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## A method for assessing of ship fuel system failures resulting from fuel changeover imposed by environmental requirements

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### Highlights

- Low sulfur fuels influence the failure rate of fuel injection system components.
- Failures were analyzed as related and not related to SECA fuel changeover.
- Quantitative and qualitative failure analysis was performed.
- Two markers were proposed for the quantitative assessment of failure frequency.
- Qualitative assessment was done by the adoption of three failure severity levels.

### Abstract

Environmental regulations instigated the technological and procedural revolution in shipping. One of the challenges has been sulfur emission control areas (SECA) and requirement of fuel changeover. Initially, many reports anticipated that new grades of low sulfur fuels might increase various technical problems in ship operation. This research develops a simple and easy to use method of the failure severity and intensity assessment in relation to fuel changeover. The scale of failure rate in the ship's fuel system was evaluated qualitatively and quantitatively, using developed failure frequency indicator and the time between failure. Based on 77 records of fuel system failures collected on seven ships, it has been found that frequency of failures related to SECA fuel changeover is on average nearly three times higher compared to the rest of sailing time. Their severity did not significantly change, but the structure of failures changed considerably. The method and presented results may help in improvement of ship's systems design and on-board operational procedures.

### Keywords

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failure frequency, fuel changeover, fuel system failure, emission control area.

## 1. Introduction

Established by Annex VI to MARPOL 73/78 Convention [18], sulfur emission control areas (SECA) followed by the global stepwise limitation of sulfur content in marine fuels, resulted in several changes in ship construction, performance and operation. Fuel oil bunkering and storage systems had to be redesigned and some fuel oil tanks had to be designated for low sulfur fuel oils (LSFO) storage [6, 12, 23, 34]. In many cases, additional cylinder oil storage and supply systems had to be provided to allow smooth and safe fuel changeover [24–26]. Additionally, the engine cylinder components, like pistons and pistons rings, had to be modified [27] to improve the engine reliability and sustainability when operating on fuel grades different from the design. An example of such modifications is the high temperature cylinder cooling system, which was introduced on very long stroke engines around the year 2014 to counteract a low temperature corrosion, and was later recommended to be deactivated for engines enduringly consuming fuel oil with 0.5% of sulfur or less [28]. All those examples show the difficulties and complexity of problems related to low sulfur fuels faced by equipment makers, shipowners and, finally, the crew. Crews in particular are burdened with additional maintenance and adjusting work, and in case of machinery failure, with extra service work [13].

After the first SECA, covering initially the Baltic Sea and the North Sea, was established, soon other were implemented in various regions of the world, starting from the North America and some regions of the Caribbean Sea, to a number of Chinese ports. That resulted in frequent fuel changeovers from high sulfur fuels used in the open ocean passage to low sulfur residual fuels or even low sulfur distillate fuels [24]. The past few years have witnessed the introduction of another fuel grade called ultra-low sulfur fuel (ULSFO), or hybrid fuel, being a stabilized blend of very low sulfur distillate fuel with residual fuel.

Low sulfur fuel oils have different properties, especially viscosity, stability and lubricity, compared to typical high sulfur fuel oils [1, 12, 34]. Viscosity, which is directly dependent on fuel temperature, may play a key role in failures of fuel injection system components [5, 6, 26]. Most of the engine arrangements could not be quickly adapted to the use of low sulfur fuels [2, 13, 29]. Consequently, ship operators faced significant problems with machinery operation and the number of reported incidents related to fuel changeover raised significantly [3, 13, 17].

To safely perform a fuel changeover, shipping companies and ship's crew developed and implemented new procedures [19, 24]. The time required for the proper and safe procedure depends mainly on the sulfur content in the high and low sulfur fuels to be altered, the en-

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gine load, and finally the fuel system volume to be flushed [6, 13, 23, 24, 26]. At least one of those parameters, namely, the engine load, is variable and depends greatly on the weather and nautical conditions, consequently, the entire procedure may take from a few hours up to two or three days even. The initial phase of changeover is crucial for the machinery and consequently ship safety. It has to be carried out slowly and with utmost care to avoid rapid changes in fuel temperature and viscosity [13, 23, 26, 36]. During this phase, the fuel pipes trace heating has to be stopped, the fuel viscosity controllers usually have to be set to manual mode and the fuel temperature gradually reduced to maintain a safe fuel lubricity level. One of the frequent problems is the deposit formulation during mixing of different fuel grades boosted by altering temperature, which leads to clogging of filters and disturbances in viscosimeter readings [21].

Even so, it is observed that despite the utmost care during fuel changeover, ship fuel systems suffer an increased number of incidents related to the malfunction of equipment, chiefly filters, centrifuges, heaters, and engine fuel injection components.

Legislative bodies, such as the International Maritime Organization (IMO), the European Union (EU), or port state authorities, impose increasingly stricter environmental requirements on sea-going ships. The necessity to reduce environmental pollution is beyond dispute. However, no means exist to verify the impact of the applied legal requirements on the technical condition of ships, their safety and reliability.

Increasingly complex and demanding devices to reduce the emission of harmful substances into the environment are being installed on ships. Ship crews are burdened with additional duties related to their operations and new environmental procedures. Shipowners do not have any incentives to increase the number of crews beyond the safety regulations and economic demand. Consequently, the risk of machinery failure or an accident may rise [6].

Although legislators make efforts to monitor and control the process of adopting new regulations, the main focus is on compliance verification and the influence on economy. For example, most classification societies issued dedicated fuel changeover guidelines for shipping companies and ships' staff [2, 12]. The European Maritime Safety Agency (EMSA) regularly issues updates to sulfur inspection guidance [14]. Problems widely analyzed by the states are the economic impact and low sulfur fuels availability. A number of related publications and reports were issued over the last decade [4, 8, 10, 15, 16, 31]. However, there are few reports or research publications analyzing the problem of machinery reliability and failure intensity related to the fuel changeover procedures. Statistics published by the French Ministry of Environment revealed that in 2015 the number of reported loss of power incidents in the English Channel doubled compared to the previous year [17]. The positions of ships report-

ing incidents suggest that they may be related to fuel changeover on entering or leaving SECA. Very similar increase in the loss of power was observed in 2019 in California after the California Air Resources Board regulation entered into force [17]. Some accidents, especially those leading to injuries or severe loss in property or environment, are reported to authorities and after investigation reports are made public [37]. However, information is scarce about the number of failures which were not officially reported. Is there a similar rate of failures compared to the pre-SECA conditions? Regulators, interested in meeting the requirements by ships, should also have ship safety and reliability in focus. Proper feedback may and should be taken into account when a regulation is revised or updated, and/or guidance for procedures is being prepared. However, the record of officially reported accidents may be insufficient. There are multiple cases of different malfunctions and incidents that have never been reported to organizations other than the shipowner's company, while each such case may trigger a chain of events leading to disaster. The newly introduced regulations have their consequences: those expected, but also unexpected side effects. Assessing possible negative consequences may play a key role in improving ship safety.

In this research, the frequency of failures and malfunctions in the ship fuel systems related to fuel changeover, including engines, supply, and injection system, was analyzed and compared to the frequency of similar incidents occurred during engines operation on one grade of fuel only.

## 2. Analysis object and method

Statistical data were collected on seven merchant ships of various types and capacity: four container carriers and three multipurpose general cargo vessels (Table 1). During the period of observation, four ships were not older than three years, while the remaining three ships were 8 to 10 years old. The selected ships entered a SECA at least once during the observation period. Because the trading areas cover almost all the oceans and to simplify the nomenclature, the SECA in this research means all areas where the limits of sulfur content in marine fuels were imposed, especially: Northern Europe, North American coast, Caribbean Sea region and Chinese Pearl River Delta, Yangtze River Delta and Bohai Bay. The deck and the engine logbooks of each ship were analyzed to determine the exact time of fuel changeover commencement and completion when entering and leaving SECA.

Due to the relatively long observation period, starting in 2010 for ship A and ending in 2020 for ship G, the requirements for SECA differ depending on the actual date and port of call. Consequently, the fuel grades used on board the selected ships also differed according to the evolution of sulfur limits inside and outside SECAs (Table 1).

Table 1. Basics of the analyzed ships and their voyages

| Ship | Year and place of build | DWT, tons | Propulsion type | Period of observation | Fuel grades used  | Number of SECA calls |
|------|-------------------------|-----------|-----------------|-----------------------|-------------------|----------------------|
| A    | 2010, China             | 50300     | Direct, FPP     | Jan 2010 – Sep 2012   | HSHFO/LSHFO/LSMGO | 7                    |
| B    | 2014, China             | 60550     | Direct, FPP     | Jun 2014 – Oct 2014   | HSHFO/LSHFO/LSMGO | 4                    |
| C    | 2012, South Korea       | 145451    | Direct, FPP     | Mar 2015 – Jul 2015   | HSHFO/LSMGO       | 2                    |
| D    | 2014, South Korea       | 149360    | Direct, FPP     | May 2015 – Jul 017    | HSHFO/LSMGO       | 38                   |
| E    | 2009, China             | 7811      | Indirect, CPP   | Apr 2017 – Jul 2017   | HSHFO/LSMGO       | 5                    |
| F    | 2011, China             | 5646      | Indirect, CPP   | May 2018 – Apr 2019   | HSHFO/LSMGO       | 6                    |
| G    | 2010, China             | 12940     | Indirect, CPP   | Mar 2020 – Jul 2020   | LSMGO/ULSHFO      | 4                    |

DWT – deadweight tonnage  
HSHFO – high sulfur residual fuel (as defined in the regulations currently in force),  
LSHFO – low sulfur residual fuel,  
LSMGO – low sulfur marine gasoil  
ULSHFO – ultra low sulfur residual fuel (hybrid fuel)  
CPP – controllable pitch propeller  
FPP – fixed pitch propeller

All selected ships, except ship A, were calling SECA regularly. The trading area of ship A was outside the SECA for the first two years of the analyzed period, followed by a series of voyages between Central America and the European SECA in 2012, therefore most of identified on this ship failures is not related to SECA fuel changeover.

Because the fuel system malfunction may occur with some delay after the fuel changeover procedure is accomplished, it was arbitrarily decided that the incident is related to fuel changeover if it occurs after the commencement of the procedure, not later than three days after its completion. All other incidents are assumed as not directly related to the fuel changeover procedure. With that assumption, callings at SECA lasting over six days were assigned six to seven days of observation per each calling, depending on the time required for completion of the changeover procedure. That was frequent case for ships calling at ports situated in the North Sea and Baltic Sea SECA region where typically more than one port were visited and the entire sea passage between them is within a single SECA. On the other hand, in case of short calls, less than three days in SECA, the time of observation was three to six days depending on the length of berthing time. This applied particularly to calls at a single port in North America, or, since January 2016, at Chinese ports in Pearl River Delta, Yangtze River Delta or Bohai Bay.

Based on the deck and the engine logbooks entries we determined the time of the fuel changeover observation  $T_{CO}$  and calculated the ratio  $R_o$  of observation time between the  $T_{CO}$  and the total observation time  $T_{tot}$ :

$$R_o = \frac{T_{CO}}{T_{tot}} \cdot 100\% \quad (1)$$

where:  $T_{CO}$  – time of the fuel changeover observation;  $T_{tot}$  – total observation time;  $R_o$  – ratio of observation time.

Similarly, the engine logbooks and other official reporting documents, like near miss reports, malfunction reports, damage reports and repair reports were analyzed for evidence of incidents related to ship fuel system failures. Identification of historical failures was frequently facilitated by ship's photo documentation, where an actual date of the failure was usually recorded. We also used monthly work reports – internal reports of the shipping companies. All identified failures were assigned the date and if possible, the time of occurrence. The study covered the entire fuel system: storage, transfer, purification, supply to the main engine, auxiliary engines and fired boiler, and finally the engine injection system. All routine service and maintenance work, such as time-based fuel injection pumps or fuel injection valves maintenance, was excluded from the analysis.

The proposed analysis makes use of some elements and techniques adopted from the reliability engineering [22, 32, 33], mainly Failure Mode and Effect Analysis (FMEA). Because of the varying nature and location of failures, it is practicable to group them with respect to the most relevant parameter [33, 38]. A similar method was applied in this study and the identified failures were classified into three classes of location:

1. Class A. Failure of the engine fuel injection system. This group includes malfunction of fuel injection valves (FIV), fuel injection pumps (FIP), high pressure injection pipes, and their safety system – leakage detection system for both main engine and auxiliary engines.
2. Class B. Failure of the fuel supply system. This group includes fuel supply and circulation pumps, fuel safety filters, fuel automatic filters, fuel preheaters and coolers, viscosity sensors, fuel supply pipes, and their tracing heating.
3. Class C. Failure of the fuel storage, transfer, and preparation system, including the purification system. This group includes mainly problems in storage, settling, or service tanks (sediments, contamination, foaming), difficulties with transporta-

tion related to fuel properties, contaminated filters, strainers, or purifiers and their preheaters.

The definition of failure is always problematic and a variety of approaches are proposed by different researchers [9, 20, 32, 35]. In essence, based on the ISO 8402 the definition of reliability [32], failure may be defined as the inability to perform a required function under given environmental and operational conditions and for a stated period of time. However, in ship service, situations occur where a component or subsystem is functioning, but the risk of accident or loss of property is very high. Such a situation is called a near miss incident. Therefore, for this research, a total inability to perform a function, as well as a near miss condition and malfunctions likely leading to a near miss are recognized as failures. Similar approach is described in the literature [7, 11].

For every recorded failure, the severity of its actual or possible consequences was evaluated too. Again, similarly to the definition of failure, there is no single universal definition of severity levels. For example, Morais [30] proposes a very simple classification into three levels of severity: no problem, moderate problems, and extreme problems, which seems to be very universal and applicable in various disciplines. However, in case of failure consequences analysis, the lowest of proposed levels may be inadequate. A more suitable definition was proposed by Kaidis [20], who related the severity levels to the required service time. Sasmito and Untung proposed a criticality of failure matrix with four categories of failure severity for the analyzed ship's fuel system [33]. In fact, severity should be individually defined to the needs of the specific problem. Therefore, in this work three levels of severity were defined:

1. High risk failure – when the vessel had to be stopped, departure was delayed or an auxiliary engine or fired boiler could not be started for at least one hour.
2. Medium risk failure – when the ship operation was not disturbed, but there was a direct and significant risk of disturbance leading to a high-risk incident, similar to a near miss condition.
3. Low risk failure – when the ship operation was not disturbed and there was no direct and significant risk of disturbance leading to a high-risk incident.

Of all identified failures, those related to the fuel changeover procedure were selected based on the date and time of occurrence. Additionally, they were evaluated by an experienced engineer on board the ship for possible relation to fuel changeover procedure. Even if it is unavoidable to have such evaluation biased by an individual and subjective judgment, the authors chose to do so as the risk of erratic qualification was thought to be lower when engineer's evaluation is done than when it is not. Finally, the number of failures related to fuel changeover  $n_{CO}$  and the total number of failures  $n_{tot}$  were used to calculate the ratio of failure occurrence  $R_{foc}$  for every individual ship and for the whole analyzed population:

$$R_{foc} = \frac{n_{CO}}{n_{tot}} \cdot 100\% \quad (2)$$

where:  $n_{CO}$  – number of failures related to fuel changeover observed during the time  $T_{CO}$ ;  $n_{tot}$  – total number of failures observed during the time  $T_{tot}$ .

Dividing the ratio of failure occurrence  $R_{foc}$  by the ratio of observation time  $R_o$ , we can determine the failure frequency indicator  $F_i$ :

$$F_i = \frac{R_{foc}}{R_o} \quad (3)$$

The failure frequency indicator  $F_i$  should be close to unity if the frequency of failures related to fuel changeover in SECA and the

overall failures frequency are similar. In case failures related to fuel changeover in SECA are more frequent, the value of  $F_i$  rises above unity. That makes the  $F_i$  very easy to interpret.

Additionally, the time between failures (TBF) was calculated for each class of failure and each ship using the formula:

$$TBF_{class, condition} = \frac{T_{condition}}{n_{class, condition}} \quad (4)$$

where: *class* – is the location of failure according to the presented classification A, B, C; *condition* – is the condition of observation: related to SECA fuel changeover or not related to fuel changeover;  $TBF_{class, condition}$  – time between failure of a specific class in a specific condition [days];  $T_{condition}$  – time of observation [days];  $n_{class, condition}$  – number of incidents of a specific class and in specific conditions.

For calculation of TBF related to SECA fuel changeover,  $T_{CO}$  was used in the formula (4) numerator, while to calculate TBF not related to SECA fuel changeover, the difference  $T_{tot} - T_{CO}$  was applied. This approach is different from the way the failure frequency indicator  $F_i$  is calculated, for which the time of the fuel changeover observation  $T_{CO}$  is divided by the total observation time  $T_{tot}$  instead of the difference  $T_{tot} - T_{CO}$ . That is mainly to bring the formula (4) as close as possible to the way the MTBF (mean time between failures) is calculated in the theory of reliability. However, the above defined TBF should not be understood as a typical MTBF. It is rather a quantitative estimation of the likelihood of a specific malfunction in specific conditions. By definition, the MTBF is calculated from the working time of the component, while in this study the *TBF* was evaluated from the failure-to-failure time span regardless of whether the component was running or stopped during that time. Moreover, the limited statistical sample makes the generalized result very uncertain to use the term MTBF.

### 3. Analysis of failure structure

77 failures were identified on all seven ships during the total observation time. Only one of them was officially reported to a Vessel Traffic Service (VTS) on the French coast, while the remaining 76 failures were just recorded in the ship's documentation; only 40 of them were also reported to the owner's office. The remaining 36 failures were only noted in the ship's documentation without any official reporting. The number of minor failures without sufficient documentation is not known, although evidence was found, like improperly described photos, that such failures also had occurred.

The structure of failures with respect to the affected component is presented in Table 2. The component with the highest number of recorded failures in class a is the fuel injection valve (FIV) with the

total 16 cases. The fuel injection pump (FIP) ranks second with 12 cases of failure recorded.

For the analyzed population of ships, there is no difference observed in the severity of FIV failure between related and not related to SECA fuel changeover (Fig. 1). However, it should be noticed, that the number of analyzed failures is only 16. It is very likely, that longer observation time or larger population of ships could reveal some differences.

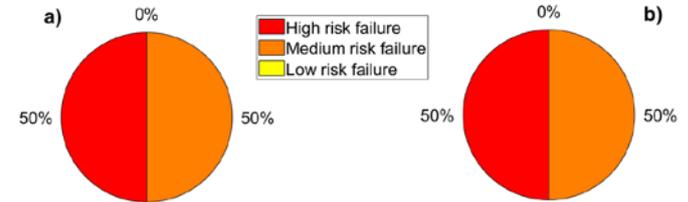


Fig. 1. Comparison of the FIV failures structure with respect to the failure severity: a) failures not related to SECA fuel changeover; b) failures related to SECA fuel changeover

It is symptomatic that due to the function of FIV, there are no low-risk failures observed at all. Once the FIV performance is deteriorated, it usually requires urgent or even immediate action. In most cases of high-risk failures, severe mechanical destruction of the FIV is observed, frequently accompanied by fuel leakage into the engine combustion chamber. Figure 2 depicts two different cases of two-stroke engine FIV with broken nozzle tips. The left-hand photo presents damage not related to SECA fuel changeover, while the damage presented in the right-hand photo was observed 20 hours after the fuel changeover procedure commencement. In both cases, the engine had to be stopped for FIV replacement.

An additional example is shown in Fig. 3, where the damaged FIV suffered a strong impact of exhaust gas blow-by through the seating. The failure occurred six hours after changeover from residual to low sulfur distillate fuel commencement while entering the European SECA. This specific incident resulted in damaged engine cylinder cover, temporary cut-out of the failed engine cylinder, and emergency steaming to the port of destination. That was the only officially reported incident in the entire analyzed population.

Generally, the most severe failure of FIP is the seizing of the plunger and barrel. It is nearly always qualified as a high-risk failure as it usually requires engine shutdown. It may be caused by inadequate fuel purifying or filtering. It also frequently happens as a result of a low viscosity and lubricity of the fuel, especially when the introduced distilled fuel has a low sulfur content or experiences a drastic decrease

Table 2. Comparison of the number of failures for classes of location A, B, C with respect to the affected components

| Affected component  | Number of failures not related to SECA fuel changeover |         |         | Number of failures related to SECA fuel changeover |         |         |
|---------------------|--|---------|---------|--|---------|---------|
|                     | Class A  | Class B | Class C | Class A  | Class B | Class C |
| FIP                 | 7  | -       | -       | 5  | -       | -       |
| FIV                 | 10   | -       | -       | 6  | -       | -       |
| HP pipes            | 3  | -       | -       | -  | -       | -       |
| Return/supply pipes | 5  | 3       | -       | -  | 3       | -       |
| Pumps               | -  | 5       | -       | -  | 1       | -       |
| Filters             | -  | 8       | 1       | -  | 7       | -       |
| Tank contamination  | -  | -       | 2       | -  | -       | 1       |
| Purifiers           | -  | -       | 1       | -  | -       | 4       |
| Tank structure      | -  | -       | 1       | -  | -       | -       |
| Heating and tracing | -  | -       | 2       | -  | -       | -       |
| Tank level sensor   | -  | -       | 2       | -  | -       | -       |



Fig. 2. FIV nozzle tip damages assigned to the high risk failure group: left-hand photo – failure not related to SECA fuel changeover; right-hand photo – failure related to SECA fuel changeover



Fig. 3. High risk damage of FIV related to SECA fuel changeover, i.e. seating burnt out by combustion gas blow-by

in viscosity due to excessively high temperature. This effect can be significantly accelerated by a large amount of heat accumulated in the elements of injection pumps during the changeover from residual to distillate fuels. Most of the engines accept the distillate fuel kinematic viscosity not lower than 2-3 mm<sup>2</sup>/s, which means that the temperature of the distillate fuel supplied to the engine should be maintained below 50°C. But the temperature of the residual fuel frequently exceeds 140°C. Consequently, during changeover the viscosity of the distillate fuel may drop below that recommended by the engine maker. Even more problematic is the changeover from distillate to residual fuels. If the warm-up process is too fast, the plunger expands faster than the barrel, causing a dangerous decrease of a very fine clearance required for movability of the elements, frequently resulting in seizures [26].

For the analyzed population of ships, most FIP failures were qualified as high or medium risk (Fig. 4), but the share of high-risk failures requiring immediate engine shutdown raised from 29% to 50% in relation to SECA fuel changeover. An example of a FIP plunger damage occurred during rapid fuel changeover is shown in Fig. 5.

Observed medium risk failures were usually FIP non-return valve malfunctions or moderate fuel leaks. In one case it was short stuck of the plunger and barrel which became movable after a few seconds. The FIP was replaced in the next port, a few days after the incident.

The only case of low-risk failure observed in a group of failures not related to SECA fuel changeover (Fig. 4a) was a fuel leakage through an internal seal resulting in minor lubricating oil contamination.

Other components of the fuel system with a sufficient number of recorded failures are the filters in the supply system of failure class b. Surprisingly, in the analyzed population of ships, the severity structure of filter failures due to SECA fuel changeover or other causes is much different than expected. Seafarers, when interviewed, tend to complain about the incompatibility of different fuels grades and frequent problems with filter clogging, formation of sediments, and extreme gasification. The graphs presented in Fig. 6 do not confirm that the severity of those problems is greater when fuel is changed over in SECA compared to the severity of similar incidents during changeover of fuel not related to SECA. However, the frequency of problems with proper filtration is still higher

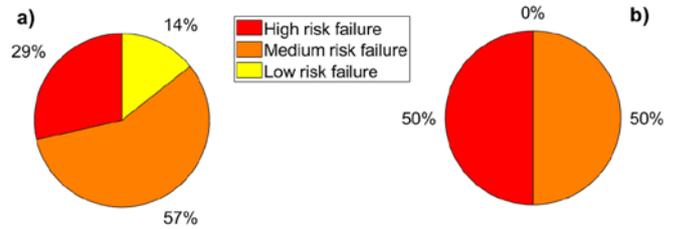


Fig. 4. Comparison of the FIP failures structure with respect to the failure severity: a) failures not related to SECA fuel changeover; b) failures related to SECA fuel changeover



Fig. 5. Fuel injection pump plunger seizure occurred during rapid fuel changeover from residual to low sulfur distillate fuel

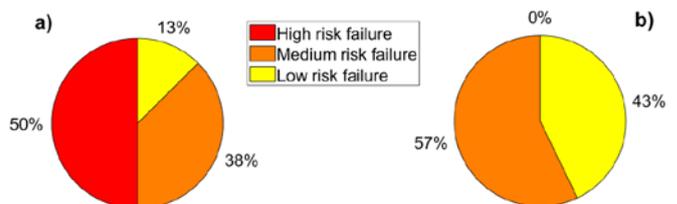


Fig. 6. Comparison of the fuel filter failures structure with respect to the failure severity: a) failures not related to SECA fuel changeover; b) failures related to SECA fuel changeover

in SECA related group. It is possible that the ship crew is much more careful and prepared for possible problems when fuel changeover is carried out in SECA, which results in the actual elimination of high-risk failures. Nevertheless, in the proposed analysis this hypothesis has not been verified.

#### 4. Results and discussion

The total observation time  $T_{tot}$  of the selected population of ships was 2652 days. During this time the analyzed ships entered SECA with various frequencies, and the time spent in SECA differed from single days to a week or more. Consequently, the individual ship observation time ratio  $R_o$  calculated by formula (1) varied from 4.4% to 19.8%. The observation time ratio was also calculated for the entire population of the analyzed ships:

$$R_{ofleet} = \frac{\sum_i T_{COi}}{\sum_i T_{toti}} \cdot 100\% \quad (5)$$

where:  $T_{COi}$  – time of the ship  $i$  fuel changeover observation;  $T_{toti}$  – total observation time of the ship  $i$ .

The overall span of  $R_o$  is only 15.4 %, with the fleet observation time ratio  $R_{ofleet}=11.9\%$  (Table 3), which indicates that no extreme differences existed between ships in the intensity of callings at SECA.

After thorough verification of available documentation, 27 failures were qualified as failures related to fuel changeover during entering or leaving SECA. Failures occurred during routine changeover of the

Table 3. Comparison of the total observation time  $T_{tot}$  and time of changeover observation  $T_{CO}$  for the analyzed ships

| Ship         | $T_{tot}$ , day | $T_{CO}$ , day | $R_o$ , % |
|--------------|-----------------|----------------|-----------|
| A            | 958             | 42             | 4.4       |
| B            | 127             | 22             | 17.3      |
| C            | 141             | 12             | 8.5       |
| D            | 801             | 158            | 19.7      |
| E            | 111             | 22             | 19.8      |
| F            | 357             | 36             | 10.1      |
| G            | 157             | 24             | 15.3      |
| Total        | 2652            | 316            | -         |
| $R_{ofleet}$ |                 |                | 11.9      |

same grades of fuels from different bunker suppliers, but those not related to entry or leaving from SECA were not assigned to this group. The number of failures, divided into three classes: a, b or c, and into groups of related and not related to SECA fuel changeover, are presented in Table 4.

Based on the number of failures identified for each ship (Table 4), the ratio of failure occurrence  $R_{foc}$  was calculated with formula (2). Similarly to the observation time ratio, the results varied, but the span was much wider: from 12% to 83.3% (Table 4). For each ship except ship E, the values of  $R_{foc}$  are significantly higher than  $R_o$ . The average  $R_{foc}$  for all ships (35.1%) is nearly three times higher than the overall average of  $R_{ofleet}$  (11.9%). This indicates that for the analyzed population of ships, failures in the fuel system were observed on average three times more frequently during fuel changeover in SECA compared to the total average frequency.

Table 5. Comparison of average TBF for classes of location A, B, C of failure related and not related to SECA fuel changeover

| Ship    | TBF not related to SECA fuel changeover, day |         |         | TBF related to SECA fuel changeover, day |         |         |
|---------|--|---------|---------|--|---------|---------|
|         | Class A                                      | Class B | Class C | Class A                                  | Class B | Class C |
| A       | 65   | 305     | 183     | 21                                       | 42      | -       |
| B       | 105  | 105     | -       | 11                                       | 22      | -       |
| C       | 43   | 129     | -       | -  | 4       | -       |
| D       | 92   | 129     | 322     | 40                                       | 53      | 40      |
| E       | -  | 30      | 89      | -  | 22      | -       |
| F       | -  | 161     | 321     | 36                                       | -       | -       |
| G       | -  | 133     | -       | 12                                       | 12      | 24      |
| average | 76   | 142     | 229     | 24                                       | 26      | 32      |

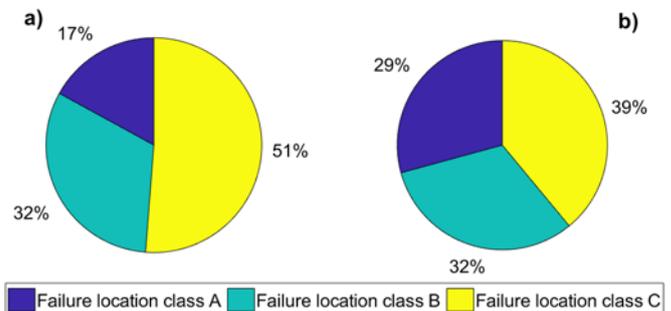


Fig. 7. Comparison of the failures structure with respect to the failure location class: a) failures not related to SECA fuel changeover; b) failures related to SECA fuel changeover.

Table 4. Number of failures related and not related to fuel changeover in SECA

| Ship   | Number of failures not related to SECA fuel changeover ( $n_{tot} - n_{CO}$ ) |         |         | Number of failures related to SECA fuel changeover $n_{CO}$ |         |         | Ratio of failure occurrence $R_{foc}$ , % | Failure frequency indicator $F_i$ |
|--|---|---------|---------|---|---------|---------|---|-----------------------------------|
|  | Class A   | Class B | Class C | Class A   | Class B | Class C |   |                                   |
| A  | 14  | 3       | 5       | 2   | 1       | -       | 12.0                                      | 2.7                               |
| B  | 1   | 1       | -       | 2   | 1       | -       | 60.0                                      | 3.5                               |
| C  | 3   | 1       | -       | -   | 3       | -       | 42.9                                      | 5.0                               |
| D  | 7   | 5       | 2       | 4   | 3       | 4       | 44.0                                      | 2.2                               |
| E  | -   | 3       | 1       | -   | 1       | -       | 20.0                                      | 1.0                               |
| F  | -   | 2       | 1       | 1   | -       | -       | 25.0                                      | 2.5                               |
| G  | -   | 1       | -       | 2   | 2       | 1       | 83.3                                      | 5.4                               |
| total  | 25  | 16      | 9       | 11  | 11      | 5       | -   | -                                 |
| Average value for entire population of ships |   |         |         |   |         |         | 35.1                                      | 2.9                               |

The TBF calculated with formula (4) and presented in Table 5 is even better indicator of SECA fuel changeover influence on the machinery reliability. The average TBF related to SECA fuel changeover is three to seven times shorter for each class of location: A, B, and C, compared to the TBF not related to SECA fuel changeover. Moreover, for every individual ship and class of location, TBF related to SECA fuel changeover is shorter. The structure of the failures is different, too (Fig. 7). The share of the fuel injection system failures (failure class a) increased from 17% of the total not related to SECA fuel changeover cases to 29% of related to SECA fuel changeover cases. While the share of failure class b of the fuel supply system remains unchanged (32%), the share of failures in the fuel storage and preparation system dropped when fuel is changed over in SECA from the initial 51% to 39%. The presented results suggest that the fuel changeover in SECA affects the injection system rather than the fuel storage and preparation system. However, the problems in the latter system are likely to occur prior to the actual commencement of the fuel changeover procedure, mostly due to the necessity to commence new fuel preparation well in advance: preheating, purifying, and transfer. The method used in this research does not allow confirming this hypothesis and should be verified in a separate research.

## 6. Conclusion

The presented analysis is aimed at emphasizing the problem of technical consequences related to the changeover to low sulfur fuel while entering or leaving SECA. The population of analyzed ships is not numerous to draw a generalized conclusion for the larger fleet. However, even for a small sample, differences are observed between the failure frequencies and time between failures of specific components. The presented analysis results and the method of data processing is a proposal highlighting the fuel oil changeover problem rather than a general recommendation.

The proposed method of analysis allows for both quantitative and qualitative assessment. There are two indicators proposed for the quantitative assessment of failure frequency. The failure frequency indicator  $F_i$  allows us to assess promptly and easily whether the failures occur more or less frequently in relation to SECA fuel changeover. For all the examined ships, the individual  $F_i$  is greater than 1. The average for the entire population is  $F_i=2.9$  (Table 4), which suggests that the likelihood of failure in the fuel oil system is on average nearly three times higher while entering or leaving SECA compared to the entire operation time of all analyzed ships. Presented in Table 5, the values of time between failure  $TBF$  correspond with  $F_i$ . In the group of failures related to SECA fuel changeover, the average  $TBF$  is 24, 26, and 32 days for the respective failure location class A, B and C, compared to  $TBF$  not related to SECA fuel changeover, 76, 142 and 229 days, respectively. It means that in the analyzed population of ships, the  $TBF$  related to SECA fuel changeover is threefold shorter in the failure location class A, over fivefold less in the failure location class B, and seven times shorter in the failure location class C.

The qualitative assessment was achieved by the adoption of the failure severity metrics, where three levels of severity were defined: low, medium, and high. While failures of nearly all analyzed components in all classes are observed much more frequently when the

ship enters or leaves SECA compared to the frequency of failures not related to SECA fuel changeover, the observed severity of failures is not necessarily increased in relation to SECA fuel changeover. Due to the limited amount of data, only failures of three components: FIP and FIV of failure location class A, and fuel filters of failure location class B were analyzed qualitatively. Only in case of FIP, the share of high-risk failures grew from 29% to 50% with a simultaneous decrease of low-risk failures from 14% to 0%. For the remaining two components, namely FIV and filters, no increase in failure severity was observed. The presented qualitative results, due to the relatively small samples of the input data, show only the feasibility of the analysis rather than the overall conclusion for the larger fleet.

In the proposed method, most data were derived from the ship's internal records. Only one out of 77 failures qualified in the research were officially reported to the authorities, which shows the scale of unknown technical problems faced by the ships and their crews. It also proves that there is a space for improvement in terms of technical monitoring procedures.

In this research, the fuel system was chosen as an example. However, there are also other systems and machinery on board the ship which may be affected by the fuel changeover, like exhaust gas system, heating system, boilers, main and auxiliary engines. It might be especially important to establish how the specific low sulfur fuel grades influence the machinery reliability during changeover. Unfortunately, the insufficient population of seven ships prevents effective analysis. The proposed method is very flexible and may be easily adapted to the specific needs of any ship system or machinery and to any existing or future regulatory requirements.

Even if the applied methods are very simple, they proved to be effective: similar methods are used in industrial reliability analyses. The simplicity is a great advantage in this case. Availability of source data should not pose any difficulty, the utilized data are relatively easy to access on every sea-going ship, so what remains is standardized processing. Moreover, the crew engaged in data collection should not be burdened with additional work, provided a standardized and anonymized system of reporting failures, damage and incidents is introduced. Such a uniform system would probably significantly facilitate the process for crews by elimination the need to learn new procedures of reporting when changing the shipowner.

In the Authors opinion, a similar approach might be a good tool for a large-scale analysis. Information derived may be useful for fleet operators, the authorities and legislators, and especially for ships and machinery designers. Proper cooperation of ship operators, designers, shipbuilders, policymakers, authorities and ship personnel is crucial for effective and safe introduction of new environmental policies.

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