Proceedings of the 35th European Safety and Reliability & the 33rd Society for Risk Analysis Europe Conference
Edited by Eirik Bjorheim Abrahamsen, Terje Aven, Frederic Bouder, Roger Flage, Marja Ylönen

Published by Research Publishing, Singapore.
doi: 10.3850/978-981-94-3281-3_ESREL-SRA-E2025-P6472-cd

RAM Analysis in propulsion system in Submarines

Dr. Manuel Gonzalez

Reliability Manager, SMS group GmbH, Germany. E-mail: Manuel.GonzalezPrieto@sms-group.com

This paper presents a comprehensive analysis of the reliability, availability, and maintainability (RAM) of a submarine propulsion system. The study aims to enhance understanding of the critical factors influencing the performance and operational readiness of these systems. A detailed case study is conducted, employing advanced RAM methodologies to evaluate failure rates, mean down time (MDT), and reliability calculations. The analysis is supported by theoretical frameworks and empirical data, highlighting the importance of robust design and maintenance strategies. Key findings indicate that optimizing component reliability and implementing predictive maintenance can significantly improve system availability. The insights gained from this research provide valuable guidance for engineers and decision-makers in the defense sector, seeking to improve the efficiency and effectiveness of submarine propulsion systems.

Keywords: RAM, RBD, Reliability, Submarine propulsion systems.

1. Introduction

The construction and operation of a submarine represent one of the most complex and technically demanding projects in the maritime industry. Submarines are critical assets for national defense, capable of performing a variety of missions such as surveillance, reconnaissance, and strategic deterrence. Diesel-electric submarines, in particular, offer a cost-effective solution with advanced stealth capabilities, making them a preferred choice for many navies around the world.

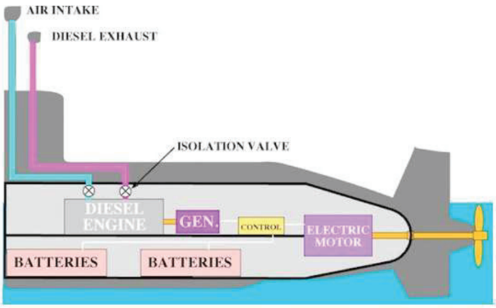


Fig. 1. Main Propulsion equipments diagram of a conventional submarine propulsion system

Conventional submarines cannot use combustion engines underwater because there is no oxygen. Instead, they use large-capacity batteries for underwater operation. These batteries need to be recharged by diesel engines when the submarine is on the surface. The next image shows the block diagram of a conventional submarine propulsion system.

The propulsion systems of submarines are critical components that ensure operational success and mission readiness in naval operations. As submarines operate in isolated and demanding underwater environments, the reliability, availability, and maintainability (RAM) of their propulsion systems become paramount. This paper explores the intricacies of RAM analysis applied to submarine propulsion, emphasizing the need for robust engineering solutions and strategic maintenance practices.

The increasing complexity of modern submarine systems necessitates a comprehensive approach to understanding and mitigating potential failures. Reliability, defined as the probability of a system performing its intended function without failure, is crucial for sustaining prolonged underwater operations. Availability, the measure of a system's readiness for use, directly impacts mission success, while maintainability ensures that any required repairs can be conducted efficiently, minimizing downtime.

This study aims to provide a detailed examination of the factors influencing RAM in submarine propulsion systems. By integrating theoretical models with empirical data, the paper seeks to identify key components and processes that contribute to system performance. The analysis includes the evaluation of failure rates, mean down time (MDT), and reliability block diagrams (RBD), offering insights into the optimization of maintenance strategies.

The findings of this research are intended to assist engineers and decision-makers in the defense sector, providing them with actionable recommendations to enhance the design and maintenance of submarine propulsion systems. Ultimately, the goal is to improve the operational effectiveness and longevity of these vital assets, ensuring that they meet the rigorous demands of modern naval warfare.

2. Propulsion System Blocks

For conducting a comprehensive RAM analysis of submarine propulsion systems, it is essential to understand the key components and their interactions within the overall system architecture. The propulsion system's performance and reliability depend on several interconnected subsystems, each playing a crucial role in ensuring operational efficiency and mission success.

The primary systems involved in this analysis include the power generation system, which comprises diesel generators and battery systems that provide the necessary energy for propulsion. The propulsion system itself consists of electric motors, propeller shafts, and propellers, which convert generated power into thrust.

Control systems are integral for navigating and managing propulsion operations, including navigation controls, propulsion control units, and automation systems. Supporting these are the cooling and lubrication systems, which maintain optimal operating conditions through cooling pumps, heat exchangers, and lubrication pumps.

Auxiliary systems, such as hydraulic, compressed air, and fuel management systems, further support the propulsion system's functionality. Finally, safety and monitoring systems, equipped with sensors, alarms, diagnostic tools, and emergency shutdown mechanisms, ensure the system's reliability and safety.

Understanding these systems' roles and interdependencies is critical for identifying potential failure modes and optimizing maintenance strategies in submarine propulsion.

Summary of System Block Diagrams are as follows:

- Power Generation System: Diesel Generators, Battery Systems
- Propulsion System: Electric Motors, Propeller Shafts, Propellers
- Control Systems: Navigation Controls, Propulsion Control Units, Automation Systems
- Cooling and Lubrication Systems: Cooling Pumps, Heat Exchangers, Lubrication Pumps
- Auxiliary Systems: Hydraulic Systems, Compressed Air Systems, Fuel Management Systems
- Safety and Monitoring Systems: Sensors and Alarms, Diagnostic Systems, Emergency Shutdown Mechanisms

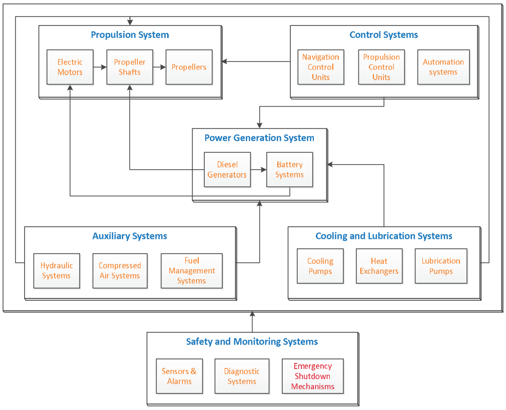


Fig. 2. Propulsion System Blocks Diagram

3. Theoretical basis and Summary of formulas for a RAM analysis

The reliability, availability, and maintainability (RAM) analysis is conducted based on the international standard ISO 14224 (Petroleum, petrochemical, and natural gas industries - Collection and exchange of reliability and maintenance data for equipment), in a simplified manner given the preliminary nature of the initial design, and adapted to the system under study in this document. Equipment in any industrial system must consider a large number of constraints and conditions. Components or subsystems present potential failure mode ranges that must be considered from the initial design stage of the complete system, according to their mode of operation, environmental conditions, failure times, etc. RAM analysis provides an approximate assessment of the behaviour of equipment operating in severe conditions, such as those elements belonging to complex systems in the aerospace, defense, automotive, industrial, telecommunications sectors, etc. The terms of the RAM acronym convey the following concepts:

- Reliability is the ability of a system or component to perform its expected functions under established conditions during a specific period of time.
- Availability is the degree to which a system or component can be used during a given time interval. It is usually expressed as a time ratio.
- Maintainability is a characteristic of the design and installation of an element, in which it must be restored or replaced after a certain period of time, with maintenance performed according to prescribed procedures.

Next, the variables referred to as RAMS will be obtained for two subsystems arranged in series or parallel, as well as in the case of a system composed of "n" identical subsystems in parallel, where the system is considered to fail if "m" or more subsystems fail. For these cases, the characteristics of the system mentioned in the introduction will be deduced: "Failure Rate," "Mean Time Between Failure," "Availability and Unavailability," and "Mean Down Time".

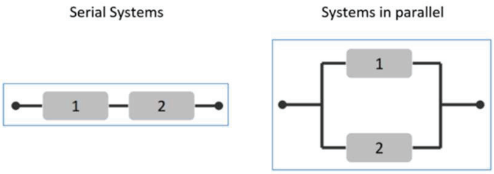


Fig. 3. Serial and parallel systems

Table 1. RAM Formulas for serial & parallel systems

	2 Serial systems	2 Systems in parallel
System Failure Rate	$\lambda_{series} = \lambda_1 + \lambda_2$	$\lambda_{parallel} = \lambda_1 \cdot \lambda_2 \cdot (MDT_1 + MDT_2)$
System MTBF	$MTBF_{series} = \frac{MTBF_1 \cdot MTBF_2}{MTBF_1 + MTBF_2}$	$MTBF_{parallel} = \frac{MTBF_1 + MTBF_2}{MTBF_1 \cdot MTBF_2}$
System Availability (A)	$A_{series} = A_1 \cdot A_2$	$A_{parallel} = A_1 + A_2 - A_1 \cdot A_2$
System Unavailability (UA) = 1-A	$UA_{series} = UA_1 + UA_2 - UA_1 \cdot UA_2$	$UA_{parallel} = UA_1 \cdot UA_2$
System Mean Down Tome (MDT)	$MDT_{series} = \frac{MTBF_1 \cdot MDT_2 + MTBF_2 \cdot MDT_1}{MTBF_1 + MTBF_2}$	$MDT_{parallel} = \frac{MDT_1 \cdot MDT_2}{MDT_1 + MDT_2}$
Reliability (R)	$R_{series} = R_1 \cdot R_2$	$R_{parallel} = 1 - (1 - R_1) \cdot (1 - R_2)$

The reliability calculation (see Eq. (1)) is performed considering a Weibull distribution for the failure rate.

$$\text{Reliability } R(t)=1-F(t)=e^{-\left(\frac{t}{MTBF}\right)^{\beta}}=e^{-(\lambda \cdot t)^{\beta}} \qquad (1)$$

4. RAM analysis

4.1. *Analysis Hypothesis*

4.1.1. *Failure Rate (λ) and Mean Down Time (MDT)*

Since failure data is unavailable due to the new design of the submarine, the following failure rates and MDT (Mean Down Time) are considered:

- Large equipment (e.g., compressors, heat exchangers): OREDA database.
- Small equipment (e.g., temperature sensors): World-Class applied standard data.

These parameters should be calculated within a Reliability-Centered Maintenance (RCM) analysis of the complete system.

4.1.2. Reliability data

In the absence of specific historical failure data for a new design submarine, selecting the Weibull shape parameter (β), System Failure Rate (λ) and Mean Time To Repair (MTTR) for each system can be challenging. However, industry standards and typical values based on similar systems can provide a useful starting point.

Parameters considered for reliability calculations are as follows:

Table 2. β parameters for systems & sub-systems

Systems / Sub-systems	β	λ [failures/h]	MDT [h]
⊟ **Auxiliary Systems**			
Compressed Air Systems	0.8	26.15E-06	2.0
Fuel Management Systems	0.8	36.92E-06	3.0
Hydraulic Systems	0.8	44.62E-06	3.5
⊟ **Control Systems**			
Automation Systems	0.8	32.31E-06	2.5
Navigation Controls	0.8	36.15E-06	2.0
Propulsion Control Units	0.8	43.08E-06	3.5
⊟ **Cooling and Lubrication Systems**			
Cooling Pumps	1.0	53.53E-06	4.5
Heat Exchangers	1.0	41.54E-06	3.0
Lubrication Pumps	1.0	51.54E-06	4.0
⊟ **Power Generation System**			
Battery Systems	0.8	221.54E-06	2.5
Diesel Generators	0.8	353.08E-06	4.0
⊟ **Propulsion System**			
Electric Motors	0.8	33.08E-06	3.0
Propeller Shafts	0.8	18.46E-06	5.0
Propellers	0.8	16.15E-06	6.0
⊟ **Safety and Monitoring Systems**			
Diagnostic Systems	0.7	28.46E-06	2.5
Emergency Shutdown Mechanisms	0.7	17.69E-06	1.5
Sensors and Alarms	0.7	22.31E-06	1.0

Explanation of (β) Values:

- $\beta < 1$: Indicates a decreasing failure rate, often associated with early "infant mortality" failures
- $\beta = 1$: Represents a constant failure rate, characteristic of random failures
- $\beta > 1$: Denotes an increasing failure rate, typically due to wear-out mechanisms

The often-used bathtub curve shows the relationship between the Weibull shape parameter (β) and the hazard function throughout the life of an item. Not all items, however, display all elements of the bathtub curve during their lifetimes.

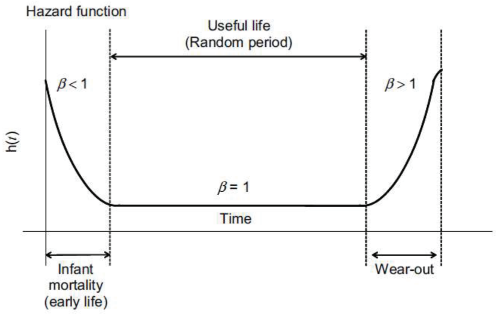


Fig. 4. Typical bathtub curve for an equipment

4.2. Failure Modes

4.2.1. *Failure Modes and Pareto Distribution*

In the context of submarine systems, understanding and prioritizing failure modes is crucial for enhancing reliability and operational readiness. This chapter presents a detailed examination of potential failure modes across various sub-systems, followed by a Pareto distribution analysis to identify and prioritize the most critical issues.

4.2.2. *Identification of Failure Modes*

A comprehensive list of potential failure modes has been identified for the submarine's complex systems. These include issues such as diesel generator overheating, battery system failure, electric motor short circuits, and navigation control malfunctions. Each failure mode represents a potential risk to the system's performance and requires careful analysis and mitigation.

Key failure modes across different sub-systems are as follows:

- Power Generation System: Diesel generator overheating and battery system failure
- Propulsion System: Electric motor short circuit and propeller shaft misalignment
- Control Systems: Navigation control malfunction and propulsion control unit failure
- Cooling and Lubrication Systems: Cooling pump failure and heat exchanger blockage
- Auxiliary Systems: Hydraulic system pressure loss and compressed air system leak
- Safety and Monitoring Systems: Sensor calibration drift and alarm system false trigger

4.2.3. *Pareto Distribution Analysis*

The Pareto distribution analysis ranks these failure modes by their hypothetical frequency or impact, following the Pareto Principle, which suggests that roughly 80% of the problems are often due to 20% of the causes. In this analysis, the top failure modes, such as diesel generator overheating (10%) and battery system failure (9%), account for a significant portion of the overall impact.

By focusing on these critical failure modes, maintenance strategies can be optimized to address the most significant risks, thereby improving system reliability and reducing downtime. The Pareto distribution provides a clear framework for prioritizing resources and efforts, ensuring that the most impactful issues are addressed first.

The identification and prioritization of failure modes through a Pareto distribution analysis are essential steps in the reliability engineering process. By understanding the most critical failure modes, engineers can develop targeted strategies to mitigate risks, enhance system performance, and ensure the submarine's operational effectiveness. This proactive approach not only improves reliability but also contributes to the overall safety and efficiency of submarine operations.

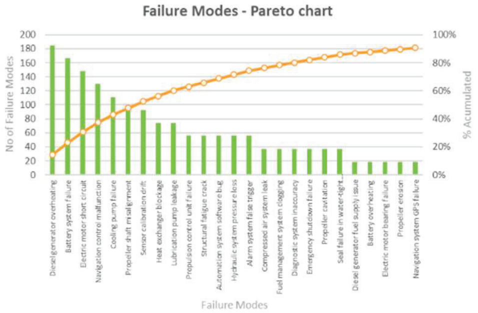


Fig. 5. Pareto chart for Failure Modes

4.3. RBD (Reliability Block Diagrams)

4.3.1. *Submarine Propulsion RBD*

In the context of submarine propulsion, constructing a Reliability Block Diagram (RBD) involves modelling the six key systems—power generation, propulsion, control, cooling and lubrication, auxiliary, and safety and monitoring—as a series configuration. This configuration reflects the operational reality that the failure of any single system can lead to the failure of the entire propulsion system.

In a series RBD, each system is represented as a block, and these blocks are connected sequentially. The overall system reliability is the product of the reliabilities of the individual systems. This means that the reliability of the submarine's propulsion system is highly dependent on the weakest link in the series.

The series arrangement underscores the critical importance of ensuring high reliability for each system. It necessitates thorough maintenance and monitoring strategies for all sub-systems to prevent any single point of failure. By focusing on improving the reliability of each component, the overall system reliability can be enhanced, thus ensuring the operational readiness and safety of the submarine. This approach highlights the interdependence of systems and the need for comprehensive reliability management.

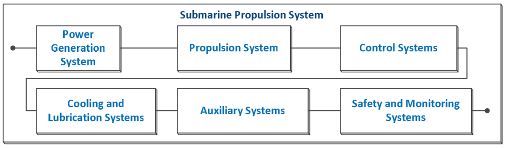


Fig. 6. Submarine Propulsion RBD

4.3.2. *Systems RBD*

In constructing a Reliability Block Diagram (RBD) for submarine systems, the power generation system is distinct in its parallel configuration. The diesel generators and battery systems are arranged in parallel, meaning that the failure of one component does not lead to the failure of the entire power generation system. This parallel arrangement provides redundancy, ensuring a continuous power supply even if one component fails, thereby enhancing system reliability.

In contrast, the other systems—propulsion, control, cooling and lubrication, auxiliary, and safety and monitoring—are configured in series. In these systems, each component is critical to the overall function, and the failure of any single component results in the failure of the entire system. This series configuration highlights the importance of ensuring high reliability for each component to prevent system-wide failures.

The parallel configuration of the power generation system necessitates effective maintenance and monitoring to maximize the benefits of redundancy. Meanwhile, the series configurations of other systems require comprehensive reliability strategies to address potential single points of failure. Together, these configurations underscore the need for a balanced approach to reliability management, ensuring both robustness and resilience in submarine operations.

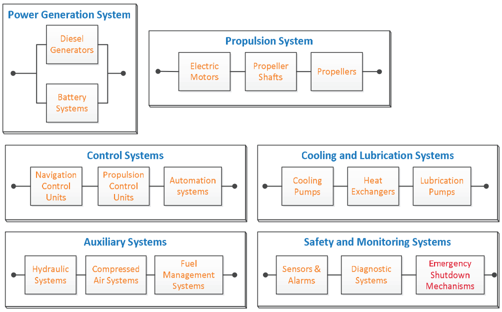


Fig. 7. Systems RBD

4.4. Final Results

Based on the analysis of the submarine propulsion system's reliability, availability, and maintainability, the results indicate a robust performance across all major systems and sub-systems. The overall submarine propulsion system demonstrates a failure rate of ($502.5 \cdot 10^{-6}$ failures/hour) failures per hour, with a mean time between failures (MTBF) of 1,990 hours, and an impressive availability of 99.8397%. This high availability underscores the system's reliability and operational readiness.

Power Generation System: The power generation system, comprising diesel generators and battery systems, exhibits an exceptionally low failure rate of ($508.43 \cdot 10^{-9}$ failures/hour) failures per hour and an MTBF of 1,966,836 hours. The system's availability is nearly perfect at 99.9999%, indicating that the redundancy in power components effectively mitigates the risk of failure.

Propulsion System: With a failure rate of ($67.69 \cdot 10^{-6}$ failures/hour) failures per hour and an MTBF of 14,773 hours, the propulsion system maintains an availability of 99.9712%. The electric motors, propeller shafts, and propellers each contribute to this reliability, with MTBFs ranging from 30,233 to 61,905 hours, reflecting their durable design and effective maintenance strategies.

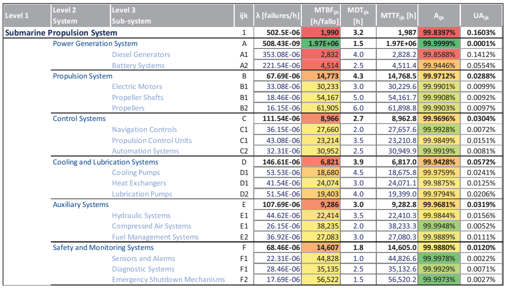
Control Systems: The control systems, including navigation controls, propulsion control units, and automation systems, show a failure rate of ($111.54 \cdot 10^{-6}$ failures/hour) failures per hour and an MTBF of 8,966 hours. The availability of 99.9696% highlights the effectiveness of these systems in maintaining operational control and precision.

Cooling and Lubrication Systems: These systems are critical for maintaining optimal operating conditions, with a failure rate of ($146.61 \cdot 10^{-6}$ failures/hour) failures per hour and an MTBF of 6,821 hours. The availability stands at 99.9428%, indicating a need for focused maintenance to further enhance reliability.

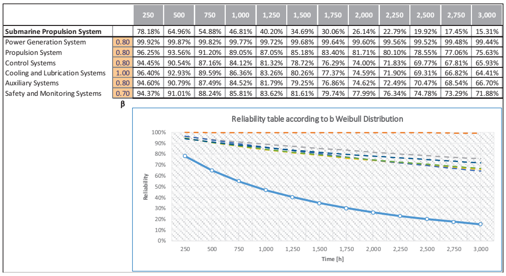
Auxiliary Systems: These systems, including hydraulic, compressed air, and fuel management systems, exhibit a failure rate of ($107.69 \cdot 10^{-6}$ failures/hour) failures per hour and an MTBF of 9,286 hours. An availability of 99.9681% suggests these systems are well-maintained and reliable.

Safety and Monitoring Systems: With a failure rate of ($68.46 \cdot 10^{-6}$ failures/hour) failures per hour and an MTBF of 14,607 hours, these systems ensure operational safety with an availability of 99.9880%. The sensors, alarms, and emergency shutdown mechanisms are particularly reliable, contributing to a safe operational environment.

Table 3. Systems & Sub-Systems Reliability Results



Level 1	Level 2 System	Level 3 Sub-system	ijk	λ [failures/h]	$MTBF_{ijk}$ [h/fallo]	MDT_{ijk} [h]	$MTTF_{ijk}$ [h]	A_{ijk}	UA_{ijk}
Submarine Propulsion System			1	**502.5E-06**	**1,990**	**3.2**	**1,987**	**99.8397%**	**0.1603%**
	Power Generation System		A	**508.43E-09**	**1.97E+06**	**1.5**	**1.97E+06**	**99.9999%**	**0.0001%**
		Diesel Generators	A1	353.08E-06	2,832	4.0	2,828.2	99.8588%	0.1412%
		Battery Systems	A2	221.54E-06	4,514	2.5	4,511.4	99.9446%	0.0554%
	Propulsion System		B	**67.69E-06**	**14,773**	**4.3**	**14,768.5**	**99.9712%**	**0.0288%**
		Electric Motors	B1	33.08E-06	30,233	3.0	30,229.6	99.9901%	0.0099%
		Propeller Shafts	B1	18.46E-06	54,167	5.0	54,161.7	99.9908%	0.0092%
		Propellers	B2	16.15E-06	61,905	6.0	61,898.8	99.9903%	0.0097%
	Control Systems		C	**111.54E-06**	**8,966**	**2.7**	**8,962.8**	**99.9696%**	**0.0304%**
		Navigation Controls	C1	36.15E-06	27,660	2.0	27,657.6	99.9928%	0.0072%
		Propulsion Control Units	C1	43.08E-06	23,214	3.5	23,210.8	99.9849%	0.0151%
		Automation Systems	C2	32.31E-06	30,952	2.5	30,949.9	99.9919%	0.0081%
	Cooling and Lubrication Systems		D	**146.61E-06**	**6,821**	**3.9**	**6,817.0**	**99.9428%**	**0.0572%**
		Cooling Pumps	D1	53.53E-06	18,680	4.5	18,675.8	99.9759%	0.0241%
		Heat Exchangers	D1	41.54E-06	24,074	3.0	24,071.1	99.9875%	0.0125%
		Lubrication Pumps	D2	51.54E-06	19,403	4.0	19,399.0	99.9794%	0.0206%
	Auxiliary Systems		E	**107.69E-06**	**9,286**	**3.0**	**9,282.8**	**99.9681%**	**0.0319%**
		Hydraulic Systems	E1	44.62E-06	22,414	3.5	22,410.3	99.9844%	0.0156%
		Compressed Air Systems	E1	26.15E-06	38,235	2.0	38,233.3	99.9948%	0.0052%
		Fuel Management Systems	E2	36.92E-06	27,083	3.0	27,080.3	99.9889%	0.0111%
	Safety and Monitoring Systems		F	**68.46E-06**	**14,607**	**1.8**	**14,605.0**	**99.9880%**	**0.0120%**
		Sensors and Alarms	F1	22.31E-06	44,828	1.0	44,826.6	99.9978%	0.0022%
		Diagnostic Systems	F1	28.46E-06	35,135	2.5	35,132.6	99.9929%	0.0071%
		Emergency Shutdown Mechanisms	F2	17.69E-06	56,522	1.5	56,520.2	99.9973%	0.0027%



	β	250	500	750	1,000	1,250	1,500	1,750	2,000	2,250	2,500	2,750	3,000
Submarine Propulsion System		78.18%	64.96%	54.88%	46.81%	40.20%	34.69%	30.06%	26.14%	22.79%	19.92%	17.45%	15.31%
Power Generation System	0.80	99.92%	99.87%	99.82%	99.77%	99.72%	99.68%	99.64%	99.60%	99.56%	99.52%	99.48%	99.44%
Propulsion System	0.80	96.25%	93.56%	91.20%	89.05%	87.05%	85.18%	83.40%	81.71%	80.10%	78.55%	77.06%	75.63%
Control Systems	0.80	94.45%	90.54%	87.16%	84.12%	81.32%	78.72%	76.29%	74.00%	71.83%	69.77%	67.81%	65.93%
Cooling and Lubrication Systems	1.00	96.40%	92.93%	89.59%	86.36%	83.26%	80.26%	77.37%	74.59%	71.90%	69.31%	66.82%	64.41%
Auxiliary Systems	0.80	94.60%	90.79%	87.49%	84.52%	81.79%	79.25%	76.86%	74.62%	72.49%	70.47%	68.54%	66.70%
Safety and Monitoring Systems	0.70	94.37%	91.01%	88.24%	85.81%	83.62%	81.61%	79.74%	77.99%	76.34%	74.78%	73.29%	71.88%

Fig. 8. Systems & Sub-Systems Reliability

Based on the reliability analysis of the submarine propulsion system, the Weibull shape parameter (β) using the reliability at 1,000 hours is calculated to be approximately 0.819. This value suggests a decreasing failure rate, indicative of early "infant mortality" failures that stabilize as the system matures. The β factor reflects the effectiveness of the design and maintenance strategies in mitigating initial failures and ensuring sustained reliability over time. This parameter is crucial for informing maintenance schedules and improving overall system performance.

Scale parameter for submarine propulsion system is $\eta = 1149$.

To estimate the mean time between failure (MTBF) using the Weibull distribution (see Eq. (2)), we can use the gamma function.

$$\text{MTBF}=\eta \cdot \Gamma\left(1+\frac{1}{\beta}\right) = 1295 \text{ h} \qquad (2)$$

4.5. Maintenance Plan Proposal

Based on the comprehensive analysis of the submarine propulsion system's reliability, availability, and maintainability, coupled with the calculated Weibull parameters and mean time between failure (MTBF), a strategic maintenance plan can be developed. This strategy aims to enhance system reliability, minimize downtime, and ensure operational readiness.

Preventive Maintenance Scheduling:

- Regular Inspections: Schedule regular inspections of all major systems, particularly the power generation and propulsion systems, to detect early signs of wear or potential failures.
- Component Replacements: Plan for timely replacements of components nearing the end of their estimated MTBF (approximately 1,295 hours) to prevent unexpected failures.
- Calibration and Testing: Regularly calibrate and test control systems and safety mechanisms to ensure they function correctly and efficiently.

Condition-Based Maintenance (CBM):

- Monitoring Systems: Implement advanced monitoring systems to track the real-time performance of critical components, such as diesel generators, electric motors, and cooling pumps.
- Data Analysis: Use data analytics to predict potential failures based on trends and anomalies detected in the operational data.

Reliability-Centered Maintenance (RCM):

- Failure Mode Analysis: Conduct detailed failure mode and effects analysis (FMEA) to identify critical failure points and prioritize maintenance resources accordingly.
- Redundancy Management: Ensure that redundant systems, particularly in power generation, are regularly tested to confirm their readiness in case of primary system failure.

Proactive Maintenance Interventions:

- Lubrication and Cooling Systems: Focus on maintaining optimal conditions in lubrication and cooling systems, as these are crucial for preventing overheating and wear.
- Sealing and Insulation: Regularly inspect and maintain seals and insulation to prevent leaks and ensure system integrity, particularly in watertight compartments.

Training and Documentation:

- Personnel Training: Provide ongoing training for maintenance personnel on the latest diagnostic tools and techniques to enhance their ability to perform effective maintenance.
- Documentation and Records: Maintain comprehensive records of all maintenance activities, inspections, and repairs to facilitate future planning and audits.

Continuous Improvement:

- Feedback Loops: Establish feedback loops to continuously gather insights from maintenance activities and adjust strategies to improve efficiency and effectiveness.
- Innovation and Technology: Stay informed about technological advancements and incorporate new tools and methods that can enhance maintenance practices

The following pie charts visually represent the distribution of maintenance activities by type, the time and personnel allocated to each activity and Maintenance Distribution by System.

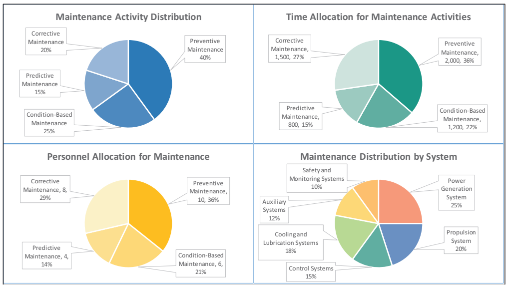


Fig. 9. Maintenance Distributions

5. Conclusions

The submarine propulsion system's high availability and reliability across all systems reflect effective design and maintenance practices. The reliability distributions provide valuable insights into areas for targeted improvements. For instance, while the power generation system exhibits high reliability, the propulsion and control systems may benefit from enhanced monitoring and maintenance strategies to address potential reliability declines over time.

The cooling and lubrication systems, with a reliability decline at extended operational hours, highlight the need for a robust preventive maintenance schedule. Similarly, the auxiliary systems require ongoing attention to sustain their performance and reliability. The safety and monitoring systems, with their critical role in ensuring operational safety, should continue to be prioritized in maintenance and monitoring efforts.

By focusing on these targeted strategies, the submarine propulsion system can enhance its performance and resilience, ensuring sustained operational readiness and safety. This proactive approach not only improves reliability but also contributes to the overall efficiency and effectiveness of submarine operations, supporting mission success in challenging environments.

References

Crespo A. (2006). The maintenance management framework. Models and methods for complex systems maintenance. Springer, London

Crespo A. (2020). Value Based and Intelligent Asset Management Mastering the Asset Management Transformation in Industrial Plants and Infrastructures. Springer, London

DIN EN 16646:2014. Maintenance - Maintenance within physical asset management

IEC 60300-3-11:2009. Reliability centred maintenance

ISO 13306. Maintenance Terminology

ISO 14224 (Petroleum, petrochemical, and natural gas industries - Collection and exchange of reliability and maintenance data for equipment)