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Executive summary

Starting with a definition of the scope and the boundaries of the considered machinery plant, the main components for the necessary systems were described. Of particular note is the change to distillate fuel, with all its advantages for the operation, maintenance and the environment (compared to heavy fuel oil with higher sulfur contents).

Based on an analysis of technical failures in the systems, their criticality was analyzed and the possibility of operation with faulty system was described.

From these investigations, necessary measures and the scope of redesign were derived. Finally the contents of the specification document were discussed with experts. This validation of the concept was carried out with experienced technical officers and professors.

List of abbreviations

ABS	Autonomous Bridge System
AE	Auxiliary engine
AEMC	Autonomous Engine Monitoring and Control
CBM	Condition-based maintenance
CO2	Carbon Dioxide
Cyl.	Cylinder
ECA	Emission Control Area
GenSet	Generator Set
GenkW	Generator Output (Kilowatt)
HFO	Heavy Fuel Oil
LNG	Liquefied Natural Gas
LO	Lubrication Oil
ME	Main engine
NOx	Nitrogen Dioxide
EGT	Exhaust Gas Turbocharger
UMS	Unattended Machinery Spaces
SAS	Ship Automation System
SCC	Shore Control Center
SECA	Sulphur Emission Control Area
SSDG	Ship’s Service Diesel Generator
WMC	Water Mist Catcher

Table of contents

1. Introduction

1.1 Scope

Of special interest for this investigation was the unmanned engine operation under opensea conditions. The machinery plant includes the engine room, stern tube, propeller, rudder, steering gear and casing with smokestack.

The main propulsion engine is a two-stroke low speed turbocharged crosshead Diesel engine with a directly coupled fixed pitch propeller. Auxiliary engines (three Diesel generator sets) and other necessary systems are included.

The technical failures in the main system groups are the basis of the analysis of the possibility of operation with faulty systems.

Another point is the interaction in terms of maintenance, requirements and possible solutions.

Main focus of the report is the analysis of the derived measures, additional redundancies and monitoring and control possibilities, ending in the scope of redesign and evaluation by experts.

1.2 Structure of report

The system boundaries of monitoring and control and the scope of the unmanned machinery plant were defined for a bulk carrier. Based on this, the main components used in the involved systems are described and the analysis of technical failures is done. The possibilities of operation with faulty systems are described and information about the necessary systems in emergency operation are given. Based on the failure analysis and the system definition, additional measures, redundancies and monitoring systems are derived. In relation to the created open sea failure scenarios, the engine operation is described. In summary, the scope of redesign is described and a technical discussion with experts was done to validate the results.

2. System boundaries of monitoring and control /1/

The Autonomous Engine Monitoring and Control (AEMC) system is part of the autonomous extensions for an unmanned vessel. The AEMC is used to control the engine related parts of the ship. The other autonomous controller is the Autonomous Bridge System (ABS) controller. Basically, the AEMC is set on top of the Ship Automation System (SAS) and uses an interface to get the measuring values and status from the SAS. A second purpose of the AEMC is getting control commands from other systems e.g. the ABS and forwarding them to the ship automation system.

The AEMC controls the systems for machinery operation. The first system is the main engine and the associated system for lubrication oil and cooling water. Starting and stopping of the main engine is controlled by superior instances which have the knowledge about the navigation and the course of the ship. This can be the ABS, the shore side control centre (SCC) or a crew on board. These instances will target values for the propulsion system as well. For example, the rudder angle or the propeller speed is one of these values. The propulsion system itself is controlled by the AEMC. Another fully controlled part of the AEMC is the power generation. This includes the auxiliary engines, the generator and the support systems like lubrication oil, fuel system and cooling system. The bilge system and the steam system are generally under control of the AEMC. The fuel system is basically handled by the AEMC but the calculation and the start of bunkering is done by the bridge.

Some systems are partly under control of the AEMC. An example is the alarm management system. The AEMC only handles the engine related alarms und reacts on raising alarms. The ballast water system is in general not part of the AEMC, but the AEMC will provide an interface for the bridge to control the ballast water system. So the AEMC gets commands on how much water is to be pumped to the ballast tanks and will directly forward these commands to the ship automation system.

The following systems are not related with the AEMC: cargo management, navigation, manoeuvring, fire fighting, air condition system, aviation system, thruster control including a pump jet and external communication. These systems are generally controlled by the ABS.

3. Scope of machinery plant

In this chapter, the scope of the machinery plant of our project bulk carrier is to be defined and described. This plant is controlled and monitored by the “Autonomous Engine Control and Monitoring System”.

Bulk carriers transport dry cargoes (e.g. grain, coal, ore) in a number of holds with double bottoms and single sideskins. Sloping angled tanks for water ballast are located at both the top and the bottom of the vertical sides (topside and hopper tanks). Additionally, some holds are capable of taking water ballast.

The basis of our project of an unmanned ship engine operation (unattended machinery plant rooms) on board of a bulk carrier is the most commonly installed main propulsion plant with a two-stroke low speed turbocharged crosshead Diesel engine with a directly coupled fixed pitch propeller.

Regarding the premises, the machinery plant includes the engine room, stern tube, propeller, rudder, steering gear and casing with smokestack, see fig. 1 and 2, /2/.

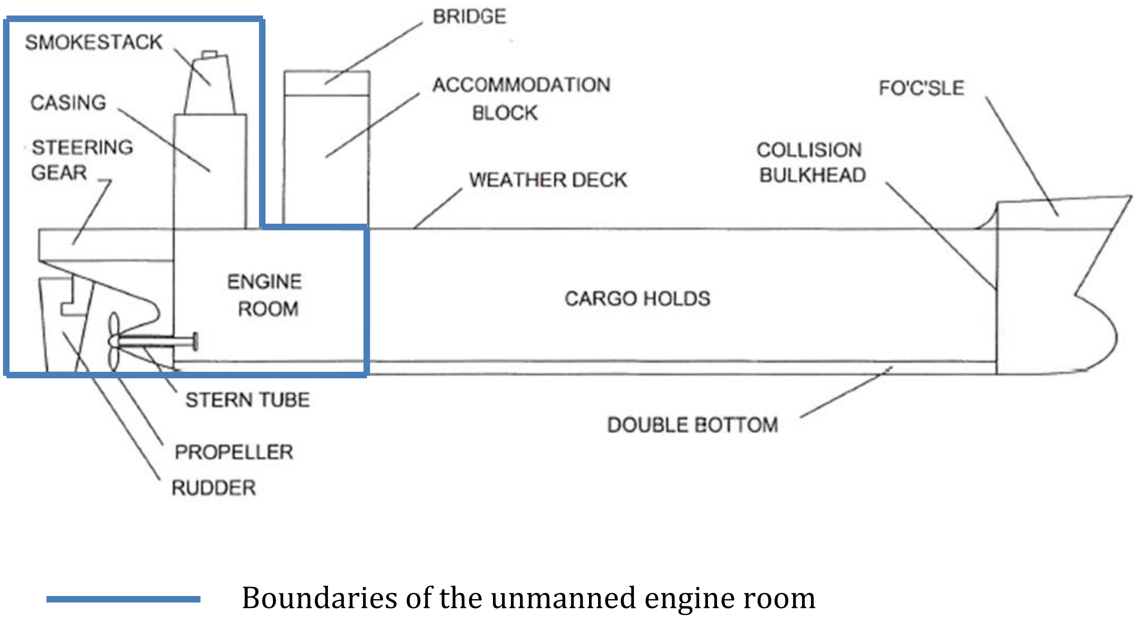


Figure 1 – Schematic arrangement of a merchant ship

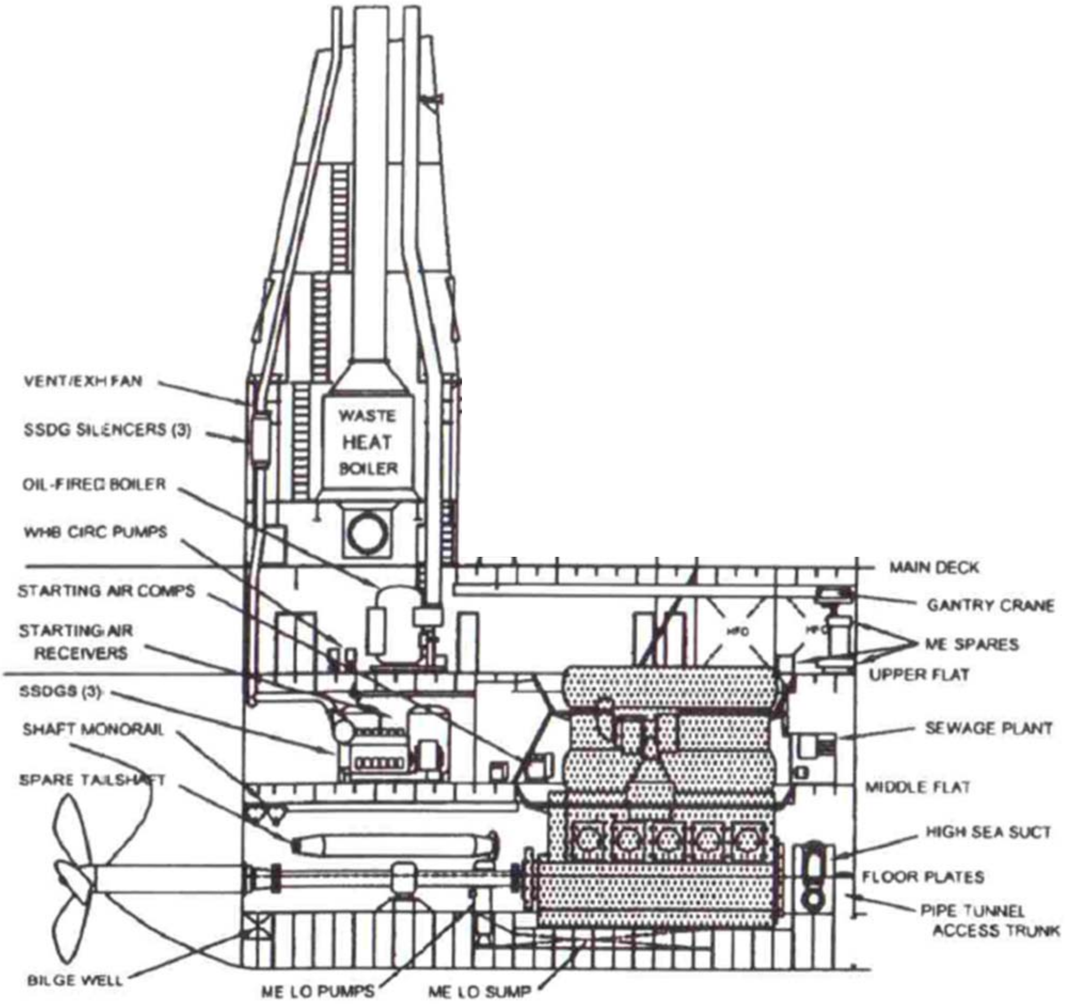


Figure 2 – Machinery arrangement for a low speed main propulsion plant /2/

In addition to the used components and the supply systems of the propulsion plant, other important auxiliary machinery and systems must be included.

In the next chapter these systems are described in more detail.

4. List of components used in the systems

4.1 Main engine with supply systems

Fuel oil system

In the MUNIN project, the unmanned engine operation is designed for the open sea voyage. Under these conditions the ships use normally Heavy Fuel Oil (HFO) and only in emission restricted areas it’s necessary to use Diesel oil or special exhaust gas treatment plants.

Derived from it, we consider the HFO system under these specific boundary conditions.

Today, the ships bunker “dirty” HFO and the fuel oil cleaning and treatment must be on board.

The system must enable a safe operation. An important step for safe operation is a simple system. Therefore, it would be obvious to use already purified HFO for bunkering and storage on board.

For operation in Emission Control Areas (ECAs) and the fulfillment of special regulations, the project ship would have to be equipped with an additional distillate supply system. HFO and distillate would be for use in main engine and auxiliary engines. Because of incompatibilities concerning the chemical composition and the thermal behavior, a mixing or a changeover between HFO and distillate contains a big unpredictable risk.

That causes, for example, the formation of adhesive solids (clogged filters and pipes) or thermal shocks (parts of the injection system are blocked). Both processes finally lead to the total failure of the engines.

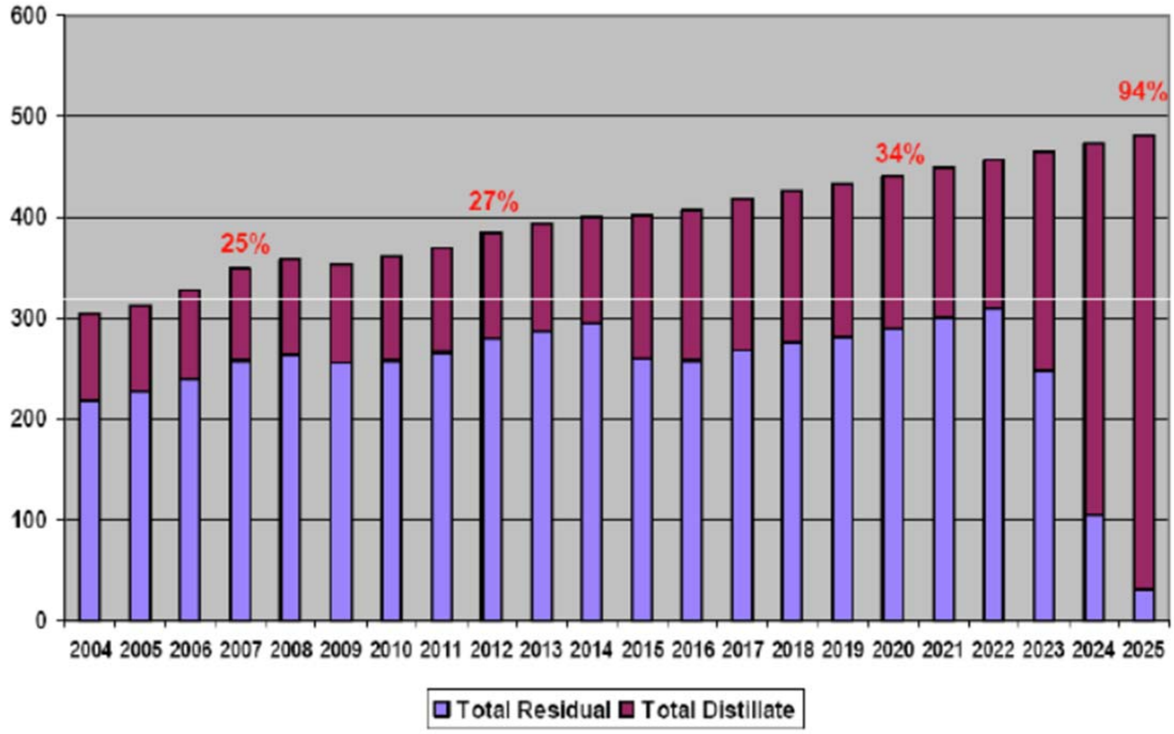
Under the boundary condition that the ship operates in Emission Control Areas during the sea voyage, a changeover between the fuel oil types is necessary. It is also necessary to enable a changeover between storage tanks with HFO of different origins during the voyage, followed by the already described mixing problems.

All these risks are too high for an autonomous operation.

Therefore, the technically best and simplest solution is a distillate fuel oil system without mixing and thermal problems and without expensive purifying, heating and treatment necessities.

The fuel prices and construction costs are not considered, but it is likely that the predicted availability of distillates in relation to the residuals will increase, (see table 1 /3/), while construction costs will decrease.

Table 1 – Availability of fuel oils



Basically, the system is designed as follows. For such a system, we need storage tanks, settling tanks and service tanks.

The fuel oil is normally stored in bottom tanks and in side tanks. The tanks have to be provided with equipment for checking the amount of oil in the tanks. A transfer pump sucks fuel oil through a coarse filter and feeds it to one of two settling tanks. Both settling tanks must be large enough to contain fuel oil for at least 12h of engine operation at full load. While one settling tank is operated, the other tank is in stand-by mode. The stand-by mode allows water and other heavier impurities to settle. After draining of sludge and water, the fuel oil is pumped to the respective service tanks (each for 12h of full load operation). From service tanks the fuel flows to the auxiliary engines and to the electrically driven supply pump (second pump on stand-by) of the main engine. This supply pumps replenish the consumption in the fuel circulating system. The circulating and injection system must be adapted by the engine builder on operation with distillate fuel. The construction expense will probably decrease because of the easier fuel oil system with distillate fuel. An automatic full flow filter has to be installed before the injection pumps.

Common rail system

The internal engine injection system will be run as a common rail system. This means that in these systems a cylinder-specific fuel injection rate shaping, rate control and single cylinder switch off is possible. For the distillate fuel system a completely new layout and redesign is required.

Both leading manufacturers of two-stroke crosshead engines (MAN-BW and Wärtsilä) have their own common rail system.

At MAN-BW ME type engines needs a hydraulic high pressure unit that supplies high pressure lubrication oil for driving the fuel pumps and the operation of the exhaust valves. This servo oil is taken from the main lubrication oil system via an automatic fine filter. The discharge lines of the servo oil system lead back to the lube oil discharge tank of the main engine. The high pressure fuel injection pumps are driven by the high pressure servo oil, as well as the plunger pumps of the exhaust valves.

They are driven by electronic inputs from the cylinder control units.

Figure 3 shows the schematic diagram for drive and controls of the high pressure pumps and exhaust valve of two-stroke crosshead MAN-BW ME engines.

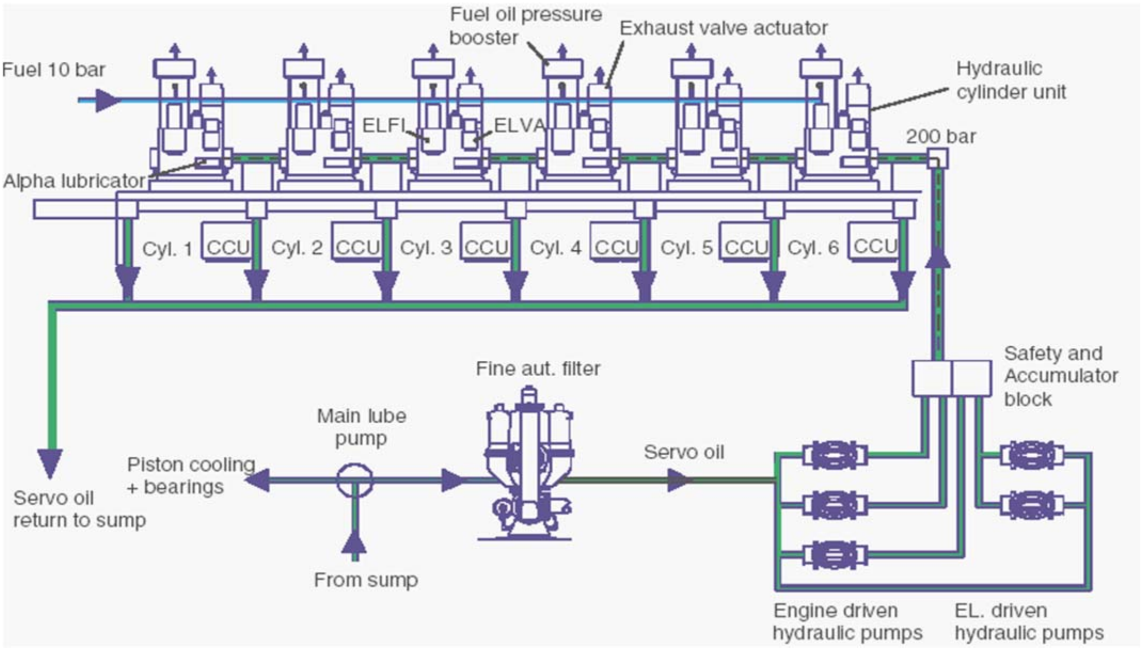


Figure 3 – Schematic diagram for MAN-BW ME hydraulic system/4/

The cylinder lubrication is incorporated in the electronic control units.

At Wärtsilä RT-FLEX common rail systems, a crank shaft driven high pressure pumps unit delivers the fuel to the common rail. The engine management system (Wärtsilä Engine Control System, WECS) controls the supply, tuned to the requirements, of the fuel from the common rail to the injectors. The control unit is electronically driven (by a WECS) and hydraulically operated by a high pressure lubrication oil system. The pressure is supplied by a separate pump system.

In addition to regulating the fuel injection, the system also controls the opening and closing of exhaust and start air valves. It is possible to control and adjust all valves individually.

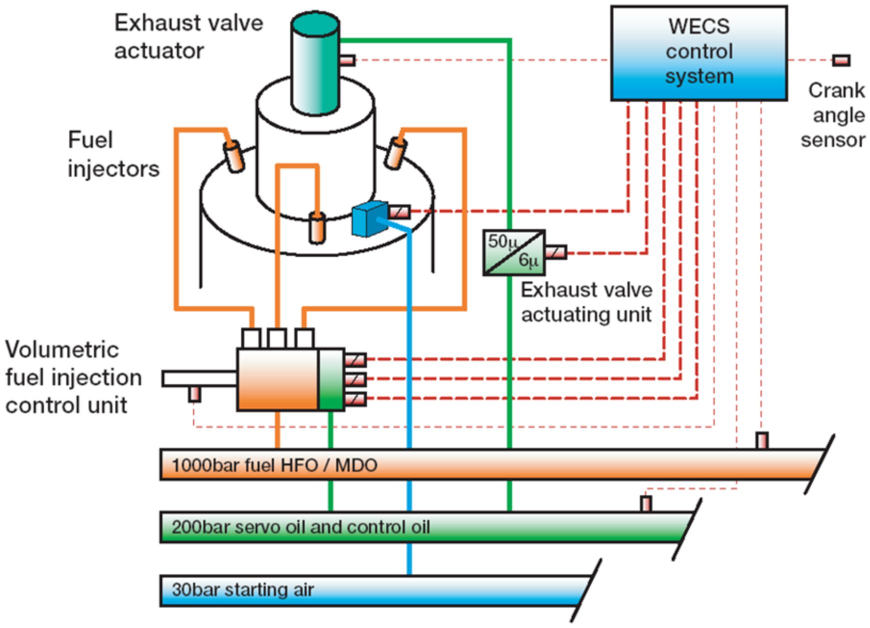


Figure 4 – Schematic diagram for Wärtsilä RT-Flex common rail system /5/

Also for the auxiliary engines common rail systems are available.

For example, by eliminating the necessary heating systems for operation with heavy fuel oil, the fuel oil injection system, based on distillate, will be simplified compared to the current heavy fuel oil systems.

Lubrication oil system

The lubrication oil system of two-stroke crosshead engines consists of three separate systems:

a) Lubrication of crankshaft, crosshead with guides, thrust block, drive gear and piston cooling.

b) Cylinder lubrication with the use of special cylinder lubrication oil. It is a completely separate system for the lubrication of pistons, piston rings and cylinder liner. The tribological system of piston/piston ring/cylinder liner on a two-stroke crosshead engine is lubricated with oil via separate injection pumps.

c) Oil system for controlling the exhaust valves and fuel pumps (see description of common rail systems). This system uses the same lubrication oil as the system in point a).

Figure 5 illustrates the lubrication oil system of a MAN B&W ME engine.

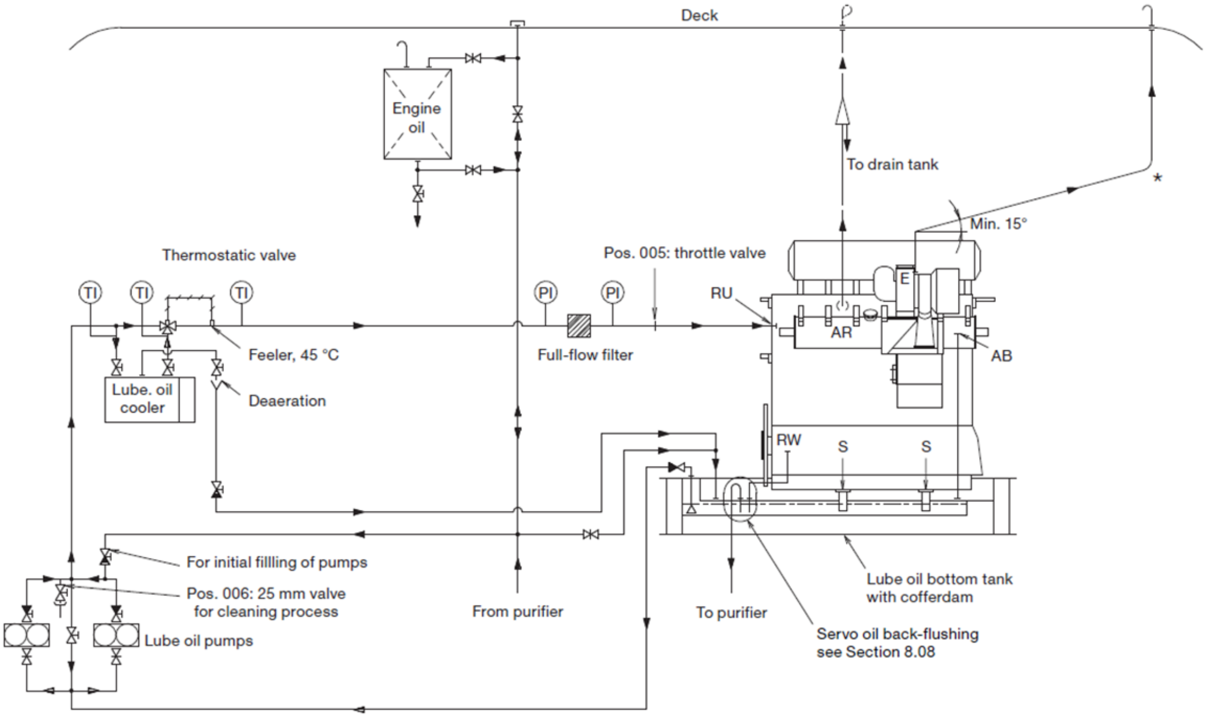


Figure 5 – Lubricating oil system of ME /6/

Due to the partition between the scavenging-air space and the crank case by the bottom of the cylinder frame with piston rod stuffing box, it is ensured that the contaminated cylinder oil (that leaks down from piston and cylinder liner) cannot enter the crank case. The lubrication oil in the crank case remains very clean and is additionally cleaned with a separator and an automatic fine filter.

Figure 6 shows an example for a current electronically controlled cylinder lubrication system.

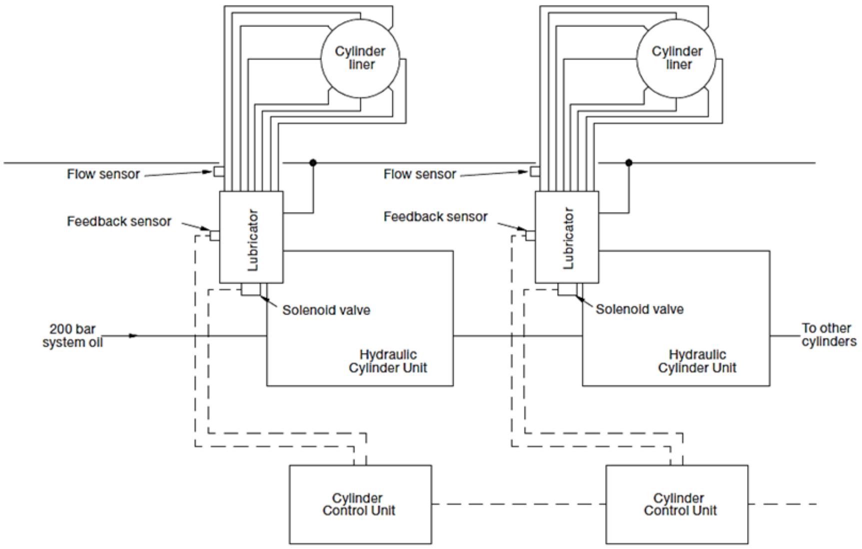


Figure 6 – Cylinder lubrication with Alpha lubricator for ME /6/

Cylinder oil is pumped from the cylinder oil storage tank to the service tank. For our use, this tank is dimensioned for a minimum 10 day cylinder oil consumption. It is possible to have only one tank if the capacity is higher. The whole system is controlled by the cylinder control units. They calculate the injection frequency, based on engine speed and fuel index.

The cylinder lubrication system of Wärtsilä is electronically controlled too.

Cooling water system

The following figure shows a modern cooling water system with a short seawater section. It is a central cooling water system for a two-stroke crosshead main engine.

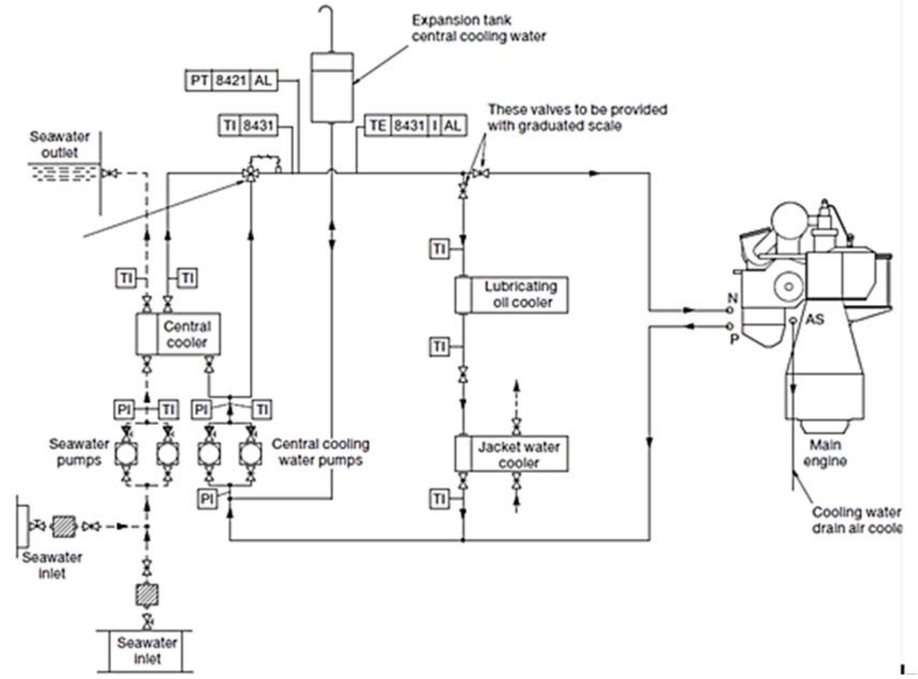


Figure 7 – Central cooling water system /6/

From the seawater inlet (high or low) to the outlet, the seawater passes two seawater pumps and the central cooler. In the fresh water circulation system, two pumps deliver the water to the central cooler, the air cooler unit, the lubrication oil cooler and jacket water cooler which are arranged in a parallel manner. The jacket cooling water is used to cool the cylinder liners, cylinder covers and exhaust valves of the main engine. The outlet temperature of the engine is controlled thermostatically. The jacket cooling water must be treated carefully. It must be possible to preheat the main engine jacket cooling water.

Control and starting air system (see fig. 8.)

Controlling the starting in electronically controlled engines (MAN B&W ME and Wärtsilä Flex) is simple. It is electronically activated (see common rail systems).

Two automatically operating compressors keep the air pressure in the starting air receivers (30bar) to directly deliver it to the main engine in order to start it. After the pressure was reduced in a reduction unit, the compressed air (reduced pressure) is supplied as control air (maneuvering air, safety system air).

Starting air and control air for the auxiliary engines are supplied from the same starting air receivers, if necessary via the reduction valves.

An emergency compressor and a starting air bottle are installed. They enable an emergency start of the auxiliary engines.

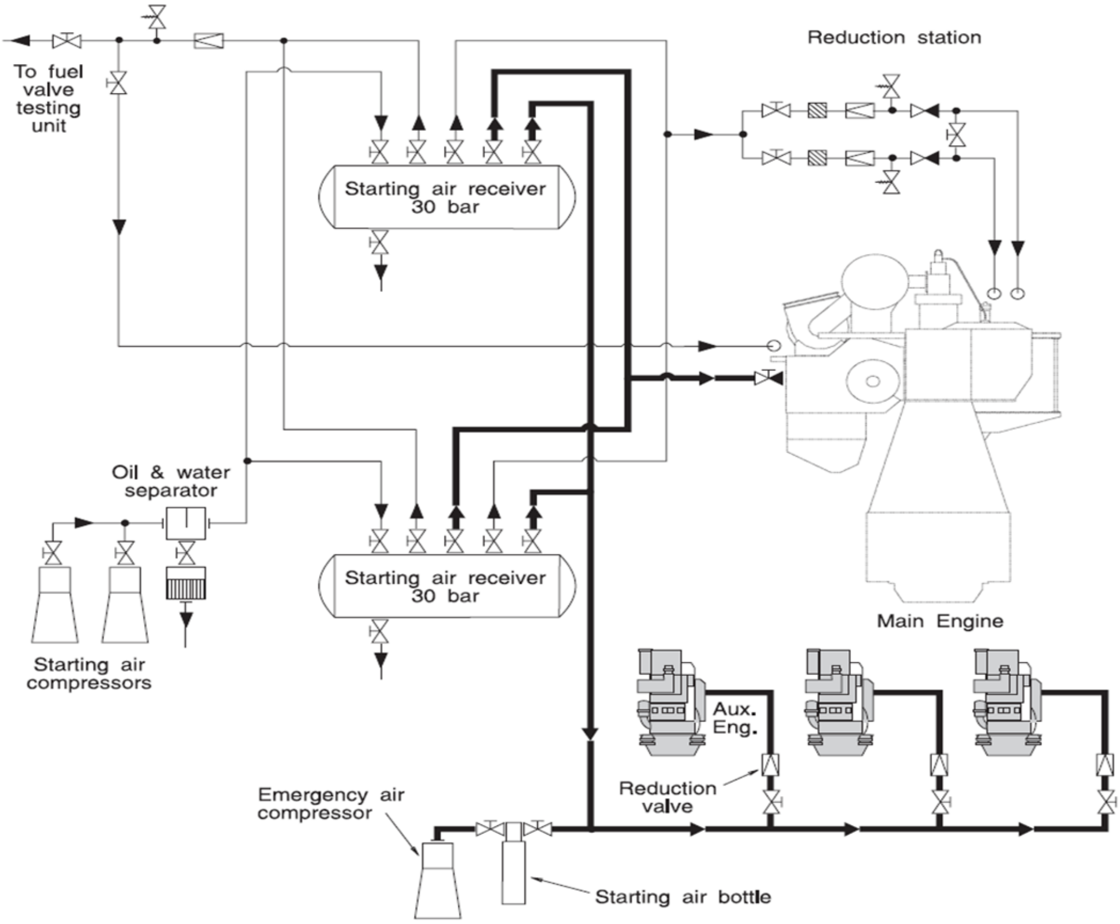


Figure 8 – Starting air system of the main engine and the auxiliary engines /6/

It is possible to extend the described cooling water system for the main engine to a common system with the auxiliary engines. This solution would to be preferred and is described in chapter 4.2.

Waste-heat recovery and steam generation system

The following figure shows a scheme of a heat recovery system for large two-stroke crosshead engines /5/.

In this system exhaust gas energy can be recovered and used in a steam turbine and in an exhaust gas turbine to generate electrical power for additional ship propulsion (through a shaft motor) and/or shipboard services.

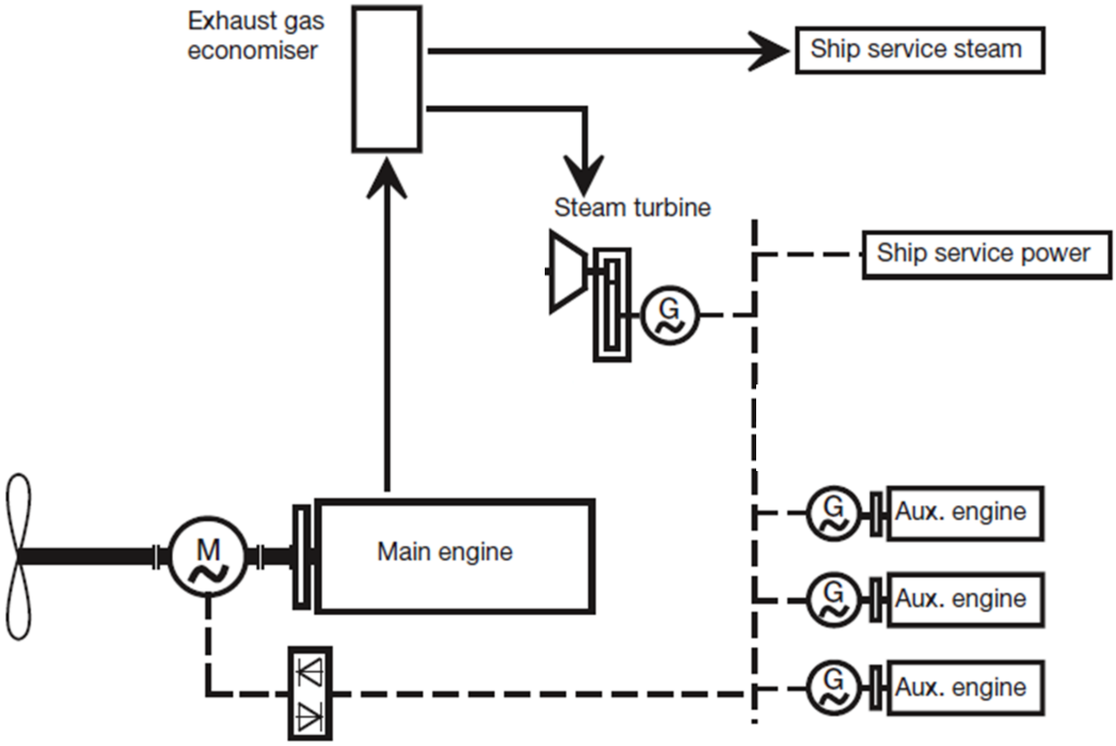


Figure 9 – Schematic of the Total Heat Recovery Plant /7/

4.2 Auxiliary engines with supply systems

The auxiliary engine system shall consist of three Diesel generator sets. Each of this GenSets has enough electrical output, which is sufficient for the electric energy consumption of the ship. Therefore, here is a high level of redundancy. The GenSets deliver their energy, as does the heat recovery system, via the main switch board power distribution.

Boundary conditions for the energy requirements are the following:

- During the open sea voyage enough electrical power is supplied by waste heat recovery unit (steam turbine),
- During the operation in the port, no additional power is needed,
- During open sea operation one GenSet with roughly 1000 Gen kW (60% load optimized) is sufficient,
- During maneuvering one GenSet with roughly 1800-2000 Gen kW is sufficient.

The supply system for the auxiliary engines consists of their own fuel oil and lubrication oil system. The other supply systems (cooling water, starting air) shall be integrated in a common auxiliary system for the two-stroke crosshead main engine and the four-stroke auxiliary engines.

Central cooling system

The common central cooling system has additional pumps to support the auxiliary engines operation in port.

The low and high temperature systems are directly connected for preheating the main and auxiliary engines during standstill.

For the whole freshwater system (low and high temperature), only one expansion and one deaeration tank are necessary. Between the tanks an alarm device is installed, which gives signals if excess gas (air) can be found in the cooling water. This may be the result of damages of the engine or system components.

The seawater cooling pump circulates the seawater from the sea chest through the central cooler to the seawater outlet valve. The central cooler freshwater pump directly circulates the low temperature freshwater through the lubrication oil coolers of the main engine, the scavenge air coolers and the auxiliary engines.

The auxiliary engine jacket water cooling system has engine-driven pumps and is integrated in the low temperature system (by-pass). The main engine jacket water cooling system is an independent pump circuit.

During operation in port with a stopped main engine, a small central cooling water pump (port pump for aux. engines) circulates the necessary flow of water through the auxiliary engines (air coolers, lubricating oil cooler, jacket cooler). A preheating of the stopped main engine and the stopped auxiliary engines must be possible.

The common central cooling system is shown in figure 10.

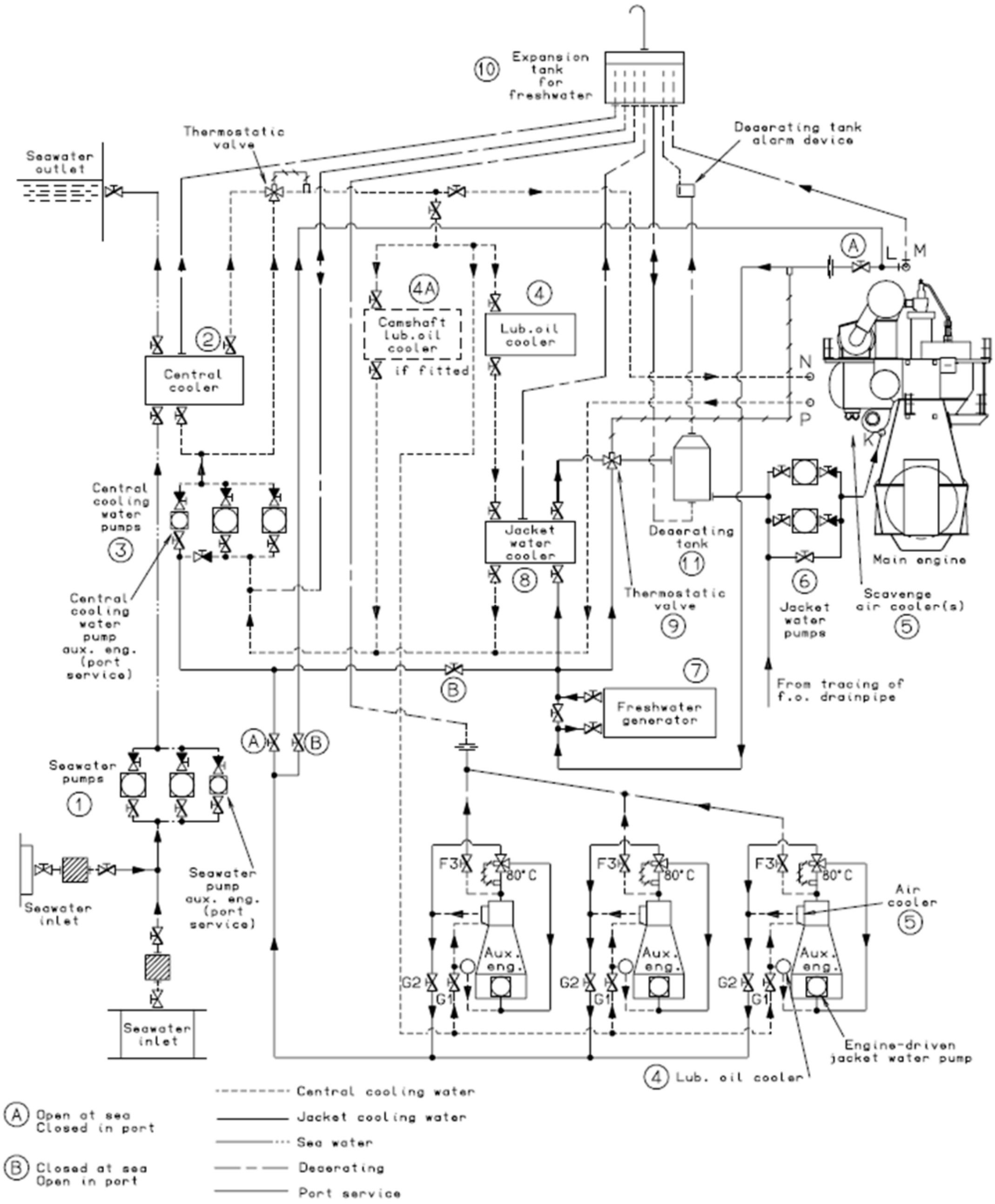


Figure 10 – Common central cooling system /8/

Starting air system

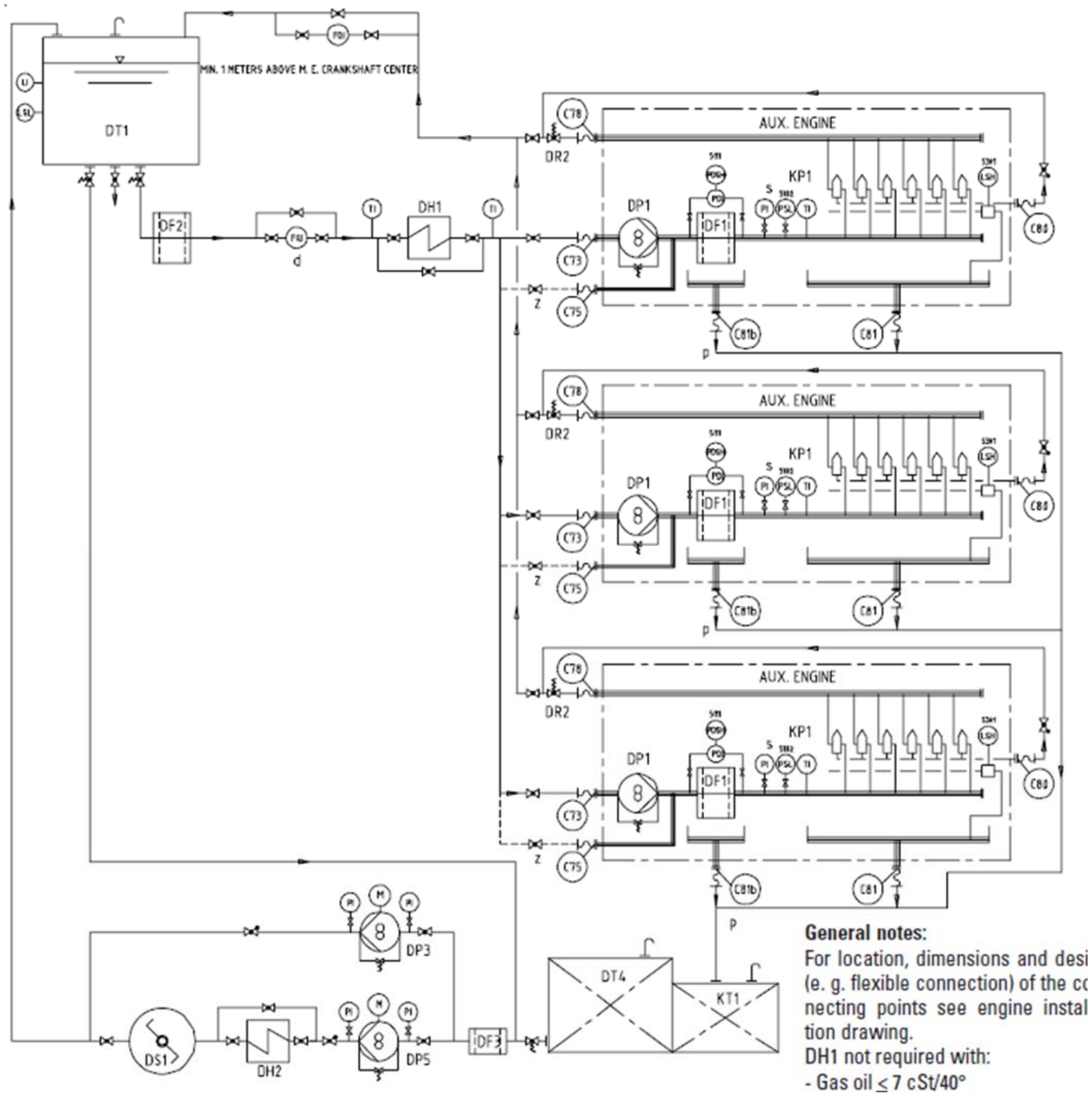
The starting air system builds a common system with the main engine. It is described in chapter 4.1.

Fuel oil system

The fuel oil system for the three auxiliary engines consists of a common part and the single components for each engine.

The common system includes the line from the storage tank, a separator unit with electrical preheater to the day tank. From the day tank the distillate fuel flows through the primary filter and the preheater to each auxiliary engine. There, the own engine systems with feed pump and fine filter continue the circulation. Also the drip system with drip tank is common for all three engines.

Figure 11 shows a fuel oil system for a medium speed Diesel engine.



General notes:
For location, dimensions and desi
(e. g. flexible connection) of the co
necting points see engine instal
tion drawing.
DH1 not required with:
- Gas oil ≤ 7 cSt/40°

Figure 11 – Fuel oil system for medium speed Diesel engine/9/

Lubrication oil system

The lubrication oil system of the auxiliary engine plant (three GenSets) /MAK/ is shown in fig. 12. Each engine has its own sump tank, pre-lubrication pump, forced circulation pump, filter and cooler. The lubrication oil systems of the engines are connected to one another via filling and drain pipes. This pipe system is also connected to one common separator, which cleans the lubrication oil of the auxiliary engine plant.

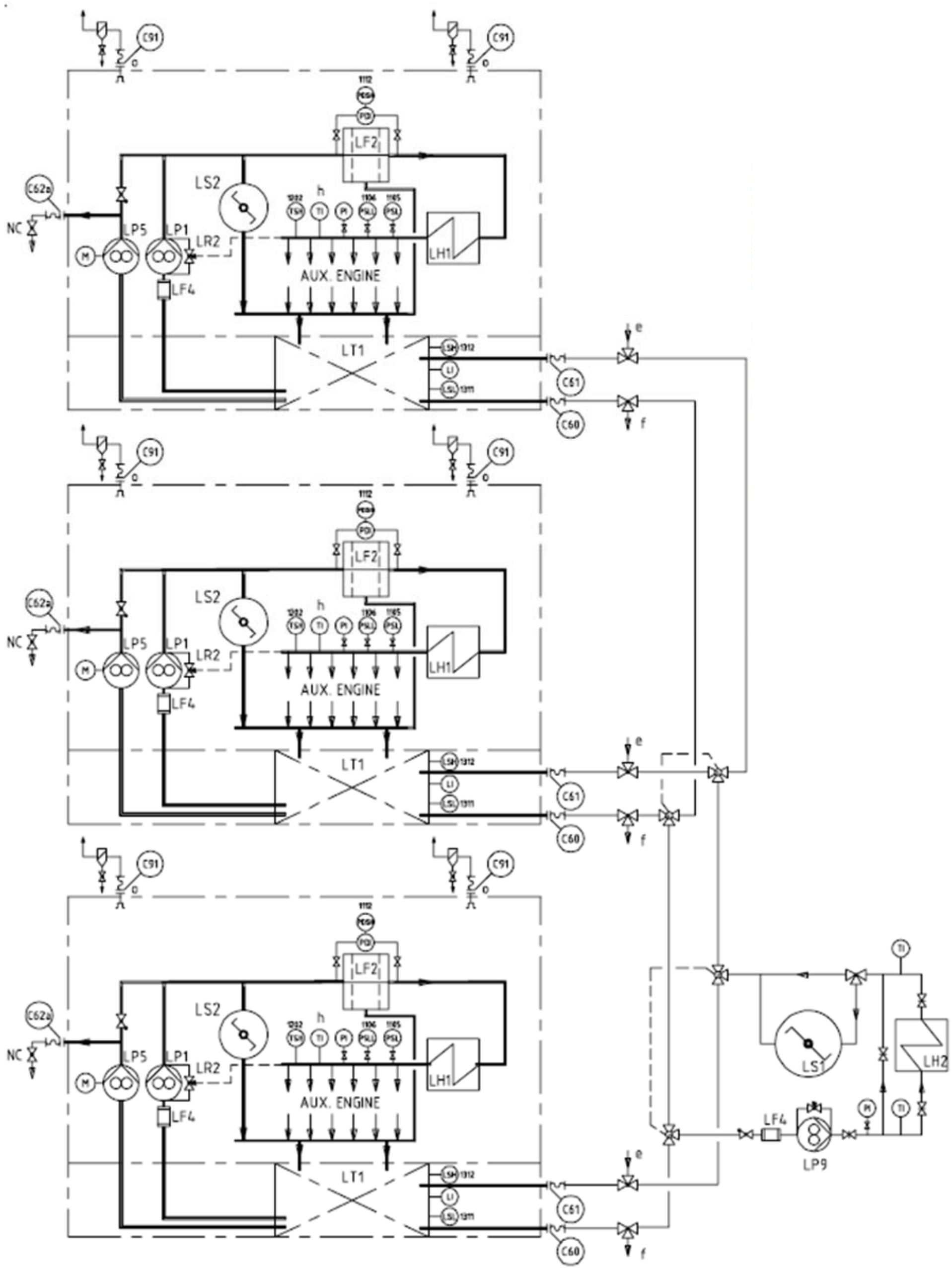


Figure 12 – Lubricating oil system for medium speed engine/9/

4.3 Propulsion, rudder, steering gear

Figure 13 shows a propulsion plant with main engine, shafting with bearings, stern tube, fixed pitch propeller and the rudder with steering gear.

The aftmost shaft after the intermediate shafts is the propeller shaft. It runs through a stern tube, which is provided with bearings and stuffing boxes. The propeller is mounted at the end of the propeller shaft. Behind it the rudder is attached. It can be turned by using the steering gear.

The ship must be provided with an efficient main steering gear and an auxiliary steering gear.

Main types of steering gears are the following:

- Fully hydraulic type
- Electro-hydraulic type
- Fully electric type

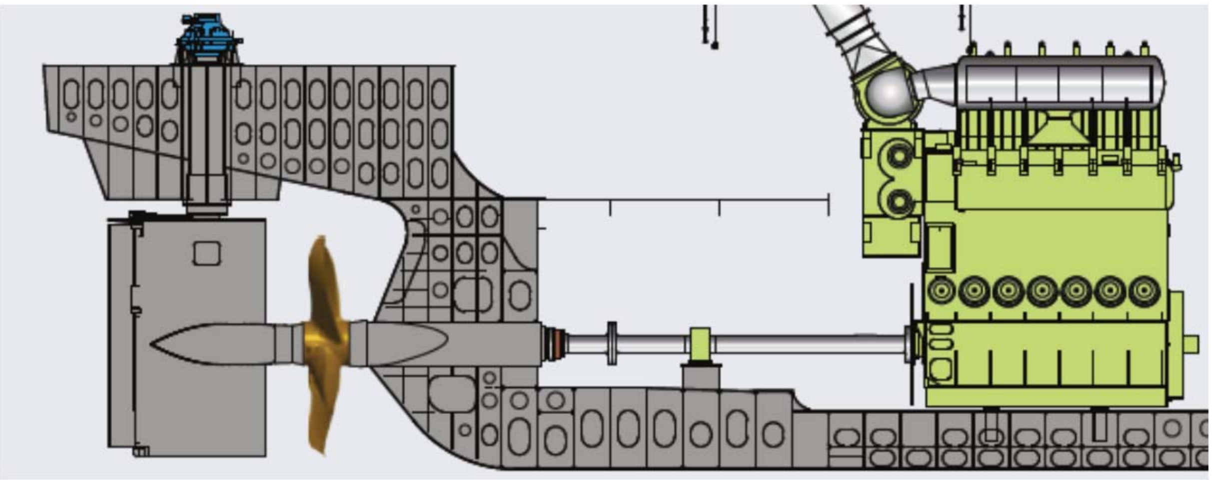


Figure 13 – Propulsion plant /10/

4.4 Bilge and ballast system

The following figures show two systems as an example. Figure 14 shows a system for clean bilge and ballast /2/ and figure 15 shows a system for oily machinery space bilges /2/.

The bilge and ballast systems must make it possible to empty every compartment in the ship. The ballast system is connected to all spaces within the ship to, which ballast water can be supplied. The bilge system is connected to gutters in the holds etc.

In principle, a ballast pump is used to suck water from the ballast valve chest. A bilge pump is used to suck water from a bilge valve chest.

For oil-contaminated water it is necessary to use a water–oil separator to prevent oil pollution of the sea. An example for such a system is the bilge system for machinery spaces.

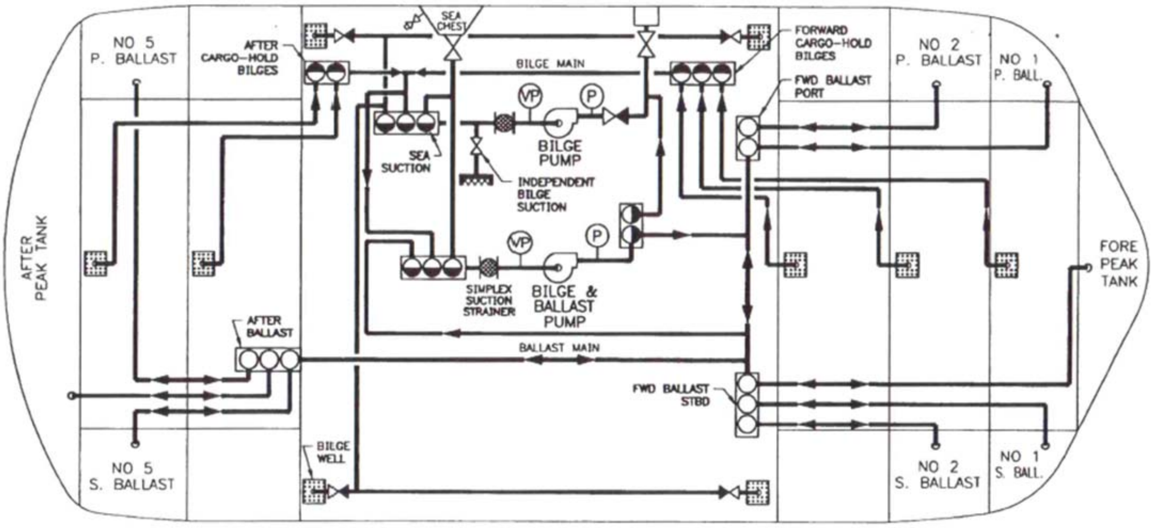


Figure 14 – Clean bilge and ballast system /2/

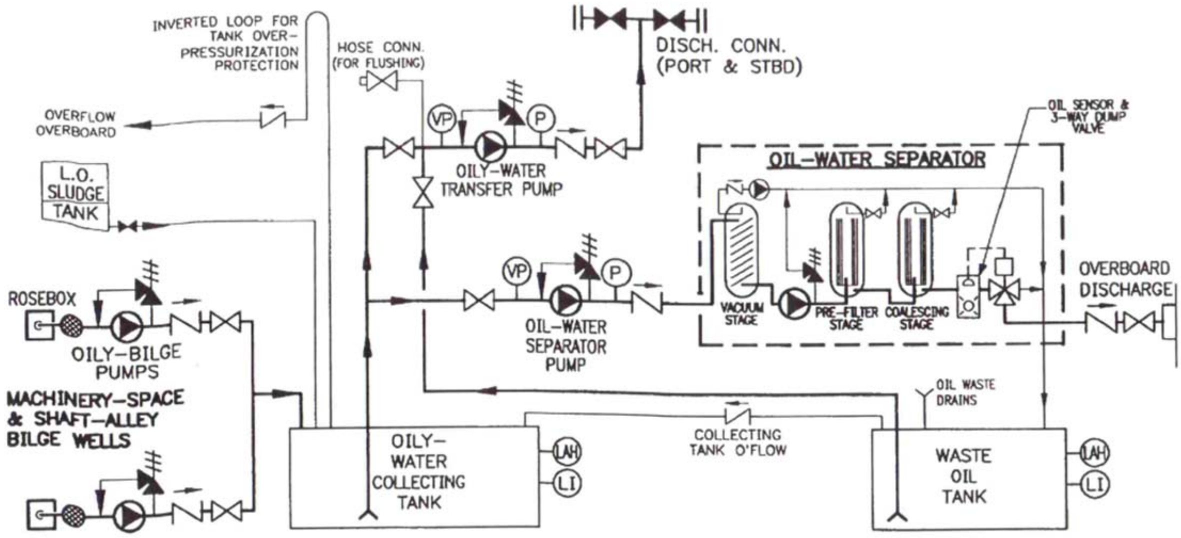


Figure 15 – Bilge system for oily bilges in machinery spaces /2/

4.5 Fire main system

A ship's main emergency fire system consists of a specific number of fire hydrants, which are located at strategic positions across the ship. A series of dedicated pumps are provided to supply these fire hydrants.

All these pumps are supplied with power from the main power system. Apart from that, an emergency fire pump is provided. This pump is located remote from the machinery space. The pumps are connected to the main seawater connection.

Other possibilities to extinguish fires, such as foam, dry-powder and CO2 fire extinguishers, must be installed too. If needed, they shall be used by the boarding crew. Further to be installed is the possibility to extinguish a fire by filling spaces with inert gas. This system must be automized or shore base controlled. Figure 16 shows an example of a fire main system with seawater.

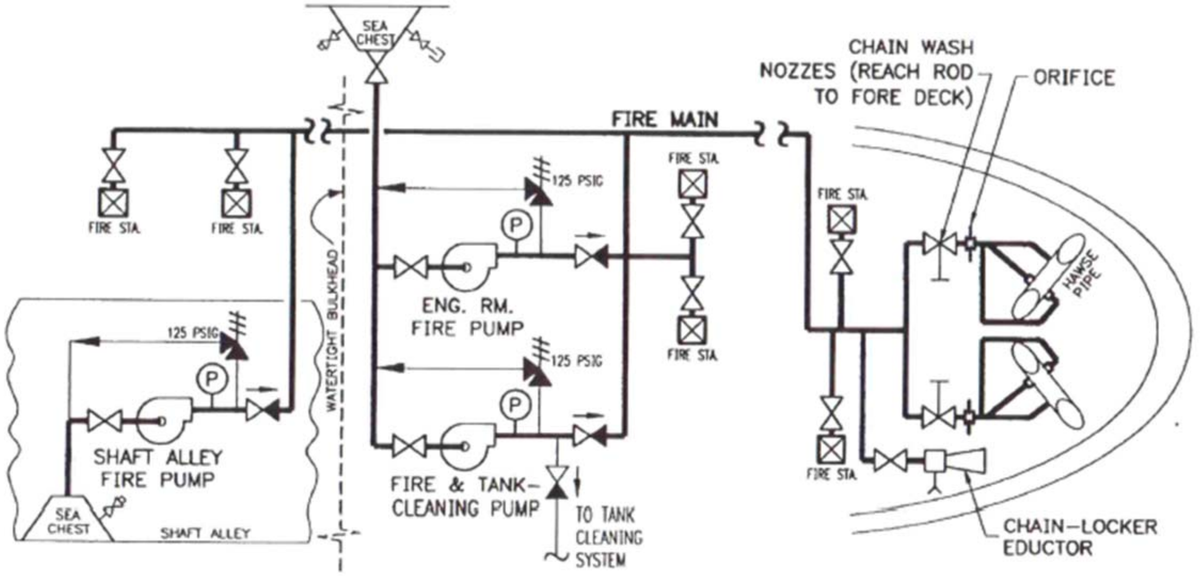


Figure 16 – Fire main system /2/

5. Technical failures in the system groups

The basis of the analysis and evaluation of technical failures in the main system groups of ship machinery plants is the “Annual Report 2011” of the BG Traffic, ship safety department /11/. In the report 2010/2011, technical failures at national and international seagoing vessels in German waters were analyzed and evaluated.

These flag-independent results demonstrated that the main system groups – main engine, fuel oil system, cooling water system, electrical system and rudder plant – were the most frequently affected groups.

Table 2 - Technical failures in the system groups /11/

Main engine	37.3%
Fuel oil system	15.5%
Cooling water system	13.6%
Electrical plant	12.7%
Rudder plant	11.8%
Propulsion plant, shafting	5.5%
Diesel generator	3.6%

Almost half of all failures of the main engine are caused by start, reverse and control devices. It is possible that the causes lie in the improper maintenance of these complex systems which combine electrics, electronics, pneumatics and mechanics. Approx. one-third of all failures are standard failures, e.g. faulty inlet/outlet valves, sticking injection pump, cracked or leaking cylinder covers, cracked cylinder liners, broken or leaking injection pipes etc. Other malfunctions are caused by total failures of Exhaust Gas Turbochargers (EGT).

The malfunctions that occur in the fuel oil system often cause total failures of main engines or Diesel generators. About half of the failures are caused by the incompatibility of mixing fuel oils.

The autonomous ship can prevent these problems from occurring because it does not use fuels of different qualities.

The failures occurring in the cooling water system include cooling water pumps, piping, high temperature controllers and sensors as well as low temperature and seawater systems.

Often faults in the electrical system led to black out, caused by over- or underload switch off, over- or underfrequency. They also cause problems with the electronics, e.g. failures of the main switchboard. Therefore, an electrical system with automatic standby systems should be installed at an unmanned ship.

Main causes of failures in rudder plants were failures in power supply and control devices as well as human errors (in cases of short time failures).

Assessment of criticality of the main failures, which are to be analyzed for engine operation:

Main engine failures:
  Start, reverse and control device: High criticality
  Faulty inlet/outlet valves: Low criticality
  Sticking injection pumps: Low criticality
  Cracked or leaking cylinder covers: High criticality
  Cracked cylinder liners: High criticality
  Broken or leaking injection pipes: Low criticality
  Total failures of Exhaust Gas Turbochargers (EGT): Low criticality
Fuel oil system malfunctions:
  Incompatibility of mixing fuel oils: High criticality

Cooling water system failures:
  - Cooling water pumps: Low criticality
  - Piping, controller and sensors: Low criticality

Faults in electrical system:
  - Black out (caused by over- or underload switch off, over- or underfrequency): Low criticality
  - Electronics, e.g. failure main switch board: Low criticality

Failures in rudder plants:
  - Power supply and control devices: Low criticality

6. Possibilities of operation with faulty systems, interactions in terms of maintenance

The unmanned machinery operation should take place during the open sea voyage.

This operation is the basis of the evaluation of the failures named in chapter 5. It also is the focus of the now following possibility of ship engine operation with faulty main engine groups.

Main engine failures:

In cases of main engine power losses, there is enough ship service power supplied by the GenSets. The 1000 kW GenSet and the other two GenSets are able to deliver roughly 3800 kW to the emergency propulsion and steering unit "pump jet". Of course, other combinations are possible too.

Under the specified conditions of operation, the following GenSets were applicable:

1x 5 L 28/32 H (1000 Gen kW) and
2x 9 L 28/32 H (each 1880 Gen kW).

Start, reverse and control devices

The starting air system is rarely used during open sea operation.

Therefore, possible failures cannot be determined. Neither are they highly critical.

However, these devices are necessary if sudden maneuvers (e.g. in dangerous situations) must be executed. In these cases, possible failures must be analyzed, because they would be highly critical.

Through being integration into the electronically control individual cylinders or parts of the system, these devices can be decommissioned, or redundancies can be used.

Faulty inlet/outlet valves

Since an electronically controlled motor is used as a basis, it is possible to exclude the affected cylinders from the operation. It is then possible to operate the engine with reduced power.

Sticking injection pumps

Since an electronically controlled motor is used as a basis, it is possible to exclude the affected cylinders from the operation. It is then possible to operate the engine with reduced power.

If a high pressure fuel common rail is used, it is not necessary to install an injection pump for every single cylinder. The injection pressure is created by high pressure pump units with their own redundancies.

Cracked or leaking cylinder covers

It is very risky to operate engines with cracked or leaking cylinder covers, because there is no way to eliminate these failures during engine operation.

An immediate exchange of these cylinder covers is necessary. The engine has to be stopped.

It is necessary to develop diagnosis systems, which can detect such crack formations.

Cracked cylinder liners

It is also very risky to operate engines with cracked cylinder liners, because there is no way to eliminate this failure during engine operation.

An immediate exchange of the cylinder liner is necessary. The engine has to be stopped. It is also necessary to develop diagnostic systems, which can detect cylinder liner crack formations.

Broken or leaking injection pipes

Since an electronically controlled motor is used as a basis, it is possible to exclude the affected cylinders from the operation. It is then possible to operate the engine with reduced power.

Total failures of Exhaust Gas Turbochargers (EGT)

In case of a total failure of an EGT, it is necessary to fix the rotating parts (e.g. brake redesign).

A system to automatically fix the rotor of the affected turbocharger must be developed for that.

It is possible to operate the ship with matched load (reduced) by using the engine's auxiliary blowers.

All functions of the turbocharger must be electronically controlled, including a daily cleaning of compressor and turbine side.

Incompatibility of mixing fuel oils

It is extremely unlikely that mixing fuel oils are incompatible because the unmanned ship's engine is only operated with distillate fuels.

Failures in supply systems:

Cooling water pumps,

When the pump malfunctions, it is possible to continue operation automatically with stand-by pumps. The defective pump can be replaced in port.

Piping, controller and sensors of the high temperature, low temperature- and seawater systems

It is necessary to have double implementation of sensors and monitoring, which detect cable breaks. In case contamination is detected, it is possible to operate with a correspondingly reduced load.

Electrical system:

Black out, caused by over- or underload switch off, over- or underfrequency

The immediate transfer to an emergency supply of key consumer and the ecommissioning, activation of GenSets and the normal load distribution must be automatically done.

Problems on electronics, e.g. failure of the main switch board

The major systems of the main switchboard must be redundant and switched automatically.

Sufficient redundancies, like the redundancy at the electronic controls of the engines, must reduce the total failures to zero.

Rudder plants:

- Failures in the power supply and control devices

If the main steering gear fails, the redundant steering gear is usually of limited use only. Therefore, there should be the possibility to supply energy (2 large GenSets) to the pump jet and thus obtain maneuverability.

In the individual assessment of errors in supply systems, it has to be considered that this has an impact on main and auxiliary engine operation.

Because there is no crew on board during the open sea voyage, the input of human operator errors is only possible by the SCC.

The usual repair and maintenance works done by the crew (e.g. pump overhaul) are no longer feasible.

This has major consequences on the maintenance concept. Three possible strategies have been identified:

- Development of maintenance free equipment (unrealistic)
- Use of normal equipment and concentration of maintenance and repair at wait time in port (increased need of personnel, tools, transport…)
- Development of an exchange system, components are used until the assumed end of life, without maintenance and then exchanged completely (plug system needed, requirements for development and standardization)

The concentration of maintenance in ports by using standard plug-ins will lead to more efficiency and shorter berthing times.

Efficient possibilities to transport and lift spare parts must be developed, including tools and equipment. Such short-time actions further need specially qualified staff.

Parallel to an increasing efficiency of maintenance, the time for failure identification and preparation of work can be reduced by using condition-based maintenance.

Repair and maintenance planning has to be done on shore.

In case of faulty operation, with reduced power of the main engine, this leads to an increased specific exhaust emission.

This can be limited by appropriate influence on the electronic controlled engine by the SCC.

7. Minimum scope of necessary systems for reduced emergency operation

- Minimum shaft power

To ensure a minimum shaft power, which may be different depending on the operating conditions of the vessel, e.g. decreasing the main engine output, 4000 kW can be fed through the electrical shaft motor as additional power to the shaft or they can be used over the pump jet for propulsion purposes.

- Minimum electrical power

In normal sea operation, an electric power of 600 kW should be sufficient. For the maneuver operation an additional 1000 kW must be available (e.g. bow thruster, anchor).

To provide minimal electric power during open sea operation with the main engine, the electrical output of the steam generator and the three redundant GenSets are available. In maneuver operation, the supply with electrical energy could be carried out by one of the two large auxiliary diesel engines.

- Minimum function of steering

Steering the ship must always be guaranteed. In cases of failures of the rudder gear, this can be done via steering by the emergency rudder gear. But it is not sure that the emergency operation can be carried out for all kinds of failures of the steering gear. Therefore, it is proposed that an additional pump jet in the forward part of the ship can be put into operation and thus ensures steering and maneuvering.

- Emergency function of main fire system

Flooding the holds and the engine room with inert gas must be possible, i.e. the current amount of carried along gas must be significantly increased and distributed on board in a different manner. The initiation must be automatic or it can be controlled by the SCC. In addition to the installed fire alarms, hotspots can also be detected by infrared cameras; smoke or leaking fluids by regular cameras.

- Emergency functions of bilge and ballast system

The emergency bilge suction or bilge injection valve is used to prevent the flooding of the ship. It is a direct suction from the machinery space bilge, which is connected to the largest capacity pump or pumps. It must be a completely independent unit capable of operation even if submerged. The power supply for the pump is arranged via the emergency generator. The various pumps and lines are interconnected to some extent so that each pump can act as an alternative or stand-by of the other pump.

8. Derived measures, additional redundancies, additional condition monitoring systems

- If necessary, all operating functions that are possible in the engine control room (ECR) must be carried out from shore-side control center,

- Pump jet as a solution for defective main propulsion or steering system to obtain a minimum of maneuverability,

- Full access to the electronic control systems of the main engine for the shore-side operation center (incl. monitoring, modifying of parameters, orders),

- Double implementation of sensors and monitoring of cable breaks,

- High redundancy in electrical power generation, that means that one GenSet is able to deliver the required electrical power,

- Additional stand-by pumps in the supply systems of the main engine and the auxiliary engines are not necessary because operation with only one pump is possible, optionally with reduced load,

- Additional automatic filters for fuel oil and lubrication oil of the main engine,

- Installation of an electrically driven shaft motor (or electric motor to an engine installed “power take in” gear) for more shaft power, if necessary, by taking electrical power from the GenSets,

- Automatically, autonomously functioning module for waste heat recovery (exhaust gas boiler, steam turbine with generator, feeding into main switchboard),

- Changeover of all necessary heating and pre-heating to electrical operation,

- Design an automatic, redundant system for switching the tanks,

- Automatic, redundant system for cleaning the lubrication oil (separator/filter module) for main and auxiliary engines,

- Possibility of shore-based control of the Exhaust Gas Turbocharger (EGT) during operation (lubrication, cooling, fixing of rotor),

- Shore-based control of the normally installed emergency steering plant, diagnostic system for the steering plant is necessary,

- Additional noise, vibration monitoring in the machinery spaces,

- Monitoring of the machinery spaces and bilges via infrared cameras and corresponding lighting for normal cameras,

- More fire alarm and bilge monitoring,

- Filling the main engine crankcase with inert gas so that explosions are avoided and the risk of fire is reduced,

- Equipping with technical diagnosis systems, e.g. for the main engine plant:

Revolution uniformity, load balance control

This system continuously monitors the uniformity of the engine operation. It controls the balance of power output of the cylinders and instantly detects any non-uniformity.

Leakage measurement system

This is a system for early leakage detection on the combustion chamber parts (exhaust valves, injection valves). The principle is based on the measurement of ultrasonic sound.

Cylinder pressure and injection pressure monitoring

This monitoring is possible by cylinder and injection analysis systems. They work in combination with the precise crank angle sensor of the basic Revolution Uniformity System and calculate repeatable parameters.

Piston ring monitoring

A continuous monitoring of piston rings can be done by the piston ring analysis module. It only gives alarm in the event of wear or faults the system.

As a result the sensor detects the faults: “burnt-in ring”, “broken ring” and “missing ring”. When the sensor operates in combination with coated piston rings, the condition of ring wear can be detected. Additionally, the piston ring monitoring system is able to detect the thermal overload of the piston.

Liner temperature monitoring

This system monitors the piston/piston rings/liner performance by measuring the temperature of the upper part of the cylinder liner. A higher friction between the piston/piston rings and the liner results in an increased characteristic temperature level, which may lead to scuffing.

Torque measurement

This system takes the torsion measurement on the running propeller shaft. In relation to the torsion forces on the propeller shaft, it calculates torque and power output.

Performance monitoring

This system continuously checks the quality of the ship operation process. The efficiency, safety and environmental impact of the propulsion plant under current operating conditions are presented. For example, the effects of reducing engine speed in heavy seas, on ship speed and fuel oil consumption can be determined for consideration in process management.

Bearing temperature monitoring

The system monitors the main bearing temperatures, displays their values and gives alarm.

It is a monitoring system to prevent the overheating of bearings or shafts before they are permanently damaged.

This system can also be used to monitor the bearings of the shafting.

Bearing distance monitoring system

Based on a continuous distance measuring in the crankcase, a detection of bearing wear is carried out and a prediction of the remaining lifetime of the bearings is possible.

9. Description of engine operation under created failure scenario conditions

Open sea passage with malfunctions

The "baseline" situation is a voyage through tropical regions with high air and seawater temperatures as well as an atmospheric moisture above 90%. The main engine load is about 95%.

The described conditions provoke the system failure known as “carry water overflow”. It is specified as a steady alteration in the tribological piston-cylinder complex. Due to high humidity and high temperature too much water condenses behind the charge air cooler. The water has to be blown out by the water separator (WMC). A decrease in WMC effectiveness, which may lead to a partial lubrication oil tear-off at the cylinder liner and the final scuffing, will be simulated.

The process is to be identified by the constantly running diagnostic tool “Piston Ring Analysis“. Suitable actions have to be carried out before the engine is seriously damaged. Under strong monitoring, at a reduced engine power, increased scavenging air temperature and increased feeding of cylinder lubrication to the affected cylinder, a further operation of the motor in spite of incorrect outlet of condensate from the charge air is possible.

However, at the next stop in port an immediate repair or a replacement of the water mist catcher or the drain is necessary.

Also necessary is a check on the affected cylinder/piston complexes, possibly in combination with other derived measures.

Maneuvering with malfunctions (possible during open sea voyage)

The scenario’s initial situation correlates with the previous scenario’s (Scenario 3) initial state.

In addition to the transient operating conditions and alarm messages, a system defect will be implemented.

A defective fuel injection pump at one of the main engine cylinders is simulated. Both main engine and global ship system parameters will be affected. To enable maneuvering, an overlay of the systems’ “normal” alarm messages and alarm messages generated by the defect will be originated. Alarms and their possible causes have to be evaluated.

As a result of fault detection, the affected cylinder injection can be taken out of service (input to the electronic control of the injection system from SSC) and the engine can be operated at reduced power.

At the next stop in port an immediate repair, the replacement of the defective injection pump, is necessary.

10. Summarized scope of redesign

For unmanned engine operation during open sea voyages only little additional equipment has to be installed. In this solution, the most redesign activities are necessary in the fuel oil systems. The one fuel system with distillate is simpler than today's heavy fuel oil systems. A lot of components used to carry out preheating and heating, cleaning and resulting activities in other supply systems (e.g. cylinder lubrication oil-TBN, jacket cooling) can be reduced.

The entire fuel oil system has to be converted to a distillate fuel oil system, this applies to both the on board (bunkering, storage, cleaning, supply) and the internal engine systems (injection).

The mechanical and naval engineering effort will be significantly lower. On the other side, the operation costs will be increased by the distillate fuel price. But this approach of the increased fuel costs depends on the sea area and the operating hours inside and outside the ECAs and SECAs. Within the emission control areas it is already necessary to operate with a distillate fuel or a significant effort to reduce emission.

The necessary scope of monitoring equipment and the measurement lists are shown in report 6.1, based on the regulations of an unattended machinery operation.

Special attention must be paid to the installed redundancies. The automatic functions must be checked by harbor crews continuously.

There will be a high redundancy in electrical power generation. That means that one GenSet is able to deliver the required electrical power, if two other GenSets fail and are out of operation. The other possible situation is that, caused by failures, the main engine can only operate at low loads and that the ship needs more shaft power. Then, the electrical power of the two GenSets can drive an additional e-motor and can realize a power take-in to the shaft.

High redundancy in electrical power generation means that one GenSet is able to deliver the required total electrical power, if two GenSets are failured and out of operation. The other possible situation is that the main engine can, caused by failures, only operate with low load and the ship needs more shaft power. Then the electrical power of the two GenSets can drive an additional e-motor and can realize a power take-in to the shaft.

The installation of a pump jet in the forward part of the ship as a solution for defective main propulsion or steering system to obtain a minimum of maneuverability is an important measure of redesign.

Therefore, an electrical system with automatic stand-by systems should be installed in an unmanned ship.

It is necessary that all monitoring and control functions for the described engine room systems can be controlled by the shore-side center.

Bunkering, standard procedures of checking, condition- and time-based maintenance and repairs are tasks for the harbor crews.

Especially for the condition monitoring during unmanned operation and for preparing the condition-based maintenance, the diagnostic tools (see chapter 8) are very important.

A possibility to reduce the necessary time for maintenance is an exchange of complete units. This requires the initiation of the corresponding developments for plug in solutions.

11. Technical discussions for validation of the concept

The discussion and validation of the concept was concluded at a meeting with experienced technical officers and professors.

The current concept with a main engine (two stroke low speed turbocharged crosshead Diesel engine) with directly coupled fixed pitch propeller, three GenSets, waste heat recovery plant, shaft motor and pump jet were confirmed. Focus of validation was the technical feasibility and interaction with the environment.

Technical feasibility

It is assumed, that the electronic control of the engines will increase more and more.

Because all important functions can be monitored and controlled by the SCC, targeted manipulation of electronically controlled components is possible. In case of malfunctions, the possibilities of continuation of engine plant operation will increase.

Special attention should be paid to continuous communication between the ship and the SCC. If necessary it must be possible to bring a crew on board during the open sea voyage in case of damages.

To fulfill the tasks in the SCC, personnel are required with at least equal qualifications as today's technical officers and must be available around the clock.

It was pointed out that the permanent residence of a crew member on board, for emergency situations, is recommended.

A high level of redundancy in the supply systems is required, up to installation of complete redundant systems with all components. In this context, the possibility of use of two independent machinery plants was discussed. Another point was the use of Diesel electric propulsion systems and the use of lowerable azipods. But the two stroke engine was preferred.

Overall, the proposed solution with distillate fuel oil has been assessed as currently feasible option. With the introduction of safe solutions for the marine engine operation with LNG as fuel, this variant can be seen as an option for the future in terms of environmental impact and this is a direct connection to the following interactions with the environment.

Interactions with the environment

Due to the operation of distillate fuel with very low sulphur content, the environmental impact of sulphur oxides and acids will be less in open sea operation.

Better fuel injection and spray formation, better thermal distribution during combustion, lower NOx formation due to better and more uniform combustion can be achieved when using distillate without mixing problems as it is more homogeneous fuel.

When operating with distillate with its relatively constant properties, it is possible to operate with optimized combustion and, therefore, with the best possible fuel economy.

This is a measure to reduce the CO2 emission.

Environmental hazard is not greater than on manned engine operation of the ship on the open sea.

The risk of environmental pollution by ship fires is significantly reduced:

- Due to the possibility of the immediate use of the inert gas, firefighting ability in holds and engine room is improved and

- Due to the possible inert gas filling of the crank case of the main engine, the fire risk is also significantly reduced.

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