



Optimizing Planned Maintenance Systems to Prevent Rocker Arm Bushing Wear and Exhaust Valve Stem Failure in Medium-Speed Marine Diesel Engines: A Case Study of KM. Mutiara Berkah II

Abu Bakar^{1*}, Sarifuddin Sarifuddin², Bayu Nanda¹

¹ Politeknik Pelayaran Barombong, Makassar, Sulawesi Selatan, Indonesia

² Politeknik Ilmu Pelayaran Makassar, Sulawesi Selatan, Indonesia

* Email: abubakar@poltekelbarombong.ac.id

Abstract. The reliability of marine diesel engines is a critical factor in ensuring safe and efficient vessel operation. Failures in the valve train system, particularly those related to rocker arm bushings and exhaust valves, may reduce propulsion performance, increase fuel consumption, interrupt voyages, and create safety risks. This study analyzes how suboptimal implementation of a Planned Maintenance System (PMS) contributed to rocker arm bushing wear and exhaust valve stem failure on KM. Mutiara Berkah II, a Ro-Ro passenger vessel powered by a medium-speed SEMT Pielstick 12PC4-2V diesel engine. A descriptive engineering case-study design was applied using shipboard observations, PMS records, running-hour documentation, engine logbook data, exhaust gas temperature (EGT) records, maintenance documentation, and interviews with engine personnel. The results show that the PMS was not optimally implemented due to irregular alignment inspections, clearance checks without precision instruments, inconsistent running-hour recording, and delayed replacement of bushings caused by spare-part unavailability. The bushing clearance increased from the normal range of 0.30-0.60 mm to approximately 0.95-1.00 mm. This condition caused rocker arm misalignment, abnormal vibration, knocking noise, increased EGT up to 365°C, uneven loading on the valve stem, and eventual exhaust valve stem fracture in cylinder 6B. The study proposes an enhanced PMS framework incorporating operating-hour-based inspection, precision clearance measurement, EGT trend monitoring, critical spare-part management, and improved maintenance documentation. The findings demonstrate that disciplined preventive maintenance and early condition monitoring can reduce the recurrence of valve train failures and improve main engine reliability.

Keywords: *Planned Maintenance System; marine diesel engine; rocker arm bushing; exhaust valve failure; preventive maintenance; reliability engineering*

1. INTRODUCTION

Marine transportation depends strongly on the reliability of propulsion machinery. For Ro-Ro passenger vessels, main engine failure does not only create a technical problem but may also disrupt passenger service, cargo movement, voyage scheduling, and safety assurance. A propulsion engine is a complex system in which mechanical, thermal, lubrication, and maintenance factors interact continuously. Therefore, reliability is not determined only by component design, but also by the quality of inspection, documentation, spare-part readiness, and maintenance decision making.

In medium-speed diesel engines, the valve train system plays a central role in controlling air intake and exhaust gas discharge during the combustion cycle. The rocker arm transmits camshaft motion to the valve stem, while the bushing functions as a sliding bearing that stabilizes rocker arm movement around the rocker shaft. When the bushing experiences excessive wear, the rocker arm may no longer move in a stable and aligned manner. The resulting clearance enlargement can generate vibration, knocking noise, uneven contact pressure, and misalignment between the rocker arm and the valve stem. Under repeated cyclic loading, these conditions may accelerate fatigue damage in the exhaust valve stem.

Planned Maintenance System (PMS) is intended to prevent such progressive failures through scheduled inspection, lubrication, measurement, adjustment, replacement, and documentation. In marine practice, however, PMS effectiveness depends on discipline in carrying out inspection intervals, the availability of precision measuring instruments, accurate running-hour records, and adequate stock of critical spare parts. If PMS is treated mainly as an administrative schedule rather than an engineering control system, early symptoms such as rising EGT, abnormal noise, or increasing clearance may not be translated into timely preventive action.

The case of KM. Mutiara Berkah II illustrates this problem. During operation in February and March 2025, abnormal symptoms were detected on the main engine, particularly knocking noise and elevated EGT in cylinder 6B. Subsequent inspection revealed severe rocker arm bushing wear and fracture of the exhaust valve stem. The incident forced emergency corrective maintenance and exposed weaknesses in inspection discipline, clearance measurement, running-hour recording, and spare-part readiness. The case is important because it shows how a relatively small bearing component can trigger a chain of failures affecting engine reliability and vessel operation.

This study aims to transform the shipboard failure case into an engineering maintenance analysis. The objectives are: (1) to identify the PMS implementation deficiencies contributing to rocker arm bushing wear; (2) to analyze the failure mechanism connecting bushing clearance growth, rocker arm misalignment, and exhaust valve stem fracture; and (3) to propose an optimized PMS framework for preventing recurrence. The main contribution of this study is the integration of maintenance management, component wear analysis, operational symptom monitoring, and practical PMS improvement in a real shipboard context.

2. LITERATURE REVIEW AND CONCEPTUAL FRAMEWORK

The valve train of a four-stroke marine diesel engine converts camshaft motion into precise valve opening and closing. The rocker arm is a mechanical lever that transfers oscillating motion to the valve stem and enables correct timing of intake and exhaust processes. A bushing located between the rocker arm and rocker shaft reduces friction, supports rotation, and keeps the lever movement stable. The reliability of this arrangement depends on adequate lubrication, proper clearance, component alignment, and material integrity [9]-[11].

Bushing wear is a common mechanical degradation process caused by friction, inadequate lubrication, cyclic loading, contamination, excessive clearance, or misalignment. In a valve train, wear does not remain isolated at the bushing surface. Once clearance exceeds the allowable limit, the rocker arm may tilt or vibrate, causing side loading on the valve stem. This side loading increases contact stress on the valve guide and can accelerate fatigue damage in the stem. Exhaust valves are especially vulnerable because they operate under high thermal load and are exposed to repeated mechanical and thermal cycles [3], [4].

PMS provides a structured maintenance approach for preventing failure before it disrupts operation. Corrective maintenance restores function after a failure, whereas preventive maintenance attempts to reduce the likelihood of failure through scheduled actions. Recent shipboard maintenance literature emphasizes that modern maintenance should move beyond calendar-based tasks toward condition-based and predictive approaches that use monitoring data, trend analysis, and risk-based inspection priorities [1], [2]. In the context of rocker arm bushings, such improvement means that visual inspection alone is insufficient; clearance measurement, EGT monitoring, vibration observation, and documentation must be integrated into decision making.

Previous studies on marine diesel failures have discussed exhaust valve damage, seating failure, high temperature, fuel consumption, and shipboard maintenance strategies. However, many of these studies focus either on the failed valve component or on maintenance scheduling in general. Fewer studies provide a direct chain of evidence linking PMS weaknesses to bushing wear, rocker arm misalignment, EGT increase, and exhaust valve stem fracture in an actual vessel. This creates an applied research gap for a case-based maintenance model that connects operational symptoms, component condition, and maintenance improvement as seen in the Table 1.

Table 1. Summary of Selected Research Gaps

Source	Focus	Main contribution	Limitation	Gap addressed in this study
Jimenez et al. [1]	Predictive maintenance for vessel machinery	Shows the value of data-driven maintenance models	Limited focus on specific valve train failure mechanism	Applies failure analysis to a specific shipboard valve train case
Park and Lee [2]	Shipboard maintenance management	Reviews maintenance strategies for	Broad maintenance discussion without	Links PMS implementation to bushing and

		vessel machinery	component- level case evidence	exhaust valve failure
Pouranvari et al. [3]	Exhaust valve failure in diesel engines	Explains material and thermal factors affecting exhaust valves	Limited connection to shipboard PMS and spare-part management	Connects valve failure with PMS and operational monitoring
Agung et al. [4]	Exhaust valve damage in main engines	Highlights operational impact of exhaust valve failure	Does not emphasize rocker arm bushing as initiating factor	Identifies bushing wear as the upstream failure trigger
This study	PMS, bushing wear, and valve stem failure	Integrates maintenance, mechanical wear, EGT evidence, and improvement model	Single-vessel case study	Provides a practical PMS optimization framework for similar vessels

3. METHODOLOGY

This study used a descriptive engineering case-study design. The approach was selected because the objective was to examine a real failure event and interpret it through maintenance records, operational data, inspection findings, and crew explanations. The case-study design is appropriate for identifying how technical degradation and maintenance practices interact in a specific shipboard environment.

The unit of analysis was the main engine valve train system of KM. Mutiara Berkah II, with particular attention to the rocker arm bushing and exhaust valve assembly of cylinder 6B. The analysis was not intended to statistically generalize to all vessels, but to develop a transferable maintenance logic that can be applied to similar medium-speed diesel engines and Ro-Ro vessel operations.

Data were collected from primary and secondary sources. Primary data consisted of direct observation during shipboard practice, visual inspection of the rocker arm and bushing condition, and interviews with engine officers and crew. Secondary data consisted of PMS records, running-hour information, engine logbook entries, EGT records before and after repair, maintenance documentation, and vessel technical particulars. The use of multiple data sources enabled triangulation between symptoms, component condition, and maintenance practices.

The main variables observed were EGT per cylinder, running hours of rocker arm components, bushing clearance, alignment condition, spare-part availability, and maintenance implementation. The key measurement indicators were EGT in degrees Celsius, operating hours, and bushing clearance in millimeters. In the original shipboard

records, EGT was obtained from engine monitoring and logbook data, whereas bushing condition was assessed through inspection and measurement using appropriate tools such as feeler gauges, bore gauges, dial gauges, and related measuring instruments, the details provided in Table 2.

Table 2. Data Sources and Analytical Uses

Data source	Information extracted	Use in analysis
PMS records	Inspection schedule, component replacement plan, maintenance task history	Assessment of maintenance compliance and missing tasks
Engine logbook	EGT by cylinder, operating condition, watch period, RPM	Identification of abnormal operating symptoms
Running-hour records	Operating time of rocker arm and bushing components	Evaluation of interval-based maintenance control
Inspection findings	Bushing wear, clearance, alignment condition, valve stem failure	Failure mechanism reconstruction
Interviews with engine personnel	Crew explanation of symptoms, repair constraints, spare-part delay	Root cause interpretation and verification
Ship particulars	Engine type, cylinder configuration, rated power, operating profile	Contextualization of technical findings

Data analysis was carried out in five stages. First, operational symptoms were identified from EGT records, reported knocking noise, and abnormal vibration. Second, the physical failure was described by comparing normal and observed bushing clearance and by documenting the exhaust valve stem fracture. Third, PMS implementation was assessed by reviewing inspection intervals, running-hour recording, measurement practices, and spare-part readiness. Fourth, root cause analysis was used to group causal factors into maintenance procedure, measurement, documentation, spare-part logistics, and human decision making. Fifth, an optimized PMS framework was developed by converting the failure evidence into preventive maintenance actions.

The analysis followed a reduction, presentation, and conclusion approach consistent with qualitative data analysis. Reduction was performed by selecting only data relevant to PMS implementation, bushing condition, EGT change, and valve failure. Data were then presented in comparative tables and a failure progression matrix. Conclusions were drawn by linking the operational indicators with component condition and maintenance deficiencies.

4. RESULT AND DISCUSSION

4.1 RESULT

Engine and Component Characteristics

KM. Mutiara Berkah II is a Ro-Ro passenger vessel operating with a SEMT Pielstick 12PC4-2V medium-speed diesel engine. The main engine is a four-stroke V-12 engine with a rated output of 13,092 kW at 380 RPM and uses Marine Diesel Oil or Heavy Fuel Oil. The valve train is therefore subjected to continuous mechanical and thermal load during vessel operation. The rocker arm system includes exhaust and intake rocker arms supported by bushings made of phosphor bronze or tin bronze bearing alloy. The exhaust rocker arm uses a Y-type arrangement to actuate two exhaust valves through a valve bridge, making alignment and clearance control especially important. The details provided in Table 3 and Table 4.

Table 3. Main Engine Particulars of Km. Mutiara Berkah II

Parameter	Specification
Vessel type	Ro-Ro passenger vessel
Main engine manufacturer	SEMT Pielstick (NKK/Japan license)
Model	12PC4-2V
Engine type	Four-stroke, medium-speed diesel
Cylinder configuration	V-type, 12 cylinders
Rated power	13,092 kW
Speed	380 RPM
Fuel type	Marine Diesel Oil / Heavy Fuel Oil

Table 4. Rocker Arm and Bushing Characteristics

Parameter	Specification
Engine type	Medium-speed diesel, four-stroke, V-12
Rocker arm per cylinder	4 units (2 intake + 2 exhaust)
Total rocker arms	48 units
Exhaust rocker arm type	Y-type rocker arm actuating two exhaust valves via valve bridge
Intake rocker arm type	Individual rocker arm for each intake valve
Rocker arm material	Forged alloy steel, heat treated
Bushing material	Phosphor bronze / tin bronze bearing alloy
Lubrication system	Pressurized lubrication from oil gallery in cylinder head

Operational Symptoms Prior to Failure

The earliest operational symptoms were abnormal knocking noise, high vibration, and elevated EGT in the B-bank cylinders, especially cylinder 6B. At 300 RPM, several

cylinders recorded EGT above the expected normal operating range of approximately 280-320°C. Cylinder 6B reached 360°C during the 00.00-04.00 watch and 365°C during the 04.00-08.00 watch. The engine was subsequently stopped at the 08.00-12.00 watch, as indicated by Finish With Engine (FWE). These records show that thermal abnormality appeared before the complete corrective maintenance action, as seen in Table 5 and Table 6.

Table 5. Exhaust Gas Temperature During Incident at 300 RPM

Watch period	1A	2A	3A	4A	5A	6A	1B	2B	3B	4B	5B	6B
00.00-04.00	314	323	343	323	330	324	327	348	327	363	353	360
04.00-08.00	316	323	346	324	332	325	329	349	350	364	355	365
08.00-12.00	FWE	FWE	FWE	FWE	FWE	FWE	FWE	FWE	FWE	FWE	FWE	FWE

After repair, EGT values decreased substantially and returned closer to the normal range. Cylinder 6B decreased from 365°C during the incident to 304-312°C after repair. The reduction supports the interpretation that the abnormal valve train condition had affected combustion and exhaust behavior before the repair action.

Table 6. Exhaust Gas Temperature After Repair at 300 RPM

Watch period	1A	2A	3A	4A	5A	6A	1B	2B	3B	4B	5B	6B
16.00-20.00	273	276	289	279	283	281	283	292	281	302	289	304
20.00-24.00	283	286	294	293	298	291	296	301	304	314	310	312
00.00-04.00	FWE	FWE	FWE	FWE	FWE	FWE	FWE	FWE	FWE	FWE	FWE	FWE

Inspection Findings and Failure Evidence

The inspection confirmed that the rocker arm bushing had experienced excessive wear. The normal clearance range was 0.30-0.60 mm, while the observed clearance increased to approximately 0.95-1.00 mm. This increase is important because it changes the rocker arm from a guided oscillating component into a less stable lever with a tendency toward lateral movement. The enlarged clearance also explains why the valve actuation became less precise, causing uneven loading on the exhaust valve stem, in the Table 7.

Table 7. Comparison of Normal and Observed Conditions

Parameter	Normal/expected condition	Observed condition	Engineering implication
Bushing clearance	0.30-0.60 mm	0.95-1.00 mm	Excessive wear and unstable rocker arm motion
Rocker arm alignment	Within tolerance	Misaligned with valve stem	Uneven force transfer to valve assembly
Operational sound	Normal mechanical noise	Knocking noise	Impact and irregular contact in valve train
Engine vibration	Normal	Excessive	Dynamic imbalance and unstable actuation
EGT cylinder 6B	Approximately 280-320°C	Up to 365°C	Abnormal combustion/exhaust behavior
Exhaust valve stem	Intact	Fractured at cylinder 6B	Failure requiring corrective maintenance

Root Cause Analysis

The root cause analysis indicates that the failure was not caused by one isolated factor. Instead, it was the result of a combination of maintenance, measurement, documentation, logistics, and operational decision-making weaknesses. The first weakness was irregular alignment inspection. Although the component was approaching the relevant inspection interval, alignment was not consistently documented. The second weakness was reliance on visual inspection without sufficient precision measurement. Because bushing wear is a dimensional problem, visual inspection alone cannot reliably detect early clearance growth. The third weakness was inconsistent running-hour recording, which made it difficult to determine whether the bushing had exceeded the safe operating interval. The fourth weakness was spare-part unavailability, because bushing replacement required ordering with a lead time of approximately 2-3 weeks. Finally, early symptoms such as EGT rise and knocking noise were not escalated quickly enough into preventive action. Table 8 is the root cause analysis.

Table 8. Root Cause Analysis of the Failure

Category	Finding	Effect on failure progression	Preventive control
Maintenance scheduling	Alignment inspection not routinely documented	Wear was not detected before clearance became excessive	Strict operating-hour-based inspection schedule
Measurement practice	Inspection relied mainly on visual checks	Clearance growth was not quantified early	Use feeler gauge, dial gauge, bore gauge, inside micrometer

Documentation	Running hours were inconsistently recorded	Maintenance interval could not be controlled accurately	Daily update and signed PMS records
Spare-part logistics	Bushing not available onboard; ordering lead time 2-3 weeks	Replacement was delayed after wear symptoms appeared	Classify bushing as critical spare part
Operational response	EGT rise and knocking noise not immediately escalated	Failure progressed to valve stem fracture	Trigger limits for EGT and clearance alarms

Failure Progression Matrix

The failure progression can be interpreted as a sequential deterioration pathway. Initial bushing wear enlarged the clearance between the rocker arm and rocker shaft. This increased free movement caused misalignment between the rocker arm and valve stem. Misalignment generated uneven pressure on the valve stem, and the repeated force cycles introduced bending stress. In parallel, abnormal valve operation contributed to elevated EGT, increasing thermal stress. The combination of cyclic mechanical stress and high temperature accelerated fatigue until the exhaust valve stem fractured. The details provided in the Table 9.

Table 9. Failure Progression Matrix

Stage	Condition	Physical mechanism	Observable indicator
1	Initial bushing wear	Friction and material loss at bushing surface	No clear symptom if not measured
2	Clearance enlargement	Rocker arm movement becomes unstable	Clearance approaches or exceeds warning limit
3	Rocker arm misalignment	Force transfer no longer acts along valve stem axis	Knocking and abnormal movement
4	Uneven valve loading	Side loading and repeated bending on valve stem	Vibration and irregular valve operation
5	Thermal-operational abnormality	Combustion/exhaust timing disturbance	EGT rises above normal range
6	Fatigue accumulation	Repeated mechanical and thermal stress	Progressive weakening of valve stem
7	Exhaust valve stem fracture	Final failure of overstressed component	Loss of propulsion reliability and emergency repair

4.2 DISCUSSION

The findings confirm that PMS effectiveness is central to preventing valve train failure. The direct technical cause of the incident was severe bushing wear and excessive clearance. However, the deeper maintenance cause was the inability of the PMS process to detect and respond to the deterioration early enough. In this case, inspection was not sufficiently measurement-based, running-hour documentation was inconsistent, and the absence of critical spare parts delayed corrective replacement. This means that the PMS existed as a schedule, but it did not function fully as a risk control system.

The EGT evidence is especially important. Before repair, cylinder 6B reached 365°C, while after repair it decreased to a range of 304-312°C. This difference shows that EGT can be used as an early warning indicator for valve train abnormalities. Although EGT alone cannot identify bushing wear, a rising EGT trend combined with knocking noise and vibration should trigger immediate inspection of valve clearance, rocker arm alignment, bushing clearance, lubrication passages, and exhaust valve condition. Therefore, EGT should be treated not only as an engine performance record but also as a diagnostic signal within the PMS framework.

The comparison between normal and observed clearance demonstrates that dimensional inspection is essential. The increase from 0.30-0.60 mm to 0.95-1.00 mm represents a major loss of guidance in the rocker arm assembly. Once the rocker arm loses stable guidance, force transmission to the valve stem becomes uneven. This finding is consistent with the mechanical principle that misalignment increases local stress concentration and cyclic bending. In the high-temperature environment of an exhaust valve, this condition accelerates fatigue and may lead to fracture even when the valve material itself is not the original cause of failure.

The incident also highlights the importance of spare-part strategy. A PMS cannot be effective if inspection identifies a degraded critical component but replacement cannot be performed due to stock unavailability. For components with high operational consequence, such as rocker arm bushings and exhaust valve parts, critical spare stock must be determined based on risk rather than purchase convenience. In this case, the recommended minimum stock of one set of bushings per cylinder, plus safety stock, is reasonable because the lead time of 2-3 weeks is too long relative to the risk of propulsion failure.

From a maintenance management perspective, the study supports the transition from purely time-based maintenance to a hybrid PMS combining time-based, operating-hour-based, and condition-based elements. Time-based scheduling provides structure, operating-hour control ensures maintenance is aligned with actual use, and condition monitoring captures early symptoms that may appear before the next scheduled task. For the rocker arm bushing, the most practical condition indicators are EGT trend, knocking noise, vibration observation, and direct clearance measurement. Table 10 is the PMS improvement.

Table 10. PMS Improvement Model for Rocker Arm Bushing Maintenance

Maintenance component	Conventional/observed practice	Improved PMS practice
Inspection basis	Routine visual inspection and general PMS checklist	Operating-hour-based inspection with specific bushing and alignment checklist
Measurement method	Visual observation and limited clearance measurement	Mandatory use of feeler gauge, dial gauge, bore gauge, and inside micrometer
Clearance control	Action taken after obvious symptoms appear	Warning at clearance ≥ 0.70 mm; replacement at or before excessive limit
EGT monitoring	Recorded as operating parameter	Used as diagnostic trend; EGT $>320^{\circ}\text{C}$ triggers valve train inspection
Spare-part management	Replacement depends on shore supply availability	Bushing classified as critical spare; minimum 1 set per cylinder onboard
Documentation	Manual records with inconsistent running-hour update	Standardized PMS form with running hours, measurement values, signatures, and follow-up status
Maintenance philosophy	Reactive-corrective after fault appears	Preventive and condition-based maintenance to stop progression before failure

Based on the empirical findings and failure mechanism, this study proposes a practical PMS optimization framework for rocker arm bushings and associated exhaust valve components. The framework is built on five pillars: operating-hour-based inspection, precision measurement, critical spare-part management, condition-based monitoring, and documentation discipline.

The first pillar is operating-hour-based inspection. Daily monitoring should be performed to confirm abnormal symptoms such as knocking, vibration, and EGT deviation. At 500 hours, lubrication pressure and oil delivery to the rocker arm should be checked. At 1000 hours, valve clearance should be inspected and adjusted. At 3000 hours, visual inspection and bushing clearance measurement should be performed. At 6000 hours, the bushing surface and rocker shaft condition should be examined. At 9000 hours, internal diameter should be measured using precision instruments. At 12,000 hours, planned replacement of bushings should be performed or accelerated if condition indicators show deterioration.

The second pillar is precision measurement. Because bushing failure is fundamentally a dimensional wear problem, measurement values must be recorded, not merely described as normal or abnormal. The PMS form should include measured

clearance, instrument used, inspector name, running hours, EGT trend, and recommended action. This will create a traceable maintenance history that supports engineering decisions.

The third pillar is critical spare-part management. Rocker arm bushings should be categorized as critical spare parts because their failure may lead to exhaust valve damage and propulsion interruption. A minimum onboard stock of one set per cylinder is recommended. The fourth pillar is condition-based monitoring. EGT above 320°C, clearance approaching 0.70 mm, abnormal knocking, or increasing vibration should trigger immediate inspection. The fifth pillar is documentation discipline, including signed forms, updated running hours, repair evidence, and follow-up verification after maintenance. Table 11 is the operating hour-based PMS schedule.

Table 11. Operating-Hour-Based PMS Schedule for Bushing and Valve Train Control

Interval	Maintenance activity	Purpose
Daily / every watch	Monitor EGT, knocking noise, vibration, lubrication indication	Detect early abnormality during operation
500 hours	Check oil pressure and lubrication path to rocker arm	Prevent friction-related wear
1000 hours	Inspect and adjust valve clearance	Maintain correct valve timing and loading
3000 hours	Inspect alignment and measure bushing clearance	Detect clearance growth before severe wear
6000 hours	Inspect bushing surface, rocker shaft, and oil passage condition	Identify surface degradation and lubrication problems
9000 hours	Measure internal bushing diameter and compare with tolerance	Quantify wear and plan replacement
12,000 hours	Replace bushing set or overhaul as required	Prevent end-of-life failure

5. CONCLUSION

This study analyzed the relationship between PMS implementation, rocker arm bushing wear, and exhaust valve stem failure in the main engine of KM. Mutiara Berkah II. The findings show that the incident was not simply a sudden component failure. It was a progressive failure caused by the interaction of excessive bushing clearance, rocker arm misalignment, abnormal vibration, elevated EGT, uneven valve stem loading, and fatigue accumulation.

The main maintenance deficiencies were irregular alignment inspection, visual inspection without adequate precision measurement, inconsistent running-hour documentation, delayed bushing replacement due to spare-part unavailability, and insufficient response to early symptoms such as EGT increase and knocking noise. The

bushing clearance increased from the normal range of 0.30-0.60 mm to approximately 0.95-1.00 mm, while EGT in cylinder 6B reached 365°C before repair. These findings support the failure pathway from bushing wear to exhaust valve stem fracture.

The proposed PMS optimization framework emphasizes operating-hour-based inspection, precision measurement, EGT trend monitoring, critical spare-part management, and improved documentation. For practical implementation, the bushing should be treated as a critical spare part, valve train inspection should be triggered by EGT above 320°C or abnormal noise, and clearance measurement should be performed systematically at defined operating-hour intervals. Future research may develop sensor-based monitoring using vibration and temperature data to compare the effectiveness of condition-based maintenance against conventional time-based PMS.

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