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Original Research Article

Improved Maintenance Strategy for Reciprocating Compressor Based on Reliability and Safety

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Abstract

Reciprocating compressors are critical equipment in air separation unit plant systems designed to convey fluids from the site to the customer through pipelines. The key point is long component life without compromising reliability and safety systems. Therefore, appropriate maintenance strategies are required to improve system reliability and safety, considered key performance indicators that strongly impact cost, safety, and environmental sustainability. Functionality risks are assessed based on several relevant documents from the original equipment manufacturer's (OEM) best practices regarding international and community standards applied to each component. This paper shows the integration of bibliographical research and vulnerability study assessment; it provides additional information by preventing failure and identifying opportunities for continuous improvement, where the process is carried out using failure mode and effect analysis (FMEA) by issuing recommended action to the planned maintenance routine task list. The following paper aims to determine reliable and safe maintenance requirements to obtain up to 99.9% availability.

Keywords: Reciprocating compressor; Critical equipment; Maintenance strategy; FMEA.

Nomenclature

Symbol	Description
AIM	Asset Integrity Management
CD	Condition Directed
CE	Critical Equipment
FMEA	Failure Mode and Effect Analysis
HAZID	Hazard Identification
HAZOP	Hazard and Operability
LTA	Logic Tree Analysis
OEM	Original Equipment Manufacturer
PHA	Process Hazard Assessment
PdM	Predictive Maintenance
PID	Piping & Instrumentation Diagram
PSM	Process Safety Management
RCM	Reliability Centered Maintenance
RPN	Risk Priority Number
RTF	Run to Failure
TD	Time Directed

1. Introduction

Maintenance programs are an important concept required in different industries. This was confirmed by 2022 data, which showed the application of 38% of preventive maintenance programs based on estimated cycle times, 35% on reactive or run-to-failure, 14% on predictive maintenance (PdM) using analytical tools, 10% on reliability-centered maintenance (RCM) through operational data analysis, and 3% for other aspects [1]. The process was required to reduce cost, minimize equipment downtime, improve quality, increase productivity, and ensure reliability [2].

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equipment downtime, improve quality, increase productivity, and ensure reliability [2].

A maintenance strategy is normally applied to enhance the effectiveness of resource allocation and systematically manage equipment to achieve the designed purpose. According to Ade et al. [3] and Zafar [4], the strategy to minimize the estimated total costs of maintenance needs to contain achievable, measurable, and trackable elements. Moreover, the concept was classified into time-directed (TD), condition-directed (CD), and run-to-failure (RTF) in line with the observation of Fathurohman [5] and Rasindyo [6]. The classification is based on the time, cost, and resources required to maintain components and equipment. The TD aspect is the annual maintenance schedule required after the agreement between all the necessary and relevant stakeholders is reached.

Equipment is normally in two main conditions before any maintenance work is conducted, which include normal or abnormal working situations due to certain anomalies. Completing maintenance also leads to two conditions: the equipment regaining satisfactory performance or failing and requiring rework. Meanwhile, the backlogs often experienced in the scheduling process are associated with several reasons, such as ineffective inventory for spare parts, lack of Bill of Materials management, unavailability of time execution due to production demands, inadequate competency of personnel, and the need to obtain some other resources through third party agents. There is a need to avoid these reasons by using an appropriate strategy to reduce and prevent the loss of business. This can be achieved by proactively identifying the root cause of equipment-related problems. Furthermore, a proper maintenance strategy needs to be implemented to ensure the safety and reliability of machines by identifying, reviewing, and mitigating risks. This is necessary due to the failure mechanism associated with equipment aging and the need to prioritize maintenance to close the loop.

Most strategies normally focus on each piece of equipment, but recent industrial practices have led to the implementation of process safety management (PSM) through asset integrity management (AIM). This focuses on the whole process, starting from the commission to the decommissioning phase. Moreover, several studies have used different strategies, such as hazard identification (HAZID), hazard and operability (HAZOP), and process hazard assessment (PHA) to identify hazards in systems and processes.

The prevention of major hazards and customer satisfaction need to be prioritized in the maintenance process. This requires delivering products through critical equipment (CE) related to safety, reliability, and safety-reliability, specifically through spare part inventory strategies [7].

Inspection, testing, and maintenance need to be conducted regularly and based on schedule to prevent major accidents [8]. There is also the need to design acceptance criteria for the operating procedure, maintenance task list, and evidence. This is necessary to generate the data for future decisions regarding the frequency of maintenance, spare parts needed, and the next project.

The prioritization and fulfillment of consistent, correct maintenance tasks can be achieved by implementing Reliability-Centred Maintenance (RCM) designed to identify failure modes. This is normally conducted through Failure Mode and Effect Analysis (FMEA) as well as Logic Tree analysis (LTA) [9]. The process is often through selecting the system, identifying the failure mode, designing the priority list, and selecting tasks to be performed. This leads to the definition of RCM as a systemic strategy to plan the maintenance of technical systems [10].

A reciprocating compressor is a reliable equipment normally used to deliver products to uses through a pipeline. It has a pressure safety valve designed to function as critical equipment to ensure safety and avoid causing harm to business and the environment. Reciprocating compressors must be subjected to the simplified RCM, a proposed strategy aimed at overseeing equipment or systems in line with the report of a risk study. The strategy is normally applied based on the outcomes of the AIM process. It focuses on developing reliable and safe systems through risk-based reliability maintenance with due consideration for the potential consequences of failure. Therefore, this study aimed to improve the maintenance strategy of reciprocating compressors by mitigating the potential and historical failure. The process included the presentation of FMEA applied to explore the risk and action based on occurrence, severity, and detection in Section 3 and the conclusion in Section 4.

2. Methods

The maintenance strategy was improved by combining the results of AIM and RCM to design an appropriate plan for ensuring the proper functioning of equipment without wasting time, cost, and labor. This study applied a qualitative method focused on interacting with stakeholders such as risk engineers, maintenance personnel, and operational teams to assess the selection criteria. The procedure implemented was in three steps: system and information selection, system boundary and function determination, and logic analysis, as presented in Figure 1 and explained comprehensively in the following subsections.

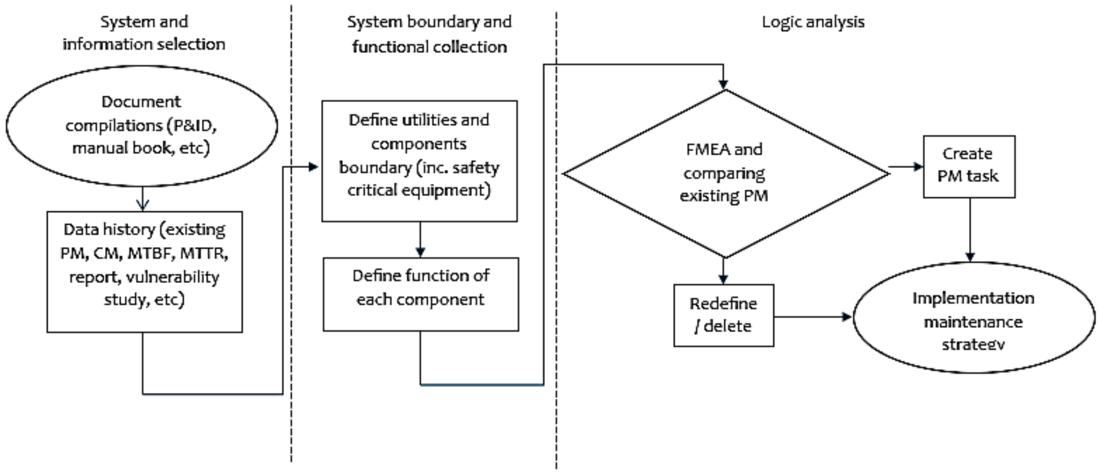

Figure 1. Maintenance Strategy Integration

2.1 System and Information Selection

The systems analyzed were selected based on the vulnerability studies conducted on safety and reliability in line with the information retrieved from the risk engineer as well as the operational and maintenance team. Moreover, the support documents required were maintenance history, piping, instrumentation diagram (PID), manual book, operation manual, and other technical data related to the equipment.

2.2 System boundary and function determination

The boundary system was used to define the IN and OUT interface and identify the component list correctly. The history of the equipment is normally feasible when it is in service to support operational activities, but determining system failures in newly established plants can be challenging. Therefore, it is important to clearly define the functional system for each piece of equipment before proceeding to the subsequent steps.

2.3 Logic analysis

The step is an important process that requires focused and live discussion, the development of functional failure, and the application of logic tree analysis. Moreover, the selection of personnel and facilitators with relevant knowledge and skills is necessary to identify the failure modes and apply the risk priority number (RPN) based on Table 1 (severity, occurrence, and detection) using FMEA [11].

Fig. 2 shows the level of criticality based on RPN. Red is the top priority, yellow is a medium priority, and green is a low priority. The strategy was to develop a risk ranking system to prioritize the tasks and compare existing actions to improve the future maintenance plan. Implementation and work control were considered important through the participation of several stakeholders to achieve the desired objective.

Table 1. Risk category

No	Severity	Occurrence	Detection
1	No effect	Remote	Almost certain
2	Very minor	Very low	Very high
3	Minor	Low	High
4	Very low		Moderately high
5	Low	Moderate	Moderate
6	Moderate		Low
7	High	High	Very low
8	Very high		Remote
9	Failure with warning		Very remote
10	Failure to meet regulatory requirements	Very high	Almost impossible

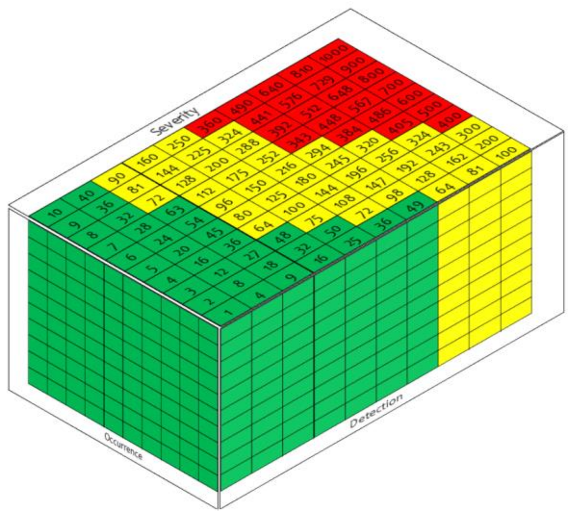

Figure 2. RPN ranking

3. Results and discussion

The maintenance tasks required for the reciprocating compressor were determined through the vendor recommendations, which specified frequent assessment based on the hours of operation. The evaluation process was conducted through corrective maintenance history, and root cause analysis showed damage to the equipment a few years later. This was associated with the lack of maintenance required by the manual to perform the functions related to upstream and downstream.

3.1 System and Information Selection

The vulnerability study showed that the reciprocating compressor was a critical piece of equipment requiring reliability and safety due to delivering fluid containing combustible gases to customers using a pipeline system. The reciprocating compressor has two main parts: the mechanical aspect for the crank mechanism and the pneumatic aspect for distance pieces and cylinders. Some other sub-equipment pieces are also required for better performance and are categorized as common and protected parts, as seen in Table 2.

Table 2. Component identification

Comp no.	Boundary system	Component Description	Type
1	Driver	Electric motor	Part
2	Lubrication system	Main and auxiliary oil pump	Part
3	Lubrication system	Oil cooler	Part
4		Aftercooler	Part
5	Compressor unit 1st stage	Piston assembly	Part
6	Compressor unit 1st stage	Suction discharge valve	Part
7	Compressor unit 1st stage	Cylinder liner	Part
8		Automatic valve (inlet, recycle, outlet, and purging area)	Part
9	Compressor unit 1st stage	Transmission belt	Part
10		Inlet filter	Part
11		Pressure safety valve (suction and discharge)	Protection
12	Control and monitoring	Instrument device (vibration, pressure, flow)	Protection

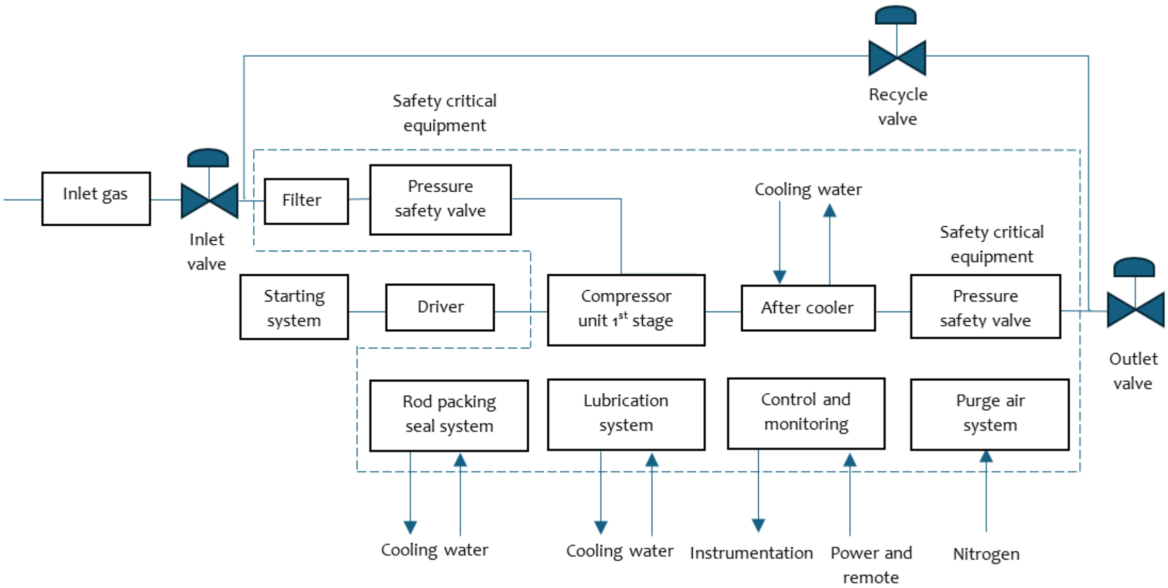

Figure 3. System boundary

3.2 System boundary and function determination

The existing maintenance strategy focuses on inspecting, cleaning, adjusting, and replacing spare parts used during operational hours. Figure 3 explains the boundary system on the reciprocating compressor, which will be analyzed further.

The unplanned event showed in Figure 4 some inadequacy leading to several anomalies. Root cause analysis was conducted to determine the anomalies and provide the maintenance team with the appropriate information for proactive equipment management.

Therefore, this study was used to modify the overall maintenance plan to ensure proper reliability and safety for equipment usage.

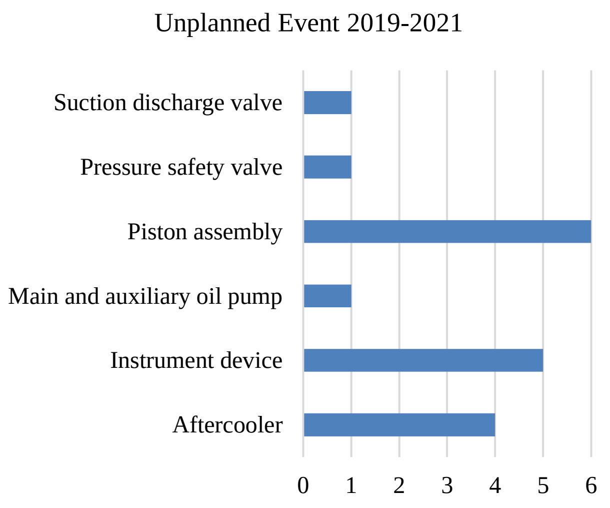

Figure 4. Unplanned event boundary

3.3 Logic analysis

FMEA was conducted to modify the existing maintenance plan to provide correct and clear instructions on the shop floor, as presented in Table 3. The focus was to comprehensively analyze the reliability and safety aspects of RPN's top three highest scores.

Previous work orders and manuals explicitly documented the severity of each failure mode for the parts affecting the equipment. The causes and frequency of failure were determined for every part, and the current controls were assessed by describing the strategies implemented to prevent or detect the failure mode.

Figure 5 shows the highest RPN score for piston assembly, applying superbolts to hold the piston assembly and crankcase based on nominal torque [12]. Moreover, there is a need for more attention to the calibration of the auxiliary tools frequently used for hydraulic systems and torque wrenches to support the maintenance requirements.

Rod drop monitoring can help predict the failure of worn pneumatic seals [13]. Carry out a visual inspection by checking the piston rod runout and coating evenness by ensuring no corrosion and piston ring thickness to prevent damage or scratch from the piston rod [14]. Maintaining critical speed at the operating range can prevent deflection in the crankcase [15].

The aftercooler and oil cooler designed using the shell and tube type material has specific characteristics, including reliance on cooled water to regulate temperatures according to design specifications. The quality of water sourced from the cooling tower can significantly affect the longevity of these coolers. Therefore, preventive measures such as backwashing and mechanical and chemical cleaning are important to maintain optimal performance. The procedures of these preventive actions also need to be implemented with clear instructions to ensure effectiveness.

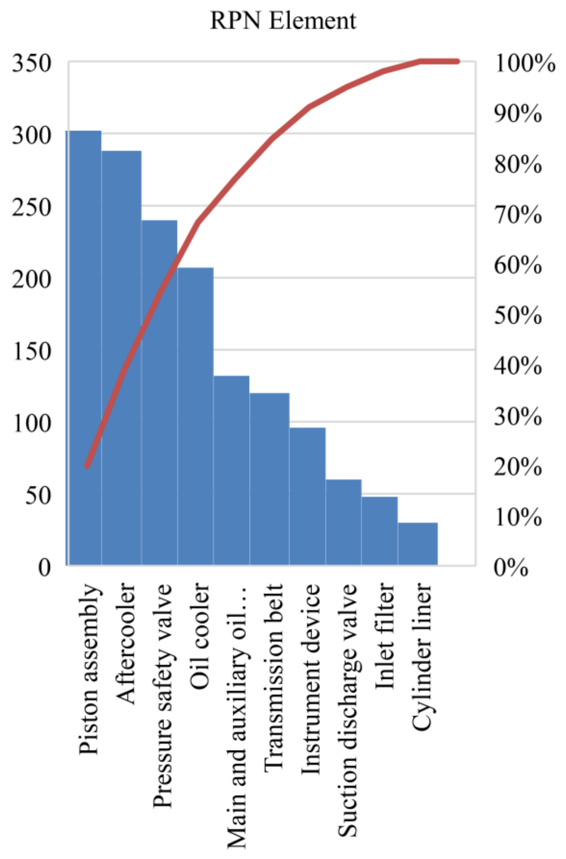

Figure 5. RPN element total

Pressure safety valve belts were observed related to safety and reliability. The calibration process ensures a set point; visual inspection should be done for each part. This showed the need to ensure recommended spare parts are available in stock, and the necessary information regarding the specifications and quality required by OEM recommendations should be passed to the storekeeper and purchasing team.

The analysis recommended predictive actions such as rod drops, water quality monitoring, and calibration. The spare parts inventory was considered important, focusing on fast delivery time in line with the wear rate. Stakeholders such as the purchasing and storekeeper team must also liaise with the third party to ensure the spare parts fulfill the requirements. Furthermore, the management should design the budget to address reliability and safety issues related to the equipment.

Table 3. Failure mode and effect analysis

No	Element Part	Critical		Failure Mode	Effects of Failure	Current	Failure Cause	Current	Current Detection	Current Prevention	Current		Action Taken	Recommended Action
		Reliability	Safety			Severity		Occurrence			Detection	RPN		
1	Main and auxiliary oil pump	X		Poor oil quality	Vibration, high temperature, trip, fail to start	9	Contamination (dirt, wear, water ingress)	2	Oil analysis	Predictive maintenance 4000 and 8000 hr	5	90	Redefine the existing maintenance plan	Collect and analyze the cost for predictive maintenance of oil analysis versus oil replacement regularly due to the volume amount not being quite big.
				Wear pressure regulator	High pressure, low pressure, trip, fail to start	7	Aging, contamination, corrosion	1	Online vibration and parameter control	N/A	6	42	Add maintenance plan	Create a maintenance plan to test the pressure regulator frequently by dismantling it from the system and testing it using a bench. Look for a quotation to consider purchasing a new spare instead of preparing a part list and delivery time.
2	Oil cooler	X		Thinning tube/shell	Loss of containment	8	Corrosion, aging	1	N/A	N/A	6	48	Add maintenance plan	Create a maintenance plan, define maintenance techniques for predictive maintenance using nondestructive examination and visual inspection
				Leak	Loss of containment	6	Deterioration seal	3	N/A	N/A	3	54	Add maintenance plan	Create a maintenance plan for doing the visual inspection
				Clogged tube	High temperature	7	Bad cooling quality	3	Online vibration and parameter control	N/A	5	105	Add maintenance plan	Define the limit operating temperature, create a maintenance plan for routine cleaning or backwash besides improving water quality
3	Aftercooler	X		Thinning tube/shell	Loss of containment	8	Corrosion, aging	2	N/A	N/A	6	96	Add maintenance plan	Create a maintenance plan, define maintenance technique for predictive maintenance using a non-destructive examination of eddy current testing and visual inspection, define the level of cleanliness of the tube due to its fluid service is combustible
				Leak	Loss of containment	6	Deterioration seal	3	N/A	N/A	6	108	Add maintenance plan	Create a maintenance plan for doing the visual inspection
				Clogged tube	High temperature	7	Bad cooling quality	3	Online vibration and parameter control	N/A	4	84	Add maintenance plan	Define the limit operating temperature, create a maintenance plan for routine cleaning or backwash besides improving water quality
4	Piston assembly	X		Worn pneumatic seal	Loss of pressure	9	Aging, wrong material	2	Visual inspection	Preventive maintenance 4000 and 8000 hr	5	90	Redefine the existing maintenance plan	Define clear information for tolerance range dimension to decide reuse or replace to have a cost reduction of replacement also ensuring no crack or deterioration of seal, ensure spare part list always on hand due to its critical

No	Element Part	Critical		Failure Mode	Effects of Failure	Current Severity	Failure Cause	Current Occurrence	Current Detection	Current Prevention	Current		Action Taken	Recommended Action
		Reliability	Safety								Detection	RPN		
				Superbolt looseness	Vibration, crack, trip, fail to start	10	Improper installation	2	Visual inspection	Preventive maintenance 4000 and 8000 hr	5	100	Redefine existing maintenance plan	Define clear information for torque of tightness piston rod; the supervisor shall ensure the process of tightening and define level of cleanliness of tube due to its fluid service is combustible, create maintenance plan to do the non destructive examination on the thread and edge of step
				Scratch piston rod	Loss of pressure, leak, loss of containment	8	Misalignment of assembly, worn seal, contamination (dirt, wear)	1	Visual inspection	Preventive maintenance 4000 and 8000 hr	5	40	Redefine existing maintenance plan	Define clear information for tolerance range dimension to ensuring no crack or deterioration of seal, check runout of rod ensure spare part list always on hand due to its critical the supervisor shall ensure the process of tightening and define level of cleanliness of tube due to its fluid service is combustible
				Defect crankcase	Vibration, trip, fail to start	8	Corrosion, aging	1	N/A	N/A	9	72	Add maintenance plan	Create maintenance plan for inspection routine and non destructive test, ensure part are purchased from OEM available and certificate must be available to compatible material
5	Suction discharge valve	X		Scratch and worn disc valve	High temperature	6	Contamination (dirt, wear)	1	Visual inspection	Corrective maintenance 8000 hr	5	30	Redefine existing maintenance plan	Define clear information for tolerance range dimension, ensure spare part list always on hand due to its critical the supervisor shall ensure the process of tightening and define level of cleanliness due to its fluid service is combustible, compare and looking for OEM or competent third party to do the refurbishment/lapping of disc
				Stucked spring	High temperature	6	Corrosion, aging	1	Visual inspection	Corrective maintenance 8000 hr	5	30	Redefine existing maintenance plan	Define clear information for inspection of part, ensure spare part list always on hand due to its critical the supervisor shall ensure the process of tightening and define level of cleanliness of tube due to its fluid service is combustible
6	Cylinder liner	X		Worn cylinder liner	Vibration, loss of pressure, trip, fail to start	6	Misalignment of assembly, worn seal, contamination (dirt, wear)	1	Visual inspection	Preventive maintenance 4000 and 8000 hr	5	30	Redefine existing maintenance plan	Define clear information for tolerance range dimension, ensure spare part list always on hand due to its critical the supervisor shall ensure the process of inspection and define level of cleanliness to its fluid service is combustible. Create maintenance plan to check the fitness of liner using ultrasonic testing

No	Element Part	Critical		Failure Mode	Effects of Failure	Current	Failure Cause	Current	Current Detection	Current Prevention	Current		Action Taken	Recommended Action
		Reliability	Safety			Severity		Occurrence			Detection	RPN		
7	Transmission belt	X		Worn of belt	Fail to start, vibration	8	Aging, misalignment	3	Visual inspection	Preventive maintenance 4000 and 8000 hr	5	120	Redefine existing maintenance plan	Define clear information for installation such as tension, belt type and dimension, alignment and inspection, ensure spare part list always on hand due to its critical
8	Inlet filter	X		Clogged filter	High pressure, wear	6	Corrosion, deterioration mesh and support	1	Visual inspection	N/A	8	48	Add maintenance plan	Create maintenance plan for cleaning and inspection routine, ensure wear part such mesh, weld joint and support condition, supervisor shall ensure the process of inspection and define level of cleanliness to its fluid service is combustible, purchased from OEM available and certificate must be available to compatible material for combustimble fluid prior inspection work
9	Pressure safety valve (suction and discharge)		X	Sticking spring	Fail to safe	10	Corrosion, aging	2	Visual inspection	Preventive maintenance and calibration every 3 years	6	120	Redefine existing maintenance plan	Define clear information for height of spring prior disassembly each part, record before and after maintenance and calibration parameter, supervisor shall ensure the process of inspection and define level of cleanliness to its fluid service is combustible, ensure spare part list always on hand due to its critical
				Scratch seat	Fail to safe	10	Corrosion, aging, wear	2	Visual inspection	Preventive maintenance and calibration every 3 years	6	120	Redefine existing maintenance plan	Define clear information for inspection, record before and after maintenance and calibration parameter, supervisor shall ensure the process of inspection and define level of cleanliness to its fluid service is combustible, ensure spare part list always on hand due to its critical, compare and looking for OEM or competent third party to do the refurbishment/repair of seat
10	Instrument device (vibration, pressure, flow)		X	Sticking solenoid	Loss of control parameter, trip, fail to start	8	Corrosion, aging	2	Online vibration and parameter control	Calibration and loop test every 8000 hr	6	96	Redefine existing maintenance plan	Create maintenance plan for inspection routine of its accessories such as tube, solenoid valve etc., ensure the parameter during calibration as its operating parameter, conduct the cleaning and inspect pf each part, the supervisor shall ensure the process of inspection and define level of cleanliness to its fluid service is combustible

4. Conclusion

RCM was selected as the maintenance strategy for the reciprocating compressor. The hidden failure and risk for each component in the equipment were identified through FMEA. The recommended action is integrating the literature in the form of sensor upgrades for rod drop and online water quality monitoring, which is required by managing the change scheme. This process led to the comprehensive mapping of spare part inventory, precise annual budget proposal, and training personnel matrix. The results further recommended conducting a review every 3 years by collecting all the supporting documents, including work orders, purchasing, and safety event records. Moreover, the strategy can be improved by liaising with stakeholders to optimize maintenance.

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Conflict of Interests

No conflict of interest has been expressed by the authors

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