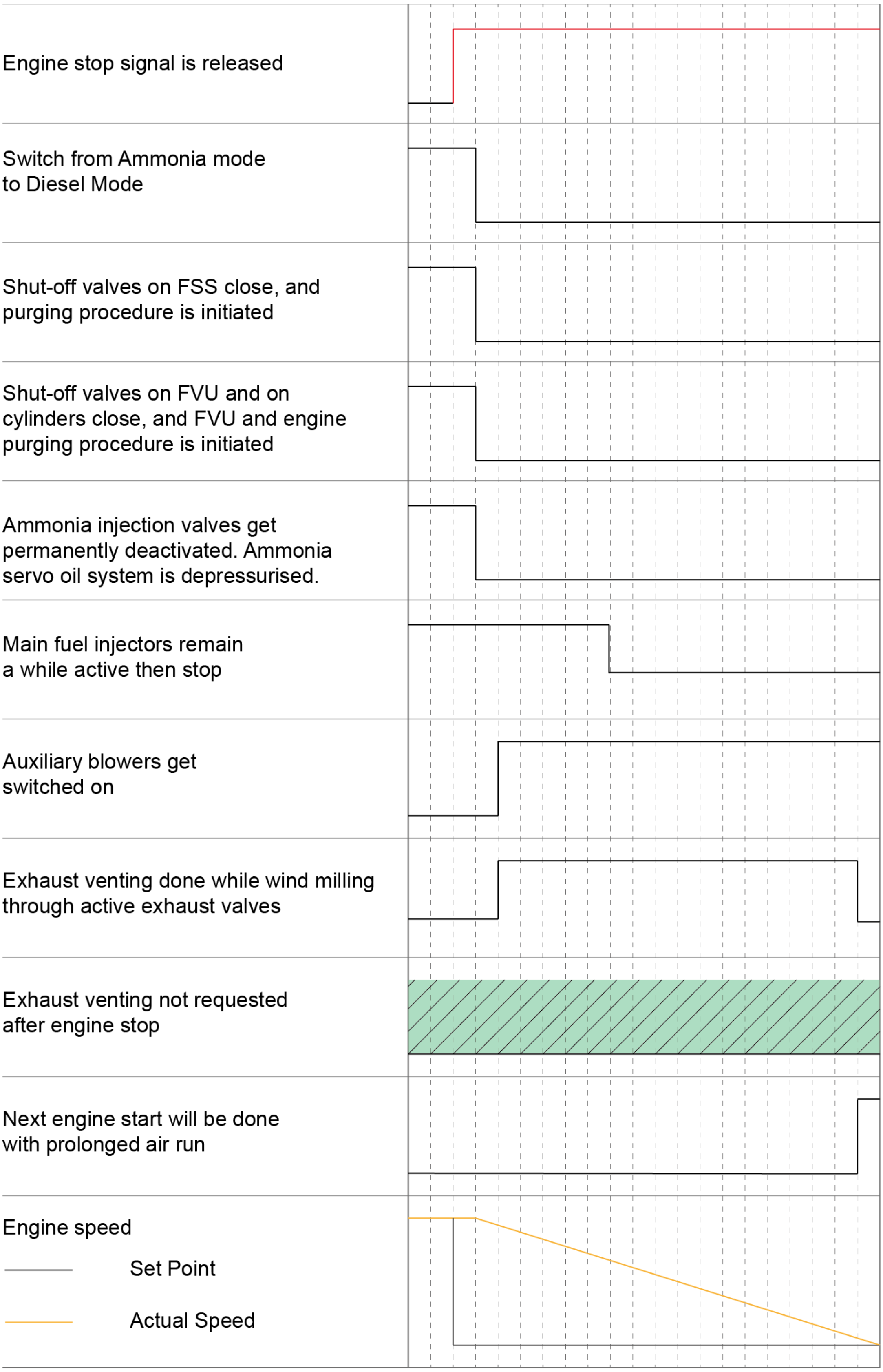

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Figure 2-6: Ammonia mode event sequence – Engine stop

2.5.4.4 Engine shutdown from ammonia mode

Shutdown mode is initiated automatically as a response to measurement signals. In case of cancellable shutdown, the operating mode is changed to diesel mode and the engine continues running as long as the Shutdown (SHD) signal does not become active (operator can cancel SHD and continue running in diesel mode). Exhaust gas ventilation is not required in this situation.

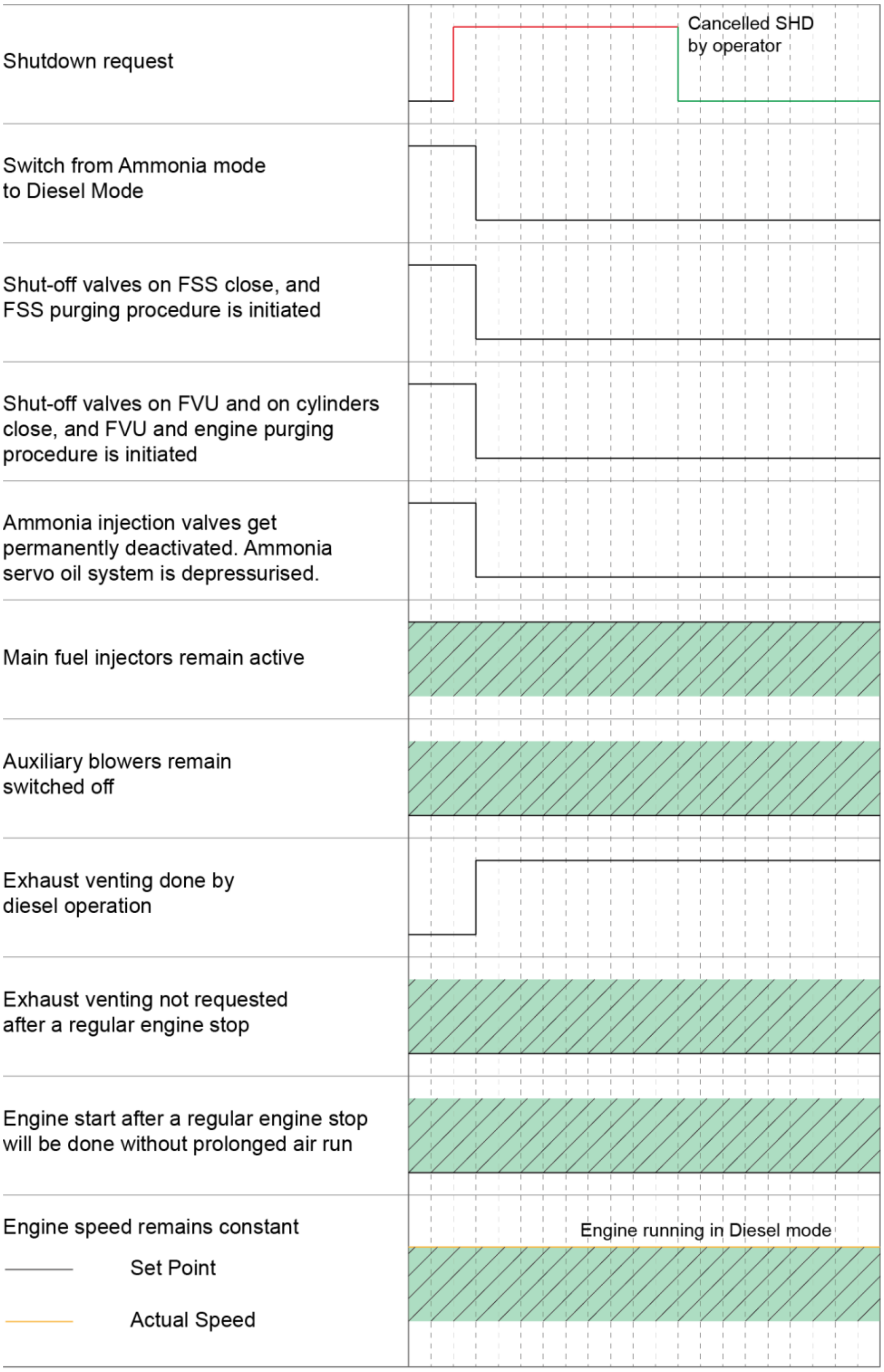

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Figure 2-7: Ammonia mode event sequence – Cancellable shutdown

If non-cancellable shutdown occurs from ammonia mode (i.e. engine overspeed or critical failure), exhaust gas ventilation is required. Defined shutdown failure states are given in the Usual Values and Safeguard Settings document as referred to in the Marine Installation Manuals (MIM). Shutdown mode must be reset by operator and root cause for shutdown must be investigated and corrected before re-start.

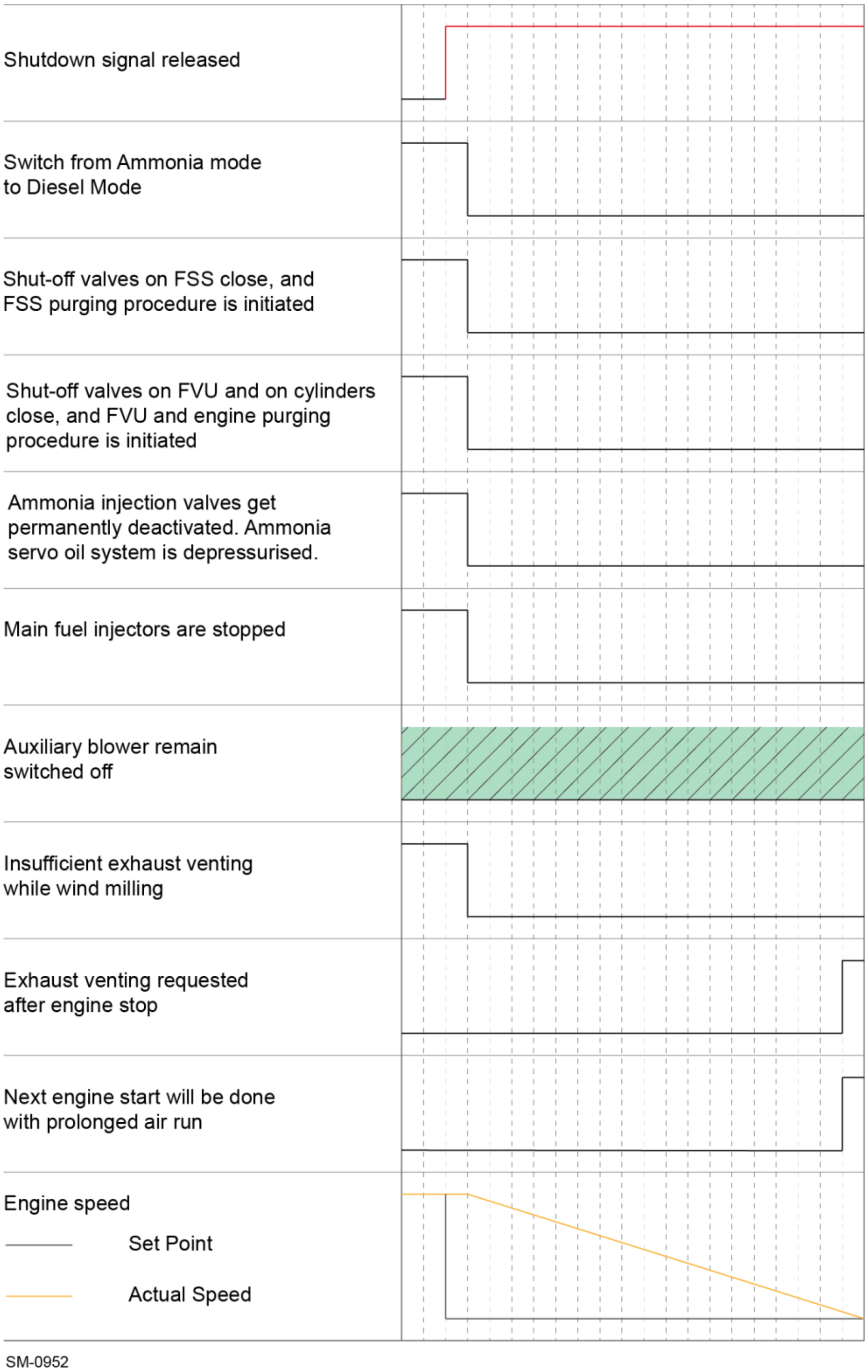

Figure 2-8: Ammonia mode event sequence – Non-cancellable shutdown and emergency stop

2.5.4.5 Emergency stop from ammonia mode

Emergency stop mode is activated manually by pressing the emergency stop push-button. Emergency stop is the fastest way to manually shut down the engine. To return to normal operation the push-button must be pulled out and alarms acknowledged (see section 8.4)

The emergency stop sequence is identical to the non-cancellable shutdown sequence and shown in Figure 2-8.

2.5.4.6 Transfer from diesel mode to ammonia mode

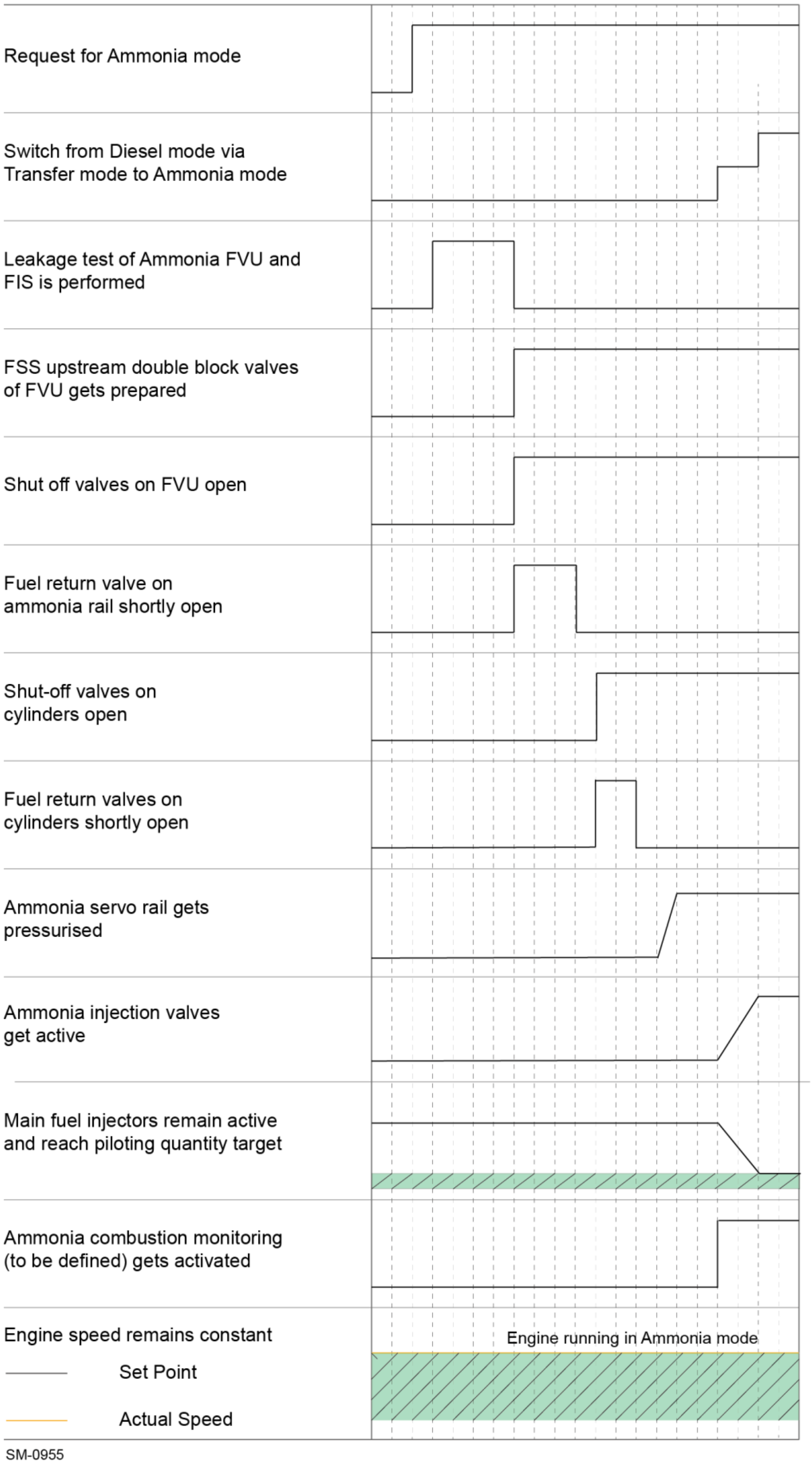

Figure 2-9: Ammonia mode event sequence – Transfer from diesel to ammonia mode

2.5.4.7 Transfer from ammonia mode to diesel mode or Ammonia Trip

For further details about the AT, please see section 8.4.

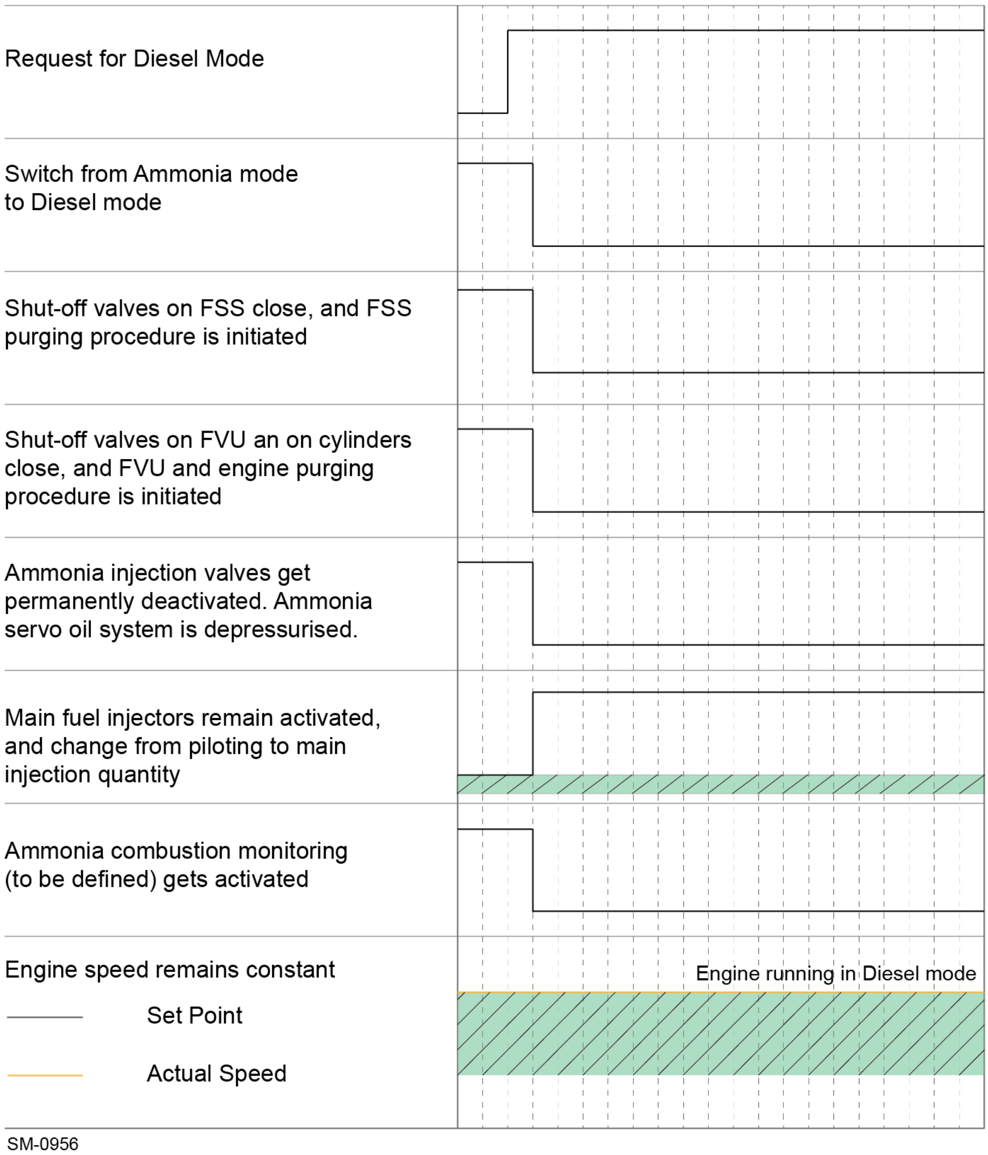

Figure 2-10: Ammonia mode event sequence – Transfer from ammonia mode to diesel mode

3 Machinery spaces arrangement to prevent fire and explosion

The flammable range of ammonia in dry air is between 14% (vol.) and 27% (vol.). It has a flashpoint of 132 °C and an auto ignition temperature of 651 °C. Therefore, the risk of an ammonia fire is lower compared to other fuel oils or gases. However, under certain conditions, there can be a risk of fire and explosion. Therefore, the fire and explosion risk must be assessed and mitigated.

The engine room design, arrangement and location as well as equipment and systems installed may vary depending on specific ship installation, but the main principles concerning fire and explosion prevention, detection, control as well as redundancy must meet the minimum requirements stated in this chapter.

3.1 Engine room arrangement

With the double-wall ammonia fuel pipe configuration, the engine room is considered a gas safe area according to the IGC Code 1.3.17.10, 1.3.18 and the IGF Code 5.4.

Permanent ammonia detectors are installed in the engine room. The ammonia detectors must be installed at least to the ceiling and at the bottom of the concerned space. Additional ammonia detectors may be required depending on the results of ammonia dispersion studies as performed by the shipyard. Independent ammonia detectors for the Alarm and Monitoring System (AMS), and the safety system must be applied.

The Fuel Valve Unit (FVU) must be installed outside the engine room (see section 2.2.3.3).

External ammonia piping to the engine room must be of the double-wall type with either annular space ventilation and ammonia leakage detection or with an inerted and pressurised annular space, following the IMO regulation.

3.2 Safety of electrical equipment in the engine room

Engine rooms of the X-DF-A engines on seagoing vessels are considered as gas safe according to the IGC and IGF codes. Therefore, electrical equipment inside the engine room does not require to be certified ex-proof apparatus. Regarding sensors in hazardous areas see section 3.4.

Engine room ventilation must be forced (the IGC code 16.2.1 and the IGF code). It means it is same as normal engine room ventilation via engine room ventilation fans. The engine may suck combustion air directly from outside with a dedicated duct (option). Ventilation must be particularly effective in the vicinity of all electrical equipment and prevent the formation of ‘dead spaces’ in accordance with the IGC Code regulations.

3.3 Ventilation arrangement of certain X-DF-A engine systems

Layout

The annular space must be provided with mechanical underpressure ventilation which has a capacity of at least 30 air changes per hour and gas detection provided accordingly. In the WinGD design the air flow in the outer pipe follows the same direction of the fuel supply in the inner pipe. Therefore, the ventilation inlet is connected to the annular space of the fuel inlet, and the ventilation outlet is connected to the outlet of the annular space of the purge line.

Actions upon ventilation failure of double-wall ammonia fuel supply piping

The negative ventilation air pressure as well as the air flow in the annular space are monitored. A possible loss of negative pressure (Δp) or air flow causes a trip to diesel mode.

3.4 Ammonia leakage detection against explosion: in the engine room, the Fuel Supply System and the engine

Ammonia leakage detectors against explosion must be installed at the following locations:

- in the annular space ventilation air outlet (extraction fan) line to detect any leakage into the annular space of the double-wall piping system. A sensor for explosion protection (the Lower Explosive Limit (LEL)) must be installed.
- on the engine side an ammonia leakage detector to measure the ammonia concentration in the piston underside area for explosion protection (LEL).

However, any additional requirements by classification society, the IGF and IGC codes, must be met. In individual cases deviations from the above precautions for detection of ammonia leakages may be approved by the classification society, based on prior acceptance from the responsible flag state.

For the sensors required for toxicity protection corresponding to the Permissible Exposure Limit (PEL), please see section 4.5.3.

The four most common types of fixed sensors used to detect ammonia vapour are:

- infrared
- chemosorption
- electrochemical (EC) sensors
- charge carrier injection (CI) sensors

Other types of sensors can be used for ammonia leakage detection. The ammonia vapour detector sensors must be installed at least to the ceiling and at the bottom of the concerned space as well as in specific locations (e.g. outlet of annular space (PEL and LEL)). Additional ammonia detectors may be required depending on the results of ammonia dispersion studies as performed by the shipyard. Independent ammonia detectors for the AMS, and the safety system must be applied.

All ammonia detector signals are connected to the external Ammonia Detection System (ADS), except for the ammonia detectors at the piston underside directly connected to the ECS. Depending on the ship's arrangement and requirements of IMO and classification society, the central alarm can be in one or more of the following locations:

- bridge
- cargo control room
- Engine Control Room (ECR)

The ammonia detectors are to be approved by the classification society. If the detected ammonia fuel concentration has increased above the class specified limit, an audible and a visible alarm is initiated in the rooms. The ADS must be tested and calibrated according to the maintenance schedule and procedure as advised by the manufacturer or classification society.

The number and position of additional ammonia detectors is in the shipyard scope of supply must be defined according to the classification society, the IGF Code and the IGC Code. All spaces and volumes, where ammonia fuel could accumulate, must be monitored.

If ammonia is detected by the external ADS, the engine automatically trips to diesel mode and the purging procedure is triggered. Further measures on the vessel must be taken as defined by the shipyard and classification society.

Although the IGC code 16.7.3.3 states that the crankcase, sumps, scavenge spaces must be provided with gas detectors, this is not fully applicable to the WinGD X-DF-A engines regarding explosion protection as the relative area according to the IGC code is the area below the pistons. This piston underside area is protected by an ammonia detector as stated before.

Currently the IGC code does not specify separate requirements for different engine designs (i.e. trunk piston or crosshead engines) nor for different cycles (i.e. 2- and 4-stroke, Diesel and Otto cycle). However, the IGF code 10.3.1.2 does recognise the difference between engine types. It states that the evaluation will vary "for engines where the space below the piston is in direct communication with the crankcase …". Consequently, the classification societies have accepted, through analysis and assessment, that the architectural features of the X-DF-A engines provide the equivalent requirement for the IGC code 16.7.3.3 and an equivalent level of safety regarding explosion protection. For these reasons, and upon prior acceptances of the responsible flag states, the absence of an LEL detector in the crankcase is deemed acceptable. The WinGD standard design includes venting of the sumps to a safe area outside the engine room. Therefore, the ammonia LEL detectors in the above-mentioned systems are only referred to as optional. The final above-mentioned system layout(s) depend(s) on the acceptance of the responsible flag state and/or the classification society to achieve IGC compliance.

For all relevant information regarding 'Mandatory' and 'Optional' requirements for ammonia detector installation, please refer to the *'Ammonia Fuel System'* MIDS package which is available on WinGD web page www.wingd.com.

The ammonia detectors must be installed in compliance with the requirements of the responsible classification society and/or flag state.

3.5 Definition of hazardous areas

Area classification is a method of analysing and classifying the areas where explosive gas atmospheres may occur. The object of the classification is to allow the selection of electrical apparatus to be operated safely in these areas. Definitions of hazardous areas according to IEC 60092-502:1999 (used as reference in the IGC and IGF Codes) are:

- Hazard Zone 0 (Z0): area in which an explosive gas fuel atmosphere is present continuously or is present for long periods
- Hazard Zone 1 (Z1): area in which an explosive gas fuel atmosphere is likely to occur in normal operation
- Hazard Zone 2 (Z2): area in which an explosive gas fuel atmosphere is not likely to occur in normal operation and, if it does occur, is likely to do so only infrequently and will exist for a short period only

The engine room and engine crankcase are considered as gas-safe, non-hazardous areas and, therefore, do not qualify as hazard zone definitions.

3.6 Actions to be taken in case of a fire in the engine room

The Engine Safety System (ESS) provides the possibility to be connected to the fire detection system. If this possibility is selected and a fire occurs, then the ESS triggers an Ammonia Trip (AT) and starts the purging procedure.

4 Machinery spaces arrangement to ensure health safety against toxicity

The conducted analysis has demonstrated that the main safety concern in relation to ammonia is associated with its toxicity and gas-dispersion properties. Toxicity adds complexity to the ship design. People on board must be protected against the high toxicity of ammonia. It already has a negative impact on health in the ppm concentration range. For explosion protection the percentage-range is relevant.

4.1 Impact on health

Ammonia is a widely used and commercially available chemical. Ammonia is toxic to humans. The odour threshold for ammonia is very low, from 5 ppm concentration it can be detected by most people, and this does not constitute a health risk.

Based on Acute Exposure Guideline Levels (AEGL) for airborne chemicals defined by the Environmental Protection Agency (EPA) US, the limits to ammonia exposure can be identified as shown in the following table:

Table 4-1: EPA Acute Exposure Guideline Levels (Source: EPA, 2016)

Guideline	10 minutes	30 minutes	1 hour	4 hours	8 hours
AEGL-1	30 ppm	30 ppm	30 ppm	30 ppm	30 ppm
AEGL-2	220 ppm	220 ppm	160 ppm	110 ppm	110 ppm
AEGL-3	2,700 ppm	1,600 ppm	1,100 ppm	550 ppm	390 ppm

AEGL 1: Notable discomfort, irritation or certain asymptomatic non-sensory effects. However, the effects are not disabling, they are transient and reversible upon cessation of exposure.
AEGL 2: Irreversible or other serious, long-lasting adverse health effects or an impaired ability to escape
AEGL 3: Life-threatening health effects or death

Toxic exposure can occur by inhalation (breathing in vapour), dermal or eye contact with ammonia vapour or liquid.

Table 4-2: Exposure guidance (Source: Karabeyoglu A, Brian E., 2012)

Effect	Ammonia concentration in air (by volume)
Readily detectable odour	20 – 50 ppm
No impairment of health for prolonged exposure	50 – 100 ppm
Severe irritation of eyes, ears, nose and throat. No lasting effect on short exposure	400 – 700 ppm
Dangerous, less than ½ hour exposure may be fatal	2,000 – 3,000 ppm
Serious oedema, strangulation, asphyxia, rapidly fatal	5,000 – 10,000 ppm

Due to its toxic effects the direct release of ammonia to open air must be limited to the lowest practicable level. Direct venting of ammonia to the atmosphere is not permitted in normal condition. Venting of ammonia for pressure control in the storage tanks is not permitted. It is only allowed in case of failure conditions if it doesn't result in dangerous ammonia concentrations.

4.1.1 Inhalation

Ammonia can be very toxic. Its inhalation can cause severe symptoms according to the exposure time and concentrations, as defined in Table 4-2. In case of ammonia vapours inhalation the affected individual must be moved to an area with fresh air. Supplemental oxygen with assisted ventilation may also be required. Symptoms may develop hours after exposure and worsen by physical effort. Long-term damage may result from a severe short-term exposure.

4.1.2 Ingestion

Ingestion is not a relevant route of exposure because at ambient temperature and pressure ammonia is in gaseous state.

4.1.3 Skin contact

In case of contact with skin it is recommended to immediately use an emergency shower and flush the exposed body area with ample amounts of lukewarm water for at least 15 minutes. Note that ammonia can freeze the exposed clothing and the skin below it. This can result in extensive skin damage. Contaminated clothing and shoes must be removed and washed before reuse. Medical attention is required.

4.1.4 Eye contact

In case of contact with eyes the ammonia irritates or burns the eyes. Such contact can lead to permanent damage, including blindness. It is recommended to immediately flush the eyes with ample amounts of lukewarm water for at least 20 minutes. Medical attention is required.

4.2 Environmental impact

Ammonia is classified as toxic to aquatic life with long lasting effects. The permissible discharge limit is defined as the maximum concentration of ammonia in the effluents. This limit depends on the international or local regulation limits. Normally effluents containing liquid or dissolved ammonia are not to be discharged overboard.

4.3 Toxic zones

In addition to a hazardous areas classification, a toxic areas classification study must also be performed to identify areas or spaces in which a toxic atmosphere is present or may be expected to be present. Therefore, appropriate safeguards can be implemented and access to such areas can be restricted.

Toxic areas must be classified into different zones based upon the frequency of the occurrence and duration of a toxic atmosphere, as follows:

- Zone A: an area in which a toxic atmosphere is present continuously or for long periods or frequently
- Zone B: an area in which a toxic atmosphere is not likely to occur during normal operation but, if it does occur, will persist for a short period only

4.4 Gas safe machinery space concept

Gas safe machinery space is defined as an area in which a single failure in the ammonia system cannot lead to ammonia release into the machinery space. Therefore, the gas safe machinery concept must be applied to all machinery spaces containing ammonia in the engine room.

4.5 General engine room design requirements

4.5.1 Engine room ventilation

Engine room ventilation must be forced (the IGC code 16.2.1 and the IGF code). It means it is same as normal engine room ventilation via engine room ventilation fans. The engine may suck combustion air directly from outside with a dedicated duct (option). Ventilation should be particularly effective in the vicinity of all electrical equipment and prevent the formation of 'dead spaces' in accordance with the IGC Code regulations.

4.5.2 Ammonia venting to the atmosphere

Direct ammonia vapour venting to the atmosphere is normally not permitted. All the ammonia vapour release to the atmosphere must be done via a vent mast and the ammonia vapour concentration must be limited to the lowest practicable level. The concentration of the ammonia vapours released to the atmosphere via the vent mast must not cause a significant health hazard. The ammonia vapour processing system must be able to intervene in case the ammonia vapour concentration exceeds safe limits.

4.5.3 Ammonia leakage detectors against toxicity

In addition to the detectors for explosion protection (the Lower Explosive Limit (LEL)) (see section 3.5), specific ammonia detectors must be installed to detect the ammonia vapour concentration against toxicity (the Permissible Exposure Limit (PEL)) in the following locations:

- In the annular space ventilation air outlet (extraction fan) line to detect any leakage into the annular space of the double-wall piping system. An independent sensor to detect leakages regarding toxicity protection (PEL) must be installed.
- On the engine side an independent ammonia leakage detector is installed to measure the ammonia concentration in the piston underside area for toxicity (PEL).
- On the engine exhaust gas system an ammonia leakage detector is required to measure the ammonia concentration for toxicity (PEL).

For information about the sensors type and the Ammonia Detection System (ADS) arrangement, please see section 3.4. The ammonia detectors must be approved by the classification society.

4.5.4 Double-wall concept against toxicity

The double-wall concept (see section 3.1) also offers a protection against toxicity. All ammonia fuel piping on the engine is of the double-wall type. The annular space between the concentric pipes can be either pressurised with inert gas at a pressure greater than the ammonia fuel pressure or equipped with mechanical ventilation of underpressure type. When the mechanical ventilation of underpressure type is applied to the annular space, the ventilation inlet for the double-walled piping must always be in a non-hazardous area away from ignition sources. The ventilation system design must ensure 30 air changes per hour during normal conditions. The inlet opening must be fitted with a suitable wire mesh guard and protected from ingress of water. Loss of ventilation of double-walled pipes after the ammonia master valve(s) must activate an automatic shutdown of the master fuel valve required to isolate the unventilated fuel supply ducts or double-wall pipes. An ammonia vapour detector must be provided at the annular space ventilation outlet. This is to ensure the ammonia vapour concentration doesn't cause a significant health hazard. Ventilation outlets from hazardous spaces must be at a proper distance to air intake, air outlet, opening to other enclosed spaces as well as decks and gangways, as defined by the classification societies.

4.5.5 Mechanical protection of ammonia containing components against damage

Fuel piping and ammonia containing components must be designed to minimise the risks of mechanical damages during ship operations. Additional mechanical protection to the piping as well as by segregation of the ammonia containing components from the areas where these may be mechanically damaged is required to minimise the risks of rupture.

4.5.6 Operational precautions

During ammonia mode and as long as the ammonia fuel system is pressurised (e.g. during stand-by stop), crane operations are prohibited in the vicinity of ammonia containing components. This is to minimise the risk of falling/touching objects during lifting operations which may cause damages to the ammonia piping and components. Storage of components in the engine room must be limited and any spare component/equipment must be properly secured against moving (lashing).

4.6 Encapsulated main engine machinery space and supply system approach

The encapsulated ammonia main engine machinery space concept follows the “gas safe machinery” principle. It means a single failure will not lead to any ammonia leakage. The engine and the ammonia supply system are designed with double-wall piping concept. In case of the encapsulated ammonia engine room design, it is not permitted to access the ammonia containing machinery space during normal ammonia operation.

4.6.1 Remote control of the engine and the ammonia system

In case of the encapsulated ammonia main engine machinery space design, the Unattended Machinery Spaces (UMS) approach must be followed. In case of UMS, there are no crew members on watch in the engine room during ammonia operation. In case of a malfunction, an alarm is activated by the Alarm and Monitoring System (AMS). The routine visual and acoustic inspections must be performed remotely by using suitable cameras and microphones.

4.6.2 Entering the encapsulated main engine machinery space

In case of the encapsulated main engine machinery space, the access to the space must be provided via an air lock. During normal ammonia operation, access to the main engine machinery space is not permitted. If it is required to enter the space, Personal Protection Equipment (PPE) must be provided, including sufficient emergency escape breathing devices (EEBD) in the main engine machinery space. When the ammonia operation is stopped, and the engine and the ammonia system are ammonia-free, unlimited access to the encapsulated main engine machinery space is possible.

4.7 Non-encapsulated main engine machinery space and supply system approach

The non-encapsulated ammonia machinery space concept follows the “gas safe machinery” principle. This means, a single failure will not lead to any ammonia leakage. The engine and the ammonia supply system are designed with double-wall piping. The ammonia containing main engine machinery space can be accessed during normal operation, while a strong focus is placed on leakage detection, together with safe and speedy escaping.

4.7.1 Limitation of the working time in areas close to ammonia containing components

All typically performed activities in the main engine machinery space close to ammonia containing components must be limited to a minimum. To support this approach, the usual working spaces, like the workshop, test benches, cleaning stations, etc. must be separated from the main engine machinery space and provided with independent escapes.

4.7.2 Personal protection to ensure a safe escape from the main engine machinery space

People entering the non-encapsulated main engine machinery space must be equipped with:

- portable ammonia detectors

In addition, sufficient Emergency Escape Breathing Devices (EEBD) must be available in the main engine machinery space.

4.7.3 Main engine machinery space design to ensure a safe and fast escape

During the design phase of the main engine machinery space, a sufficient number of independent emergency exits must be provided for speedy escape from different areas. This is to minimise the escape time as well as distance (considering the routing including stairs and ladders). Clear floor markings must be provided to guide to the closest exit, considering the limited visibility caused by the ammonia cloud.

5 Material compatibility

Ammonia is corrosive to a wide variety of metals, such as copper, zinc or copper-based alloys. Steel, stainless steel and some non-ferrous metals, such as aluminium- or nickel-based alloys, are compatible with ammonia. However, carbon steels are known to be prone to stress corrosion cracking. The susceptibility of carbon steels stress corrosion cracking increases with higher strength steels, particularly in situations with high residual or applied stresses. The risk of stress corrosion cracking can be mitigated by using minor amounts of water in ammonia of approximately 0.2%.

Polymers used, e.g. in sealings exhibit a varying degree of compatibility with ammonia.

6 Spill prevention and handling

Considering the gas safe machinery space concept, a spill prevention and handling study is not required.

During the design of the external ammonia fuel system, a risk assessment about the spill prevention and handling must be made.

7 Twin engine propulsion

For certain applications the twin engine propulsion may be applied. Specific requirements and rules of the classification society in charge must be taken into consideration, especially, but not limited to what is stated in this chapter.

7.1 Shaft locking device

On twin engine operated vessels a shaft locking device must be installed on each propeller shaft. This allows individual shaft lines to be locked during maintenance and engine shutdowns. During sailing this device protects the stopped engine against turning by the wind milling effect. Engine start interlock and turning gear interlock are applied when the shaft is locked by the shaft locking device.

7.2 Exhaust gas system protection

If there is more than one gas-fuelled engine installed, each engine must have its own exhaust gas installation to avoid mixing of the exhaust gases. Also each system must be equipped with protection pressure relief devices to protect the system against overpressure from a potential explosion. The devices should be chosen according to classification rules (spring loaded or rupture discs).

7.3 Auxiliary systems

The auxiliary systems of each engine must be independent of each other. For the Low Temperature (LT) cooling water and cylinder Lubricating Oil (LO) supply a certain combination according to the following descriptions is possible:

7.3.1 Low Temperature cooling water system

- A shared cooling water system is possible. LT cooling water supply to both engines is arranged in parallel.
- There is one independent stream per engine to LO cooler and high-temperature cooling water cooler.

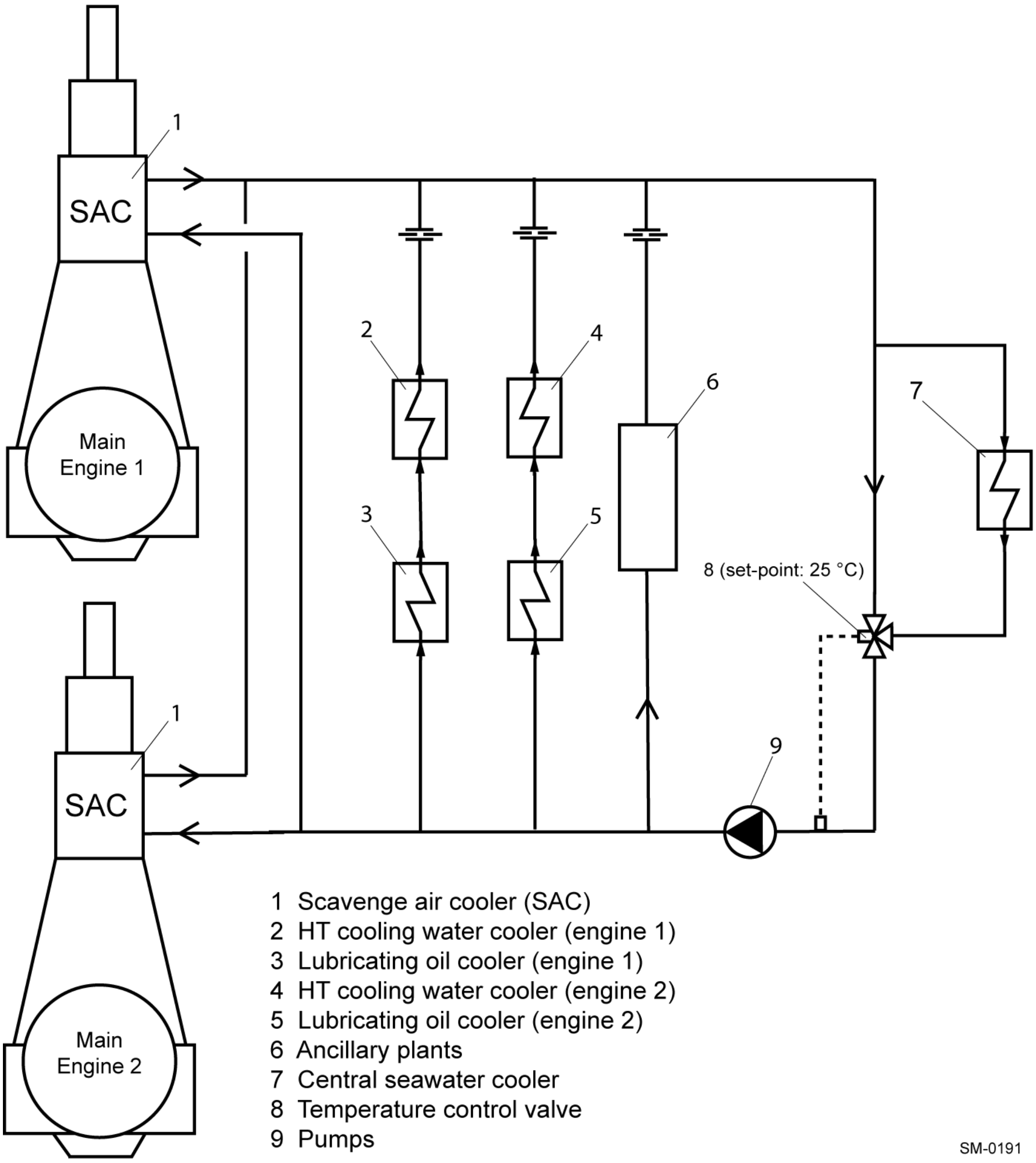

Figure 7-1: LT cooling water system layout for twin-engine installation

7.3.2 Cylinder Lubricating Oil system:

- Shared day tanks for different grades of LO are possible.
- A shared rising pipe is possible.
- A separate distribution to each engine is required.

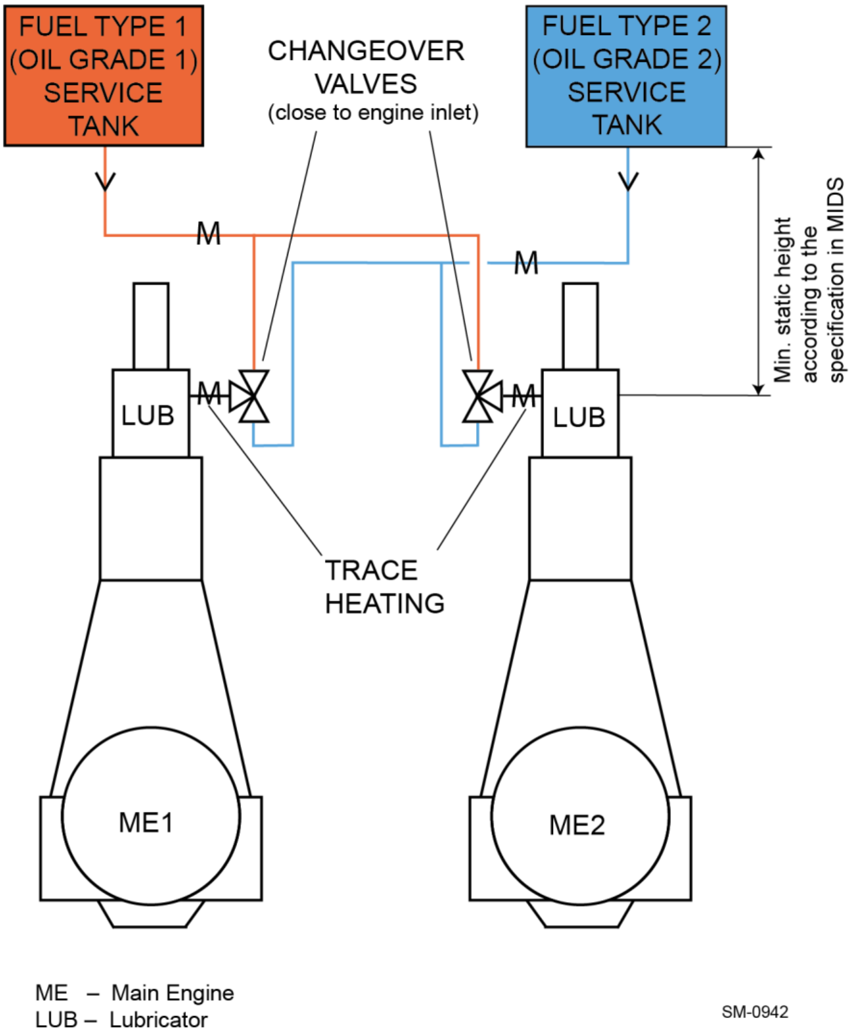

Figure 7-2: Cylinder LO system layout for twin-engine installation

8 Cause and effect of safety measures

This chapter includes the causes and effects of safety measures with focus on ammonia as fuel.

8.1 Key safety measures

- The availability of the X-DF-A engine is based on the ability to change to diesel mode while running on ammonia.
- An active Ammonia Trip (AT) blocks transfer from diesel mode to ammonia.
- A shutdown or emergency stop causes an engine starting interlock in the ECS.
- If the engine has been stopped while using ammonia with emergency shutdown or non-cancellable shutdown (i.e. before re-starting the engine in diesel mode), it is necessary to perform the exhaust gas ventilation sequence using the auxiliary blowers. Due to the system design, the auxiliary blowers are divided from the piston underside with a system border, including flaps allowing only flow from the fresh air side. Therefore, the area where the auxiliary blowers are installed is not required to be classified as an area containing ammonia source. Consequently, the auxiliary blowers are not required to be of the non-sparking type for the X-DF-A engines.
- All engine control panels will be equipped with an emergency AT button.
- The engine starts in diesel mode only.
- Ammonia mode can only be used when the engine is operating in ahead direction.
- Reversing of the engine can only be done in diesel mode.
- In case of the PCS failure, the engine can only be controlled from the Local Display Units (LDUs). Engine operation is only available in diesel mode.

8.2 Combustion control and monitoring functions

8.2.1 Cylinder compression/combustion pressure balancing

When a marked deviation of compression/combustion pressures on a cylinder is detected, the ECS adjusts the exhaust gas valve timing and the amount of ammonia injection to that specific cylinder. If there is no response to the adjustment of the injected ammonia amount within a defined period, the engine automatically trips to diesel mode.

8.2.2 Misfiring detection

When misfiring of one or more cylinders is detected for a defined number of cycles, the engine automatically trips to diesel mode.

8.3 Cause and effect chart for engine malfunctions

The following cause and effect chart of safety measures focuses on engine operation in ammonia mode, and on faults affecting ammonia safety.

Table 8-1: Cause and effect chart in ammonia mode

Fault	Detection	Action
Failure which triggers a trip to diesel mode without activating the request for engine load reduction	Explained in Tables 8.2 – 8.6	AT to diesel mode
Failure which initiates engine load reduction – engine Slowdown (SLD) in ammonia mode (no AT is activated)	Explained in Tables 8.2 – 8.6	SLD in ammonia mode
Failure which triggers a trip to diesel mode and engine load reduction	Explained in Tables 8.2 – 8.6	AT/SLD in diesel mode
Failure which leads to engine Shut Down (SHD)	Explained in Tables 8.2 – 8.6	AT/SHD
Emergency stop command	Explained in Table 5.2	AT/SHD

8.4 Extract of alarm list – only the most critical alarms for gas operation included

The below monitoring tables are grouped per system (ESS, AMS, ECS, FVU) to which the sensor and actuators are connected. Only important alarms and their related actions of those systems are mentioned, i.e. which single failure would trigger an Ammonia Trip (AT), engine Slowdown (SLD) or engine shutdown (SHD) by the connected system. Double failures are not noted in the following tables of this section. Additional requirements from authorities (classification societies and flag states) in charge may apply.

The definition of all alarms and ensuing actions is available in the final engine documentation (Marine Installation Manual (MIM) and Instruction Manual (IM)).

Engine safety is described as interactions between the following systems:

- Engine Safety System (ESS)
- Alarm and Monitoring System (AMS)
- Engine Control System (ECS)
- ammonia Fuel Valve Unit (FVU)
- ammonia Fuel Supply System (FSS)
- Ammonia Detection System (ADS)

The following interaction rules are applied:

Execution of trip to diesel mode by ECS

- Ammonia supply
  - In case of a trip triggered by the ECS, the ammonia FVU control unit and the ammonia supply are automatically stopped by the activation of the Double Block and Bleed (DBB) valves under control of ECS. The piping downstream of the DBB valves, including the engine, is purged by suppling inert gas to the system. This is done by activating the purge valve.
  - Upon completion of the purging procedure, the ammonia injection valves are permanently deactivated.
- Main fuel supply
  - The ECS increases the amount of fuel oil to be injected to prevent load changes.
- Cooling water supply
  - The cooling water flow remains active (pressurised).
- Ammonia servo oil supply
  - The servo oil supply towards the three-way valves of ammonia injectors is deactivated (depressurised).

  - The injector servo-oil supply is deactivated.
    (Three-way valves are in failsafe position (cut-off of one cylinder)
  - Ammonia servo-oil rail is depressurised.
    (In case of all cylinders: AT)
- Cooling oil supply
  - The cooling oil remains active (pressurised).
- Selective Catalytic Reaction (SCR) system for ammonia
  - The SCR system is deactivated.

Execution of trip to diesel mode by ESS

- Ammonia supply
  - In case of a trip triggered by the ESS, the ammonia FVU control unit and the ammonia supply are automatically stopped by the activation of the DBB valves under control of ESS. The piping downstream of the DBB valves, including the engine, is purged by suppling inert gas to the system. This is done by activating the purge valve.
  - Upon completion of the purging procedure, the ammonia injection valves are permanently deactivated.
  - Depending on the failure cause of the AT, additional piping sections are purged and inerted with N_2 (see Table 8-2).
  - After reset of the ESS, the ECS takes back the control of ammonia fuel system.
- Main fuel supply
  - The ECS increases the amount of fuel oil to be injected to prevent load changes.
- Cooling water supply
  - The cooling water flow remains active (pressurised).
- Ammonia servo oil supply
  - The servo oil supply towards the three-way valves of ammonia injectors is deactivated (depressurised) by ESS.
  - The injector servo oil supply is deactivated by ESS.
    (Three-way valves are in failsafe position ((cut-off of one cylinder)
  - Ammonia servo oil rail is depressurised by ESS.
    (In case of all cylinders: AT)
- Cooling oil supply
  - The cooling oil remains active (pressurised)
- SCR system for ammonia
  - The SCR system is deactivated.

Execution of emergency engine shutdown by ESS

- Ammonia supply
  - The ESS stops the ammonia supply by the activation of the DBB valves and master valve.
  - In case of an engine shutdown triggered by the ESS, the ammonia supply is automatically stopped by the activation of the DBB valves and master valve. The piping downstream of the DBB valves, including the engine, is purged by suppling inert gas to the system. This is done by activating the purge valve.
  - Upon completion of the purging procedure, the ammonia injection valves are permanently deactivated.
- Mail fuel supply
  - The ESS depressurises the main fuel rail.
  - The ECS closes the main fuel injectors and sets the fuel pump supply to zero.
- Cooling water supply (control under ESS)
  - The cooling water flow is immediately deactivated (depressurised) by ESS.
- Servo oil supply

  - The servo oil supply is immediately deactivated (depressurised) by ESS.
- Cooling oil supply
  - The cooling oil is immediately deactivated (depressurised) by ESS.
- FVU or FDS
  - The ammonia FVU is deactivated by ESS.
- Ammonia FSS
  - The ammonia FSS is deactivated by ESS.
  - All supply pumps of the ammonia FSS are stopped by ESS.
- SCR system for ammonia
  - The SCR system is deactivated by ESS.
  - All supply pumps of the SCR are stopped by ESS.

Execution of engine Slowdown

- Maximum speed and load are reduced. It is executed by the ECS when demanded via the Remote Control System (RCS)

Table 8-2: Sensors and signals connected to the ESS:
Failure monitoring and actions during ammonia mode

Engine system function	Failure	ALM	SLD	SHD	AT (close DBB combined with master valve)	Automatic shutdown of tank valve	Shutdown of fuel preparation room valve	Automatic shutdown of bunkering valve	Signal to other control /safety systems for additional action
Cylinder cooling water	Cylinder cooling water pressure inlet engine very low	X		X	X				
Main bearing oil	Main bearing oil pressure supply very low	X		X	X				
Thrust bearing oil	Thrust bearing oil temperature outlet very high	X		X	X				
Piston cooling oil	No flow	X		X	X				
Oil mist concentration	Oil mist concentration in crankcase very high	X	X						
Turbocharger oil	Turbocharger #N bearing oil pressure inlet very low	X		X	X				
Air spring air	Exhaust valve air spring air pressure very low	X		X	X				
Engine overspeed	Engine speed very high	X		X	X				
Emergency engine stop buttons	Emergency engine stop requested	X		X	X				
Emergency AT buttons	Emergency AT requested	X			X*1	X	X	X	Stop ammonia fuel supply pumps
ADS	AT due to very high concentration by ADS within annular space (within double-wall pipe)	X			X*1				
	AT due to very high concentration by ADS outside annular space (within surrounding space of pipe)	X			X*1	X	X		Stop ammonia fuel supply pumps
Fire detection system	AT due to fire detection in engine room by fire detection system	X			X*1				
Ammonia supply system (tanks)	Trip due to valve position failures by ammonia FSS	X			X	X	X	X	Stop ammonia fuel supply pumps
FSS (low pressure side)	AT by the FVU system (see supplier documentation)	X			X	X	X		Stop ammonia fuel supply pumps
Ammonia pressure control by the FVU*5	Ammonia temperature too low or too high (high pressure side)	X			X	X	X		Stop ammonia fuel supply pumps
	Temperature measurement failure	X			X				
	Ammonia outlet pressure too low or too high (high pressure side)	X			X	X	X		Stop ammonia fuel supply pumps

Engine system function	Failure	ALM	SLD	SHD	AT (close DBB combined with master valve)	Automatic shutdown of tank valve	Shutdown of fuel preparation room valve	Automatic shutdown of bunkering valve	Signal to other control /safety systems for additional action
(only high pressure side covered, for low pressure side see documentation of the supplier)	Pressure measurement failure	X			X				
Ammonia leakage detection (in drip tray below rail)	Level with drip tray too high	X			X	X	X		Stop ammonia fuel supply pumps
	Level measurement failure	X			X	X	X		Stop ammonia fuel supply pumps
Ventilation within double-wall pipe (engine room and fuel rail)	Annular space underpressure too low	X			X				
	Annular space underpressure measurement fail	X			X				
	Air flow too little	X			X				
	Air flow measurement fail	X			X				
Ventilation within fuel preparation room	Fuel preparation room suction pressure low	X			X		X		
	Fuel preparation room suction pressure measurement fail	X			X		X		
	Air flow too little	X			X		X		
	Air flow measurement fail	X			X		X		
Any valve in wrong position or loss of position feedback (valves, mounted on engine)	Position feedback valve nnn out of order	X			X				
SCR system	AT by the SCR system	X			X				
ECS	AT by ECS (see Table 8-4, Table 8-5)	X			X				

*1 In addition, these ATs trigger a request for inerting.

*2 If applicable, see documentation of the supplier. Additional actions are possible as per definition by the supplier.

Table 8-3: Sensors connected to the AMS:
Failure monitoring and actions during ammonia mode

Engine system function	Failure	Actions			
		ALM	SLD	SHD	AT
Cylinder cooling water	Cylinder cooling water pressure inlet engine low	X	X		
	Cylinder cooling water temperature outlet cylinder #N high	X	X		
Main bearing oil	Main bearing oil pressure supply low	X	X		
	Main bearing oil temperature supply high	X	X		
	Main bearing oil temperature outlet bearing #N high	X	X		
Thrust bearing oil	Thrust bearing oil temperature outlet #N high	X	X		
Crank bearing oil	Crank bearing oil temperature outlet high	X	X		
Crosshead bearing	Crosshead bearing oil temperature outlet #N high	X	X		
Oil mist concentration	Oil mist concentration in crankcase high	X			
	Oil mist concentration fail in crankcase unit	X			
Piston cooling oil	Piston cooling oil temperature outlet cylinder #N high	X	X		
Turbocharger oil	Turbocharger bearing oil pressure inlet low Turbocharger #N	X	X		
	Turbocharger bearing oil temperature outlet high Turbocharger #N	X	X		
Air spring air	Air spring air pressure low	X	X		
	Air spring air pressure high	X			
	Air spring oil leakage level high (exhaust valve)	X			
Exhaust gas (at Turbocharger)	Exhaust gas temperature before Turbocharger #N high	X	X		
	Exhaust gas temperature after Turbocharger #N high	X	X		
Scavenge air	Scavenge air temperature after air cooler #N low	X			
	Scavenge air temperature after air cooler #N high	X	X		
	Scavenge air temperature piston underside cylinder #N high	X	X		
	Charge air condense water detection in air receiver high	X	X		
	Charge air condense water drain detection before water separator #N high	X	X		
SCR system	Alarm by the SCR system	X			

Table 8-4: Sensors and signals connected to the ECS (part 1):
Failure monitoring and actions during ammonia mode

Engine system function	Failure	ALM Minor	ALM Major	SLD	SHD	AT (close DBB combined with master valve)	Automatic shutdown of tank valve	Shutdown of fuel preparation room valve	Automatic shutdown of bunkering valve	Signal to other control /safety systems for additional action
WiCE modules	Module fail Cylinder Control Unit #N		X	X		X				Stop ammonia fuel supply pumps
	Module fail Main Control Unit #1, 2	X				X				Stop ammonia fuel supply pumps
	Module fail Main Control Unit #3 (if applicable)	X								Stop ammonia fuel supply pumps
	Module fail GaTeway Unit #N	X				X				Stop ammonia fuel supply pumps
	Module fail Manual Control Panel local or Engine Control Room	X								
WiCE internal communication	Interruption of ethernet ring #N	X								
Communication to ESS and RCS	Propulsion bus #N fail	X								
	No connection to propulsion control system	X				X				
External AT	External AT	X				X				
Engine speed	Engine speed deviation from reference	X								
	Excessive engine speed		X		X	X				
External power signal	Engine load measurement fail	X								
Load limit	Excessive engine load in ammonia mode	X				X				
Control air	Control air pressure low	X				X				
Auxiliary systems	Auxiliary servo oil pump fail	X								
Servo oil pressure	Servo oil pressure measuring fail #1 or fail #2	X								
	Servo oil pressure measuring high difference	X								
	Servo oil pressure high	X								
	Servo oil pressure very low		X	X		X				

Engine system function	Failure	ALM Minor	ALM Major	SLD	SHD	AT (close DBB combined with master valve)	Automatic shutdown of tank valve	Shutdown of fuel preparation room valve	Automatic shutdown of bunkering valve	Signal to other control /safety systems for additional action
Exhaust gas valve control	Exhaust valve position measuring fail cylinder #N	X								
	Exhaust valve timing fail cylinder #N		X	X		X				
Scavenge air pressure	Scavenge air pressure measuring fail #1 or fail #2	X								
	Scavenge air pressure measuring high difference	X				X				
	Scavenge air pressure very high		X	X		X				
	Exhaust waste gate wrong position	X				X				
	Auxiliary blower #1 fail or #2 fail	X								
	Turbocharger #N speed high	X								
	Turbocharger #N speed very high		X	X		X				

The ALM Minor and ALM Major columns in Table 8-4 and Table 8-5 refer to the failure groups of the ECS. Major failures of the ECS trigger a load reduction in diesel mode SLD or engine SHD. All other failures of the ECS are tagged as minor failure, including the ones triggering a gas trip (GT).

Table 8-5: Sensors connected to the ECS (part 2):
Failure monitoring and actions during ammonia mode

Engine system function	Failure	Actions				
		ALM Minor	ALM Major	SLD	SHD	AT
Cylinder lubrication control	Cylinder lubrication oil pressure measuring fail cylinder #N		X	X		
	Cylinder lubrication oil injection pressure high cylinder #N		X	X		
	Cylinder lubrication oil injection pressure low cylinder #N		X	X		
	Wrong cylinder oil in use	X				
Cylinder balancing	Cylinder pressure measuring fail cylinder #N (max load limitation)	X				
	Cylinder peak pressure very high cylinder #N	X				X
Knock detection	Knock sensor fail cylinder #N	X				
	Both knock detection systems fail cylinder #N	X				X
	Heavy knock cylinder #N	X				X
Misfiring	Misfiring cylinder #N	X				X
	Misfiring detection by pressure sensor fail cylinder #N	X				
	Misfiring detection by Torsional Vibration Monitoring fail	X				X*3
Pilot fuel injection (done by main fuel (oil) injection)	Pilot fuel injector 1 open/short circuit cylinder #N	X				*2
	Pilot fuel injector 2 open/short circuit cylinder #N	X				*2
	Pilot fuel injector 1 and 2 open/short circuit cylinder #N	X				X
Pilot fuel oil pressure control (done by main fuel (oil) pressure control)	Pilot fuel pump control signal failure	X				X
	Pilot fuel inlet pressure measurement fail	X				*1
	Pilot fuel inlet pressure low	X				*1
	Pilot fuel inlet temperature measurement fail	X				X
	Pilot fuel inlet temperature high	X				X
	Pilot fuel rail pressure very low	X				X
	Pilot fuel rail pressure high	X				
	Pilot fuel rail pressure measuring high difference	X				X
	Pilot fuel rail pressure measurement fail #1 or #2	X				
Exhaust gas (after cylinder)	Exhaust gas temperature after cylinder #N high	X				
	Exhaust gas temperature after cylinder #N very high	X	X			
	ECS exhaust gas temperature after cylinder #N too high	X				X
	Exhaust gas temperature after cylinder high deviation	X				
	Exhaust gas temperature after cylinder very high deviation	X	X			
	ECS exhaust gas temperature after cylinder #N too high deviation	X				X

*1 Ammonia interlock in diesel mode
*2 If one pilot fuel injector is out of order at high load, it shows only minor or no effect. At low load possibly trip occurs by unstable combustion. In diesel mode an ammonia interlock is active.
*3 The misfiring detection by Torsional Vibration Monitoring (TVM) is based on the speed and crank angle measurement system. Only if the speed and crank angle cannot be determined, TVM cannot function.

Table 8-6: Sensors and signals connected to the ECS (part 3):
Failure monitoring and actions during ammonia mode

Engine system function	Failure	ALM Minor	ALM Major	Engine SLD	Engine SHD	AT (close DBB combined with master valve)	Automatic shutdown of tank valve	Shutdown of fuel preparation room valve	Automatic shutdown of bunkering valve	Signal to other control /safety systems for additional action
Ammonia injector	Ammonia injector 1 cylinder #N stays open		X	X		X[*4]				
	Ammonia injector 2 cylinder #N stays open		X	X		X[*4]				
	Ammonia injector 3 cylinder #N stays open		X	X		X[*4]				
	Ammonia injector 1 cylinder #N stays closed	X								
	Ammonia injector 2 cylinder #N stays closed	X								
	Ammonia injector 3 cylinder #N stays closed	X								
Cooling water supply to injector	Temperature too high	X				X				
	Temperature measurement failure	X								
	Pressure too low	X				X				
	Pressure measurement failure	X								
Servo oil supply to injector	Temperature too high	X				X				
	Temperature measurement failure	X				X				
	Pressure too low	X				X				
	Pressure measurement failure	X				X				
Piston underside	Ammonia detection pre-warning	X								
	Ammonia detection	X				X				
	Ammonia detection sensor failure	X								
Ammonia sealing	Ammonia injectors sealing Lubricating Oil pressure low	X				X				
	Pressure measurement failure	X								
Ammonia pressure control by the FVU[*5]	Ammonia outlet pressure low or high (high pressure side)	X				X				
	Pressure measurement failure	X								

Engine system function	Failure	ALM Minor	ALM Major	Engine SLD	Engine SHD	AT (close DBB combined with master valve)	Automatic shutdown of tank valve	Shutdown of fuel preparation room valve	Automatic shutdown of bunkering valve	Signal to other control /safety systems for additional action
(only high pressure side covered, for low pressure side see documentation of the supplier)	Ammonia pressure setpoint deviation high	X				X				
	Ammonia temperature low or high (high pressure side)	X								
	Temperature measurement failure	X								
Ventilation within double-wall pipe (engine room and fuel rail)	Annular space underpressure low	X				X				
	Annular space underpressure measurement fail	X				X				
	Air flow little	X				X				
	Air flow measurement fail	X				X				
Ventilation within fuel preparation room	Fuel preparation room suction pressure low	X				X				
	Fuel preparation room suction pressure measurement fail	X				X				
	Air flow little	X				X				
	Air flow measurement fail	X				X				
Any valve in wrong position or loss of position feedback (valves mounted on engine)	Position feedback of valve nnn out of order	X				X				
SCR system	SCR reactor not by-passed	X				X*6				
	SCR communication fail	X				X				
Ammonia control	Any criteria of fuel transfer to ammonia not fulfilled, e.g. pressure stabilization	X				X				
	Any module used for control of ammonia out of order	X				X				
Manual emergency stop	Any emergency stop button pressed	X				X	X	X	X	Stop ammonia fuel supply pumps

*4 AT, ammonia interlock and all fuel cut-out on failed cylinder unit.
*5 See the documentation of the ammonia FVU supplier for other alarms and trips to diesel mode.
*6 Unless a redundant monitoring of SCR exhaust valves via ESS is available.

9 References

- Marine Installation Drawing Set (MIDS) including the Concept Guidance for the X-DF-A
- Marine Installation Manual (MIM)