# TOWARD A RELIABLE SEA WATER CENTRAL COOLING SYSTEM FOR A SAFE OPERATION OF AUTONOMOUS SHIP

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**Abstract** - The sea water cooling system is one of the vital systems on board of conventional ship (CS). Even with the presence of human on board to intervene in case of its failure, this system has contributed to several catastrophic marine accidents. However, it must be improved in term of reliability and maintainability, to operate safely on board of autonomous ship (AS). In this paper, we analyse the existing sea water cooling system in term of reliability and maintainability and based on the obtained result, we propose an improved system, which might operate safely on board of AS. For an accurate analysis of the system, our approach consists of the collection of the relevant data on board of the visited ships, and the use of technical methodologies such as fault tree Analysis (FTA) methodology and Failure Modes and Effect Analysis (FMEA) methodology. These methodologies permit the identification of the week loops of the system, and the components which demonstrate unsatisfactory reliability. The identified weak points of the system are improved, considering safety and energy saving. A benchmarking in term of reliability of the formal system and the improved system is presented.

**Keywords -** Autonomous Ship, FTA, FMEA, reliability, Sea water central cooling system component,

## I. INTRODUCTION

The conventional ship machinery, such as main engine, auxiliary engine, starting air compressor, condensers, air conditioning plant, provision reefer plant, generate undesirable heat. This undesirable heat might lead to the damage of this machinery, if it is not controlled and kept within maker acceptable running thresholds. To ensure good running of machinery within acceptable temperature thresholds, this heat should be released. The sea water is the efficient mean used on board for the release of this heat. The sea water system arrangement extend in the engine room, must be reduced to avoid corrosion of the machinery and reduce the risk of water ingress. One way among others to reduce this extend is the use of the sea water central cooling system. This system consists of cooling of low temperature fresh water (LTFW) by sea water (SW), by heat exchange through the low temperature fresh water cooler. The SW cooling system is one of the vital systems on board of conventional ships. On the 4th October 2009, a blocked sea water inlet filter at the FW cooler has resulted in stoppage of the main engine of the oil tanker “Thames Fischer” and lead to a marine accident [2]. From 2011 to 2015, 22% of total accidental marine events were attributed to equipment failure [1]. This paper focussed on the study of this system in term of reliability and failure modes by using technical methodologies, i.e. failures tree analysis (FTA) and failure modes and effects analysis (FMEA). The approach of this study is based on the visits of 115 ships, which are equipped with similar machinery. These ships are of different types, i.e. bulk carrier ships, general cargo ships and container ships. The scope of these visits is the study of their SW cooling systems arrangements, their planned maintenance systems, and their engine log books. During these visits, the ship’s crew members were interviewed for their feedback, their experienced failure cases and the related mean time to repair (MTTR). The crew members have reported that the sea water cooling system, as it is nowadays, presents many problems, i.e. corrosion of system components, plugging of the sea chests, pumps failure, SW leakage, SW pressure drop. Despite the presence of human on board, these abnormalities have contributed in many case to the stoppage of main engine, causing several marine accidents. Whereas the autonomous ship, without crew on board, this system must. Based on the crew members feedback and the analysis result, an improved SW cooling system was proposed, which might be installed on-board of an autonomous ship.Existing researches are mainly devoted to the study of the sea cooling system components, i.e. pumping system in term of energy saving, diagnosis and corrosion protection. S. Kleinmann et al. have discussed in details the model based diagnosis approach and fuzzy logic approach for the advanced diagnosis of industrial pumps systems [3]. R. Menis et al, paper deals with the first step of integrated power system (IPS) dependable design, by application of FTA and FMEA analysis technics for qualitative approach for root causes and effects of failure modes on IPS component [4]. D. W. Handan et al. have presented a model of a reliability analysis in the System Dynamics (SD) simulation in order to recognize a potential failure and prevent a functional failure of maintainable items of ship machinery components, to prioritise the risk and minimize the maintenance cost to obtain a reliable ship machinery components [5]. Qiang Fu et al., have studied the sea water cooling system corrosion protection and recommended firstly to use suitable material, application of coating, and cleanness of the cooling surfaces [6]. Chun-Lien Su et al. have proposed an energy saving by variable frequency control of sea water cooling pump driver and that the energy saving is affected by the sea trading area [7]. In the maritime unmanned navigation through intelligence in network (MUNIN) project [8], the SW cooling system was considered one of the systems on board that needs to be improved in term of reliability to be able to function autonomously and safely.

In the available literatures, the SW cooling system, has been studied partly, focussing on the reliability and energy saving of the pumping units. The objective of this paper is to study and analyse of the SW cooling system in its globality, in term of reliability and maintainability. This analysis consists of the identification of the weak loops of the system and the components which demonstrate unsatisfactory reliability. Based on the result of the analysis, we propose an improved sea water central cooling system (SWCCS), which is reliable enough to be installed on board of AS.

The present paper is organized as follows: Section I is an introduction to the thematic, where the necessity for such study is demonstrated, the case study is defined, and the related searches were briefly presented. In section II, the data collection and analysis approach were presented. The CS SW central cooling system, which is subject to our analysis is described, analysis methodologies approach is briefly explained. The CS SW central cooling system FTA and FMEA were carried out, to identify the top event cause roots, failure modes and their effects on the system. Preventive measures, indications approach and reliability improvement were proposed. Calculation of the system reliability data approach is given. At the end of the section the result of the analysis methodologies was discussed, weak loops of the system were identified and a proposal for improvement of reliability is addressed. Based on the analysis result and recommendations, aSW central cooling system was designed and presented in section III, the raison for reconfiguration of sea chests (SC) piping and valves was given. The necessity for enhanced redundancy of some components is explained. The energy-saving of the proposed system was discussed. In section IV, we conclude this paper.

## II. CONVENTIONAL SHIP SEA WATER CENTRAL COOLING SYSTEM ANALYSIS

### A. Data collection approach

For the assessment and analysis of the sea water central cooling system SWCCS, a data collection and analysis approach has been adopted fig.1. About 115 ships of different types and with similar machinery arrangement, i.e. general cargo ships, containers ships and bulk carrier ships, have been visited. The relevant documentation, reports and drawings have been studied and analysed. This analysis has covered, the planned maintenance system (PMS) records, engine log books, system alarms records, and the systems energy consumption. The ship's crew members have been interviewed for their feedback and the SWCCS related damage cases. The relevant international association of classification societies (IACS) rules, and the international maritime organisation (IMO) requirements have been considered in the system's design. This approach is adopted in order to constitute an accurate data base, to design a reliable SWCCS, that might be safely work on board of an AS.

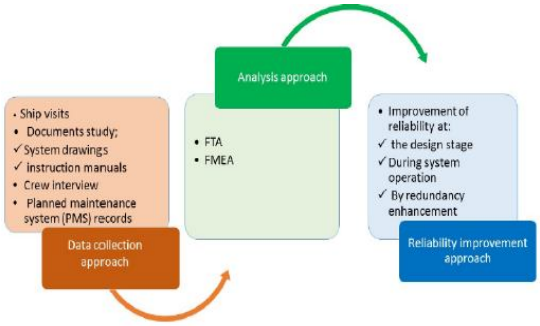


**Fig. 1 Data collection and reliability improvement approach**

### B. Sea water central cooling system description

The SWCCS fig.2, which is subject to our analysis is one of the system designs that is commonly fitted on board of the most visited ships. Its components description is presented in table 1. The SWCCS works in open loop. The sea water cooling pump 1 (SCPP1) or SCPP2 depending on which one is in use, sucks sea water and pumps it out into the system. The pumping water passes through the in service low temperature fresh water cooler 1 (LTFWCL1) or LTFWC2 and absorbs the undesirable heat from the low temperature fresh water (LTFW). The heated SW leaves the LTFWCL1 or LTFWCL2, and is thrown overboard, back to the sea. At its passage through the system, the SW is filtered, to retain the foreign matters. First is filtered through the sea chest strainers, then through the SCPP1 or SCPP2 strainer and at the last phase through LTFWCL1 or LTFWCL2 internal strainers ISTR1 or ISTR2. The high sea chest (HSC) and the low sea (LSC) grids are placed on ship hull, and must be kept submerged below the sea water line. The sea water enters by gravity through the grids to ensure a continuous fill up of the cross-manifold. The LTFW, which is not subject of our study, works in closed loop. Once the LTFW is cooled in the LTFWCL1 or LTFWCL2, then passes through the different machineries and absorbs the undesirable heat, to keep them within normal running temperature thresholds and then back to the LTFWCL1 or LTFWCL2 to be cooled down and so on. Valves are fitted at the inlet and outlet of each system's component, in order to isolate it, in case of a routine maintenance. In dirty SW, i.e. in port, or in the river, it happens that the sea chests grids might be plugged. The back-flushing system might resolve the problem temporarily of sea chest clogging, by pushing back to the sea the dirt and foreign matters, waiting for a final cleaning by a diver. For an autonomous ship, this system must function without failure at least for a period of 500 h, which is equivalent to 21 days of running, without human intervention, time to arrive to the port, where, a repair team might intervene. Therefore, it is important to identify its failures modes, root causes, and potential risks, for an adequate improvement of the system. Our analysis of the system, is supported by the FTA and FMAE analysis methodologies.

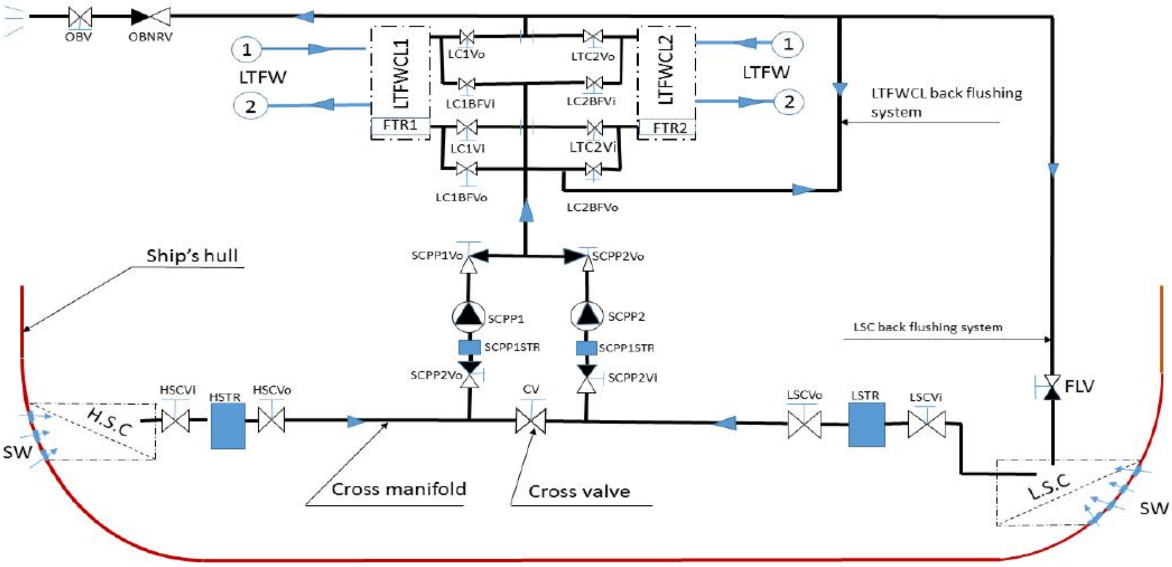


**Fig. 2 Sea water central cooling system chest**

| Code | Description | Code | Description |
|---|---|---|---|
| EJPP | Ejector pump | LTC1Vo | LTFWCL1 outlet valve |
| EJPPVi | Ejector pump inlet valve | LTC1BFVi | LTFWCL1 back flushing inlet valve |
| EJPPVo | EJPP outlet valve | LTC1BFVo | LTFWCL1 Back flushing outlet valve |
| EJPPSTR | EJPP strainer | LTFWCL2 | Low temperature fresh water cooler 2 |
| GSPP | General service pump | LTC2Vi | LTFWCL2 inlet valve |
| GSPPVi | GSPP inlet valve | LTC2Vo | LTFWCL2 outlet valve |
| GSPPVo | GSPP outlet valve | LTC2BFVi | LTFWCL2 back flushing inlet valve |
| GSPPSTR | GSPP strainer | LTC2BFVo | LTFWCL2 back flush outlet valve |
| HSCS | High sea chest starboard | OBNRV | Non-return over board valve |
| HSCSVi | HSCS inlet valve | OBV | Over board valve |
| HSCSVo | HSCS outlet valve | SCPP1 | Sea cooling pump 1 |
| HSCSBFLV | HSCS back flush valve | SCPP1Vi | SCPP1 inlet valve |
| HSCP | High sea chest port side | SCPP1Vo | SCPP1 outlet valve |
| HSCPVi | HSCP inlet valve | SCPP1STR | SCPP1 strainer |
| HSCPVo | HSCP outlet valve | LSCSBFLV | LSCS back flushing valve |
| HSCPBFLV | HSCP back flushing valve | LTFWCL1 | Low temperature fresh water cooler 1 |
| LSCP | Low sea chest port side | LTC1Vi | LTFWCL1 inlet valve |
| LSCPVi | LSCP inlet valve | SCPP2 | Sea cooling pump 2 |
| LSCPVo | LSCP outlet valve | SCPP2Vi | SCPP2 inlet valve |
| LSCPBFLV | LSCP back flush valve | SCPP2Vo | SCPP2 Outlet valve |
| LSCS | Low sea chest starboard | SCPP2STR | SCPP2 strainer |
| LSCSVi | LSCS inlet valve | SW | Sea water |
| LSCSVo | LSCS outlet valve | V1-V2-V3-V4-V5 | Interconnection valve |

**Table 1. Sea water central cooling system components coding description**

## C. Sea water central cooling system analysis methodologies

### C.1 Fault tree analysis methodology

The FTA is a widely-used logic method in shipping industry, which is used to analyse the failure roots, and to evaluate the ship equipment reliability. It is a logical representation of the relationship of the "basic fault events" that lead to the occurrence of the undesirable "top event". The FTA is illustrated by using logic gates, i.e. "AND gate" and "OR gate" fig.3. Based on the interview of the crew members, the analysis of the planned maintenance system and engine log books, we have found that, the common experienced SWCCS failure is the increase of the LTFW temperature at the outlet of the LTFWCL system, which due to drop of the SW pressure in the system. This increase of temperature, leads in the most cases to the stoppage of the main engine, or black out, causing several marine accidents. In this paper, we have taken this LTFW temperature increase as a top event of our case study, i.e. the output of the OR gate 1. The related top event's FTA is illustrated by the fig.4.

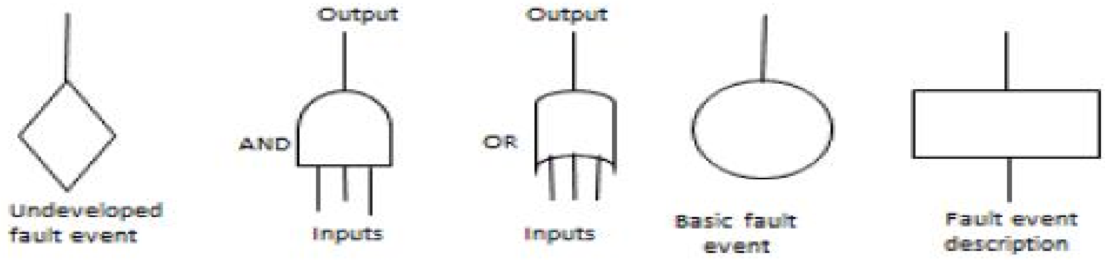


**Fig.3 Fault tree analysis shapes description**

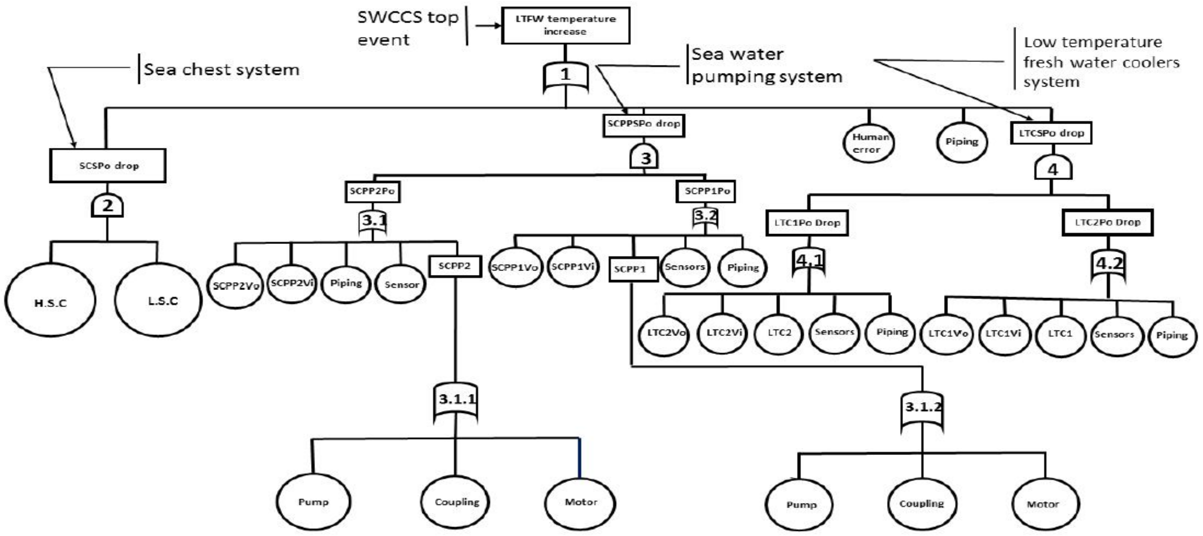
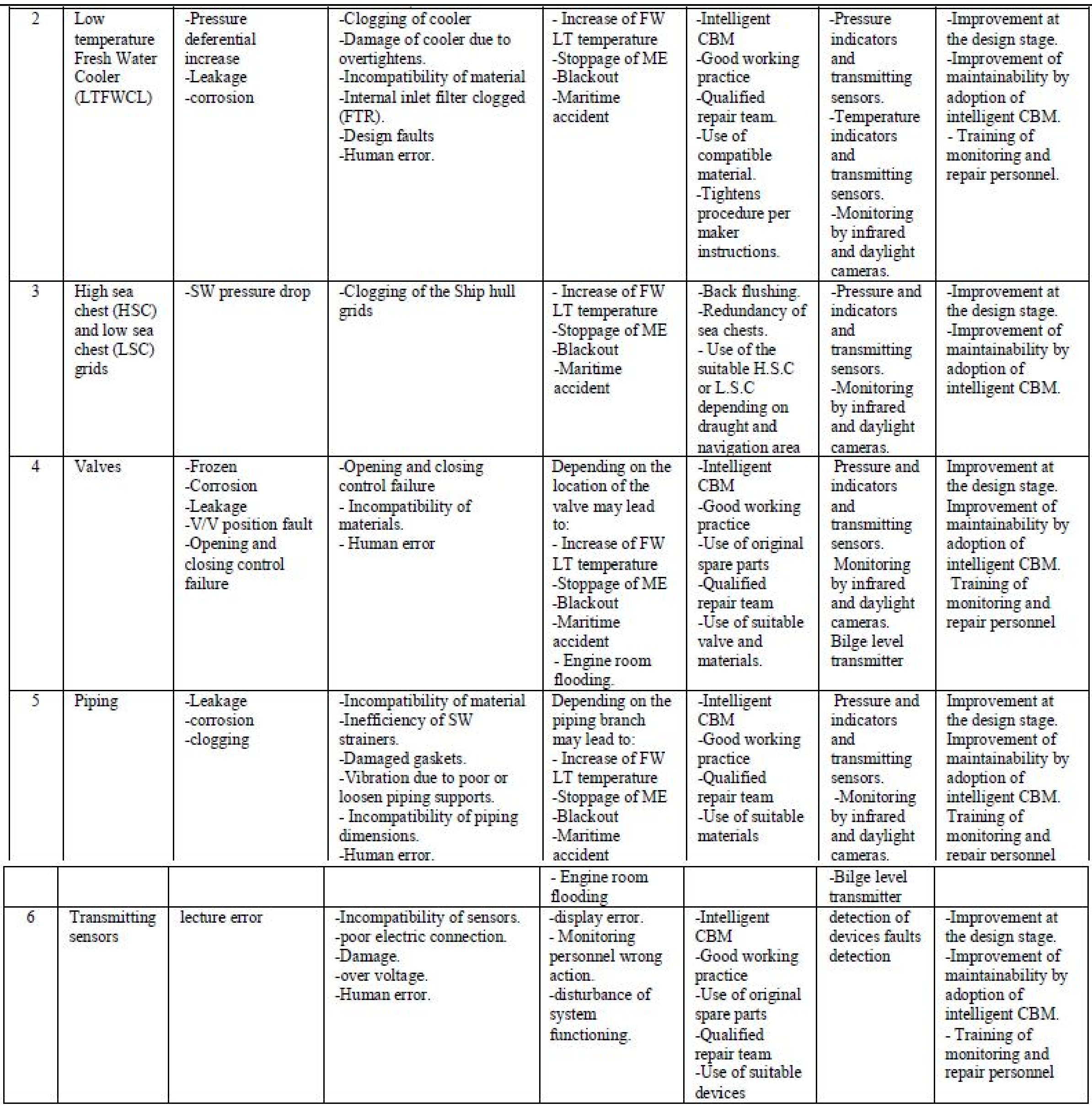


**Fig. 4 Sea water central cooling failure tree analysis methodology**

### C.2 Failure mode and effect analysis methodology

The FMEA is one of the risk analysis methodology used in the marine machinery risk assessment. It is applied at each system component, to identify systematically the potential failure modes, failure causes, failure impact, and to propose a preventive solution to reduce the root causes or to eliminate them. The table 2, presents the FMEA of the SWCCS fig.2. In this analysis, we identify and characterize exactly any potential arising faults of the system components, to trace their root causes, assess their effects on the operation of the system and their consequences on the safety of ship operation. Based on this analysis, we propose preventive measures, an early failure detection approach and improvement of its reliability at the design stage and during operation by adopting intelligent condition based maintenance (CBM) and repair good practice.

| Item | Designation | Failure mode | Failure Causes | Failure effects | Prevention measures | Detection approach | Improvement |
|---|---|---|---|---|---|---|---|
| 1 | Sea Water Cooling Pumps (SCPP) | -Outlet SW pressure drop<br>-Abnormal vibration<br>-Abnormal overheat<br>-Abnormal noise<br>-Leakage<br>- Corrosion | Pump:<br>- Impeller damage<br>- Shaft damage<br>- Mechanical seal<br>- Bearing damage<br>- Casing damage<br>-Running in dry condition<br>-Design faults<br>-Material incompatibility<br>-Human error<br><br>Coupling:<br>-Coupling flanges damage<br>-Elastic coupling damage<br>-Coupling fingers damage<br>-Misalignment<br><br>Driver:<br>-Electric failure<br>-Poor electric connection<br>-Low Winding insulation.<br>-Control system failure | -FW LT cooling temp increase<br>-Abnormal vibration<br>-Abnormal noise<br>-Stoppage of main engine<br>-Blackout<br>-Maritime accident | -Intelligent CBM<br>-Good working practice<br>-Use of original spare parts<br>-Qualified repair team<br>- Avoid overload<br>-Follow maker instruction<br>-Use suitable materials.<br>-Pre-heating of driver winding. | -Vibration analysis.<br><br>-Misalignment detection<br><br>-Pressure indicator and measuring sensors.<br><br>-Dry running detection<br><br>-Temperature indicators and sensors.<br>-Monitoring by infrared and daylight cameras | -reliability improvement at the design stage.<br>-Improvement of maintainability by adoption of intelligent CBM.<br>-Improvement supervision and early detection devices.<br>-training of repair and monitoring personnel. |



| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 2 | Low temperature Fresh Water Cooler (LTFWCL) | -Pressure deferential increase<br>-Leakage<br>-corrosion | -Clogging of cooler<br>-Damage of cooler due to overtightens.<br>-Incompatibility of material<br>-Internal inlet filter clogged (FTR).<br>-Design faults<br>-Human error. | - Increase of FW LT temperature<br>-Stoppage of ME<br>-Blackout<br>-Maritime accident | -Intelligent CBM<br>-Good working practice<br>-Qualified repair team.<br>-Use of compatible material.<br>-Tightens procedure per maker instructions. | -Pressure indicators and transmitting sensors.<br>-Temperature indicators and transmitting sensors.<br>-Monitoring by infrared and daylight cameras. | -Improvement at the design stage.<br>-Improvement of maintainability by adoption of intelligent CBM.<br>- Training of monitoring and repair personnel. |
| 3 | High sea chest (HSC) and low sea chest (LSC) grids | -SW pressure drop | -Clogging of the Ship hull grids | - Increase of FW LT temperature<br>-Stoppage of ME<br>-Blackout<br>-Maritime accident | -Back flushing.<br>-Redundancy of sea chests.<br>- Use of the suitable H.S.C or L.S.C depending on draught and navigation area | -Pressure and indicators and transmitting sensors.<br>-Monitoring by infrared and daylight cameras. | -Improvement at the design stage.<br>-Improvement of maintainability by adoption of intelligent CBM. |
| 4 | Valves | -Frozen<br>-Corrosion<br>-Leakage<br>-V/V position fault<br>-Opening and closing control failure | -Opening and closing control failure<br>- Incompatibility of materials.<br>- Human error | Depending on the location of the valve may lead to:<br>- Increase of FW LT temperature<br>-Stoppage of ME<br>-Blackout<br>-Maritime accident<br>- Engine room flooding. | -Intelligent CBM<br>-Good working practice<br>-Use of original spare parts<br>-Qualified repair team<br>-Use of suitable valve and materials. | Pressure and indicators and transmitting sensors.<br>Monitoring by infrared and daylight cameras.<br>Bilge level transmitter | Improvement at the design stage.<br>Improvement of maintainability by adoption of intelligent CBM.<br>Training of monitoring and repair personnel |
| 5 | Piping | -Leakage<br>-corrosion<br>-clogging | -Incompatibility of material<br>-Inefficiency of SW strainers.<br>-Damaged gaskets.<br>-Vibration due to poor or loosen piping supports.<br>- Incompatibility of piping dimensions.<br>-Human error. | Depending on the piping branch may lead to:<br>- Increase of FW LT temperature<br>-Stoppage of ME<br>-Blackout<br>-Maritime accident<br>- Engine room flooding | -Intelligent CBM<br>-Good working practice<br>-Qualified repair team<br>-Use of suitable materials | Pressure and indicators and transmitting sensors.<br>-Monitoring by infrared and daylight cameras.<br>-Bilge level transmitter | Improvement at the design stage.<br>Improvement of maintainability by adoption of intelligent CBM.<br>Training of monitoring and repair personnel |
| 6 | Transmitting sensors | lecture error | -Incompatibility of sensors.<br>-poor electric connection.<br>-Damage.<br>-over voltage.<br>-Human error. | -display error.<br>- Monitoring personnel wrong action.<br>-disturbance of system functioning. | -Intelligent CBM<br>-Good working practice<br>-Use of original spare parts<br>-Qualified repair team<br>-Use of suitable devices | detection of devices faults detection | -Improvement at the design stage.<br>-Improvement of maintainability by adoption of intelligent CBM.<br>- Training of monitoring and repair personnel |

**Table 2. Conventional ship sea water central cooling system FMEA**

### C.3 System weak points

The system in fig.2 presents several weak points that make it unsuitable to be installed on board of AS. Even with the arrangement of two SCCPP, one in use and one in standby, the connection to the system of another available pump on board, might enhance the redundancy without increasing the cost and without reducing the engine space, such as, the general service pump or the fire pump. Both SCCPP, deliver in the same pipe. In case of the damage of this pipe, the system fails, causing flooding of the engine room, if the leakage is not stopped at the right time. For this, the reconfiguration of the arrangement of piping is necessary to avoid the lack of cooling. The sea chest might be plugged by ice in frozen sea or by foreign matters when the ship sails in coastal area or in river where the water is usually dirty and contains various floating materials. The duplication of sea chests and its associated back flushing systems might avoid to run on dry system. This system must be improved to make it safe and reliable enough to be fitted on board of AS.

## C.4 Sea water central cooling system reliability calculation

### C.4.1 Calculation assumptions

For the calculation of the failure rate, the reliability, the mean down time, and the mean time to failure of the system, the following assumptions are made:

- The standby units are assumed to have identical, constant failure rates to the main unit
- The standby units are assumed not to fail while in the idle state.
- The failures are revealed and the failed unit is repairable.
- The crew members are satisfactory qualified to carry out the repair.

- The necessary spare parts and tools are provided on board. The repair task starts as soon as the unit fails.
- Estimated time used for calculation is t =500 h.

The table 3, summarize the system components failure rates and mean down times values. These values, are based on the study of the system components failure story, repair reports and data collection from the relevant literatures, [11] [12] [13] [14].

| Designation | Failure rate (failures per 1 million hours) | MDT (h) |
|---|---|---|
| Sea cooling pump | $\lambda_{pp}$=50.10$^{-6}$ | $MDT_{pp}$=12 |
| Driver | $\lambda_{em}$=20.10$^{-6}$ | $MDT_{em}$=08 |
| LT cooler | $\lambda_{cl}$=470.10$^{-6}$ | $MDT_{cl}$=08 |
| Sea chest | $\lambda_{sc}$=700.10$^{-6}$ | $MDT_{sc}$=2 |
| Piping | $\lambda_{pi}$=7,93.10$^{-6}$ | $MDT_{pi}$=8 |
| Valve | $\lambda_{vv}$=7,68.10$^{-6}$ | $MDT_{vv}$=8 |
| Coupling | $\lambda_{cp}$=25.10$^{-6}$ | MDT*cp* =4 |
| Sensors | $\lambda_{ss}$=10.10$^{-6}$ | $MDT_{ss}$ =2 |

**Table 3. SWCS components failure rate and mean down time**

### C.4.2 Calculation useful mathematical equations

Several mathematical equations are used for the calculation of the system reliability parameters [9] [10]:

- The reliability of a standby redundancy is given by the first n terms of the Poisson expression:

$$R_{st} = R(t) = e^{-\lambda t} \sum_{i=1}^{n-1} \frac{(\lambda t)^i}{i!} \qquad (2.1)$$

Where $R_{st}$ is the reliability of the system, λ is the failure rate of the unit, t is the time and n is the total number of units. For a system with two units, where one is in use and one is at a standby status, the equation (2.1) is reduced to:

$$R_{st} = R(t) = e^{-\lambda t}(1 + \lambda t) \qquad (2.2)$$

- By integrating equation (2.1) over the time interval [0, ∞], we get the system mean time to failure $MTTF_{st}$,

$$MTTF_{st} = \frac{n}{\lambda} \qquad (2.3)$$

- The standby system failure rate is expressed by the equation (2.4).

$$\lambda_{st} = (n-1)^2 \lambda^2 MDT \qquad (2.4)$$

Where MDT is the mean down time of the unit.

- The system mean down time $MDT_{st}$ is expressed by the equation (2.5)

$$MDT_{st} = \lambda^2 \frac{MDT^2}{2} \qquad (2.5)$$

- The equivalent output failure rate of AND gate associated with the input failure rates of the FTA is given by the equation:

$$\lambda_{eqand} = \prod_{i=1}^{n} \lambda_i \left[ \sum_{i=1}^{n} MDT_i \right] \qquad (2.6)$$

- The equivalent mean down time of AND gate associated with the input mean down times in the FTA, is given by the equation (2.7),

$$MDT_{eqand} = \frac{\prod_{i=1}^{n} MDT_i}{\sum_{i=1}^{n} MDT_i} \qquad (2.7)$$

- The equivalent failure rate of OR gate associated with the input failure rates in the FTA is given by the equation:

$$\lambda_{eqor} = \sum_{i=1}^{n} \lambda_i \qquad (2.8)$$

- The equivalent mean down time of OR gate associated with the input mean down times in the FTA is given by the equation:

$$MDT_{eqor} = \frac{\sum_{i=1}^{n} \lambda_i MDT_i}{\sum_{i=1}^{n} \lambda_i} \qquad (2.9)$$

### C.3.3 System data calculation

Our approach for the calculation of the system, $\lambda_{st}$, $MDT_{st}$ , $R_{st,}$ and $MTTF_{st}$, consists of the calculation, first of the same for all subsystems, i.e. sea chest system, pumping systems, and LTFWCL system.

- The sea chest system (output of the AND gate 2, fig. 4) failure rate $\lambda_{scst}$, mean down time $MDT_{scst}$, reliability $R_{scst}$, and the mean time to failure $MTTF_{scst}$ are calculated by using the equations (2.2, (2.3), 2.4) and (2.5) and are expressed successively by :

$$\lambda_{scst} = \lambda_{sc}^2 MDT_{sc} \qquad (2.10)$$

$$MDT_{scst} = \lambda_{sc}^2 \frac{MDT_{sc}^2}{2} \qquad (2.11)$$

$$R_{scst} = e^{-\lambda_{sc} t}(1 + \lambda_{sc} t) \qquad (2.12)$$

$$MTTF_{scst} = \frac{2}{\lambda_{sc}} \qquad (2.13)$$

Where, $\lambda_{sc}$ is the failure rate of one sea chest, and $MDT_{sc}$ is its mean down time.

- The pumping system (output of the AND gate 3, fig. 4) failure rate $\lambda_{ppst}$, mean down time $MDT_{ppst}$, reliability $R_{pps}$, and the mean time to failure $MTTF_{ppst}$, are calculated by using the equations (2.2, (2.3), 2.4),(2.5), (2.8) and (2.9), and are expressed successively by:

$$\lambda_{ppst} = (2\lambda_{vv} + \lambda_{pi} + \lambda_{ss} + \lambda_{cp} + \lambda_{em} + \lambda_{pp}) . \left[ \left( 2\lambda_{vv} MDT_{vv} + \lambda_{pi} MDT_{pi} + \lambda_{ss} MDT_{ss} + \lambda_{cp} MDT_{cp} + \lambda_{em} MDT_{em} + \lambda_{pp} MDT_{pp} \right) \right] \qquad (2.14)$$

$$MDT_{ppst} = \left[ \left( 2\lambda_{vv} MDT_{vv} + \lambda_{pi} MDT_{pi} + \lambda_{ss} MDT_{ss} + \lambda_{cp} MDT_{cp} + \lambda_{em} MDT_{em} + \lambda_{pp} MDT_{pp} \right)^2 \right] \Big/ {}_2 \qquad (2.15)$$

$$R_{ppst} = e^{-\lambda_{ppst} t}(1 + \lambda_{ppst} t) \qquad (2.16)$$

$$MTTF_{ppst} = \frac{2}{\lambda_{ppst}} \qquad (2.17)$$

Where the used parameters are as per table 3.

- The LTFWCL system (output of the AND gate 4, fig. 4) failure rate $\lambda_{clst}$, mean down time $MDT_{clst}$ reliability $R_{clst}$, and the mean time to failure $MTTF_{clst}$, are calculated by using the equations (2.2, (2.3), (2.4), (2.5), (2.8) and (2.9). and are successively expressed by:
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$$\lambda_{clst} = (2\lambda_{vv} + \lambda_{pi} + \lambda_{ss} + \lambda_{cl}) . (2\lambda_{vv}MDT_{vv} + \lambda_{pi}MDT_{pi} + \lambda_{ss}MDT_{ss} + \lambda_{cl}MDT_{cl}) \quad (2.18)$$

$$\mathrm{MDT}_{clst} = \left[ (2\lambda_{vv}MDT_{vv} + \lambda_{pi}MDT_{pi} + \lambda_{ss}MDT_{ss} + \lambda_{cl}MDT_{cl}) \right] / 2 \quad (2.19)$$

$$R_{clst} = e^{-\lambda_{clst}t}(1 + \lambda_{clst}t) \quad (2.20)$$

$$MTTF_{clst} = \frac{2}{\lambda_{clst}} \quad (2.21)$$

Where the used parameters are as per table 3.

The calculation of the SWCCS (output of the AND gate 1, fig. 4) failure rate $\lambda_{swccs}$, mean down time $MDT_{swccs}$, reliability $R_{swccs}$ and the mean time to failure $MTTF_{swccs}$, are calculated by using the equations (2.2, (2.3), (2.4), (2.5), (2.8) and (2.9).
If any one of the input of the gate 1, fig.4 fails, the system fails. In other words, all subsystems, and piping must operate normally and without human error for the system's success.

- The system is considered as a series network and the reliability is expressed by the equation (2.22),

$$R_{SWCCS} = R_{scst}R_{ppst}R_{clst}R_{pi}R_h \quad (2.22)$$

- The SWCCS failure rate $\lambda_{swccs}$ is expressed by the
  equation (2.23)

$$\lambda_{swccs} = \lambda_{ppst} + \lambda_{scst} + \lambda_{clst} + \lambda_{pi} + \lambda_h \quad (2.23)$$

- The SWCCS mean down time is calculated by using the equation (2.7),

$$MDT_{swccs} = (MDT_{ppst}MDT_{scst}MDT_{clst}MDT_{pi}) / (MDT_{ppst} + MDT_{scst}MDT_{clst} + MDT_{pi}) \quad (2.24)$$

- The SWCCS mean time to failure is expressed by the
  equation (2.25),

$$MTTF_{swccs} = 1/(\lambda_{ppst} + \lambda_{scst} + \lambda_{clst} + \lambda_{pi} + \lambda_h) \quad (2.25)$$

- From the year of 2011 to 2015, The human erroneous actions have contributed with 71% of the total of marine accidental events [1]. Therefore, in our analysis, the human error is not neglected and a pessimistic human error rate value of $\lambda_h = 0.01$ is suggested for task errors.

## III. AUTONOMOUS SHIP SEA WATER CENTRAL COOLING MODEL

The AS must operate without crew on board, and no physical repair intervention is possible, when she is far away from the coast. Therefore, the SWCCS must function reliably and safely for a period not less than 500 h, and when the vessel is in port, a repair team embarks on board, to carry out the scheduled repairs. This system must operate autonomously, and must have the possibility to be controlled remotely, by satellite or other communication carriers. To enhance the reliability of the system, we propose an improved model of SWCCS, fig, 5. This model is operating similarly as the CWCCS, fig.2. However, the weak points were improved by enhancement of the system components redundancy, and reconfiguration of the piping and valves arrangements.

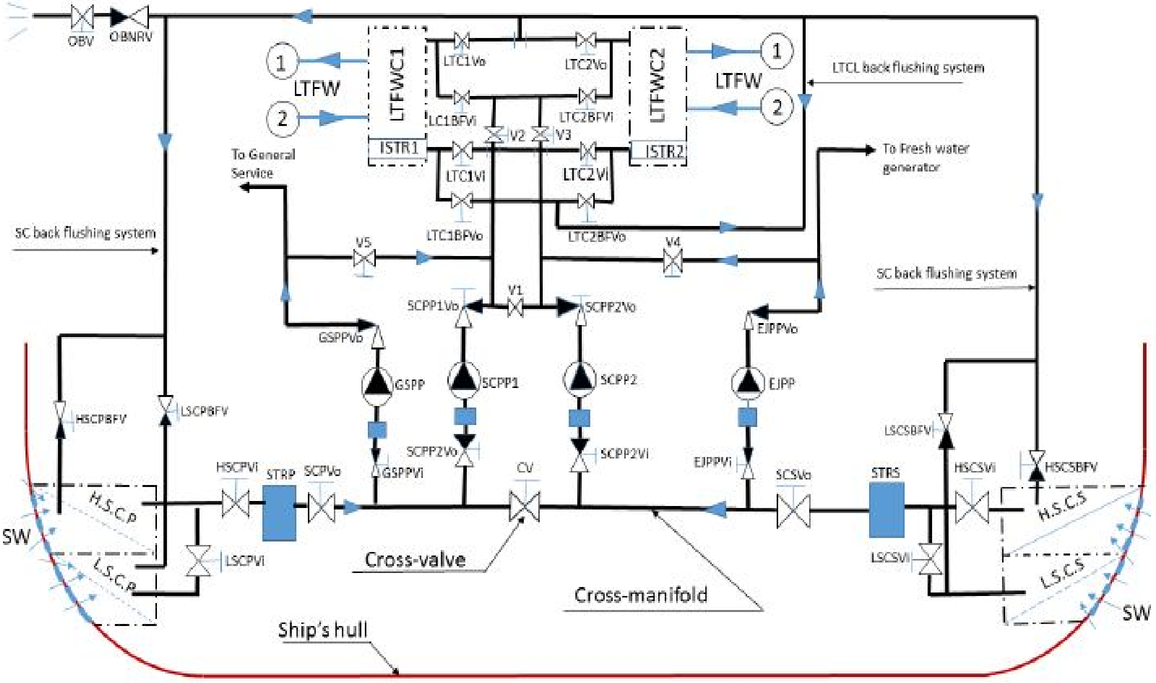


Fig. 5 Autonomous ship sea water central cooling system model

### A. Reconfiguration of piping and valves arrangement

The piping and valves were reconfigured to ensure continuous supply of the SW and to allow in case of leakage or damage to isolate the damaged branch and to switch to another branch without interruption of SW flowing. Each SWCPP delivers in separate pipe to permit in case of damage of one of them to isolate it to avoid flooding of the engine room and to use the other branch. Many valves are fitted and arranged in such a way to isolate any damaged loop of the system and to put in service the other loop. All installed valves must operate autonomously and be controllable remotely from the Shore Control Center. The piping material should be resistant to the corrosion and aggressiveness of the SW. Stainless steel and titanium are recommended to be used as material to avoid accelerated corrosion, leakage and to increase piping life cycle.

### B. Reconfiguration of sea chests

To avoid the handicap of the SWCCS by the plugging of the sea chest by dirt, we propose the arrangement of one high sea chest and one low sea chest in each side of the ship. The high sea chest HSCP and HSCS are used at river where the draught is reduced, to avoid their plugging by mat, or at high sea when the sea condition is suitable. The low sea chest LSCP and LSCS are used at port, to avoid their plugging by floating materials or at high sea in rough weather to avoid the emerging of the grid by rolling or weaving of the ship. In both sides, each sea chest is equipped with its back-flushing system to blow back the dirt to the sea. With this arrangement, we ensure continuously the fill up of the SW cross-manifold, and in case of leakage, or clogging, or for a routine maintenance, there are several possibilities to isolate the damaged branch and to put in service another, without interrupting the cooling water supply.

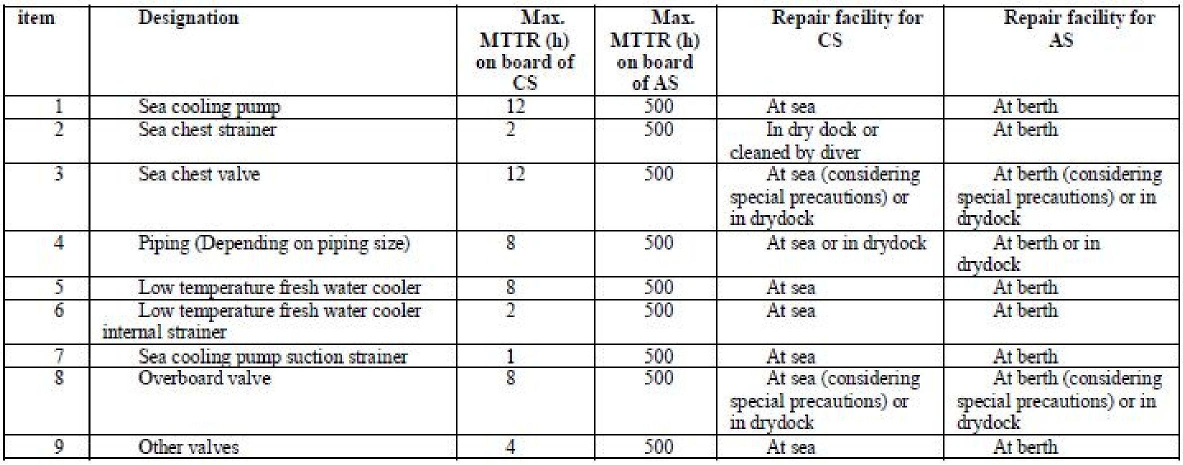
### C. Redundancy of sea water central cooling system components

All ships are equipped with at least two SCPP’s, one in service and one in standby. The compulsory installation of other pumps such as, general service pump (GSPP), ballast pump, and fire pumps on board of the ship give us the possibility to connect them to the SWCCS, to enhance its reliability, without extra cost and without reducing the engine room space. These pumps could be used in case of emergency.

### D. Transmitting sensors and condition based maintenance

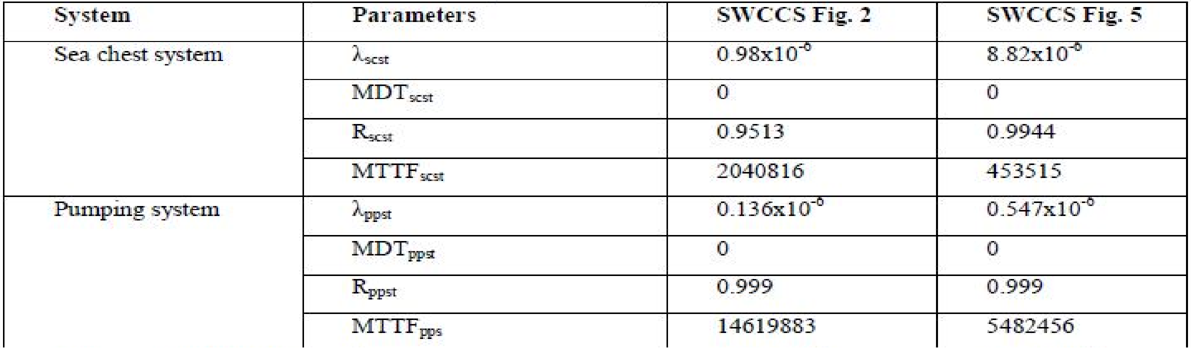
The system Pressure and transmitting sensor should be provided in each location for the monitoring of the function of the different system components and to be duplicated to avoid error indication.

For an intelligent condition based maintenance (BCM), each SWCPP should be provided with leakage detection, misalignment detection, dry running detection, bearing damage

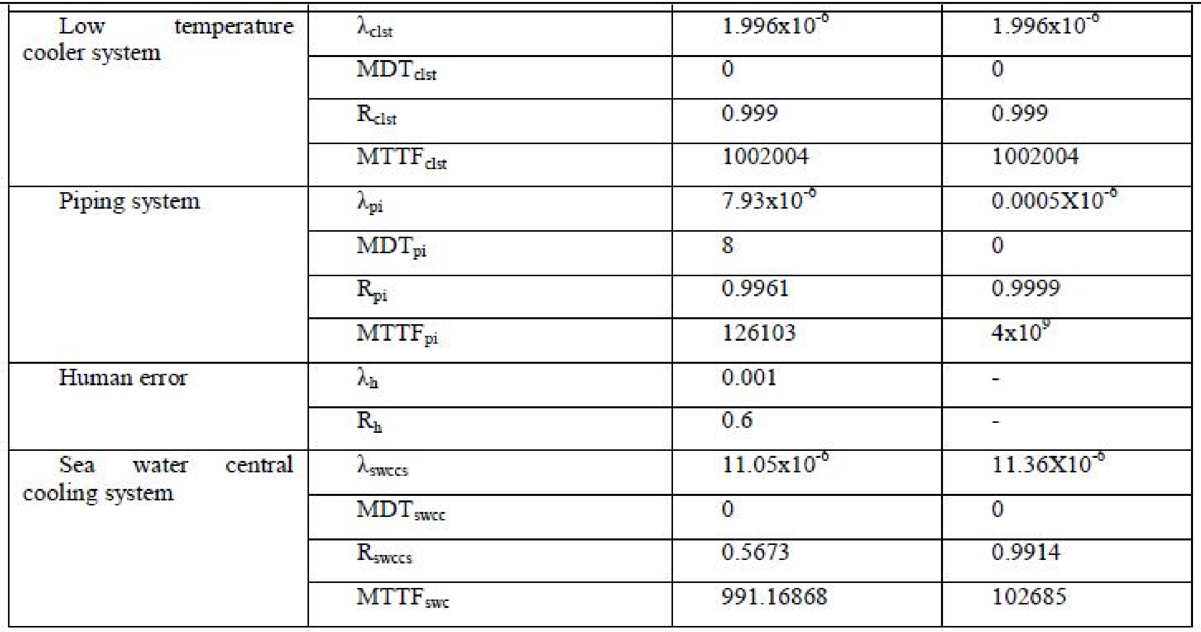


| item | Designation | Max. MTTR (h) on board of CS | Max. MTTR (h) on board of AS | Repair facility for CS | Repair facility for AS |
|---|---|---|---|---|---|
| 1 | Sea cooling pump | 12 | 500 | At sea | At berth |
| 2 | Sea chest strainer | 2 | 500 | In dry dock or cleaned by diver | At berth |
| 3 | Sea chest valve | 12 | 500 | At sea (considering special precautions) or in drydock | At berth (considering special precautions) or in drydock |
| 4 | Piping (Depending on piping size) | 8 | 500 | At sea or in drydock | At berth or in drydock |
| 5 | Low temperature fresh water cooler | 8 | 500 | At sea | At berth |
| 6 | Low temperature fresh water cooler internal strainer | 2 | 500 | At sea | At berth |
| 7 | Sea cooling pump suction strainer | 1 | 500 | At sea | At berth |
| 8 | Overboard valve | 8 | 500 | At sea (considering special precautions) or in drydock | At berth (considering special precautions) or in drydock |
| 9 | Other valves | 4 | 500 | At sea | At berth |

**Table 4. Sea water central cooling system components maintenance**



| System | Parameters | SWCCS Fig. 2 | SWCCS Fig. 5 |
|---|---|---|---|
| Sea chest system | $\lambda_{scst}$ | $0.98 \times 10^{-6}$ | $8.82 \times 10^{-6}$ |
| | $MDT_{scst}$ | 0 | 0 |
| | $R_{scst}$ | 0.9513 | 0.9944 |
| | $MTTF_{scst}$ | 2040816 | 453515 |
| Pumping system | $\lambda_{ppst}$ | $0.136 \times 10^{-6}$ | $0.547 \times 10^{-6}$ |
| | $MDT_{ppst}$ | 0 | 0 |
| | $R_{ppst}$ | 0.999 | 0.999 |
| | $MTTF_{pps}$ | 14619883 | 5482456 |



| | | | |
|---|---|---|---|
| Low temperature cooler system | $\lambda_{clst}$ | $1.996x10^{-6}$ | $1.996x10^{-6}$ |
| | $MDT_{clst}$ | 0 | 0 |
| | $R_{clst}$ | 0.999 | 0.999 |
| | $MTTF_{clst}$ | 1002004 | 1002004 |
| Piping system | $\lambda_{pi}$ | $7.93x10^{-6}$ | $0.0005X10^{-6}$ |
| | $MDT_{pi}$ | 8 | 0 |
| | $R_{pi}$ | 0.9961 | 0.9999 |
| | $MTTF_{pi}$ | 126103 | $4x10^{9}$ |
| Human error | $\lambda_h$ | 0.001 | - |
| | $R_h$ | 0.6 | - |
| Sea water central cooling system | $\lambda_{swccs}$ | $11.05x10^{-6}$ | $11.36X10^{-6}$ |
| | $MDT_{swcc}$ | 0 | 0 |
| | $R_{swccs}$ | 0.5673 | 0.9914 |
| | $MTTF_{swc}$ | 991.16868 | 102685 |

**Table 5. Benchmarking of the formal system and the approved model**

detection, abnormal vibration detection. The system should be equipped with an autonomous back-flushing of LTFWCL's and sea chests. Daylight and infrared cameras should be installed for video monitoring. All routine maintenance and repair tasks must be scheduled to be carried out when the vessel is in port. A repair team embarks on board to carry out the scheduled jobs, based on the planned maintenance system (PMS) and the CBM early detection failures. The mean time to repair (MTTR) must be reduced. Based on our study of SWCCS study on board of the ships, and the interview of the crew members, we present in Table 4, the MTTR and place of repair of the system components. To minimize the MTTR, MDT, and to avoid the off-hire cost, a repair check list, repair procedures, test and trial procedures must be established to avoid the delay of departure and human errors. Necessary spare parts and tools must be available and prepared in advance.

### E. Sea water central cooling system, energy saving

On board of CS, The SWCPP's runs continuously at their nominal speed independently of the cooling SW temperature and the needed capacity. The LTFW temperature is adjusted by a tree-ways valve installed in the FW cooling system and regulate the amount of the FW to be passed through the LTFWCL, which result in a loss of energy and an increase of fuel oil consumption. For an optimal energy-saving, the SWCPP's may be provided with driver speed controller, to adjust the pump speed depending on the cooling capacity needed and the SW temperature, which result in energy consumption decrease. As the SCPP's have capacity of 380 $M^3$/H, the GSPP has a capacity of 180$M^3$/H and the EJPP has a capacity of 42 $M^3$/H, a special program might be elaborated to choose the pump to be put in service, depending on the needed cooling capacity. This solution might save energy without extra cost and complicity of the system.

### F. Benchmarking of both system

The table 5, presents a benchmarking of the formal system fig.2, and the proposed model fig.5. The result values, which are presented in the table, are obtained by adopting the same calculation approach for both systems. The values are calculated by replacing the equation parameters by their values from the table 3. The values presented in table 5, show an improvement of system reliability by enhancement of redundancy of components and elimination of human on board.

## CONCLUSION

The SW central cooling system is one of the vital systems. Special attention should be paid at the design stage and during operation. The proposed SW central cooling system model demonstrates a high reliability, and can operate safely on board of autonomous ship, where the equipment must run without human intervention for an interval of 500 h. The enhancement of the reliability at the design stage can be supplemented by improvement of the reliability during operation of the system by intelligent CBM. The study in perspective, consists of the elaboration of an algorithm for an autonomous system operation, and to have the possibility to be controlled remotely, or to be recovered in case of "fail to safe".

## REFERENCES

[1] EMSA, Annual overview of marine casualties and incidents, 2016, European Maritime Safety Agency.

[2] http://maritimeaccident.org/tags/sea-water-cooling-system/.

[3] S. Kleinmann, R. Stetter, S. Mohan, A. Dabrowska, D. Leonardo, and A. Koller-Hodac, “Advanced Diagnosis of Industrial Pump Systems” 8th IFAC Symposium on Fault Detection, Supervision and Safety of Technical Processes (SAFEPROCESS), August 29-31, 2012. Mexico City, Mexico.

[4] R. Menis, A. da Rin, A. Vicenzutti, and G. Sulligoi, “ Dependable Design of All Electric Ship Integrated Power System: Guidelines for System Decomposition and Analysis”, 978-1-4673- 1372-8/12/$31.00 ©2012 IEEE.

[5] D. W. Handani, K. Ishida, S. Nishimura, and S. Hariyanto, “System Dynamics Simulation for Constructing Maintenance Management of Ship Machinery”, Proceedings of 2011 IEEE IEEM.

[6] Qiang Fu, Lin Tian, Rui Wang, Yupei Ning, Yue Yang, and Xuejun Xie, “Corrosion and Protection of the Condenser Seawater Cooling System”, 3rd International Conference on Material, Mechanical and Manufacturing Engineering (IC3ME 2015).

[7] Chun-Lien Su, Wei-Lin Chung, and Kuen-Tyng Yu, “An Energy-Saving Evaluation Method for Adjustable-Frequency Drives on Sea Water Cooling Pumps on Ships”,978-1-4673-5242-0/12/$31.00 © 2013 IEEE.

[8] Ornulf Rodseth, and Hans-Christoph Burmeister, Report D10.2: New ship design for autonomous vessels, Maritime Unmanned Navigation through Intelligence in Networks (MUNIN),July 2015.

[9] David J. Smith, Reliability Maintainability and Risk, Seventh edition, Elsevier 2005.

[10] B.S. Dhillon, Reliability, Quality, and safety for engineers, CRC press, 2005.

[11] Nobuo Kiriya, Statistical study on reliability of ship equipment and safety management -Reliability estimation for failures on main engine system by ship reliability database syste Bulletin of the JIME, Vol. 29. No.2, October 2001.

[12] Naval Surface Warfare Center, Handbook of reliability of prediction procedures for mechanical equipment, CARDEROCKDIV, NSWC-98/LE1, September 30, 1998.

[13] L. C. Cadwallader, Failure rate data analysis for high technology components, Eighth international topical meeting on nuclear applications and utilization of accelerators, July 2007.

[14] E. M. Brocken, “Improving the reliability of ship machinery, a step toward unmanned shipping”, DELFT university of technology, November 16, 2016. http://repository.tudelft.nl/.

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