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A Structured Multi-Domain Data Driven Framework for Improving Compressor Reliability

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A B S T R A C T

Ensuring the reliability of critical systems is crucial for maintaining equipment availability and guaranteeing safe operations. Compressors, as vital equipment in oil and gas facilities, are particularly susceptible to unexpected failures, which can result in significant production losses, safety risks, and increased maintenance costs. This paper introduces a comprehensive and structured approach designed to streamline operations and effectively tackle the longstanding challenge of reliability, ultimately ensuring seamless functionality. This approach leverages a range of reliability tools to provide sustainable, long-term solutions that maintain and enhance asset reliability. The framework employs a tiered assessment methodology, where non-critical systems undergo a Root Cause Analysis (RCA) to identify the underlying cause of the issue, while critical and chronic problems are subject to a more comprehensive data-driven assessment. The data-driven reliability assessment methodology incorporates RCA, supplemented by thorough data collection and a meticulous review of all relevant data, to support a detailed overall assessment. Furthermore, a Failure Mode, Effects, and Criticality Analysis (FMECA) is conducted to rank each identified failure mode by severity, occurrence, and detectability, producing a criticality matrix that guides resource allocation. Corrective actions are then developed, prioritized and classified as either immediate fixes or long-term improvements. The methodology emphasizes verification through post-implementation monitoring, ensuring that the measures effectively lower recurrence probability and boost compressor availability. The effectiveness of the framework is demonstrated through its application to a compressor chronic problem, highlighting the potential for significant improvements in reliability and availability.

1. INTRODUCTION

Compressors are the workhorses of the oil-and-gas value chain, providing the pressure boost required to transport, process, and store hydrocarbons across a wide range of operating conditions. In upstream facilities, gas-lift and well-head compressors increase reservoir pressure to sustain flow rates, while in mid-stream pipelines they overcome frictional losses and elevation changes to deliver gas to processing plants and export terminals. Downstream, compressors drive critical processes such as refinery feedstock handling, petrochemical synthesis, and gas-to-liquids (GTL) conversion, where precise pressure and flow control are essential for product quality and plant safety [1].

The most prevalent compressor types in the sector are centrifugal, axial, and reciprocating units, each selected according to the required pressure ratio, flow capacity, and gas composition. Centrifugal compressors as shown in Fig. 1 dominate large-scale pipeline and gas-processing applications because of their high efficiency at moderate to high flow rates and relatively low maintenance intensity. Reciprocating compressors, by contrast, are favored for high-pressure, low-flow scenarios such as well-head boosting and liquefied natural gas (LNG) feedstock compression, where their ability to achieve pressure ratios exceeding 30:1 is advantageous. Axial compressors are typically employed in high-speed, high-capacity applications such as gas turbines and certain petrochemical processes. The operation of these machines is governed by thermodynamic and fluid-dynamic principles that dictate inlet conditions, surge limits, choke points, and efficiency maps. Modern compressors are equipped with sophisticated instrumentation—including vibration sensors, temperature and pressure transducers, and oil-analysis probes—that feed real-time condition-monitoring systems. These data streams enable predictive maintenance strategies and support the implementation of reliability-centered maintenance (RCM) programs, which are increasingly mandated by industry standards such as API 617 and ISO 55001 [2, 3].

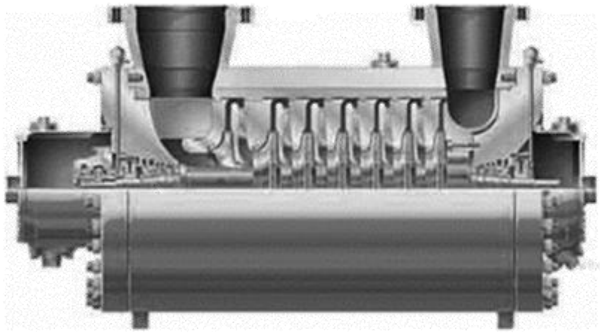

Fig. 1. Centrifugal Compressor.

Process gas compressors are vital components in petrochemical and gas processing facilities, where bushing seals are commonly used to minimize gas leakage and safeguard internal compressor components. The effectiveness of these seals relies heavily on maintaining the proper pressure differential between the seal oil and the process gas. Traditional design approaches typically assume steady-state operating conditions. However, modern compressor systems are often subjected to dynamic conditions such as: Load fluctuations, start-up and shutdown cycles, and process upsets and transient events. These variations can disrupt the static pressure assumptions that conventional seal designs are based on, increasing the risk of seal failure. A critical subsystem that determines reliability, service life, and environmental impact is the seal arrangement. While many centrifugal compressors employ dry (labyrinth) seals to avoid oil leakage, wet seals also known as oil-filled or oil-lubricated seals are increasingly used in oil-and-gas applications where high rotational speeds, elevated temperatures, and severe contaminant loads are encountered. Wet seals consist of a thin annular gap between a rotating shaft and a stationary housing, filled continuously with a low-viscosity lubricating oil. The oil forms a hydrodynamic film that carries the load, prevents direct metal-to-metal contact, and extracts heat generated by friction. The sealing fluid is typically recirculated through a seal oil system that includes a pump, heat exchanger, filtration unit, and a pressure-regulating valve to maintain a constant differential pressure across the seal face.

Despite advances in design and monitoring, compressors remain a major source of unplanned outages in the oil-and-gas sector. Failure modes such as bearing wear, seal leakage, rotor imbalance, and oil degradation can quickly propagate to system-wide disruptions, leading to production losses, safety incidents, and elevated maintenance costs . Consequently, a systematic understanding of compressor reliability rooted in robust root-cause analysis (RCA) and failure-mode evaluation is essential for sustaining asset availability and achieving operational excellence. The present work builds on this background by proposing a structured RCA methodology that integrates the “5-Why” technique, Fault Tree Analysis (FTA), and Failure Modes, Effects, and Criticality Analysis (FMECA) to diagnose and remediate critical compressor issues. By aligning diagnostic rigor with the operational realities of oil-and-gas facilities, the approach seeks to enhance reliability, reduce downtime, and support the strategic objectives of a compression system.

The objective in the operating facility is to ensure the equipment is up and running to deliver the throughput. Generally, equipment availability is the proportion of time an asset is capable of performing its intended function when required. Equipment availability is a critical factor in ensuring the overall efficiency and productivity of industrial operations. Unplanned downtime and equipment failures can result in significant losses, both in terms of revenue and reputation. Therefore, it is essential to address equipment availability as shown in Eq. 1 by improving the reliability as given in Eq. 2 and maintainability of the equipment as given in Eq. 3. In the classical reliability maintainability framework, it is expressed as:

$$A = \frac{MTBF}{MTBF+MTTR} \quad (1)$$

Where, A = Availability, MTBF = Mean Time between Failures, and MTTR = Mean Time to Repair

$$MTBF = \frac{Number\ of\ Failure}{Total\ Operatign\ Time} \quad (2)$$

Where, A = Availability, MTBF = Mean Time between Failures, and MTTR = Mean Time to Repair.

$$MTTR = \frac{Total\ Downtime}{Number\ of\ Failures} \quad (3)$$

Where, Total Downtime is the total amount of time spent on repairs and maintenance, and Number of Failures is the total number of failures or downtime incidents

2. LITERATURE REVIEW

The reliability and performance of centrifugal compressors are central to the safe, efficient, and economical operation of gas processing, pipeline, and refinery infrastructures. A growing body of research has addressed this topic from system level reliability allocation, advanced diagnostics, seal technology, organizational culture, and subsea deployment, providing a comprehensive view of current capabilities and remaining challenges.

An integrated framework is devised that couple system wide reliability allocation with maintenance planning for centrifugal compressor stations [4]. A physical model of a gas pipeline network combined with Monte Carlo simulation quantified the probabilistic contribution of each compressor to overall reliability. Particle Swarm Optimization then minimized operational costs while satisfying reliability targets, and reliability block diagrams defined optimal maintenance intervals. A real-world case study confirmed that the approach delivers cost effective schedules without compromising system reliability, underscoring the need to embed reliability analysis in maintenance decisions. A high resolution aerothermodynamic assessment tool is introduced for centrifugal compressors in natural gas processing [5]. Validation on two industrial plants showed that the algorithm detects subtle performance degradations missed by conventional monitoring, enabling more precise, real time maintenance planning and markedly improving efficiency and reliability. Qatar Petroleum’s proactive reliability program is built around the Prevent Detect Repair Recover (PDRR) framework, reinforced by Root Cause Failure Analysis and Bad Actor Best Practices [6]. The culture driven strategy reduced unplanned downtime, lowered maintenance costs, and aligned asset management with corporate revenue goals, demonstrating how systematic reliability initiatives generate sustainable operational and financial benefits. This work applied Failure Modes and Effects Analysis (FMEA) to multi stage centrifugal compressors in air separation units [7]. Systematic identification and prioritization of potential failures enhanced reliability, minimized downtime, and supported operational excellence, highlighting FMEA’s value for safety critical compressor applications. A comprehensive overview of centrifugal compressor applications across upstream, midstream, and downstream sectors including compression, refrigeration, pipeline transport, gas lift, gas gathering, export compression, and LNG operations is presented [8]. Their survey emphasized the compressors' pivotal role in maintaining continuous gas flow, boosting oil production, and ensuring safe LNG transport and storage, establishing a broad context for the more specialized studies cited above.

A case study of a gas turbine driven centrifugal compressor that experienced repeated trips due to high vibration at the drive end bearing is reported [9]. After conventional troubleshooting failed, a detailed investigation identified residual rotor unbalance and marginally excessive journal bearing clearances as root causes. High speed balancing at the manufacturer's facility and adjustment of lube oil inlet pressure restored stable operation, emphasizing the critical importance of rotor balancing and bearing clearance control for reliable compressor performance. Seal technology received extensive attention. An advanced sealing system is introduced for pipelines transporting non crude hydrocarbons, combining a primary seal with a non-contacting, bi directional secondary containment seal [10]. Field validation demonstrated enhanced safety, reduced emissions, and compliance with stringent environmental regulations. Their earlier work documented the deployment of non-Pusher Secondary Seal (NPSS) technology in more than 300 units across North America [11]. The elastomeric element of NPSS accommodates axial shaft movement without wear, eliminating O-rings and hard coating requirements, thereby reducing maintenance demands and extending seal life. Continuous face tracking further improves emission control under dynamic hydraulic conditions. Authors reviewed common seal designs and recent advancements, concluding that incremental retrofits to existing sealing systems can substantially improve reliability when full conversion to dry gas seals is impractical [12]. Authors focused on hydrogen recycle service, presenting a practical methodology for identifying contaminant sources that degrade both dry and wet seals and recommending material advancements for wet seal designs [13]. A comparative analysis of API oil seals and dry gas seals, is discussed, offering guidance for legacy compressors where pressure or surface velocity constraints preclude dry gas solutions [14]. Sears and Hosking introduced an economic evaluation framework for replacing oil seals with mechanical dry gas seals, showing that cost benefits depend on compressor type, size, and service conditions [15]. This work emphasized the economic imperative of mechanical upgrades including dry gas seals, floating ring oil seals, seal gas conditioning, damper seals, polymer labyrinth seals, and noise attenuation systems demonstrating rapid return on investment through reduced downtime and increased uptime [16]. The paper highlighted the evolution of thermoplastic labyrinth seals, which permit reduced clearances, higher efficiency, and easier installation compared with traditional metal seals [17].

Operational challenges posed by harsh process fluids were addressed [18]. The authors emphasized the need for customized turbomachinery design, robust control strategies, and careful operational management when handling wet gas, high temperature, or corrosive streams in processes such as alkylation, reforming, hydrocracking, and fluid catalytic cracking. Their tutorials provide foundational guidance for engineers confronting these demanding environments. Subsea compression has emerged as a key technology for extending the life of mature offshore fields. The authors developed a reliability model for a deep water, all subsea boosting station, concluding that three level pump redundancy and a booster compressor FIT rate ≤ 10 000 are required to achieve an MTBF of 4.25 years [19]. Ge et al. enhanced traditional FMEA with fuzzy analytic hierarchy processes and comprehensive evaluation, delivering a more robust qualitative and quantitative risk assessment tool for subsea compressor systems [20]. The paper suggested the evolution of subsea compression, describing the world's first hermetically sealed subsea compressor with integrated electric motor and active magnetic bearings, and comparing separate phase, well stream, and multiphase compression concepts [21]. Their analysis highlighted the importance of liquid mass fraction and gas volume fraction in determining system feasibility. An investigation for the impact of condensate phases on compressor performance in offshore and subsea applications is discussed [22]. Experimental tests with air water mixtures up to 8 % liquid volume fraction revealed increased vibration levels and the occurrence of sub synchronous vibration (SSV) under high flow, high density conditions. Modifications to the balance piston seal geometry successfully mitigated SSV, underscoring the interplay between seal design and rotodynamic stability in wet gas environments. Environmental considerations were explored, and proposed a structured cost benefit methodology for prioritizing methane emission reduction measures in offshore operations [23], and by Bergamini, who documented the development of high-pressure centrifugal pumps capable of handling CO_2 at up to 60 MPa, thereby supporting enhanced oil recovery and carbon capture projects [24].

Collectively, these studies illustrate a clear trajectory toward integrating system level reliability allocation, advanced diagnostics, targeted seal innovations, and robust organizational practices to achieve higher availability, lower emissions, and greater cost efficiency for centrifugal compressors. While significant progress has been made, gaps remain in long term field validation of emerging seal materials, comprehensive life cycle economic analyses that encompass capital upgrades and subsea reliability, and the seamless integration of real time performance data with predictive maintenance algorithms. Addressing these gaps will be essential for advancing compressor technology to meet the evolving demands of the global energy landscape.

3. STRUCTURED METHOD AND FRAMEWORK

A systematic and structured methodology is crucial for understanding and resolving complex problems that arise in critical systems. By employing a structured approach, organizations can effectively transition from a reactive, ad-hoc troubleshooting mindset to a proactive, data-driven process. This paradigm shift enables the identification of root causes and the implementation of targeted corrective actions, ultimately leading to enhanced reliability and performance. The proposed framework offers a comprehensive and systematic data-driven approach to problem-solving, which involves a series of interconnected steps. First the candidate system is selected based on the equipment performance and failures, later, raw data is collected and analyzed to identify trends and patterns. This data is then subjected to a root cause analysis, which involves drill down to the underlying causes of a problem. The output from this analysis is used to construct a fault tree logical model, which provides a visual representation of the relationships between different components and their potential failure modes. The fault tree model is then used to inform a quantitative Failure Mode, Effects, and Criticality Analysis (FMECA) risk assessment. This assessment involves evaluating the likelihood and potential impact of different failure modes, allowing for the prioritization of corrective actions based on their potential risk reduction. By systematically progressing through these stages, the framework delivers actionable, verified corrective actions that can be implemented to enhance compressor reliability. The benefits of this structured methodology are multifaceted. By providing a repeatable and data-driven process, organizations can reduce the variability and subjectivity associated with traditional troubleshooting approaches. Moreover, the framework enables the identification of systemic issues and the implementation of targeted corrective actions, which can lead to significant improvements in equipment reliability and overall system performance. Ultimately, the adoption of this structured methodology can help organizations to minimize downtime, reduce maintenance costs, and optimize their operations.

The methodology is structured around a risk-based approach, which enables the team to allocate the right resources to the right equipment, to the appropriate depth, in order to develop effective corrective actions. This structured methodology allows for a systematic and efficient use of resources, ensuring that the most critical equipment and issues are addressed with the necessary level of attention and expertise. The overall workflow is illustrated in Fig. 2, and Fig. 3 mainly covers the data driven streams. The framework is designed to assess the criticality of systems and the potential consequences of failure, based on which it suggests the most suitable approach to address the problem.

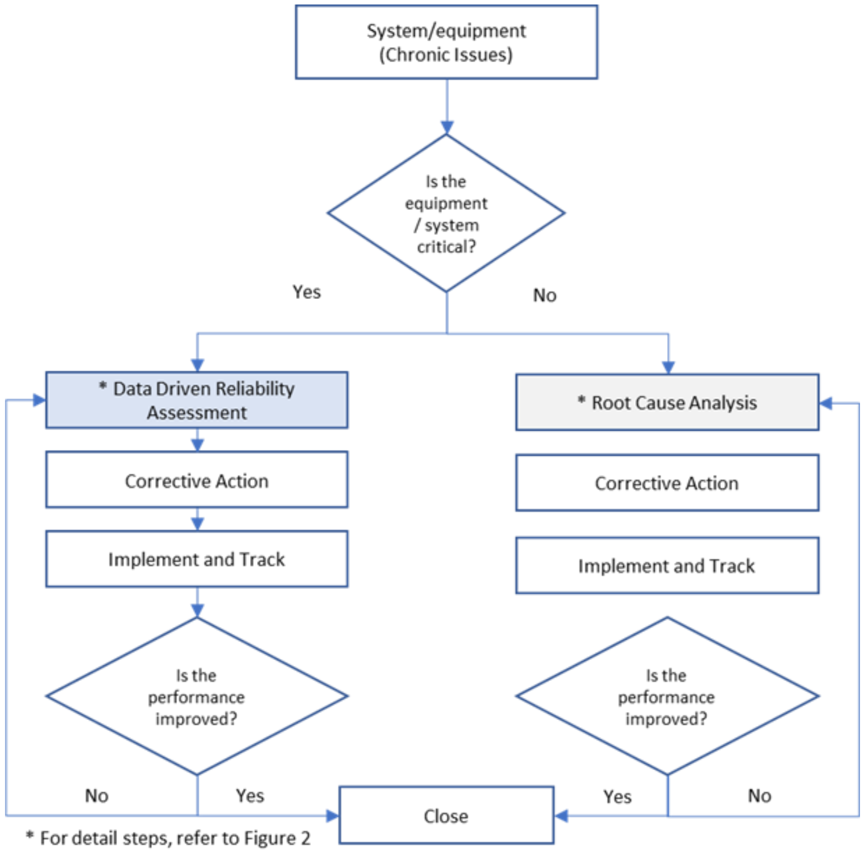

Fig. 2. Overall Assessment Model.

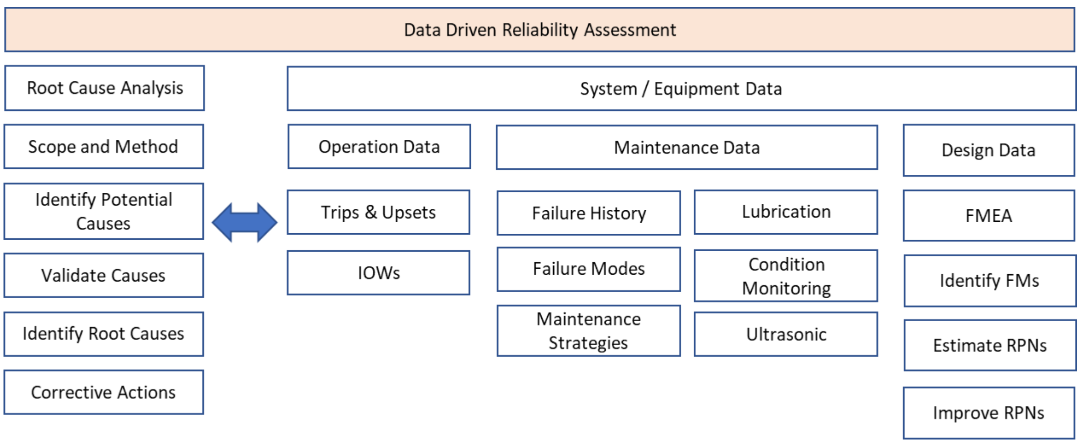

Fig. 3. Data Driven Reliability Assessment Model.

This approach ensures that the team's efforts are focused on the most critical issues, and that the resources are utilized in the most effective manner. If the problem has relatively low consequences, the approach is to perform an investigation using the 5 Whys methodology, which involves asking "why" five times to drill down to the root cause of the problem. This approach allows for a rapid and efficient identification of the root cause, and enables the development of corrective actions to prevent similar problems from occurring in the future. However, if the consequences of failure are extreme, as determined by the risk matrix, a more detailed and thorough root cause analysis is conducted through a proper investigation process. This process involves the use of tools such as Failure Mode and Effects Analysis (FMEA) and data analysis, which provide a comprehensive understanding of the problem and its underlying causes. The FMEA methodology helps to identify potential failure modes, their effects, and the likelihood of occurrence, while data analysis provides valuable insights into the trends and patterns that may be contributing to the problem. By using this structured risk-based approach, the team can ensure that the most critical issues are addressed with the necessary level of attention and expertise, and that the resources are utilized in the most effective manner. This approach also enables the team to develop effective corrective actions, which can help to prevent similar problems from occurring in the future, and to minimize the consequences of failure.

3.1 Data Driven Approach

Different data stream is available as suggested in the Figure below and suggest the areas we ought to focus on to ensure move towards right failure modes to solve the problem.

3.2 Operation Data

Operation data is a key to the assessment framework and covers operating limits, and process upsets. The operation data provides the understanding of operating profile and limits. Table 1 provides the summary, how equipment operation data help to solve the problem.

Translating operating data into life extension actions is a crucial process that enables industries to maximize equipment lifespan and minimize downtime. This process involves a series of steps that leverage advanced technologies to analyze equipment performance and identify areas for improvement. The process involves anomaly detection, predictive degradation modeling, dynamic reliability updates, and feedback loop. This process enables proactive maintenance, reduces equipment failure risk, and improves overall performance. By following these steps, industries can unlock the full potential of their equipment, reduce maintenance costs and improve reliability and availability.

Table 1. Operation data and its application.

Category	Functions	Applications
Real-time sensor streams (temperature, vibration, pressure, flow, speed, oil analysis, etc.)	Provides early-warning, i.e., wear, mis-alignment, lubrication failure etc.	• Monitoring – set thresholds or use process control to trigger alerts. • Digital twins – live data into a data-driven model
Operational profiles (run-hours, load cycles, start-stop frequency, duty-cycle patterns)	Captures the actual stress environment vs. the nominal design	• Load-history clustering, degradation models. • Fatigue analysis – calculate cumulative damage
Environmental conditions (ambient temperature, humidity, etc.)	Accelerates corrosion, oxidation, and material fatigue	• Corrosion-rate estimation • Adaptive maintenance
Performance metrics (efficiency, output quality, energy consumption)	Declining performance often precedes mechanical failure	• Trend analysis to detect loss and schedule cleaning, recalibration, or part replacement before catastrophic failure

3.3 Equipment Maintenance Data

Equipment maintenance data analysis is a crucial aspect of investigating and preventing equipment failures. By analyzing maintenance data, organizations can gain valuable insights into equipment performance, identify patterns and trends, and detect potential issues before they become major problems. This proactive approach enables investigators to determine the root cause of equipment failures, allowing for targeted maintenance and repair strategies to prevent future failures. Effective data analysis helps to identify areas of high risk, enabling maintenance teams to focus their efforts on the most critical equipment and components. By examining maintenance records, sensor data, and other relevant information, investigators can pinpoint the underlying causes of equipment failures, such as wear and tear, design flaws, or operational errors. This knowledge enables organizations to implement corrective actions, such as modifying maintenance schedules, replacing faulty components, or retraining personnel, to prevent similar failures from occurring in the future. As a result, equipment maintenance data analysis plays a critical role in minimizing downtime, reducing maintenance costs, and ensuring the overall safety and efficiency of operations.

Table 2 provides the summary, how equipment maintenance data help to solve the problem.

Maintaining accurate and comprehensive maintenance records is crucial for optimizing equipment performance and extending its lifespan. By leveraging these records, organizations can unlock valuable insights that inform maintenance strategies, reduce downtime, and improve overall equipment reliability. The process of turning maintenance records into longevity gains involves several key steps: data cleansing and standardization, statistical reliability modeling, root cause linkage, and knowledge base creation.

Table 2. Maintenance data and its application.

Category	Functions	Applications
Work orders & service logs (what was done, who, when)	Provides a chronological map of interventions, enabling root-cause analysis of recurring issues.	• Failure mode and effect analysis (FMEA) enrichment – link specific failures to prior maintenance actions. • Effectiveness tracking – measure MTTR (Mean Time to Repair) and MTBF (Mean Time Between Failures) before/after change.
Spare-part histories (part numbers, lifetimes, failure dates)	Reveals parts with systematic premature wear.	• Database – prioritize redesign or higher-grade materials for weak links. • Inventory optimization: Keep critical spares on-hand to reduce downtime.
Inspection findings (visual, NDT, oil-analysis reports)	Direct evidence of degradation mechanisms (e.g., corrosion pits, wear scars).	• Trend-based inspection scheduling and increase inspection frequency when early signs appear. • Condition-based replacement: Replace components at a measured wear level rather than a fixed time.
Corrective vs. preventive actions	Allows assessment of whether preventive maintenance (PM) is actually preventing failures or just adding cost.	• PM effectiveness ratio – compare failure rates before/after PM implementation. • Optimization of PM intervals – use Bayesian updating to refine optimal PM frequency.

Table 3. Equipment design data and applications.

Category	Functions	Applications
Original design specifications (material grades, wall thickness, safety factors)	Baseline for assessing if equipment can tolerate observed operating stress.	• Design-vs-actual gap analysis to quantify excess stress and decide on retrofits or operational limits.
Engineering drawings & 3D models (CAD)	Enable precise location mapping of sensor data and maintenance actions.	• Spatial analytics to overlay vibration hot-spots on a 3D model to pinpoint critical joints.
Finite-element analysis (FEA) results (stress, thermal, fatigue)	Provide a theoretical life expectancy under ideal conditions.	• Model updating to calibrate FEA with field data to improve prediction accuracy.
Design intent documents (operating envelope, failure criteria)	Define acceptable limits; deviations signal a risk of accelerated aging.	• Operational envelope enforcement – embed limits into SCADA/HMI alarms.
Materials data sheets (corrosion resistance, creep properties)	Degradation rates under specific environmental exposures.	• Material-selection feedback to recommend alternative alloys or coatings for future builds.

3.4 Equipment Design Data

Table 3 provides the summary, how equipment design data help to solve the problem.

Extending the life of equipment is a critical goal for industries seeking to minimize downtime, reduce maintenance costs, and optimize overall performance. One effective way to achieve this goal is by leveraging design data, which provides valuable insights into the equipment's original specifications, tolerances, and performance characteristics. By integrating design data with operational and maintenance data, organizations can create a comprehensive understanding of their equipment's behavior, identify potential weaknesses, and develop targeted strategies for extending its life. By analyzing design data in conjunction with operational data, organizations can identify potential issues before they become major problems, such as excessive stress or temperature fluctuations.

Another important application of design data is in setting design-driven alarm set points. By translating allowable stress and temperature limits into real-time alarm thresholds, organizations can ensure that their equipment is operating within safe and optimal parameters. This enables early detection of potential issues, reducing the risk of equipment failure and minimizing downtime.

In conclusion, leveraging design data is a critical step in extending the life of equipment. By integrating design data with operational and maintenance data, organizations can create a comprehensive understanding of their equipment's behavior, identify potential weaknesses, and develop targeted strategies for extending its life. Whether through digital twin integration, design-driven alarm set points, retrofit prioritization, or lifecycle cost modeling, design data provides a powerful tool for optimizing equipment performance and minimizing downtime.

4. CASE STUDY

This paper presents a real-world case study involving persistent reliability problem such as bushing seal failures that continued despite standard troubleshooting and mechanical fixes. The case highlights the limitations of traditional approaches and emphasizes the importance of adopting a structured method rather than relying solely on mechanical redesign. Seal performance in compressors has been widely researched, with significant focus on technologies such as dry gas seals, labyrinth seals, and oil film seals. However, bushing seals remain relatively understudied, particularly in terms of how they respond to dynamic pressure variations during operation. Industry standards like API 614 (for seal oil systems) and API 617 (for centrifugal compressors) offer general design and operational guidelines, but they do not specifically address or mandate active control of differential pressure during transient events such as startups, shutdowns, or process upsets.

This study fills that gap by examining real-world failure data, implementing innovative control strategies, and validating performance improvements through operational testing. The findings also highlight the importance of integrating control system enhancements with mechanical design to enhance bushing seal reliability under dynamic operating conditions.

4.1 System Description

A compression system utilizes two compressors for each train arranged in two stages as shown in the Fig. 4. Each compression train consists of one first-stage (5 stages impeller) and one second-stage (7 stages impeller) compressor. Both types utilize long, slender shafts with "Bushing seals" (a cone seal design) to prevent gas leakage. The primary function of these compressors is to raise gas pressure for transport through pipelines to export lines.

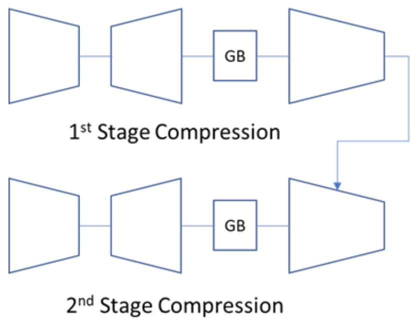

Fig. 4. General Layout of Compression System.

4.2 Bushing Seal Operating Description

Some of the key systems are shown in Fig. 5 and their explanation given below. The Bushing Seal System uses oil to create a dynamic barrier against process gas. It operates on a dual-layer principle: Oil Supply & Pressure is important; oil is supplied at "Point B" at a pressure 5-10 PSI higher than the reference gas pressure. This pressure is maintained by an Overhead Seal Oil Tank positioned 15-30 feet above the compressor centre line. This hydrostatic head ensures stable pressure and provides a backup supply for safe shutdown during main supply failures. Cooling and separation oil flows between inner and outer seal rings to cool them, as tight fits generate heat. Sweet Seal oil flows through the outer ring area (higher pressure differential) and drains out at "Point C" as clean, untreated oil. This oil has not contacted process gas. Sour Seal Oil in smaller amount of oil flows through the inner ring, contacting the process gas to form a barrier. This oil becomes contaminated ("Sour") and drains via "Point A" to special traps. To prevent sour oil from migrating back into the compressor, a small flow of gas (often inert nitrogen or treated natural gas) is introduced via buffer gas ports at a pressure 3-5 PSI higher than the balance port. This gas flow, regulated by orifices in the vent lines, ensures gas moves outward, pushing sour oil away from sensitive areas.

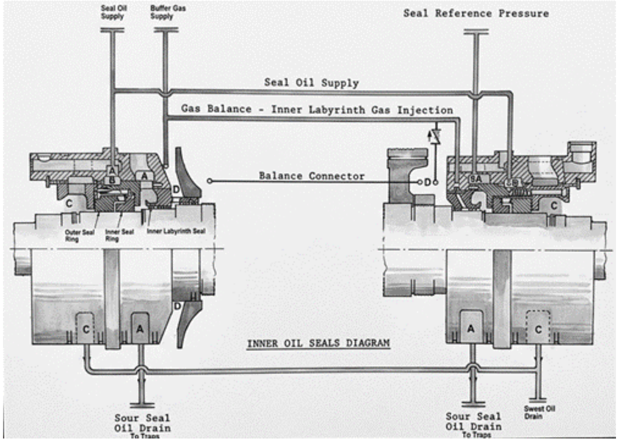

Fig. 5. General Layout of Seal System.

4.3 Application of Data Driven Framework

For over a decade, the compressors had been plagued by recurring failures of their bushing seals, with nine separate incidents occurring during this time. The symptoms of these failures were consistent, including excessive wear, scoring, gas leakage into the oil system, and elevated temperatures are shown in Fig. 6-8. Despite initial attempts to address the issue through standard maintenance procedures, such as replacing seals, checking shaft alignment, and verifying oil quality and filtration, the problems persisted. It became clear that the root cause of these failures was not a mechanical defect, but rather a deeper, systemic control issue that required a more comprehensive solution. The repeated failures suggested that a more structured approach was needed to identify and address the underlying cause of the problem.

Fig. 6. Drive End Cone Seal Abrasion.

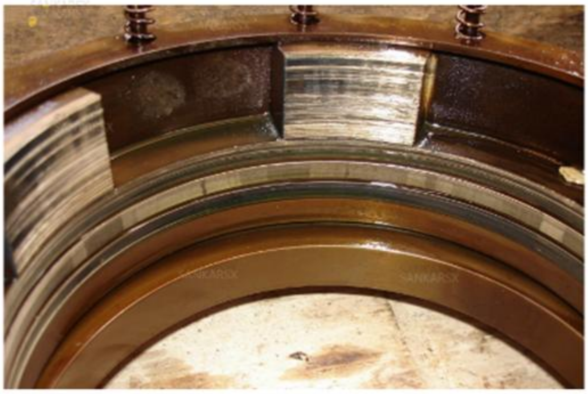

Fig. 7. Damper Bearing Damage.

Fig. 8. Cone Seal Abrasion.

A structured stepped approach used to ensure all basis are covered to investigate the causes of long-term reliability issue to this critical system, using the process we have used data driven method to successfully investigate the root causes of the problem.

4.4 Investigation (RCA) Analysis Results

A structured RCA and detailed review of operating data, process parameter trend analysis, and material inspection data revealed four key factors:

- Inadequate Pressure Differential: Seal oil pressure intermittently dropped to or below gas pressure, allowing gas to breach the seal. (Process data).
- Reverse Flow Conditions: During transients (startups, shutdowns, load changes), insufficient oil pressure allowed process gas to backflow into the seal oil system. (Process and Design data).
- Dynamic Instability: The control strategy was designed for steady-state conditions and failed to account for real-time pressure fluctuations during normal operations. (Design Data).

- Instrumentation Limitations: Existing pressure sensors did not accurately reflect conditions at the seal interface, leading to ineffective regulation (Design and operating data).

After identifying the all the causes, a detailed priority based corrective actions have been developed to resolve this long-term issue using the structured approach.

4.5 Corrective Actions Implementation and Validation

Upon completing the comprehensive analysis of the data, which encompassed all potential areas and their respective contributions, the root causes of the equipment failure were successfully identified. Subsequently, a tailored solution was developed to address the identified issues, leveraging the insights gained from the data-driven approach. This solution was designed to mitigate the underlying causes of the failure, thereby preventing similar incidents from occurring in the future. The development of this solution was informed by a thorough understanding of the complex interrelationships between the various factors that contributed to the failure, and was guided by the principles of reliability-centered maintenance and design for reliability. The solution was deployed which includes modification of control logic within the Distributed Control System (DCS), installation of accurate pressure transmitters as shown in Fig. 9, operator training and, a phased commissioning approach. The implementation yielded significant operational improvements, such as:

- Zero Failures: There have been zero seal failures for 8 years post-implementation, compared to nine failures in the prior 12 years as shown in Fig. 10.
- Reduced Maintenance: The stable pressure differential eliminated the fluctuations that caused wear, drastically reducing maintenance interventions and downtime.
- Increased Availability: Compressor availability improved due to higher reliability and fewer unscheduled shutdowns. The Fig. 11 shows the overall system availability along with pre and post modification availability. It has been observed that after the modification, no seal failure has been experienced, hence 100% availability of the system.

Fig. 9. Installed Transmitters for seal cavity pressure monitoring.

Fig. 10. Seal Reliability Profile.

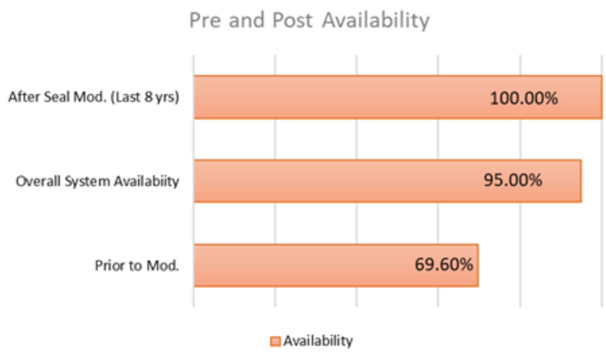

Fig. 11. Pre and Post Availability.

4.6 Lesson Learned

The structured methodology employed in this study not only facilitated the identification of the root causes of equipment failure, but also enabled the determination of critical factors that must be incorporated into future design iterations to prevent similar failures from occurring. Some of the key factors that emerged as crucial to ensuring the reliability and performance of the equipment include:

- Dynamic Nature: Seal systems are complex and dynamic, not static. Designs must account for real-time process fluctuations.

- Pressure Differential Control: Maintaining a precise, stable pressure differential is more critical than mechanical component selection. Even small pressure deviations can lead to failure.
- Advanced Control: Control algorithms outperform purely mechanical solutions by adapting to changing conditions in real-time. When combined with accurate instrumentation and a deep understanding of system dynamics, algorithms provide a flexible, cost-effective, and reliable solution for optimizing seal performance.

5. CONCLUSION

To effectively address chronic problems, a meticulous and well-structured approach is essential. This involves a planned process that encompasses comprehensive data analysis, covering all relevant aspects such as design, operating conditions, maintenance history, and other pertinent factors. This study highlights that recurring bushing seal failures in process gas compressors can be successfully addressed by implementing precise control over the pressure differential. The developed control algorithm, which maintains the seal oil pressure consistently above the reference gas pressure, has proven to be an effective and dependable solution.

In conclusion, the design and implementation of seal systems require a comprehensive understanding of their dynamic nature, the critical importance of pressure differential, the need for accurate instrumentation, and the potential of control algorithms to outperform traditional mechanical solutions. By recognizing the complex interplay between these factors, designers and engineers can develop seal systems that are more efficient, reliable, and effective, ultimately leading to improved performance and reduced maintenance costs.

Authors are confident that the structured framework can be effectively applied to a wide range of equipment and systems, beyond its current application. A next step would be to utilize this framework to enhance the performance and reliability of other critical equipment, such as pumps and turbines. Additionally, the development of a generalized model that can be applied to various types of seal systems and equipment would provide a valuable resource for designers and engineers, enabling them to optimize performance and reliability across different systems.

Moreover, integrating the developed control algorithm with other maintenance strategies could yield a comprehensive approach to optimizing equipment performance and reliability. This could involve the creation of a real-time monitoring system capable of detecting potential seal failures, alerting operators to take corrective action, and thereby reducing downtime and maintenance costs.

Ultimately, this research has the potential to drive significant improvements in equipment performance, reduce maintenance costs, and increase overall efficiency across a broad spectrum of industries, leading to enhanced productivity and competitiveness.

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