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Analysis of Risk-Based Inspection (RBI) and Reliability-Centred Maintenance (RCM)

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Abstract: *Pipe systems in petroleum and gas industries as well as in process industries are subjected to harsh mechanical, thermal and environmental conditions. The pipeline's failure may cause serious accidents like fire, explosion, and environmental problems over a long period, which evokes the necessity of organized Pipeline Integrity Management (PIM) activities. The chosen paper is the extensive review of the maintenance and integrity management strategies in the O&G piping systems with a specific emphasis on the Risk-Based Inspection (RBI) and Reliability-Centered Maintenance (RCM). It talks about piping stress analysis as a basic necessity of providing structural integrity in both the static, and dynamic loading conditions with the aid of advanced engineering software like the CAESAR II and AutoPIPE. The paper also gives the RCM framework of determining functional failures, failure modes and suitable maintenance activities as well as the RBI method of determining the likelihood of failure and effects of failure to prioritize the inspection activities. Comparative analysis has shown that RBI is inspection-based and efficient in dealing with high-risk and corrosion-prone piping systems whereas RCM is a function-based and improves the overall system reliability by optimized maintenance planning. The article concludes that optimising oil and gas pipeline safety, dependability, and cost-effectiveness through the integration of RBI and RCM is a powerful and complementary strategy.*

Keywords: Risk- Based inspection, Piping System, Reliability Centred Maintenance, Piping Techniques, Piping System Analysis

I. INTRODUCTION

The pipelines that transport oil and gas are expensive and often pass through densely inhabited areas and environmentally fragile zones [1]. Furthermore, pipelines can break due to improper maintenance, which could have significant, long-lasting, and irreversible effects for both human and natural ecosystems [2][3]. Oil and natural gas are mainly transported over long distances through pipelines. Unfortunately, in the event of a failure of a pipeline, the subsequent release of flammable materials may, in turn, lead to fires and explosions, causing the spread of severe accidents [4]. Pipeline Integrity Management (PIM) is a systematic approach to testing, inspecting, assessing, maintaining, repairing, and training pipelines in order to maintain an acceptable level of risk. As a percentage of total equipment damage, piping damage is the most common in petrochemical plants. A lot of the machinery used in construction has simpler designs than pipes. The amount of piping is huge, and only inspection specialists who are familiar with piping design are efficient at piping inspection planning. This has long been a blind spot in inspection planning. In Taiwan, because the piping inspection standard is not regulated, greater risk is incurred from piping damage [3]. Piping inspection strategies may reduce piping risks, safety, and production efficiency. Efficient strategy application [5], well-developed planning, highly reliable implementation, professional analysis, and substantial improvement are all indispensable to piping inspection theory.

The oil and gas sectors are heavy users of risk-based inspection (RBI), a method for organizing and prioritizing inspections based on risk. This approach to inspection planning considers both the possibility of failure and its potential outcomes while formulating an inspection strategy [6][7]. With the help of RBI, a business can: choose

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inspection and maintenance tasks and techniques that are both appropriate and cost-effective; optimise these efforts and costs; transition from a reactive to a proactive maintenance regime; create an auditable system; establish an agreed-upon "operating window"; foster teamwork; and integrate a risk management tool.

The Reliability-Centred Maintenance (RCM) approach was first used in the civil aviation industry as a cost-effective way to ensure the physical asset's reliability capabilities through planned maintenance. So, it lays out the plans for maintenance in a way that is economical, allowing the equipment to be operational again and again [8]. The item under inspection is broken down to its component parts until all of its functions, functional failures, possible failure mechanisms, causes of failure, and repercussions of failure are recognised. Then, the maintenance activities are selected. The first version of RCM came out in the late 1970s, and since then, it has been used basically everywhere in the industrialised world.

A suitable maintenance schedule that can keep the performance of the machinery at a good level is definitely needed. RCM combined with Planning is a tool that can result in a lower number of machine breakdowns. In case machines are handled through RCM planning, it is discovered that the breakdown of machinery has lessened [9]. In addition to that, RCM planning is able to lower the occurrence of defective equipment that is not yet quite enough for their time and also facilitate planned maintenance at a higher level of accuracy. The most important thing is to figure out how to maintain each model so as to make the machines with different applications such as Preventive Maintenance, Predictive Maintenance [10], or Condition-Based Monitoring compatible with one another.

Due to the complicated nature of the creation and management of maintenance programs, companies are still relying on reliability-centred maintenance (RCM) to provide them with the necessary assistance [11]. The goal of root-cause analysis (RCM) is to determine the most cost-effective maintenance program for a piece of equipment by analysing its failure modes. The procedure aims to achieve the needed level of reliability.

A. Structure of the Paper

This paper presents a review of oil and gas pipeline systems with a focus on maintenance and integrity management. Section II discusses the Piping stress analysis; Section III explains the RCM and RBI framework for piping systems, while Section IV presents a Comparative analysis of RBI AND RCM. Section V describe a past literature study, Section VI conclude and future work.

II. PIPING STRESS ANALYSIS

Pipe-stress is a program that can be used to do a linear elastic study of three-dimensional pipe systems that are loaded in different ways (Figure 1). To demonstrate that pipes not burst under different loads, engineers conduct stress analyses and evaluations. Both static and dynamic analyses are part of pipe stress analysis [12]. Standard elements of static analysis include pressure, thermal expansion, endpoint displacement, and sustained load. Seismic analysis is a crucial component of dynamic analysis, which is typically used for unintentional loads. The five basic steps of using Peps for stress analysis and evaluation in nuclear pipework are as follows: 1) Figure out the geometry and the finite element setup. Boundary conditions should be applied. 3) Use the loads that are specified for each condition type. Four, examination of stress. Five, assessment of stress. Some of the most well-known programs used for pipe engineering include CAESAR II and AutoPIPE. The intuitive interface makes it easy for engineers to input data and build analytical models. Automated calculations and processing by the program could simplify the process.

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Fig. 1. Pipe stress analysis

- Pipe systems subjected to a wide range of static and dynamic loads—including earthquake, weight, pressure, heat, and more—can be quickly and accurately analysed with CAESAR II. It can analyse pipe systems of any size or complexity.
- Bentley Systems' Auto PIPE is a powerful and versatile program for analysing and designing pipe stress. The oil and gas, power sector [13], and petrochemical industries, among others, can benefit from the tool's ability to help engineers and designers analyse the effects of various loads and stresses on piping systems. Because of its many useful features, user-friendliness, and conformity to standards, Auto PIPE stands out [14].

Critical Parameters Influencing Piping Flexibility and Structural Integrity

Stress evaluation features prominently in flexibility analysis as it can be wise both together and separately to include static and dynamic loads, and more like self-weight, pressure and temperature [4]. Displacement factors take into account movements of the part due to thermal expansion or contraction in order to include operational movements and ensure that failure does not occur due to excessive deformation. Loads constitute operating loads, sustained loads and expansion loads, each of which has its own impact on design, safety and performance of the system [15].

III. RCM AND RBI FRAMEWORK FOR PIPING SYSTEMS

Reliability Centred Maintenance (RCM) is a decision-making approach that aids in the identification of appropriate and cost-effective proactive preventative and condition-based maintenance tasks with the goal of preserving the necessary functionalities of an asset or system. The technical accounting of an asset or system is the RCM workshop's execution process. It finds the asset or system's functions and functional failures, and then, in a systematic way, guides the workshop team through a series of decisions to find maintenance tasks that prevent or reduce the occurrence of functional failures. Whenever maintenance work is executed in accordance with the RCM's findings and recommendations, the rationale behind its identification and the expected benefit are crystal clear. Acquiring a comprehensive grasp of a system or asset can be facilitated via RCM analysis [16].

A. Functional Failure Analysis and Criticality Assessment in Piping Networks

Pipes are categorised using a risk-oriented assessment method that takes into account both the likelihood of failure—determined by a Random Forest analysis—and the impact of failure—measured by a composite index called Link Hydraulic Criticality—which combines the number of disconnected nodes and the flow conveyed by each pipe. Link Hydraulic Criticality can overstate the topological impact of network branch pipes, which is one of the method's weaknesses. Another issue is that when demand-driven (DD) analysis is used, problems with unmet demand can be missed [17].

B. Selection of Maintenance Tasks Using RCM Logic for Piping Systems

RCM is a systematic method of identifying the most suitable maintenance needs for the plant and equipment in real operating conditions. In piping systems, the goal of RCM is to improve PM and PM techniques by systematically identifying functional failures, failure modes, and their repercussions. The planned PM programs facilitate the reduction of situations like corrosion, leakage, erosion, fatigue, and rupture resulting in enhanced operational safety and reliability of piping networks. RCM is an instrument extensively utilized to maintain the performance of process and steam piping systems while managing the high costs of corrective maintenance against the cost of planned preventive and condition-based maintenance policies and considering the possible shortening of the service life of piping components [18].

C. Risk-based inspection (RBI) for piping system

Risk-based inspection and maintenance (RBI/M) methodologies are founded on the core principles of risk management, focusing on the identification, analysis, and mitigation of risks associated with equipment failure[19]. The primary objective is to maximize the effectiveness of inspection and maintenance processes by giving top priority to assets that are most likely to compromise safety, the environment, or the continuity of the business. First, we'll have a look at what an RBI is and how it works, including the tools and procedures that are normally used. Then, we'll go over some important topics including risk, risk assessment, and risk ranking.

D. Tools and Techniques in RBI

Several analytical tools and methodologies support the risk assessment and prioritization process:

- **Failure Modes and Effects Analysis (FMEA):** A technique that can be used to assess the probability and impact of failures by methodically identifying possible failure modes, their sources, and the ways in which they impact system performance.
- **Fault Tree Analysis (FTA):** An approach to deductive analysis that starts from the top and works its way down to help comprehend complicated failure relationships by drawing a map of the paths that lead to system failure.
- **Risk Matrices and Risk Ranking Tables:** Visual tools that classify risks into categories (e.g., low, medium, high) based on their likelihood and consequences, facilitating prioritization.
- **Software Tools:** Various commercial software packages are available to automate RBI processes, integrating data management, risk calculations, and inspection planning (e.g., API RBI software, Siemens COMOS, DNV GL Synergi Plant).
- **Condition Monitoring Techniques:** Vibration analysis, ultrasonic testing, infrared thermography, corrosion monitoring, and other similar methods can detect early indications of degradation, which allows for more precise likelihood evaluations.

IV. COMPARATIVE ANALYSIS OF RBI AND RCM

RBI and the Reliability-Centred Maintenance (RCM) are common asset integrity and maintenance strategies to piping systems, which have different objectives but the common end goal of enhancing safety, reliability, and cost effectiveness [14]. With a comparative analysis of these approaches, it is possible to note that they are complementary to each other and suitable depending on the situation at hand.

A. Major Differences and Similarities

Both RBI and RCM are formalized, systematic approaches, which are based on the concept of risk and reliability to make the choice of actions and allocate maintenance resources. Their goals are to minimize unwanted failures, increase system availability and become regulatory compliant [20]. Nonetheless, RBI is more interested in determining the probability and impact of equipment failure so as to prioritize on inspection activities, unlike RCM, which maintains the functionality of the system by determining key functions, failure modes as well as the right maintenance activities. RBI is asset- and risk-focused whereas RCM is function- and reliability-focused.

B. Inspection-Centred and Function-Centred Approaches

The philosophy of RBI is inspection-oriented, which focuses on the location, timing, and frequency of inspections regarding a measured degree of risk. It has been largely useful in controlling degradation processes like corrosion and erosion in piping systems. RCM, on the other hand, is concerned with how people understand the role of pipe systems and how to keep them functioning properly through maintenance. RCM is holistic as it takes into account operational, safety and environmental functions, and not inspection.

C. Data Requirement and Analytical Complexity

RBI is a very data-intensive and highly analytically complicated process that involves detailed data on degradation, past inspection, corrosion rates, operating conditions, and consequence modelling. RCM, though also necessitating the availability of reliable failure and maintenance history, is based more upon qualitative and semi-quantitative studies like FMEA or FMECA. Accordingly, RCM may be less computational, but could require a large amount of expert judgment and structured decision reasoning.

D. Implication on Cost, Safety and Reliability

RBI can greatly minimise costs of inspections since it can focus on risky segments of piping and yet the margins of safety are upheld. It is a direct method of mitigating risks as it concentrates on those elements that have a drastic failure impact. RCM lead to the enhancement of long-term dependability by synchronizing maintenance plans with failure behavior and functions of the system, lessening unexpected outages and redundancy of maintenance. Both solutions are more secure, yet RBI provides prioritization based on risks immediately, whereas RCM provides long-term reliability benefits.

E. Applicability to Alternative Piping System situations

RBI is most effectively applied to complex, corrosion-sensitive, and safety-critical piping systems with high consequences of failure which occur in oil and gas or chemical processing plants. RCM is more appropriate for systems in which operational continuity and functional availability are of great concern, such as utility piping, power plants, and integrated networks of processes. Practically, RBI and RCM together may perform better in uniting the priorities of the inspection with the goals of functional reliability.

Table 1: Comparison Table: RBI vs. RCM for Piping Systems

Aspect	Risk-Based Inspection (RBI)	Reliability-Centred Maintenance (RCM)
Primary Focus	Risk-driven inspection prioritization	Function-driven maintenance planning
Core Principle	Probability and consequence of failure	Functional failure and failure modes
Data Requirement	High (inspection, degradation, risk data)	Moderate (failure history, expert analysis)
Analytical Complexity	High, quantitative risk modelling	Medium, qualitative/semi-quantitative
Impact on Safety & Reliability	Improves safety through risk reduction	Enhances long-term system reliability
Best Suited for	High-risk, corrosion-prone piping systems	Function-critical piping networks

V. LITERATURE REVIEW

Reliability-Centred Maintenance (RCM) and Risk-Based Inspection (RBI) are two approaches to pipe inspection that have recently been studied. Examine the research papers in Table II.

Mejia-Portillo et al. (2025) offer the concept of implementing an RCM strategy to enhance the fire-tube boiler maintenance program. In order to determine the Risk Weighting Number (RWN), the researchers examined the potential causes and consequences of failure. The maintenance jobs were assigned using the RWN value and the RCM diagram. After developing the boiler system's dependability block diagram, they used the Weibull distribution to determine optimal time intervals for the system's key components. No studies that used RCM on textile industry fire-tube boilers were found in a literature study that attempted to cover every possible angle. By conducting a case study to assess the suggested maintenance plan's availability, reliability, and economic feasibility, and able to raise availability by 0.004% and reliability by 16.15%. Moreover, there is a possibility of saving maintenance costs by up to 27.54% annually [21].

Lao et al. (2025) have demonstrated that traditional heat pipes have their heat flux reduced by 20−40% in lunar conditions due to an improper fluid return caused by reduced gravitational forces. To overcome this limitation, the newly developed LHP has a sintered nickel wick and a small pump, and it employs benzene (density 876 kg/m3, latent heat 433 kJ/kg) as the working fluid, thereby achieving thermal efficiency in the range of 90−95%. A series of simulations carried out with MATLAB R2024b display a system-level net power output (Wnet) varying between 94−102 kW, thus being very close to the target of 101.25 kW, and a specific power (SP) of 21.08 W/kg. By 25.5% increase in single-tube Wnet LHP is making possible what conventional heat pipes can hardly do, hence it can be a great leverage in the thermal management of lunar bases and the clean energy sector can benefit from it to reach the inaccessible places further. [22].

Vilbrad Rishøj Jensen et al. (2025) as the data had a significant class imbalance (~1:215), numerous oversampling (OS) methods were tested. The AUC and fault capture versus length capture (FCLC) curves show how well the model is doing. The model detects almost 40% of the defects with just 10% of the network evaluation, and adding pressure data is projected to increase the AUC by 4.5%. These results suggest that ML-based fault vulnerability prediction could be a useful tool for DHNs in planning predictive maintenance and asset replacement [23].

Liu et al. (2024) the regulation characteristics of flexibility resources are analyzed, flexibility resource flexibility supply indexes are proposed, and the system flexibility supply capacity is calculated; secondly, the source of system flexibility demand is analyzed, and the system flexibility demand model is established to calculate the flexibility demand; finally, according to the system flexibility supply-demand equilibrium relationship, the system flexibility assessment indexes based on probabilistic statistical theory are proposed, the system flexibility is calculated, and the actual data of a certain region is collected Flexibility calculation is carried out [24].

Haris, Chik and Anuar (2024) The purpose of this research article is to examine how various insulation thicknesses impact the precision of portable diagnostic device measurements of pipe vibration. The findings show that the amplitude of measurement increases with increasing insulation thickness. Loose insulation is found to give higher amplitude deviation compared to a good insulation condition. This trend is particularly noticeable at 100 Hz, where the highest amplitudes were observed. The study highlights the significance of taking insulation thickness and condition into account when measuring vibrations in pipe systems [25].

Lawal and Afolalu et al. (2024) research further points out that one of the major factors in efficient asset management is the use of digital technologies like the IoT and information model building. Finally, the oil and gas industry's asset integrity management stages could be approached with varying degrees of digitisation [26].

Zhao et al. (2023) figured out proper maintenance plans for the stationary equipment at an oil and gas station. This paper brings in risk-based inspection technology to evaluate the risk of six-core static equipment. Next, as the leakage mode is taken as an example, the failure effect areas of the static equipment can also be calculated. At last, a risk matrix is used to identify the risk levels of the static equipment [27].

Song, Zhang and Lind (2023). Most of the complex industries use RCM as a tool to identify the necessary maintenance and optimise the maintenance strategies. By using RCM, it is possible to classify a piece of equipment as one that requires preventive maintenance if its breakdown leads to the worsening of the performance of the system. This study aims to illustrate the possibility of a noncoherent problem in RCM by means of a straightforward industrial example. An analysis of the incoherent system is carried out using the newly developed RCM automation system. The paper talks about the effects of performing a noncoherent RCM and how it can be done [28].

Table II provides a Summary of Key Research Advances, Methods, Findings, Limitations, and Practical Implications Across Recent Engineering, Thermal, Mechanical, and Piping System-Related Studies.

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Table 2: Literature Study on Risk-Based Inspection (RBI) and Reliability-Centred Maintenance (RCM) Techniques For Piping Systems

Reference	Study On	Approach	Key Findings	Challenges / Limitations	Future Directions
Mejia-Portillo et al. (2025)	Optimization of maintenance program for fire-tube boilers using RCM in textile industry	Criticality analysis using AHP; FMEA; Risk Weighting Number (RWN); Reliability Block Diagram (RBD); Weibull distribution	Reliability increased by 16.15%, availability by 0.004%, and annual maintenance cost saving up to 27.54%	First RCM study on fire-tube boilers in textile sector; case-specific results	Wider industrial application of RCM-based boiler maintenance
Lao et al. (2025)	Thermal management of lunar heat pipes	Modified Loop Heat Pipe (LHP) with sintered nickel wick and pump; MATLAB R2024b simulation	Thermal efficiency 90–95%; Net power 94–102 kW; 25.5% increase in Wnet over traditional pipes	Reduced fluid return in low-gravity conditions; pump reliability dependence	Improve LHP robustness for extreme environments; optimize wick–pump integration
Vilbrad Rishøj Jensen et al. (2025)	Fault vulnerability prediction in district heating networks	Machine learning with oversampling strategies; AUC and FCLC evaluation	AUC improved by 4.5% using pressure data; 40% failures detected by inspecting 10% of the network	Severe class imbalance (~1:215); generalization issues	Stronger predictive maintenance tools; multi-sensor data integration
Liu et al. (2024)	System flexibility calculation in energy networks	Probabilistic statistical modelling of flexibility supply–demand	Flexibility indexes developed and validated with regional data	Requires extensive operational data; probabilistic model complexity	Improved grid flexibility estimation tools; enhanced grid stability
Haris, Chik & Anuar (2024)	Effect of insulation thickness on piping vibration measurement	Experimental vibration measurement using portable diagnostic instruments	Vibration amplitude increases with insulation thickness; loose insulation causes higher deviations	Accuracy strongly depends on insulation condition	Standardized correction factors for insulated piping measurements
Lawal & Afolalu (2024)	Digital technologies in asset integrity management for oil and gas	Conceptual framework using IoT and information modelling	Digitization significantly improves asset management efficiency	High implementation cost and infrastructure dependency	Stage-wise digitization strategy for oil and gas sector
Zhao et al. (2023)	Risk-based inspection of static equipment in oil & gas	RBI using failure probability modelling and risk matrix	Risk levels identified for six critical static equipment units	Accuracy depends on quality of failure probability data	Integration of real-time monitoring with RBI

	stations				
Song, Zhang & Lind (2023)	Noncoherent systems in RCM automation	RCM automation applied to an industrial noncoherent system	Demonstrated impact of noncoherent logic on maintenance decisions	Limited to a single industrial example	Expansion of RCM automation to complex noncoherent systems

VI. CONCLUSION AND FUTURE WORK

Oil and gas pipeline systems are highly operational risk systems that require well-organised and systematic maintenance plans as they are environmental sensitive and economically significant. This paper has conducted a review of the current practices in the management of pipeline integrity with specific attention to the piping stress analysis, RBI and RCM. The analysis of stress was emphasized as an important premise to guarantee structural safety in both the undercarriage of the structure and the conditions of the dynamic load. RBI proved to be effective in prioritizing the resources of the inspection through assessing the probability and impact of failure, which ensured its particular application to high-risk piping systems and corrosion-prone ones. By comparison, RCM offers a functional-based model that improves the reliability over time through predicting functional failure and choosing the right preventive, predictive, and condition-based maintenance measures. The comparison analysis reveals that RBI and RCM are not rival methods but complementary techniques.

A. Limitations

Although this is a very broad research, it has its limitations. The review is mainly anchored on existing literature and conceptual frameworks as opposed to specific real-life case studies or operational datasets of particular pipeline networks. The empirical validity of quantitative comparisons of the results of RBI and RCM, either cost savings or failure rates, was not established. Also, the differences in the regulatory requirements, data accessibility, and inspection methods were not examined in-depth, which can also affect the practical relevance of the findings.

B. Future Work

The future study may be aimed at creating integrated RBI-RCM schemes that are reinforced by real-time monitoring and digital tools like IoT sensors, digital twins, and predictive risk assessment models based on ML models. Field data of pipelines in operation would be useful to use as case studies to prove the effectiveness of the proposed approaches and measure their advantages in terms of safety, cost, and reliability.

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