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Risk Analysis of Tugboat Cooling System Using FSA and FMEA Based on Accident Data

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Abstract: Tugboats play an essential role in port activities, but their cooling systems are vulnerable to failures that can potentially trigger serious accidents. This study aims to analyze the risks of tugboat cooling systems through a Formal Safety Assessment (FSA) using the Failure Mode and Effects Analysis (FMEA) method based on field surveys and accident data. Data collection was conducted via questionnaires to 12 engine room crew (including the Chief Engine Room Officer, Engineer, and Technician) and the accident investigation report of TB. Kawan Kita XI (2025), which was used as external validation by cross-referencing the documented failure causes with the high-priority FMEA result. This study identified 14 failure modes in 9 key components of the cooling system, assessed based on severity (Severity), frequency (Occurrence), and detection (Detection) on a scale of 1–10. The average value of the 12 respondents was used to calculate the Risk Priority Number (RPN) and Pareto analysis. Key findings revealed six priority risks: mechanical seal leakage (RPN=405), cylinder head cooling jacket cracking (RPN=300), freshwater pump bearing failure (RPN=243), sea chest strainer corrosion (RPN=216), temperature control valve sticking (RPN=216), and internal cooler leakage (RPN=168). These six modes accounted for 82.6% of the total risk, consistent with the Pareto principle. The uniqueness of this study lies in the integration of multi-vessel survey data, a more accurate 1–10 rating scale, and validation from actual accidents. Recommendations include preventive seal replacement, installation of leak sensors, regular valve maintenance, and anti-corrosion protection. This study contributes to strengthening the operational safety of tugboats in Indonesia.

Keywords: FSA; FMEA; cooling system; tugboat; risk analysis

1. Introduction

Tugboats play a crucial role in port operations, assisting large vessels during berthing, undocking, and towing. The reliability of a tugboat's main engine is crucial [1], and the cooling system is crucial for maintaining ideal operating temperatures by removing combustion heat. A closed cooling system consisting of freshwater and seawater circuits protects the engine from corrosion [2].

Data on tugboat accidents in Indonesia is alarming. A towing service company in Surabaya reported an increase from three incidents in 2021 to four in 2022 and 2023, including collisions, groundings, and sudden engine

failure [3], [4]. The TB. Kawan Kita XI accident (2025) provided valuable validation data for this study, as five failure mode identified in the FMEA were directly observed in that accident report. An empirical study of the Kresna 315 tugboat using FMECA revealed that approximately 30% of failure modes were high-risk, with critical components such as the seawater pump, cooling pipes, and coolers [4]. Field reports also noted that strainers and auxiliary coolers frequently clogged, requiring annual repairs [5]. These facts confirm that cooling system failures on tugboats are not a terrorist threat, but rather a real problem that requires systematic handling.

Previous studies have identified several

critical components. Lindyawati et al. (2025) used FMEA to identify three critical components in the main engine cooling system, namely the seawater pump, heat exchanger, and freshwater pump [6]. Risk analysis of the main engine support system was developed using Fuzzy FMECA [7], and FMEA has been applied to the cooling pumps of fishing vessels to determine maintenance strategies [8]. Siswantoro et al. (2020) assessed criticality with Fuzzy FMECA which is in line with the methodology of this study [7], while Siahaan et al. (2025) identified impeller corrosion as the highest RPN mode [8].

However, there are still research gaps. First, most previous studies used a 1–5 rating scale, which limits the differentiation of RPN. Second, previous studies relied on data from a single vessel, thus reducing generalizability. Third, no previous studies have validated FMEA findings with actual accident data. This study addresses these gaps by: (1) using a 1–10 scale, (2) collecting data from 8 different tugboats, and (3) cross-validating failure modes with TB. Kawan Kita XI.

Other studies reinforce the importance of risk analysis on tugboats. Zaman et al. (2020) applied Reliability Centered Maintenance (RCM) to the Kresna 315 cooling system [4]. Gasca et al. (2023) identified 473 potential failures on tugboats, with 17 high-risk failures, mostly in the engine cooling system [9]. Gürgen & Ada (2025) used a fuzzy-based FMEA on a tugboat towing system, identifying 23 failure modes, including three critical risks [10]. These findings further confirm that the FMEA approach is very effective for tugboat risk analysis.

To analyze these risks, Formal Safety Assessment (FSA) is a structured methodology recommended by International Maritime Organization to strengthen maritime safety through hazard elimination, risk assessment, and risk control options [11]. This study implemented Steps 1 (Hazard Identification) and 2 (Risk Assessment) of the FSA frameworks. Steps 3 (Risk Control Options) and 4 (Cost-Benefit Assessment) are recommended for further research. Meanwhile, Failure Mode and Effects Analysis (FMEA) offers a systematic approach to uncovering potential failure modes

along with their causes, impacts, and calculations. Risk Priority Number (RPN) as a reference for intervention priorities [12]. This study used a 1-10 assessment scale which provided an RPN range of 1-1000, which was more accurate than the 1-5 scale because it allows finer differentiation of risk priorities and reduces central tendency bias.

The Pareto principle (80/20 rule) states that approximately 80% of the effects come from 20% of the causes [13]. In the context of risk assessment, this principle implies that a small number of failure modes contribute to a large portion of the total risk. By applying Pareto analysis to RPN values, maintenance resources can be focused more efficiently on critical components.

Based on the existing research gaps, namely limited empirical data from ship crews and minimal use of the 1-10 scale on tugboats, this study aims to analyze the risks of tugboat cooling systems using the FSA-FMEA approach that integrates three main data sources: (1) literature collection, (2) library studies from previous studies [3][4],[10] and (3) questionnaire surveys from engine room crews from various tugboats.

2. Materials and Methods

2.1 Research Object

The object of this research is the main engine cooling system of a tugboat operating in Indonesian waters. The cooling system analyzed includes a freshwater circuit and a seawater circuit with nine main components: sea chest & strainer, seawater cooling pump, freshwater cooling pump, freshwater cooler, expansion tank, temperature control valve, piping & connection, cylinder head cooling jacket, And lubricating oil cooler.

2.2 Data Collection

Primary data were collected through a questionnaire distributed to 12 respondents, including Chief Engineer Officers, Chief Engineers, Second Engineers, Third Engineers, Masters, and Port Engineers, all of whom had 4–25 years of work experience and were directly involved in addressing cooling system issues.

Respondents came from eight different tugboats operating in Indonesian waters. Table 4a presents detailed respondent profiles, including position, years of experience, vessel type, and role in cooling system operations. Secondary data are sourced from literature reviews, IMO documents, KNKT reports, and news coverage related to the TB. Kawan Kita XI (2025). Accident data is used to: (1) identify failure modes that actually occur in real operations, (2) cross-validate failure modes reported by respondents, and (3) prioritize risks that have led to actual accidents. Appendix Table A1 maps accident findings to identify failure modes.

2.2.1 Questionnaire Design

The questionnaire was designed in three sections. First, respondents provided demographic information (position, experience, vessel assignment). Second, the Severity, Occurrence, and Detection criteria (1–10) were explained using operational examples from everyday tugboat operations. Third, a pilot test was conducted with three senior engineers (each with >15 years of experience) to ensure the clarity and relevance of the questions. Based on the pilot test feedback, minor wording adjustments were made.

2.3 Failure Mode and Effect Analysis (FMEA) Analysis Method with a Scale of 1-10

Failure Mode and Effects Analysis (FMEA) was applied to systematically identify potential failure modes within the cooling system, evaluate their consequences, and determine appropriate preventive or corrective actions. The analysis was conducted using three primary risk parameters: Severity (S), Occurrence (O), and Detection (D), each assessed on a scale from 1 to 10. The use of a 1–10 scale was selected because it provides a wider range of possible Risk Priority Number (RPN) values, from 1 to 1000, enabling more detailed differentiation among risk levels compared with a 1–5 scale. In addition, this scale is consistent with commonly applied FMEA practices and provides respondents with greater flexibility in distinguishing different levels of operational risk. The assessment criteria for Severity, Occurrence, and Detection were adapted from Fitrah (2024) [14]. To reduce subjectivity in the assessment process, the respondents were provided with clearly defined scoring criteria and operational examples relevant to tugboat cooling-system conditions. Previous studies have also demonstrated the value of integrating FMEA with complementary approaches such as evidential reasoning and FMECA to improve the reliability of risk assessment [15].

Table 1. Severity Assessment Criteria (S)

Scale	Category	Criteria
1	No effect	No impact on safety/operations
2	Very small	Very minor disturbance
3	Small	Minor disruption, repairs can be postponed
4	Very low	Minor issues, need scheduled repairs
5	Low	Limited disturbance, needs to be monitored
6	Currently	Significant disruption, scheduled
7	High	Major disruption, needs immediate repair
8	Very high	The system is partially down
9	Dangerous	Total system failure
10	Very dangerous	Fatal failure, loss of life

Table 2. Occurrence Criteria (O)

Scale	Category	Criteria
1	Almost never	<1× in 10 years
2	Very rarely	1× in 5-10 years
3	Seldom	1× in 2-5 years
4	Very low	1× in 1-2 years
5	Low	1× in 6-12 months
6	Moderate	1× in 3-6 months
7	Quite high	1× in 1-3 months
8	High	1× in 1 month
9	Very high	1× in 1-3 months
10	Almost certainly	>1× in 1 week

Table 3. FSA Step Applied in This Study

FSA Step	Description	Applied in This Study
Step1	Hazard Identification	Yes (Section 3.1)
Step 2	Risk Assessment	Yes (RPN calculation, Pareto analysis)
Step 3	Risk Control Options	Partially
Step 4	Cost-Benefit Assessment	No
Step 5	Recommendations	Partially (conclusions and recommendations)

Table 4. Detection Criteria (D)

Scale	Category	Criteria
1	Almost certainly	Automatic alarm, real-time sensor
2	Very easy	Simple measuring tools
3	Easy	Visual inspection every shift
4	It's quite easy	Daily temperature check
5	Moderate	Weekly inspection
6	Quite difficult	Monthly inspection
7	Difficult	Periodic testing (3-6 months)
8	Very difficult	Partial demolition required
9	Almost impossible	Only visible after failure
10	Impossible	No detection method

2.4 Calculation of Average Severity Value (S)

The average Severity (S) score for each failure mode was obtained from the assessments provided by the 12 respondents. Each respondent evaluated the potential consequences of a failure on equipment performance, cooling-system operation, and operational safety. The individual Severity scores were subsequently averaged to obtain a

representative value for each identified failure mode. As presented in Table 5, the highest Severity score was assigned to a cylinder head cooling jacket crack, with a value of 10, reflecting its potential to cause extensive engine damage. Several other failure modes also received high Severity values, demonstrating their substantial potential impact on the reliability of the cooling system.

Table 5. Average Severity Score (S)

Failure Mode	S	Description
Sea chest obstruction	9	Very heavy, can cause overheating
Corrosion on the filter	9	Very heavy, risk of tearing
Seawater pump pressure drop	9	Very heavy, interferes with coolant flow
Mechanical seal leak	9	Very heavy, loss of cooling water
Freshwater pump pressure loss	8	Heavy, freshwater circulation is disrupted
Water pump bearing damage	9	Very heavy, causing the pump to jam

Failure Mode	S	Description
Fouling cooler	7	Moderate-severe, decreased efficiency
Internal cooler leak	8	Severe, seawater contamination to freshwater
Low water level in expansion tank	3	Lightweight, easy to handle with charging
Air inlet expansion tank	3	Light, causes aeration
Temperature Control Valve stuck	8	Heavy, unstable temperature
Pipe/connection leak	5	Moderate, leaks can be fixed
Crack cylinder head cooling jacket	10	Very dangerous, total engine damage
LO cooler blockage	9	Very heavy, overheat lubricating oil

Table 6. Respondent Profile Summary

Respondent	Position	Years Experience	Vessel Type	Role in Cooling System
R1	Chief Engineer	25	Tugboat	Supervision & maintenance
R2	Chief Engineer	18	Tugboat	Supervision & maintenance
R3	Second Engineer	12	Tugboat	Daily operation & repair
R4	Second Engineer	10	Tugboat	Daily operation & repair
R5	Third Engineer	7	Tugboat	Monitoring & troubleshooting
R6	Third Engineer	6	Tugboat	Monitoring & troubleshooting
R7	Oiler	15	Tugboat	Routine inspection
R8	Oiler	8	Tugboat	Routine inspection
R9	Oiler	5	Tugboat	Routine inspection
R10	Port Engineer	20	Multiple tugboats	Maintenance planning
R11	Port Engineer	12	Multiple tugboats	Maintenance planning
R12	Technician	4	Tugboat	Repair & replacement

Table 7 presents the mean and standard deviation of the Severity, Occurrence, and Detection assessments for each identified failure mode. The relatively low standard deviation values observed for most failure

modes indicate a generally consistent assessment among respondents. This level of agreement provides a reasonable basis for using the resulting scores in subsequent RPN calculations and risk prioritization.

Table 7. Mean $\pm$ Standard Deviation of S, O, and D Scores

Failure Mode	Mean S $\pm$ SD	Mean O $\pm$ SD	Mean D $\pm$ SD
Sea chest obstruction	9.0 $\pm$ 0.8	4.0 $\pm$ 0.9	1.0 $\pm$ 0.0
Corrosion on the filter	9.0 $\pm$ 0.6	3.0 $\pm$ 0.7	8.0 $\pm$ 1.1
Seawater pump pressure drop	9.0 $\pm$ 0.7	5.0 $\pm$ 0.8	1.0 $\pm$ 0.0
Mechanical seal leak	9.0 $\pm$ 0.5	5.0 $\pm$ 0.6	9.0 $\pm$ 0.9
Freshwater pump pressure loss	8.0 $\pm$ 0.9	5.0 $\pm$ 0.7	3.0 $\pm$ 0.8
Water pump bearing damage	9.0 $\pm$ 0.6	3.0 $\pm$ 0.8	9.0 $\pm$ 0.7
Fouling cooler	7.0 $\pm$ 1.0	5.0 $\pm$ 0.9	1.0 $\pm$ 0.0
Internal cooler leak	8.0 $\pm$ 0.8	3.0 $\pm$ 0.6	7.0 $\pm$ 1.2
Low water level in expansion tank	3.0 $\pm$ 0.5	5.0 $\pm$ 0.8	1.0 $\pm$ 0.0
Air inlet expansion tank	3.0 $\pm$ 0.4	5.0 $\pm$ 0.7	1.0 $\pm$ 0.0
Temperature control valve stuck	8.0 $\pm$ 0.9	3.0 $\pm$ 0.8	9.0 $\pm$ 0.8
Pipe/connection leak	5.0 $\pm$ 1.1	2.0 $\pm$ 0.5	1.0 $\pm$ 0.0
Cylinder head cooling jacket crack	10.0 $\pm$ 0.0	3.0 $\pm$ 0.6	10.0 $\pm$ 0.0
LO cooler blockage	9.0 $\pm$ 0.7	5.0 $\pm$ 0.9	1.0 $\pm$ 0.0

2.5 Average Value Calculation Occurrence(O)

The Occurrence (O) assessment reflects the estimated frequency with which each failure

mode occurs during tugboat operation. Scores were assigned based on respondents' operational experience and the frequency

criteria defined in Table 2. Failure modes such as seawater pump pressure drop, mechanical seal leakage, freshwater pump pressure loss, cooler fouling, low water level in the expansion tank, air ingress into the expansion tank, and LO

cooler blockage received an Occurrence score of 5. Pipe or connection leakage received the lowest score of 2, while the other failure modes were assigned intermediate values according to the frequency reported by respondents.

Table 8. Average Value Occurrence (O)

Failure Mode	O	Description
Sea chest obstruction	4	Occurs occasionally (1-2 times per year)
Corrosion on the filter	3	Rarely (1 time per 2-5 years)
Seawater pump pressure drop	5	Occurs frequently, (1-2 times per year)
Mechanical seal leak	5	Occurs frequently, (1-2 times per year)
Freshwater pump pressure loss	5	Often occur
Water pump bearing damage	3	Seldom
Fouling cooler	5	Often occur
Internal cooler leak	3	Seldom
Low water level in expansion tank	5	Often occur
Air inlet expansion tank	5	Often occur
Temperature Control Valve stuck	3	Seldom
Pipe/connection leak	2	Very rarely
Cylinder head cooling jacket crack	3	Seldom
LO cooler blockage	5	Often occur

2.6 Average Value Calculation Detection (D)

The Detection (D) score represents the ability to identify a failure mode before it develops into a more serious operational problem. A high Detection score indicates that the failure is relatively difficult to identify before its consequences occur, whereas a low score indicates that the failure can be recognized

through routine monitoring, alarms, gauges, or visual inspection. The broad range of Detection values obtained in this study demonstrates substantial differences in the detectability of individual failure modes and highlights the need for improved condition-monitoring strategies, particularly for failures associated with high Detection scores.

Table 9. Average Value Detection (D)

Failure Mode	D	Description
Sea chest obstruction	1	Very easy (pressure alarm)
Corrosion on the filter	8	Very difficult (only found out during inspection)
Seawater pump pressure drop	1	Very easy (pressure gauge)
Mechanical seal leak	9	Almost impossible (only after failure)
Freshwater pump pressure loss	3	Easy (pressure gauge)
Water pump bearing damage	9	Almost impossible (sound drowning)
Fouling cooler	1	Very easy (temperature increase)
Internal cooler leak	7	Difficult (periodic pressure test)
Low water level in expansion tank	1	Very easy (level indicator)
Air inlet expansion tank	1	Very easy (bubble)
Temperature Control Valve stuck	9	Almost impossible (without indicators)
Pipe/connection leak	1	Very easy (visual inspection)
Crack cylinder head cooling jacket	10	Impossible (without NDT)
LO cooler blockage	1	Very easy (oil temperature rise)

2.7 Calculation Risk Priority Number (RPN)

The Risk Priority Number (RPN) was calculated by multiplying the Severity, Occurrence, and Detection scores:

$$RPN = S \times O \times D \quad (1)$$

The calculated RPN represents the relative

priority of each failure mode and provides a quantitative basis for determining which failures require greater maintenance attention. The risk classification used in this study consists of Low (1–50), Medium (51–150), High (151–300), and

Very High (>300). These thresholds were established based on the distribution of RPN values obtained in this study and with reference to previous FMEA applications in maritime engineering [12], [16].

Table 10. Risk Assessment Results and RPN Calculation (Scale 1-10)

Failure Mode	S	O	D	RPN	Risk Level
Sea chest obstruction	9	4	1	36	Low
Corrosion on the filter	9	3	8	216	High
Seawater pump pressure drop	9	5	1	45	Low
Mechanical seal leak	9	5	9	405	Very high
Freshwater pump pressure loss	8	5	3	120	Medium
Water pump bearing damage	9	3	9	243	High
Fouling cooler	7	5	1	35	Low
Internal cooler leak	8	3	7	168	High
Low water level in expansion tank	3	5	1	15	Low
Air inlet expansion tank	3	5	1	15	Low
Temperature Control Valve stuck	8	3	9	216	High
Pipe/connection leak	5	2	1	10	Low
Crack cylinder head cooling jacket	10	3	10	300	Very high
LO cooler blockage	9	5	1	45	Low

The results indicate that mechanical seal leakage represents the highest-priority failure mode, with an RPN of 405. Other major risk contributors include cylinder head cooling jacket cracks, water pump bearing damage, filter corrosion, a stuck temperature control valve, and internal cooler leakage. The results demonstrate that risk priority is determined not only by the frequency of occurrence but also by the severity of the consequences and the ability to detect failure before significant damage occurs.

2.8 Pareto Analysis Method

Pareto analysis was subsequently applied to determine which failure modes contribute most significantly to the overall RPN. The procedure consisted of arranging the failure modes in descending order of RPN, calculating the percentage contribution of each failure mode to the total RPN, determining the cumulative percentage, and identifying the failure modes contributing to approximately 80% of the overall risk. This analysis provides a practical basis for focusing inspection, maintenance, and risk-control resources on the most influential failure modes. The results are presented in Table 12 and Figure 1.

3. Results

3.1 Component Identification and Failure Modes

A total of 14 distinct failure modes were identified across nine major components of the tugboat cooling system. The identified failures represent several recurring degradation mechanisms, including blockage or fouling, corrosion, mechanical wear, leakage, flow or pressure degradation, and structural failure. Blockage-related failures were identified in the sea chest and LO cooler, while corrosion was primarily associated with the sea chest strainer and piping components. Mechanical degradation was observed in pump-related components, particularly mechanical seals, bearings, and impellers, whereas leakage was associated with seals, coolers, and piping connections. Structural deterioration was represented by cracking of the cylinder head cooling jacket. These failure modes reflect the combined influence of seawater exposure, thermal cycling, mechanical loading, contamination, and prolonged operating conditions. Table 11 summarizes the identified components and their corresponding potential failure modes.

Table 11. Potential Failure Modes of Tugboat Cooling Systems

Component	Failure Mode
Sea Chest & Filter	Total/partial blockage
Sea Chest & Filter	Corrosion on the filter
Seawater Cooling Pump	Pressure/flow drop (impeller wear)
Seawater Cooling Pump	Mechanical seal leak
Freshwater Cooling Pump	Loss of pressure/unsteady flow
Freshwater Cooling Pump	Bearing damage
Freshwater Cooler	Fouling (buildup of crust/moss)
Freshwater Cooler	Internal leak
Expansion Tank	Low water level
Expansion Tank	Air entering the system
Temperature Control Valve	Stuck/unresponsive
Piping & Connections	Leakage
Cylinder Head Cooling Jacket	Crack
LO Cooler	Blockage (oil cooling is not optimal)

The distribution of the failure modes indicates that the cooling system is exposed to both

progressive degradation and sudden mechanical failure. Progressive mechanisms such as corrosion, fouling, and wear may develop gradually and therefore require condition-based inspection, whereas failures such as mechanical seal leakage, bearing damage, or cylinder head cracking may lead to more immediate operational consequences. This distinction is important because the maintenance strategy should consider not only the likelihood of failure but also its detectability and potential consequences.

3.2 Pareto Analysis of Risk Priority

Pareto analysis was performed to determine which failure modes contribute most significantly to the overall system risk. The failure modes were ranked in descending order according to their Risk Priority Number (RPN), followed by calculation of their individual percentage contribution and cumulative percentage of the total RPN.

As shown in Table 12, the six highest-ranked failure modes contribute approximately 82.6% of the total cumulative risk, indicating that a relatively small group of failure mechanisms accounts for most of the overall risk exposure. This result is consistent with the underlying concept of Pareto analysis, in which risk-control efforts can be concentrated on a limited number of dominant failure modes to achieve a substantial reduction in overall system risk.

Table 12. Pareto Analysis of Risk Priority

Rank	Failure Mode	RPN	Percentage (%)	Cumulative (%)	Risk Level
1	Mechanical seal leak	405	21.6	21.6	Very High
2	Cylinder head jacket crack	300	16.0	37.6	Very High
3	Freshwater pump bearing damage	243	13.0	50.6	High
4	Sea chest strainer corrosion	216	11.5	62.1	High
5	Temperature control valve stuck	216	11.5	73.6	High
6	Internal cooler leak	168	9.0	82.6	High
7	Freshwater pump pressure loss	120	6.4	89.0	Medium
8	LO cooler blockage	45	2.4	91.4	Low
9	Seawater pump pressure drop	45	2.4	93.8	Low
10	Sea chest & strainer blockage	36	1.9	95.7	Low
11	Fouling	35	1.9	97.6	Low
12	Low water level in expansion tank	15	0.8	98.4	Low
13	Air inlet expansion tank	15	0.8	99.2	Low

Rank	Failure Mode	RPN	Percentage (%)	Cumulative (%)	Risk Level
14	Pipe/connection leak	10	0.5	100.0	Low

The Pareto distribution shows that the highest risk is associated with mechanical seal leakage, which contributes 21.6% of the total RPN. This is followed by cylinder head cooling jacket cracking at 16.0% and freshwater pump bearing damage at 13.0%. Together, these three failure modes account for more than half of the cumulative risk. When sea chest strainer corrosion, a stuck temperature control valve,

and internal cooler leakage are included, the cumulative contribution reaches 82.6%.

These results demonstrate that maintenance priorities should not be distributed equally across all cooling-system components. Instead, inspection and preventive maintenance should primarily target the six dominant failure modes identified by the Pareto analysis.

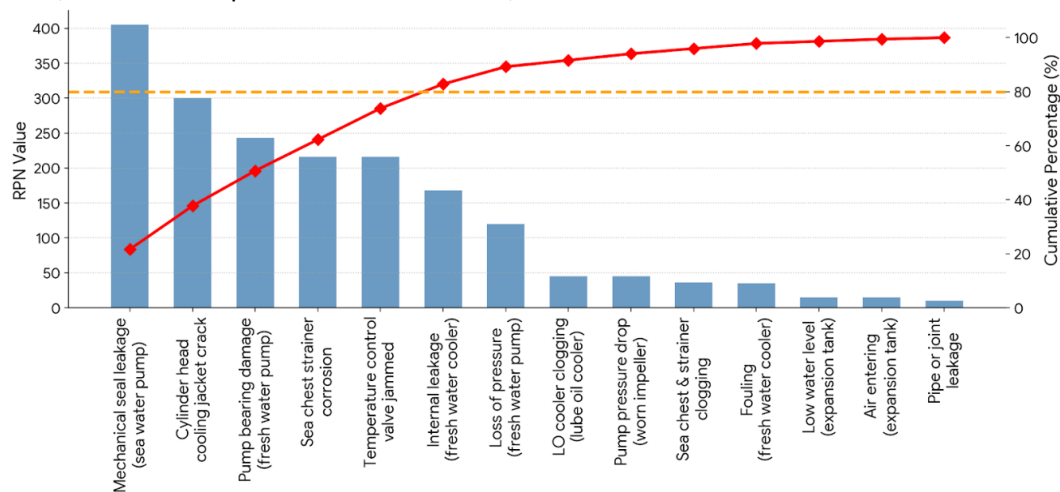


Figure 1. Pareto Diagram of Risk Priority

3.3 Critical Failure Mode Interpretation

The six failure modes within the cumulative 82.6% threshold can be considered the primary risk-control priorities of the tugboat cooling system. Among them, mechanical seal leakage presents the highest RPN because of the combination of high Severity, relatively frequent Occurrence, and poor Detection capability. Failure of the mechanical seal can lead to loss of cooling water, reduced pump performance, and subsequent engine overheating if the condition is not detected and corrected promptly.

Cylinder head cooling jacket cracking represents another critical failure mode. Although its occurrence is relatively less frequent, its high Severity and very poor detectability result in a Very High-risk classification. A crack within the cooling jacket may permit coolant leakage, loss of cooling efficiency, contamination between systems, or severe thermal damage to the engine. Because such deterioration may not be detectable

through routine visual inspection, more advanced diagnostic or non-destructive testing methods may be required.

Freshwater pump bearing damage also contributes significantly to the cumulative risk. Bearing deterioration may initially develop through vibration, abnormal noise, increasing temperature, or shaft misalignment and can eventually result in pump seizure or complete loss of freshwater circulation. The relatively high Detection score suggests that improved condition monitoring, such as vibration and bearing-temperature monitoring, could substantially reduce this risk.

Sea chest strainer corrosion and internal cooler leakage represent degradation mechanisms associated with prolonged exposure to seawater and corrosive operating environments. Strainer corrosion may reduce structural integrity and potentially allow debris to enter downstream components, while an internal cooler leak can cause cross-

contamination between seawater and freshwater circuits. Both conditions therefore require periodic inspection and integrity assessment.

The stuck temperature control valve is also classified as a High-risk failure mode because malfunction of the valve can disrupt temperature regulation and produce unstable cooling conditions. Continuous or more frequent monitoring of cooling-water temperature and valve response can therefore improve early detection and reduce the probability of operational disruption.

Overall, the Pareto analysis indicates that effective risk reduction should focus primarily on mechanical seal condition, cylinder head cooling jacket integrity, freshwater pump bearing condition, sea chest strainer corrosion,

temperature control valve functionality, and cooler integrity. Targeting these six failure modes provides the greatest potential reduction in the total cooling-system risk.

3.4 Recommended Risk Mitigation and Maintenance Strategy

Based on the FMEA and Pareto analysis, risk mitigation should be concentrated on the failure modes that contribute most significantly to the cumulative system risk. The maintenance strategy should therefore prioritize the six dominant failure modes identified in Section 3.3, while lower-ranked failure modes should continue to be controlled through routine inspection and preventive maintenance. The recommended actions are summarized in Table 13.

Table 13. Recommended Risk Mitigation and Maintenance Strategy

Failure Mode	Risk Level	Recommended Action	Inspection/Monitoring Method	Maintenance Priority
Mechanical seal leak	Very High	Replace degraded seals, inspect shaft alignment, verify seal flushing and lubrication condition	Leakage inspection, seal condition check, pump performance monitoring	Very High
Cylinder head cooling jacket crack	Very High	Conduct periodic integrity inspection and repair or replace damaged cylinder head components	NDT, pressure testing, coolant-loss monitoring	Very High
Freshwater pump bearing damage	High	Implement bearing lubrication control, alignment checks, and planned bearing replacement	Vibration monitoring, temperature monitoring, abnormal-noise inspection	High
Sea chest strainer corrosion	High	Apply corrosion control, inspect structural thickness, and replace heavily corroded strainers	Visual inspection, ultrasonic thickness measurement	High
Temperature control valve stuck	High	Inspect valve movement, clean or overhaul valve mechanism, and verify temperature-control response	Functional testing, temperature monitoring	High
Internal cooler leak	High	Perform cooler integrity inspection,	Pressure test, leak test, coolant contamination	High

Failure Mode	Risk Level	Recommended Action	Inspection/Monitoring Method	Maintenance Priority
		tube cleaning, and repair or replacement of leaking sections	monitoring	
Freshwater pump pressure loss	Medium	Inspect impeller condition, suction line, and pump clearances	Pressure and flow monitoring	Medium
LO cooler blockage	Low	Perform routine cleaning and monitor lubricating-oil temperature	Temperature monitoring, scheduled cleaning	Routine
Seawater pump pressure drop	Low	Inspect impeller wear, suction obstruction, and pump efficiency	Pressure gauge, flow monitoring	Routine
Sea chest & strainer blockage	Low	Conduct periodic cleaning and remove marine growth or debris	Visual inspection, differential pressure monitoring	Routine
Fouling	Low	Clean cooler surfaces periodically and control scaling or marine growth	Temperature-difference monitoring, scheduled inspection	Routine
Low water level in expansion tank	Low	Maintain adequate coolant level and inspect for leakage	Level indicator, daily visual inspection	Routine
Air inlet expansion tank	Low	Inspect for air ingress and ensure proper venting and sealing	Visual inspection, bubble observation	Routine
Pipe/connection leak	Low	Tighten or replace leaking joints and inspect pipe integrity	Visual inspection	Routine

The highest maintenance priority should be assigned to mechanical seal leakage and cylinder head cooling jacket cracking because both failure modes are classified as Very High risk. Mechanical seal leakage requires more frequent inspection because deterioration may result in rapid cooling-water loss and reduced pump performance. Preventive actions should include seal-condition inspection, shaft alignment verification, and timely replacement before leakage becomes severe.

For the cylinder head cooling jacket, the principal concern is the combination of severe

consequences and poor detectability. Routine inspection alone may therefore be insufficient. Periodic non-destructive testing and pressure testing should be considered to identify cracking before significant coolant leakage or engine damage occurs.

Freshwater pump bearing damage, sea chest strainer corrosion, temperature control valve malfunction, and internal cooler leakage should be managed as High-priority conditions. Their risk can be reduced through improved condition monitoring, scheduled inspection, and planned replacement or overhaul. Vibration and

temperature monitoring can improve early detection of bearing degradation, while ultrasonic thickness measurement can provide quantitative information on the progression of sea chest strainer corrosion.

For Medium- and Low-risk failure modes, routine preventive maintenance remains appropriate. However, these failure modes should not be ignored because deterioration in operating conditions may increase either their occurrence or severity over time. Periodic reassessment of Severity, Occurrence, Detection, and RPN values is therefore recommended whenever significant changes occur in vessel age, operating profile, maintenance history, or equipment condition.

Overall, the proposed maintenance strategy follows a risk-based approach in which inspection frequency and maintenance resources are allocated according to the relative importance of each failure mode. By focusing maintenance activities on the dominant contributors identified through FMEA and Pareto analysis, the tugboat cooling system can achieve more efficient resource allocation, improved reliability, and reduced likelihood of unplanned operational interruption.

5. Conclusions

This study identified 14 failure modes within tugboat cooling systems based on a survey of 12 engine-room personnel representing eight tugboats and evaluated their risks using an integrated FSA–FMEA approach with a 1–10 assessment scale. The analysis identified six dominant failure modes: mechanical seal leakage (RPN = 405), cylinder head cooling jacket cracking (RPN = 300), freshwater pump bearing failure (RPN = 243), sea strainer corrosion (RPN = 216), temperature control valve jamming (RPN = 216), and internal cooler leakage (RPN = 168).

Collectively, these failure modes accounted for 82.6% of the total cumulative risk, demonstrating that a limited number of failure mechanisms contribute disproportionately to overall cooling-system risk. The main contribution of this study is the integration of multi-vessel operational survey data, a more

detailed 1–10 FMEA scoring scale, and cross-validation of identified failure modes using actual accident information, including the TB. Kawan Kita XI case.

The findings support a risk-based maintenance strategy that prioritizes mechanical seals, cylinder head cooling jackets, freshwater pump bearings, sea chest strainers, temperature control valves, and cooler integrity. Recommended actions include preventive seal replacement, installation of leak-detection devices, periodic manual operation and functional testing of control valves, corrosion protection of strainers, vibration and temperature monitoring of pump bearings, and non-destructive testing of critical cooling components.

The study is subject to several limitations, including the relatively small respondent sample, variations in expert judgment, and the absence of a formal cost-benefit assessment corresponding to FSA Step 4. Future studies should therefore involve a larger and more diverse respondent population, incorporate quantitative cost-benefit and life-cycle maintenance analyses, and apply approaches such as Fuzzy-FMEA to better account for uncertainty in expert-based risk assessments.

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