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Risk-Based Inspection Applied to Cost Savings in Pumped Energy Storage Scheme Pressure Vessels †

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Abstract

Pumped Energy Storage Schemes play a critical role in electricity grid stability and energy security by storing excess electricity for later use. Pressure vessels in these systems are subject to rigorous inspection regimes because of their potential risks to safety and performance. Traditional Time-Based Inspection, while effective, can be costly and inefficient. This paper investigates the application of Risk-Based Inspection methodologies to optimise inspection planning, reduce costs, and maintain safety in Pumped Energy Storage Scheme pressure vessels. The study presents a structured framework for implementing Risk-Based Inspection, demonstrates the potential for cost savings through comparative analysis, and highlights its alignment with regulatory requirements in South Africa.

Keywords: risk-based inspection; pumped energy storage scheme; pressure vessels; cost savings

1. Introduction

South Africa's transition toward a more flexible, lower-carbon grid has renewed attention on long-duration energy storage [1]. Pumped Energy Storage Schemes (PESS) play a vital role in balancing electricity supply and demand by providing peak shaving, spinning reserve and ancillary services. Pressure vessels such as accumulators, surge tanks and auxiliary air receivers are essential components whose integrity directly affects safety and availability. Conventional Time-Based Inspection (TBI) strategies rely on fixed intervals dictated by statutory codes or conservative practice [2,3]. These intervals do not fully reflect actual degradation behaviour and may lead to both over-inspection of low-risk vessels and under-inspection of critical components.

Risk-Based Inspection (RBI), as outlined in API 580 and API 581 [4,5], offers a structured method to prioritise inspections based on the combined effect of Probability of Failure (PoF) and Consequence of Failure (CoF). RBI is widely adopted in the oil, gas and petrochemical sectors [6,7], yet its application in pumped-storage schemes, particularly within the African context, remains limited. This paper addresses this gap by applying a

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Risk-Based Inspection framework to Pumped Energy Storage Scheme pressure vessels and evaluating cost and risk outcomes over a 10-year period.

This study contributes a multi-site simulated case evaluation of Risk-Based Inspection for Pumped Energy Storage Scheme pressure vessels. The study combines academic rigour (equations and quantitative modelling) with practical deployment guidance (governance and digital enablers).

Despite advances in inspection methodologies, the South African energy sector still relies heavily on Conventional Time-Based Inspection regimes [2,3]. These approaches do not sufficiently account for individual vessel risk profiles, resulting in both over-inspection of low-risk components and potential under-inspection of critical assets. There is also limited integration of Risk-Based Inspection in Pumped Energy Storage Scheme pressure vessels despite global success stories. This study addresses this gap by proposing a structured Risk-Based Inspection application tailored to Pumped Energy Storage Scheme systems, motivated by the potential for significant cost reductions and enhanced operational safety [6,7].

Risk-Based Inspection is grounded in international standards such as API 580 [4], API 581 [5], ASME PCC-3 [8], EN 16991 [9] and DNV RP-G101 [10]. These documents provide methodologies for identifying damage mechanisms, quantifying failure probabilities, classifying risk and optimising inspection plans. Cheung and Karim [7] report that Risk-Based Inspection implementation in mechanical systems can achieve 25–40% reductions in inspection cost without compromising safety. Choi et al. [6] demonstrate similar benefits in power-generation environments, emphasising the role of probabilistic risk models in scheduling inspections and outages.

Singh et al. [11] highlight that Probability of Failure modelling using statistical tools derived from reliability engineering, such as exponential and Weibull distributions [12], improves the prediction of end-of-life for pressure components. ISO 55000 [13] and IEC 60300 [14] further reinforce the importance of risk-based asset management strategies in large utilities. However, there is limited application of Risk-Based Inspection in African Pumped Energy Storage Scheme assets, presenting a knowledge gap this study addresses.

2. Materials and Methods

The methodology adopted in this study follows the core principles of API 580/581 and ASME PCC-3 [4,5,8]. The key steps are summarised below, and illustrated in Figure 1.

(1) Asset Register and Data Collection (DC): Compilation of design data, historical inspection records, degradation rates, and operational loading profiles for Pumped Energy Storage Scheme pressure vessels [13].
(2) Degradation Mechanism Identification: Determination of active mechanisms such as general corrosion, erosion–corrosion, fatigue, and stress-corrosion cracking using API 581 and plant-specific experience [5,14,15].
(3) Probability of Failure modelling: Application of exponential and Weibull models, guided by API 581 procedures, to estimate Probability of Failure as a function of time and damage accumulation [5,12].
(4) Consequence of Failure Assessment: Evaluation of safety, environmental, production, and financial consequences using a semi-quantitative scoring system aligned with EN 16991 and DNV RP-G101 [9,10,16].
(5) Risk ranking: Combination of Probability of Failure and Consequence of Failure scores into a risk matrix, classifying vessels into low, medium, high, and extreme risk categories for prioritisation [4,10].
(6) Risk-Based Inspection Plan Development: Determination of inspection intervals, methods (e.g., Visual Inspection, Ultrasonic Testing, Magnetic Particles Inspection), and scope for each risk category, ensuring alignment with statutory requirements [2–5].

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(7) Ten-Year Simulation: Comparative simulation of Time-Based Inspection and Risk-Based Inspection strategies for a representative Pumped Energy Storage Scheme vessel population, quantifying inspection frequency, cost, and residual risk [6,7].

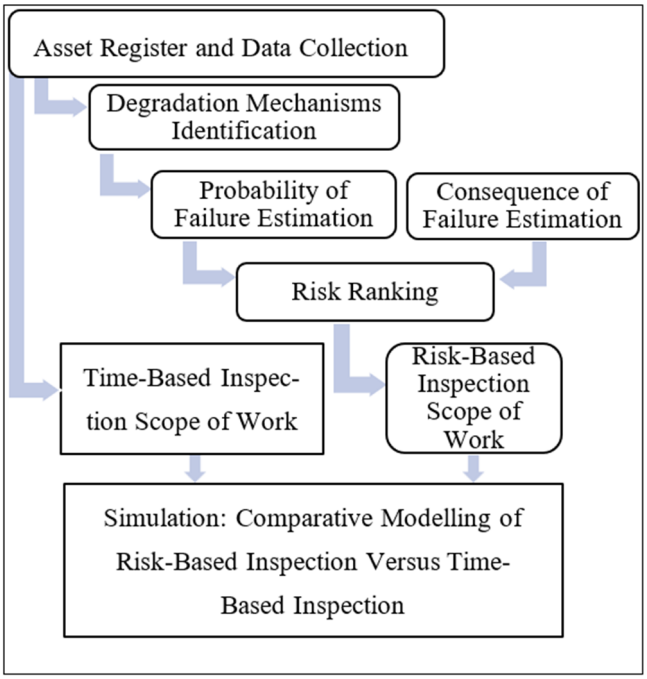


Figure 1. Risk-Based Inspection process workflow and comparative simulation of Risk-Based Inspection versus Time-Based Inspection adopted in this study.

A hybrid risk formulation combining semi-quantitative scoring and probabilistic expressions was adopted [15,17]:

$$Risk = P_f \times C_f \tag{1}$$

$$\mathrm{P_f} = \frac{\mathrm{DM} \times t}{\mathrm{Q}} \tag{2}$$

$$P_f(t) = 1 - \exp(-\lambda t) \tag{3}$$

$$\beta = -ln\left(P_f\right) \tag{4}$$

where

P_f : is the Probability of Failure, representing the likelihood of a system exceeding a limit.
C_f: is the Consequence of Failure, quantifying the severity of the safety, economic and/or environmental impact.
DM: is the Deterioration Magnitude in mm/year or percentage.
t: is service time in years or hours.
$P_f(t)$: is the time-dependent Probability of Failure, representing the cumulative distribution function of the failure time.
Q: is inspection confidence.
λ : is the failure rate per year.
β : is a reliability index that indicates how many standard deviations the mean state is from the failure threshold; as the probability of failure decreases, the reliability index increases.

Equations (2)–(4) link observed or inferred damage (degradation) rates to inspection intervals and confidence. Higher inspection confidence (Q) reduces the effective probability

of failure for the same exposure time. λ represents the failure intensity related to the underlying damage process and is mitigated by inspection and maintenance actions.

3. Results and Discussion

The simulated multi-site case study across representative Pumped Energy Storage Scheme facilities revealed substantial advantages of adopting Risk-Based Inspection over traditional Time-Based Inspection. Over a 10-year inspection cycle, Risk-Based Inspection reduced the total number of inspections by approximately 35% as shown in Figure 2. Under Time-Based Inspection, vessels were inspected at fixed two-year intervals, resulting in five major inspection campaigns per vessel. In contrast, Risk-Based Inspection assigned intervals between one and five years depending on risk category, leading to fewer inspections for low-risk vessels and more focused effort on higher-risk equipment.

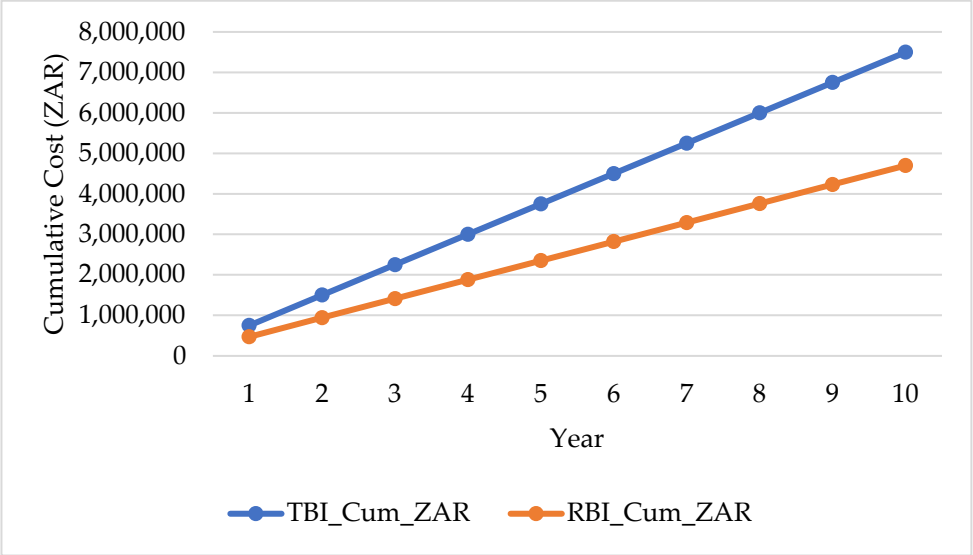


Figure 2. Risk-Based Inspection vs. Time-Based Inspection cumulative inspection cost over a 10-year simulation.

This reduction in inspection burden translates into fewer planned outages, reduced labour requirements and less disruption to plant operations. It also enables maintenance teams to concentrate effort and specialist Non-Destructive Testing (NDT) resources on vessels where the risk reduction benefit is highest. These findings are consistent with international experience reporting inspection workload reductions between 20% and 40% after Risk-Based Inspection implementation [6,7].

Lifecycle cost modelling demonstrated that Risk-Based Inspection yields notable financial benefits. For the representative Pumped Energy Storage Scheme vessel population, the cumulative inspection cost under Time-Based Inspection was estimated at approximately ZAR 7.15 million over 10 years. By contrast, the Risk-Based Inspection strategy resulted in a projected cost of around ZAR 4.65 million, corresponding to an estimated cost saving of approximately ZAR 2.5 million.

The cost savings arise from several factors: (i) reduced frequency of inspections on low-risk vessels; (ii) optimisation of inspection scope and technique selection; and (iii) improved outage planning, which minimises the need for additional access and mobilisation costs. These results align closely with published studies on Risk-Based Inspection in other sectors, which report cost reductions of 25–40% while maintaining or improving safety performance [6,7].

The Risk-Based Inspection approach also improved risk visibility at both the vessel and system level. The integration of Probability of Failure and Consequence of Failure into a semi-quantitative risk matrix allowed clear differentiation between low- and high-risk assets.

Analysis based on the risk matrix showed that roughly 30% of vessels fell into the low-risk band, 55% into the medium-risk band, and 15% into the high-risk category, with no vessels classified as extreme risk during the simulated period. The risk matrix also highlighted two vessels whose Probability of Failure scores trended upwards over time because of higher-than-expected corrosion rates. These assets were flagged for earlier inspection and potential mitigation actions, demonstrating how Risk-Based Inspection can pre-empt emerging integrity threats.

Degradation modelling revealed distinct deterioration patterns across the vessel population. Vessels located in the lower reservoirs, exposed to higher moisture and more aggressive water chemistry, showed elevated general corrosion rates relative to upper-reservoir vessels. Components subjected to frequent transients and water-hammer events exhibited higher fatigue damage accumulation. Figure 3 shows a representative degradation progression curve used to estimate wall-thickness loss over time.

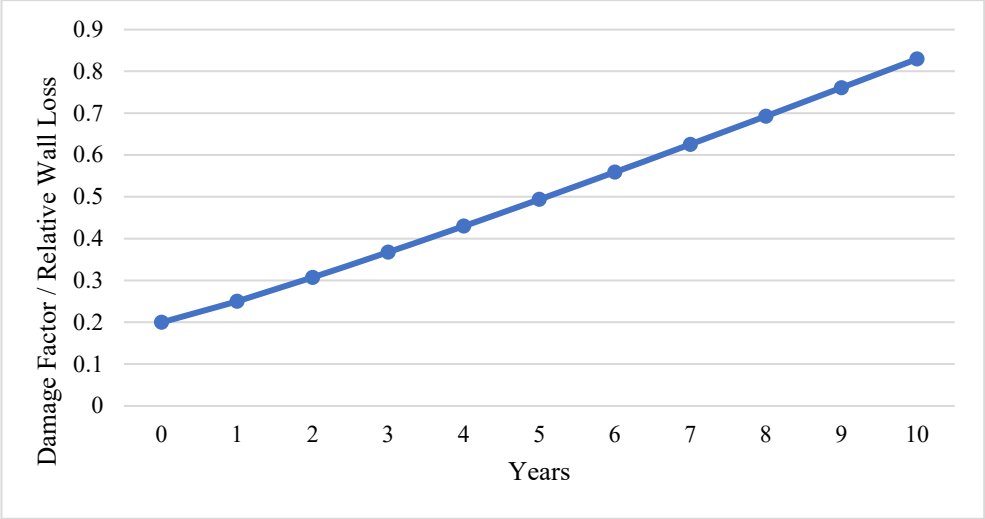


Figure 3. Degradation progression curve for a representative Pumped Energy Storage Scheme pressure vessel.

These degradation insights were directly incorporated into the Probability of Failure calculations and inspection interval decisions. As corrosion rates or fatigue damage indicators increased, Risk-Based Inspection automatically reduced inspection intervals or recommended more sensitive Non-Destructive Testing methods. This dynamic linkage between condition monitoring and inspection planning is a key advantage of Risk-Based Inspection compared to static Time-Based Inspection approaches [5,12,14].

Figure 4 presents the risk ranking for a subset of vessels, expressed as normalised risk scores that combine Probability of Failure and Consequence of Failure. The chart illustrates how Risk-Based Inspection provides a clear prioritisation basis, enabling asset managers to focus engineering attention and capital expenditure on higher-risk assets first.

By planning the inspection and maintenance of the vessels according to their risk score rather than inspection due dates alone, the maintenance teams can develop more strategic outage plans. This supports the broader asset management objectives articulated in ISO 55000 [13] and EPRI guidance on risk and reliability in power generation [16].

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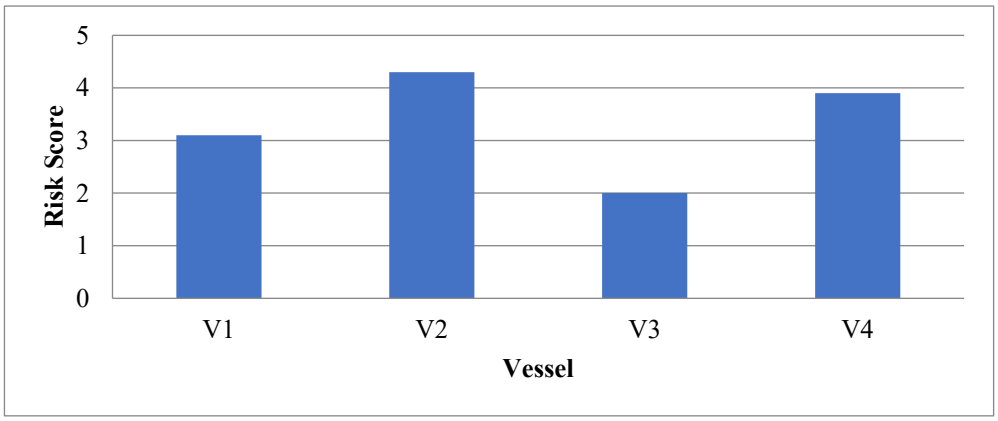


Figure 4. Risk ranking of selected Pumped Energy Storage Scheme pressure vessels (V1, 2, 3 and 4) based on Risk-Based Inspection assessment results.

The Risk-Based Inspection process demonstrated strong alignment with South Africa's Pressure Equipment Regulations (PER) and SANS 347 [3] requirements. PER requires inspection intervals and methods to be based on sound engineering judgement and risk considerations [2,3]. Risk-Based Inspection provides traceable justification for inspection decisions and improves readiness for statutory audits.

By documenting risk assessments, inspection plans and mitigation actions, Risk-Based Inspection contributes to demonstrable compliance and supports continuous improvement of integrity-management systems. This is particularly valuable in regulated utility environments, where audit trails and regulatory assurance are critical [2,3].

The key quantitative indicators comparing the Time-Based Inspection and Risk-Based Inspection strategies over the 10-year simulation horizon are summarised in Table 1.

Table 1. Summary of the key quantitative indicators comparing the Time-Based Inspection and Risk-Based Inspection strategies over the 10-year simulation horizon.

Metric	Time-Based Inspection	Risk-Based Inspection	Improvement
Inspection Frequency (10 years)	5 cycles	3–4 cycles	≈35% reduction
Lifecycle Inspection Cost	ZAR 7,150,000.00	ZAR 4,650,000.00	≈ZAR 2,500,000.00 saved
Aggregate Risk Exposure (index)	125	82	≈34% reduction
Regulatory Compliance	Reactive, Time-Based	Risk-Based, PER-aligned	Higher assurance

4. Conclusions and Recommendations

This study demonstrates that Risk-Based Inspection provides a practical and effective approach to optimising inspection of Pumped Energy Storage Scheme pressure vessels. By prioritising inspections based on risk, risk engineers and asset managers can achieve significant cost savings while maintaining safety and asset integrity. It is recommended that the industry continues to implement Risk-Based Inspection programmes, invest in digital tools to support model-based inspection planning, and integrate Risk-Based Inspection into regulatory compliance frameworks. Future research should validate the proposed framework in live operational settings and explore integration with digital twins and artificial intelligence-driven predictive maintenance systems.

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Conflicts of Interest: Thendo Mphaphathi and Shanil Narain Singh were employed by the company Eskom. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

RBI	Risk-Based Inspection
TBI	Time-Based Inspection
PoF	Probability of Failure
CoF	Consequence of Failure
PESS	Pumped Energy Storage Scheme
PER	Pressure Equipment Regulation
SANS	South African National Standards
API	American Petroleum Institute
ASEM	American Society of Engineering Management
EN	European Norm
EPRI	Electric Power Research Institute
DNV	Det Norske Veritas
DC	Data Collection
ISO	International Organization for Standardization
NDT	Non-Destructive Testing
ZAR	South African Rand

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