Multicore Int. J. Multidiscip, Vol 2, No 2, November 2026
e-ISSN: 3108-933X

OPEN ACCESS

Reliability-Based Preventive Maintenance Planning of Pressure Regulator Shut-Off Valve Components on CN235 Aircraft

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Abstract— Aircraft component reliability is essential for maintaining flight safety and operational continuity. The Pressure Regulator Shut-Off Valve (PRSOV) is a critical component of the CN235 bleed air system because it regulates and shuts off pressurized air supplied to the aircraft environmental control system. Historical maintenance records indicated 17 PRSOV-related failures during 0–8,952 flight hours, including failures involving the valve, connector, diaphragm, seal O-ring, spring, and solenoid. This study aims to characterize PRSOV reliability, identify dominant failure modes and their causes, and develop reliability-based preventive maintenance recommendations. A quantitative reliability analysis was conducted using a two-parameter Weibull distribution, supported by Failure Mode and Effects Analysis (FMEA) and Fault Tree Analysis (FTA). Weibull analysis indicated a shape parameter greater than one, representing an increasing failure-rate pattern and suggesting the influence of component aging and wear-out mechanisms. FMEA was used to prioritize failure modes based on severity, occurrence, and detection, while FTA was applied to identify the logical relationships among basic failure causes. The integrated results indicate that preventive maintenance intervals should be differentiated according to component-specific reliability characteristics and failure risks rather than relying solely on the manufacturer's general maintenance interval. The proposed approach provides a basis for improving PRSOV reliability, reducing unscheduled maintenance, and supporting CN235 operational safety.

Keywords: *PRSOV; reliability analysis; Weibull distribution; FMEA; preventive maintenance*

1. Introduction

Aircraft operational safety depends strongly on the reliability and maintainability of critical components. Maintenance activities are required to preserve equipment performance, prevent unexpected failures, reduce downtime, and maintain operational continuity. Maintenance management should therefore consider not only the occurrence of failures but also the expected behavior of components during their operating life. Preventive maintenance is particularly important for components whose failure can affect system performance and operational safety [1].

Reliability represents the ability of a component or system to perform its intended function for a specified period under specified operating conditions. Reliability and maintainability analysis provides a quantitative basis for understanding failure behavior, estimating component life, and developing maintenance strategies [2]. In industrial systems, maintenance planning is also closely related to productivity because unexpected equipment failures may generate downtime, additional repair activities, and operational losses [3], [4]. These considerations become more critical in aviation because component failure may have consequences beyond maintenance costs, particularly when the affected component contributes to aircraft system performance.

Received: 5 August 2026, Revised: 31 August 2026 , Accepted: 31 August 2026
https://doi.org/10.64123/mijm.v2.i2.4

The Pressure Regulator Shut-Off Valve (PRSOV) is an important component of the CN235 bleed air system. It regulates and shuts off pressurized air supplied to the aircraft environmental control system, including air conditioning and cabin pressurization functions. Failure of the PRSOV or its associated components can affect bleed air regulation and may result in corrective maintenance or unscheduled aircraft maintenance.

Maintenance activities for aircraft components must also consider the relationship between component aging and failure probability. Components may experience different failure patterns depending on material characteristics, operating conditions, environmental exposure, installation conditions, and maintenance practices. Failure behavior can therefore be analyzed using reliability models to identify whether failure probability decreases, remains relatively constant, or increases with operating time [5]. Reliability-centered approaches have also been applied to maintenance planning in industrial systems to establish maintenance activities according to failure characteristics and operational consequences [6].

Historical maintenance records at PT Dirgantara Indonesia (Persero) identified 17 PRSOV-related failures during the observed operating period, with failure times ranging from 653 to 8,952 flight hours. The recorded failures involved connectors, valve sticking, diaphragms, seal O-rings, solenoids, and springs. Several failures occurred before the manufacturer's specified preventive maintenance interval of 4,000 flight hours. This condition indicates that a general maintenance interval may not fully represent the actual reliability behavior of individual PRSOV components.

Previous studies have demonstrated the application of reliability analysis for aircraft maintenance planning. Setiawan et al. [7], for example, applied reliability analysis, Weibull distribution, and FMEA to preventive maintenance planning for a ram air actuator on a Boeing 737 Next Generation aircraft. Their study demonstrates the usefulness of reliability-based maintenance planning for aircraft components. FMEA has also been applied to identify critical failure modes in aircraft components and establish priorities for corrective action. In a study of the CN-235 wing structure, Djunaidi and Ryantaffy [8] demonstrated that FMEA could be used to identify critical nonconforming components and prioritize inspection and improvement activities. These studies indicate the importance of integrating reliability and risk-based approaches in aircraft maintenance.

FMEA provides a structured method for identifying potential failure modes, their effects, causes, and associated risks. The method is widely used to establish maintenance priorities because it considers failure severity, occurrence, and detectability [9]. In addition, FMEA has been applied to maintenance and quality improvement problems in various industrial sectors, including aircraft manufacturing and shipbuilding [8], [10]. FTA complements FMEA by providing a systematic representation of the logical relationships between a top-level failure and its underlying causes [11].

Preventive maintenance scheduling can also be strengthened through reliability-based determination of maintenance intervals. Recent studies have demonstrated the use of reliability analysis to determine optimal preventive maintenance intervals for critical industrial components [12]. In addition, production and maintenance management literature emphasizes the importance of integrating maintenance planning with operational performance and production requirements [13]. For aircraft maintenance, technical and operational requirements must also be aligned with approved maintenance documentation and applicable aviation maintenance practices [14]. Failure-mode and criticality analysis provides an established framework for systematically evaluating the effects and criticality of potential failures [15].

Although reliability analysis, FMEA, and FTA have each been widely applied in maintenance studies, their integrated application to PRSOV components on CN235 aircraft remains limited. This study therefore combines Weibull reliability analysis, FMEA, and FTA to evaluate PRSOV failure behavior and establish component-specific preventive maintenance recommendations. The novelty of the study lies in integrating statistical reliability characteristics with failure-risk prioritization and causal analysis for a critical aircraft valve assembly.

The objective of this study is to analyze the reliability characteristics of PRSOV components, identify and prioritize their dominant failure modes, determine the main causes of failure, and formulate preventive maintenance recommendations based on the actual historical failure characteristics of CN235 PRSOV components.

2. Method

This study employed a quantitative reliability-analysis approach supported by qualitative failure analysis. The research was conducted at the Maintenance, Repair, and Overhaul division of PT Dirgantara Indonesia (Persero), Bandung, during August–October 2025. The research object was the Pressure Regulator Shut-Off Valve installed on CN235 aircraft.

The selection of the PRSOV was based on the occurrence of repeated historical failures and its function within the aircraft bleed air system. The analysis followed the general principles of reliability and maintainability engineering, in which historical failure data are used to estimate component failure behavior and support maintenance decision-making [2].

The data consisted of primary and secondary information. Primary information was obtained through interviews with maintenance technicians and engineers. Secondary information was collected from maintenance logbooks, component removal records, Aircraft Maintenance Manuals, Illustrated Parts Catalogs, Component Maintenance Manuals, and historical PRSOV failure records. The historical data included operating hours and corresponding failure modes. The use of maintenance documentation and systematic failure analysis is consistent with established aircraft maintenance and failure-analysis practices [14], [15].

A total of 17 PRSOV failure observations were available, with failure times ranging from 653 to 8,952 flight hours. The failure observations were ordered according to operating time and analyzed using a two-parameter Weibull distribution. Bernard's Median Rank method was used to estimate the cumulative failure probability for each observation. The transformed data were subsequently used to estimate the Weibull shape and scale parameters through linear regression.

The suitability of the Weibull distribution was evaluated using the Kolmogorov–Smirnov goodness-of-fit test. The selected reliability model was then used to characterize reliability and failure-rate behavior and to estimate the mean time to failure. The interpretation of reliability and failure behavior followed established reliability engineering principles [5], [2].

Component-specific analysis was subsequently conducted for valve, connector, diaphragm, spring, and seal O-ring. The solenoid was not subjected to Weibull parameter estimation because only one failure observation was available. This limitation was explicitly considered when developing the maintenance recommendation.

FMEA was conducted to identify and prioritize the principal failure modes. Severity, occurrence, and detection were evaluated using a 1–10 scale, and the resulting Risk Priority Number was used to establish relative maintenance priorities. FMEA was selected because it provides a systematic approach for identifying failure modes and prioritizing corrective or preventive actions [9]. The approach is also consistent with previous aircraft component studies in which FMEA was used to identify critical failure modes and prioritize inspection activities [8].

FTA was used to investigate the causal structure of PRSOV malfunction. The top event was defined as the inability of the PRSOV to regulate or shut off bleed air correctly. Basic events considered in the analysis included electrical signal failure, loose or corroded connectors, solenoid failure, contamination, corrosion, spring fracture, diaphragm damage, seal deterioration, vibration, improper installation, excessive electrical loading, and material degradation. The FTA approach follows the use of logical failure relationships to identify potential root causes and critical failure pathways [11].

The FMEA and FTA procedures were also considered within the broader framework of maintenance risk assessment, in which failure consequences, failure causes, and maintenance priorities are jointly considered [18]. Reliability block and system-reliability approaches provide additional support for understanding relationships between component failures and system performance [17].

Finally, the results from reliability analysis, FMEA, and FTA were integrated to establish component-specific preventive maintenance recommendations. The maintenance recommendations were evaluated by considering reliability characteristics, failure priority, failure causes, and operational feasibility. This integrated approach is consistent with reliability-centered maintenance principles, which emphasize matching maintenance tasks to actual failure characteristics and operational consequences [6]. Reliability and availability considerations are also important when evaluating the effect of maintenance strategies on equipment performance [19].

3. Results and Discussion

The historical PRSOV failure data are presented in Table 1. The table is presented after describing the dataset because the failure distribution provides the basis for subsequent reliability and failure-mode analysis.

Diaphragm failure occurred four times, connector failure occurred three times, spring and seal O-ring failures occurred twice each, and solenoid failure occurred once. The distribution indicates that valve-related failure is an important contributor to PRSOV malfunction and therefore requires particular attention in the risk analysis.

The historical data were then analyzed using Bernard's Median Rank and Weibull regression. The resulting transformed dataset is summarized in Table 2. The table is provided after explaining the data transformation because the transformation results are used to estimate the Weibull parameters.

The Weibull regression produced a shape parameter of approximately 1.47 and a scale parameter of approximately 5,719.5 FH. The shape parameter greater than one indicates an increasing failure-rate pattern. This result suggests that the probability of PRSOV failure increases as operating time increases, which is consistent with an aging or wear-out mechanism.

The goodness-of-fit results are presented in Table 3. The table is introduced before its appearance because the comparison of statistical distributions determines the reliability model used in the subsequent analysis.

Table 1. Historical PRSOV failure data

No.	Failure time (FH)	Failure mode
1	653	Connector
2	951	Valve stuck
3	1,993	Diaphragm
4	2,253	Valve stuck
5	2,307	Seal O-ring
6	3,657	Solenoid
7	3,859	Spring
8	3,881	Diaphragm
9	5,455	Valve stuck

No.	Failure time (FH)	Failure mode
10	5,981	Diaphragm
11	6,369	Seal O-ring
12	6,459	Valve stuck
13	7,284	Connector
14	7,635	Spring
15	7,826	Connector
16	7,897	Diaphragm
17	8,952	Valve stuck

Table 2. Weibull regression data

Rank	Failure time (FH)	Median rank	ln(time)	Transformed failure probability
1	653	0.0402	6.4816	-3.1927
2	951	0.0977	6.8575	-2.2749
3	1,993	0.1552	7.5974	-1.7801
4	2,253	0.2126	7.72	-1.431
5	2,307	0.2701	7.7437	-1.1556
6	3,657	0.3276	8.2044	-0.9241
7	3,859	0.3851	8.2582	-0.7211
8	3,881	0.4425	8.2638	-0.5373
9	5,455	0.5	8.6043	-0.3665
10	5,981	0.5575	8.6963	-0.2043
11	6,369	0.6149	8.7592	-0.0467
12	6,459	0.6724	8.7732	0.1098
13	7,284	0.7299	8.8934	0.2692
14	7,635	0.7874	8.9405	0.4371
15	7,826	0.8448	8.9652	0.6223
16	7,897	0.9023	8.9742	0.8441
17	8,952	0.9598	9.0996	1.1673

Table 3. Kolmogorov–Smirnov goodness-of-fit results

Distribution	K–S statistic
Weibull	0.107
Exponential	0.1974
Lognormal	0.5582
Critical value	0.3298

The Weibull distribution produced the lowest K–S statistic among the evaluated distributions and its statistic was below the critical value. Therefore, the Weibull distribution was considered appropriate for describing the observed PRSOV failure data. The result is consistent with the application of Weibull analysis in reliability engineering, where the distribution is commonly used to characterize different failure-rate patterns and component life behavior [5], [2].

The reliability behavior of the PRSOV was then evaluated using the estimated Weibull parameters. The resulting reliability curve is presented in Figure 1. The figure is referred to here before its appearance because the observed reliability trend provides visual evidence of the increasing failure probability with operating time.

The reliability curve shows a continuous decline as operating time increases. The decline becomes more

https://doi.org/10.64123/mijm.v2.i2.4

pronounced at higher operating hours, supporting the interpretation of an increasing failure-rate pattern. This behavior indicates that the PRSOV should not be managed solely through corrective maintenance because the probability of failure becomes progressively higher as operating age increases.

The failure-rate behavior was also evaluated to determine whether the probability of failure changes with operating time. Figure 2 presents the estimated failure-rate trend and is introduced before the figure because it provides complementary information to the reliability curve.

The failure-rate curve shows an increasing trend as operating time increases. This behavior is consistent with the shape parameter greater than one. From a maintenance perspective, an increasing failure rate supports the implementation of age-related inspection and preventive maintenance activities. The result is consistent with maintenance strategies that use reliability information to reduce unexpected failures and improve component availability [16].

The estimated Weibull parameters also provide an estimate of the mean time to failure. The Weibull-based MTTF should be distinguished from the simple arithmetic average of observed failure intervals. Based on the estimated shape and scale parameters, the Weibull MTTF is approximately 5,176 FH. Therefore, the previously reported value of 526.6 FH should not be interpreted as the Weibull MTTF. The distinction is important because MTTF is an expected life derived from the fitted reliability model, whereas the arithmetic mean of observed intervals represents a descriptive statistic of the available observations.

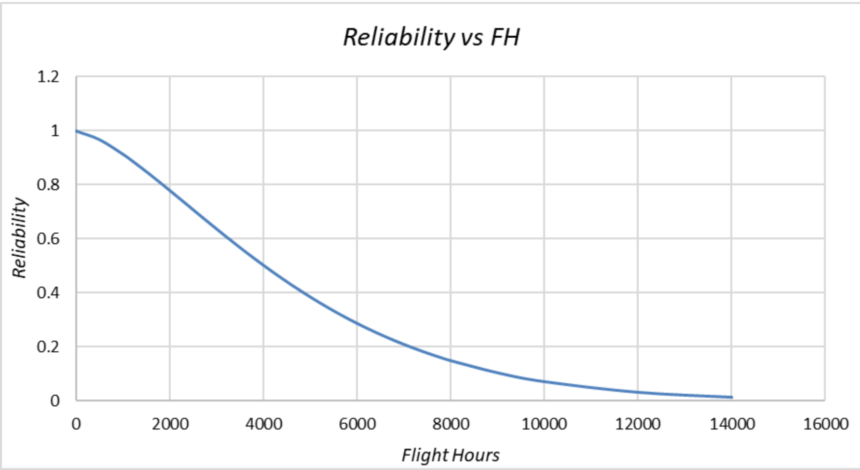

Figure 1. Reliability curve of the PRSOV

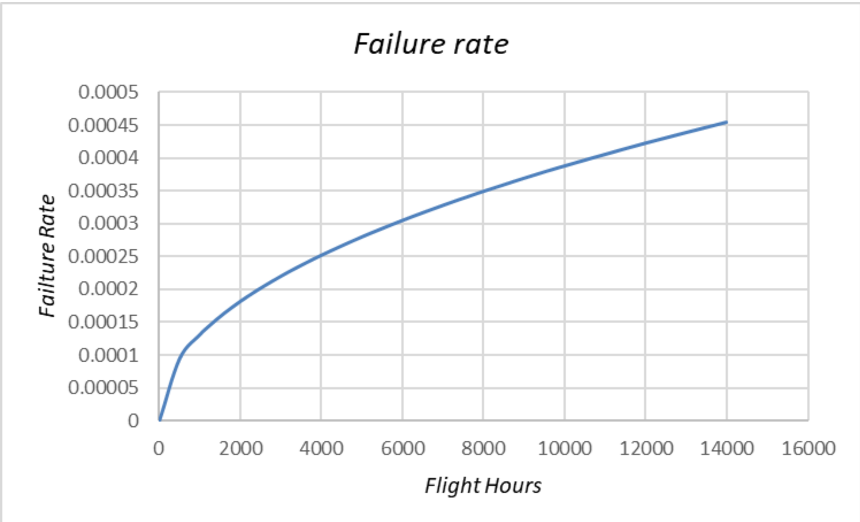

Figure 2. Failure-rate curve of the PRSOV

Component-specific analysis was subsequently conducted to determine differences in reliability behavior among PRSOV subcomponents. The results are summarized in Table 4. The table is presented after discussing the need for component-level analysis because the complete PRSOV reliability behavior may conceal differences among individual failure modes.

Table 4 shows that the component failure patterns differ considerably. The valve, diaphragm, spring, and seal O-ring have shape parameters greater than one, indicating increasing failure rates. The connector has a shape parameter below one, indicating a decreasing failure-rate pattern. This difference suggests that connector failures may be more strongly influenced by installation, early-life defects, vibration, corrosion, or external conditions than by simple wear-out.

The valve has an estimated operating life of approximately 1,491 FH at the selected 80% reliability level. This relatively short reliability-based life is important because valve sticking is also the most frequently observed failure mode. The combination of relatively high occurrence and comparatively short reliability-based life supports prioritizing valve inspection and functional checks.

The connector has the shortest estimated life at the selected reliability target, approximately 631 FH. However, its decreasing failure-rate pattern indicates that the result should not automatically be interpreted as evidence of connector wear-out. Preventive activities should instead emphasize inspection, tightening, cleaning, and corrosion control.

The diaphragm has an estimated reliability-based life of approximately 2,374 FH, while the spring has an estimated value of approximately 3,056 FH. Both components exhibit increasing failure-rate patterns, suggesting that degradation and aging may contribute to their failure behavior. The seal O-ring has an estimated reliability-based life of approximately 1,630 FH, indicating that seal condition should be monitored before the component reaches a higher-risk operating region.

Only one solenoid failure was recorded, at 3,657 FH. Because a single observation is insufficient to estimate a statistically reliable Weibull failure distribution, no component-level Weibull parameter was calculated for the solenoid. The observed failure nevertheless provides an indication that electrical and functional inspection should be incorporated into maintenance activities. A provisional maintenance interval below the observed failure time may be operationally useful, but it should be validated using additional failure observations.

The principal PRSOV failure modes were then evaluated using FMEA. The failure modes identified from historical maintenance records include valve sticking, loose or corroded connectors, solenoid failure, diaphragm damage, seal O-ring leakage, and spring failure. The FMEA results are presented in Table 5 after identifying the failure modes because the table provides the risk prioritization used in the maintenance recommendation.

The FMEA results indicate that valve sticking has the highest reported RPN of 640. This finding is consistent with the historical failure data, where valve sticking occurred five times. The result also supports the findings of Djunaidi and Ryantaffy [8], who demonstrated that FMEA can identify critical aircraft component failure modes and establish inspection priorities. Similar application of FMEA to industrial maintenance and risk assessment has also shown that failure-mode prioritization can support targeted maintenance interventions [10], [18].

Table 4. Component-specific reliability characteristics

Component	Shape parameter	Scale parameter (FH)	Estimated life at 80% reliability (FH)
Valve	1.117	5,713.50	1,491.00
Connector	0.625	6,955.20	631.3
Diaphragm	1.674	5,815.80	2,374.10

https://doi.org/10.64123/mijm.v2.i2.4

Component	Shape parameter	Scale parameter (FH)	Estimated life at 80% reliability (FH)
Spring	1.866	6,827.00	3,056.20
Seal O-ring	1.254	5,392.30	1,630.40

Table 5. FMEA results for PRSOV

Failure mode	Effect	Severity	Occurrence	Detection	RPN
Valve stuck	PRSOV unable to regulate or shut off bleed air	[verify]	[verify]	[verify]	640
Connector loose/corroded	Electrical signal interruption	[verify]	[verify]	[verify]	[verify]
Solenoid burned	Actuation failure	[verify]	[verify]	[verify]	[verify]
Diaphragm torn	Pressure regulation instability	[verify]	[verify]	[verify]	[verify]
Seal O-ring leakage	Bleed air leakage	[verify]	[verify]	[verify]	[verify]
Spring failure	Valve actuation failure	[verify]	[verify]	[verify]	[verify]

The FMEA results should nevertheless be interpreted together with the reliability analysis. A high RPN identifies a failure mode with a high relative risk, whereas Weibull analysis describes the statistical behavior of failure over operating time. Combining these two perspectives prevents maintenance decisions from being based solely on either failure frequency or risk ranking.

FTA was subsequently used to investigate the causal pathways leading to PRSOV malfunction. The fault tree identifies the inability of the valve to open, close, or regulate correctly as the top event. Figure 3 presents the FTA structure and is referred to before the figure because the diagram provides the basis for the causal interpretation.

The FTA indicates that PRSOV malfunction can originate from electrical, mechanical, environmental, and material-related causes. Electrical causes include loose or corroded connectors and solenoid failure. Mechanical causes include spring fracture, diaphragm damage, actuator malfunction, and seal deterioration. Environmental and operational factors include contamination, corrosion, vibration, and improper installation. Material degradation and aging may further contribute to component deterioration.

The FTA findings are consistent with the reliability results because several identified causes are associated with mechanisms that can become more influential as operating time increases. Material degradation, spring deterioration, seal aging, and diaphragm damage are particularly relevant to components exhibiting increasing failure rates.

The integration of reliability analysis, FMEA, and FTA is presented in Figure 4. The figure is introduced before its appearance because it summarizes how the three analytical approaches contribute to the maintenance decision.

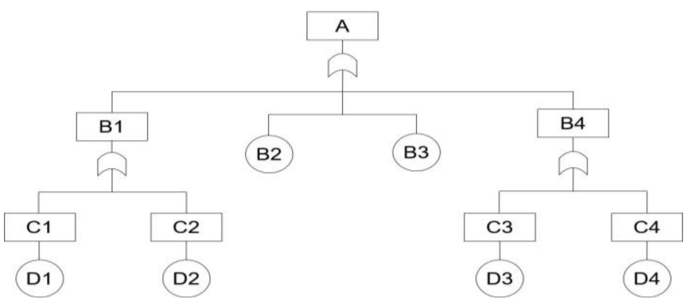

Figure 3. Fault Tree Analysis of PRSOV malfunction

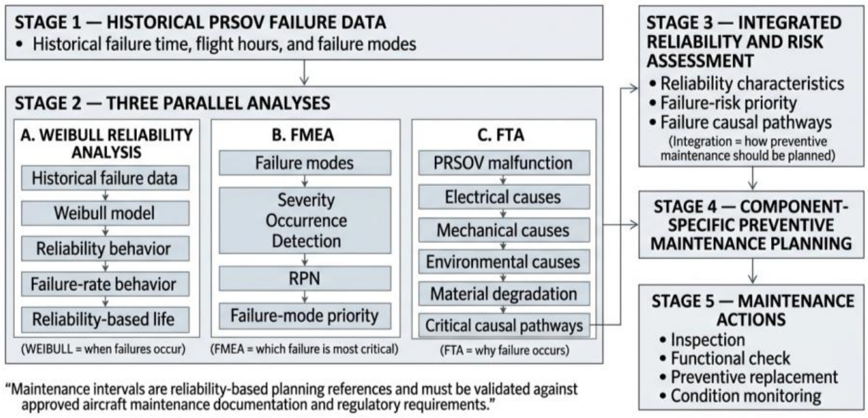

Figure 4. Integration of Weibull reliability analysis, FMEA, and FTA

The integrated analysis provides three complementary perspectives. Weibull analysis identifies the statistical failure pattern, FMEA identifies the failure mode with the highest relative risk, and FTA identifies the causal pathways leading to PRSOV malfunction. The combination indicates that the maintenance program should be differentiated according to component characteristics rather than applying a single interval to all PRSOV components.

The proposed preventive maintenance recommendations are summarized in Table 6. The table is presented after discussing the integrated analytical results because the recommended activities are derived from the combined reliability, FMEA, and FTA findings.

Table 6. Recommended preventive maintenance activities

Component	Reliability-based reference (FH)	Recommended maintenance activity
Connector	631	Inspection, cleaning, tightening, and corrosion check
Valve	1,491	Functional inspection and operational check
Seal O-ring	1,630	Inspection and preventive replacement
Diaphragm	2,374	Inspection and replacement according to condition
Spring	3,056	Inspection and replacement according to condition
Solenoid	3,500*	Electrical and functional inspection

*The solenoid interval is provisional because only one failure observation was available.

The recommended intervals indicate that the connector and valve require the earliest attention, followed by the seal O-ring, diaphragm, spring, and solenoid. The valve receives particular priority because its reliability-based life is relatively short and it also has the highest reported FMEA RPN. Connector maintenance should emphasize inspection rather than automatic replacement because its decreasing failure-rate pattern does not indicate a typical wear-out mechanism.

The proposed intervals should be regarded as reliability-based planning references rather than replacements for approved aircraft maintenance requirements. Aircraft maintenance activities remain subject to the applicable Aircraft Maintenance Manual, Component Maintenance Manual, regulatory requirements, engineering authorization, and organizational maintenance procedures. The recommendations should therefore be validated before implementation.

The results also demonstrate the importance of using component-specific maintenance strategies. Applying a single 4,000-FH interval to all PRSOV subcomponents may not adequately address components whose estimated reliability-based life is substantially shorter. Conversely, components with longer estimated lives should not necessarily be replaced prematurely if inspection and condition monitoring can adequately control the associated risk.

The findings are broadly consistent with previous reliability-based aircraft maintenance research, which has demonstrated that component-specific failure behavior can be used to establish preventive maintenance strategies [7]. The integration of reliability analysis with FMEA and FTA further strengthens the maintenance decision because it combines statistical failure behavior, risk prioritization, and causal information. This approach provides a more comprehensive basis for maintenance planning than relying solely on a manufacturer's general interval or historical average failure time.

4. Conclusion

This study evaluated the reliability characteristics and preventive maintenance requirements of Pressure Regulator Shut-Off Valve components installed on CN235 aircraft using Weibull reliability analysis, FMEA, and FTA. The complete PRSOV failure dataset was adequately represented by a two-parameter Weibull distribution, with a shape parameter of approximately 1.47 and a scale parameter of approximately 5,719.5 FH. The shape parameter greater than one indicates an increasing failure-rate pattern and suggests that aging and wear-out mechanisms contribute to the increasing probability of failure.

The component-level analysis showed different failure characteristics among the PRSOV subcomponents. The valve, diaphragm, spring, and seal O-ring exhibited increasing failure-rate patterns, while the connector exhibited a decreasing failure-rate pattern. At an 80% reliability target, the estimated reliability-based operating limits were approximately 631 FH for the connector, 1,491 FH for the valve, 1,630 FH for the seal O-ring, 2,374 FH for the diaphragm, and 3,056 FH for the spring. The solenoid could not be statistically modeled using Weibull analysis because only one failure observation was available.

FMEA identified valve sticking as the highest-priority failure mode, with the reported RPN of 640. FTA indicated that PRSOV malfunction can be associated with electrical disturbances, contamination, corrosion, spring failure, actuator problems, vibration, improper installation, and material degradation. The integration of these findings indicates that preventive maintenance should be differentiated according to component-specific reliability characteristics and failure risks.

The proposed maintenance intervals provide a reliability-based reference for planning inspections and component replacement. However, the proposed intervals should be validated against approved aircraft maintenance documentation, regulatory requirements, engineering assessments, and additional field data before implementation. Further research should incorporate a larger failure dataset, particularly for low-frequency failure modes such as solenoid failure, to improve statistical confidence and validate the proposed maintenance strategy.

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