

Corrosion-Aware Maintenance of Offshore Oil and Gas Infrastructure: A Framework for Marine Environmental Protection and Sustainable Asset Management in Nigeria

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Abstract

Offshore oil and gas equipment is subject to corrosive and mechanical attack, and operational degradation that can threaten the integrity of the equipment and in extreme cases lead to loss of containment and marine pollution. Industry fields of corrosion control, asset integrity, condition monitoring, and oil-spill prevention and preparedness already exist but require consideration of interfaces of the maintenance process in operations where maintenance could adversely affect the environment. This paper discusses how these fields can be integrated through a traceable, evidence-based maintenance process in offshore oil and gas industries, with specific reference to Nigeria and the Gulf of Guinea.

The various references in the literature are grouped into five related contexts: (i) environmental exposure and degradation; (ii) inspection and condition evidence; (iii) risk-based decision-making; (iv) environmental-barrier assurance; and (v) post-maintenance verification and organizational learning. Using this categorization, a conceptual decision architecture is proposed linking component observation to documented engineering evaluations, prioritized maintenance actions, barrier verification and closure of anomalies. The architecture is also related to an author-proposed implementation maturity levels, reporting fields, performance indicators, and a staged research plan.

The framework does not constitute a tested predictive model and does not provide estimates of reduction in spill likelihood, environmental damage, emission or maintenance cost. It aids in delineating an auditable framework by which existing engineering, operational and environmental-management practices can be incorporated while maintaining separate categories of observed evidence, model estimates and untested assumptions. Its applicability for Nigerian offshore oil industry can be assessed through field evaluation using documented inspection, maintenance, barrier-testing and incident data.

Keywords: offshore asset integrity; marine corrosion; condition monitoring; risk-based maintenance; environmental-barrier assurance; Nigeria.

1. Introduction

1.1 Structural and Operational Context of Marine Asset Integrity

Oil and gas production facilities in the offshore environment face a very complex and demanding operational environment with competing requirements of managing high pressures and high temperature process fluids, loading conditions of production structures, protecting against electrochemical damage, and minimizing effects of harsh environment. Subsea production manifolds, pipelines, export risers, umbilical networks, FPSO, fixed jackets, tension-leg platforms and their associated process equipment contend with synergistic environmental and operational parameters such as chloride laden seawater, temperature variation, dissolved oxygen, microbial activity, cyclic wave current loading, fluctuating process pressures and multiphase fluid flow (Iannuzzi et al., 2017; Amaechi et al., 2022; Xia et al., 2025). These synergistic conditions can hasten materials degradation, make inspection more difficult, and complicate the assurance of structural integrity during the operational lifespan (Iannuzzi et al., 2017; Amaechi et al., 2022; Xia et al., 2025).

Material degradation is not just an isolated maintenance issue but rather a total lifecycle integrity issue, which involves the selection, design, operation, inspection, repair and decommissioning of materials. Types of deterioration that need to be considered include general corrosion, pitting, erosion-corrosion, MIC, HIC, SCC, corrosion fatigue, structural fatigue, and seal and other containment interface degradation, which all may have different probabilities of occurrence and influences on the failure modes depending on materials alloying, chemistry of the environment, stresses, flow regime, protective coatings, cathodic protection, operational history, etc (Iannuzzi et al., 2017; Abbas and Shafiee, 2020; Xia et al., 2025). As a result, integrity management involves a multidisciplinary approach of corrosion science, structural mechanics, fluid mechanics, inspection techniques, and maintenance engineering.

The main problem is that the mechanisms may overlap with the operating conditions and may develop with varying rates on an off-shore installation. For example, corrosion may weaken the pipe wall to such an extent that pipe fatigue results from pressure cycles and wave loading. Erosion-corrosion may be significant where high-velocity fluid and particles are present together with a relatively weak material interface. In doing so it may or may not impact the asset's operational viability as it might also affect associated equipment and safety-related systems. This points towards an integrated asset management strategy as opposed to isolating corrosion management, rotating equipment management, structural inspection and assurance of safety-critical items (Abbas and Shafiee, 2020; Amaechi et al., 2022; ISO, 2024).

Organizing inspection data separately, along with CMMs, process alarms and environmental-barrier registers, may produce detection holes in asset-condition interpretation. Thus, in some cases a wall-thickness issue may be at first captured in an inspection database, but without being associated with the pressure boundary, hydrocarbon-release risk, downtime and environmental protection (IAEA, 2014). Such a situation – while perhaps not a direct result of separate systems – could have a negative impact on integrity-management, depending on how well knowledge sharing, accountability, risk and verification are managed. As asset-management best practices suggest, informed, coordinated decisions linking asset performance, risks, organizational goals and lifecycle value should be a priority (ISO, 2024; Amaechi et al., 2022).

Environmental consequences of offshore integrity become particularly apparent when failure occurs in a pressure boundary element or another boundary that prevents hydrocarbons and harmful production fluids from escaping into the environment. The effects of a release-of-containment incident are a complex function of the amount and characteristics of the escaping substance, release duration, detectability performance, shutdown and isolation reliability, ambient marine conditions, and sensitivity of the receiving environment. Protecting the environment, therefore, involves not only preventing the failure of equipment, but also ensuring the detect, shutdown, isolation and response systems perform their intended functions; API Recommended Practice 14C: Offshore Safety System Guidance is a relevant reference for the design and testing of safety systems on production facilities (API, 2017).

The additional threats are relevant especially in the Niger Delta and broader Gulf of Guinea where oil pollution poses risks to coastal systems, fishery and agriculture yields, public health, and livelihoods. Depending on the specific characteristics of a spill, location, and effectiveness of containment and remediation actions, impacts may also be short term or long term, localized or widespread. In Nigeria, spill remediation research indicates the presence of continues technical and operational concerns with contaminated-site remediation and identifying the most appropriate remediation technique (Nuhu et al., 2022). As such, avoiding and preventing unnecessary releases by ensuring well integrity and emissions management through durable equipment, rapid intervention, and environmental-barrier management should be seen as an important additional dimension to emergency response and spill-site remediation.

The framework supports the aims of Sustainable Development Goal 14, targeting the conservation and sustainable use of the oceans, seas and marine resources, including their conservation and sustainable use (United Nations, 2015), yet linking asset integrity to this goal can only be worked back as a management reason for improved outcomes rather than by implication of a demonstrable quantitative environmental advantage. A unified maintenance framework might improve the traceability of degradation evidence, the relative severity of correction and the validation of protective barriers but the actual impact of such a framework on the frequency of spills or environmental damage must be demonstrated in use and performance.

Against these lines, this review suggests a coupled, risk-guided model for relating five categories of information: environmental exposure and degradation processes; inspection and condition data; risk-based maintenance decision-making; assurance for environmental barriers; and post-maintenance verification and organizational learning. Its aim is to create a clear pathway from a degradation threat to a relevant intervention. The model as it stands as a concept that has yet to be tested in the field for its relative efficacy.

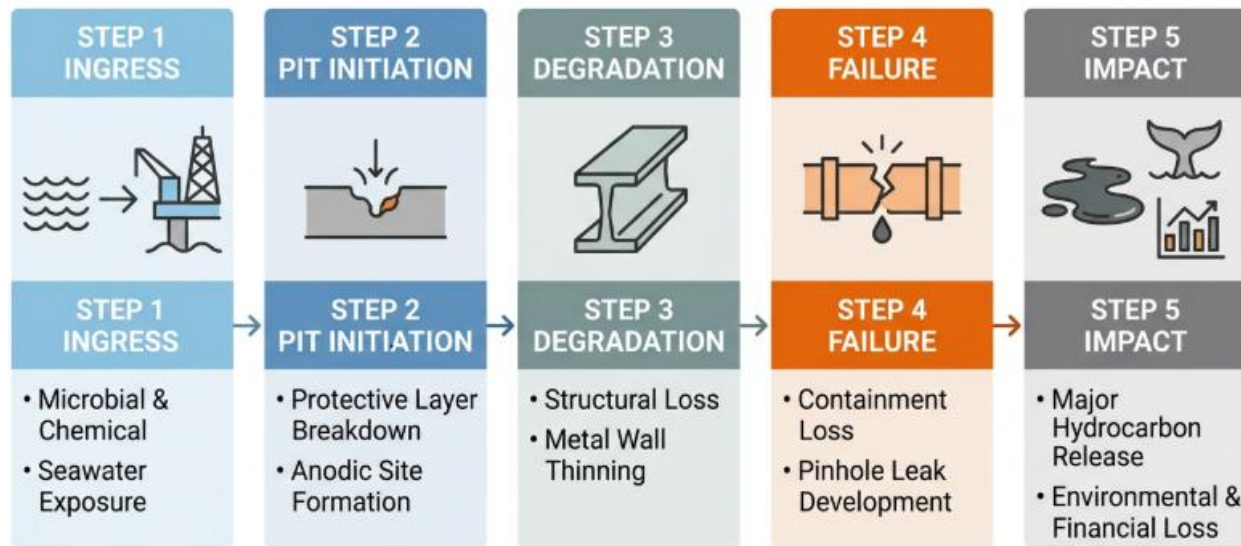


Fig 1: The Corrosion-to-Impact Pathway in Offshore Assets.

Fig 1 shows a typical evolution of failure of offshore marine assets. It would appear to be uncontroversial to suggest that chemical or microbial exposure can progress toward structure failure, then to residual structural failure, and perhaps finally to final containment failure.

1.2 Limitations of Data-Driven Predictive Systems and Black-Box Digital Twins

Affordable industrial sensors, supervisory control and data acquisition systems, Internet of Things (IoT) applications and machine-learning techniques have probably expanded the range of options for condition monitoring and predictive maintenance of off-shore assets. Measurements of parameters such as vibration, temperature, pressure, flow rate, acoustic emissions and operational hours are probably also capable of revealing potential abnormal conditions, helping maintenance personnel to decide which assets might deserve additional attention. Combined with inspection data and maintenance history, this has probably improved risk-based asset management and allowed the development of a more systematic approach to maintenance planning (ISO, 2018; Amaechi et al., 2022; Wahono et al., 2025).

In principle, model-based approaches, with or without a digital twin, may provide yet another way to correlate observed equipment behavior with a predicted mode of operation. Depending on their structure and validation, digital twins may combine sensor measurements, physics of engineering models, historical data, and computational predictions to inform condition assessment and maintenance planning. Nevertheless, the usefulness of these approaches is affected by the quality of the underlying data, the suitability of the model to the purpose, and the extent to which predicted outputs have been validated with actual observations. A digital representation should not be presumed to be validated just because it is feeding back signals or producing numeric predictions.

The main disadvantage of data-driven predictive systems, in my opinion, is that they will be affected by incomplete, faulty, and unrepresentative data, such as sensor drift, poor calibration, data communication failures, shifts in operational regimes, missing inspection records, and differences between training and operating conditions. In the offshore environment, these elements are likely to be exacerbated by accessibility constraints for equipment, shifting environment loads, and challenges in acquiring frequent physical measurements of subsea assets. State-of-the-art reviews of risk-based integrity-management techniques and offshore asset-management strategies highlight the importance of combining digital innovations with sound engineering governance rather than relying on technical complexity to overcome weak or uncertain evidence (Amaechi et al., 2022; Wahono et al., 2025).

Another concern is the interpretation of the information obtained from the model. A machine-learning anomaly score can signal that there is a departure from either the model's learned baseline or the specified baseline; it can't, on its own, determine the physical principle producing that loss of baseline. Increased centrifugal-pump vibration can signal both bearing deterioration and hydraulic cavitation, rotor imbalance, misalignment or looseness, or a change in the piping

system to which the pump is attached. Discerning between these conditions requires engineering interpretation, and in some cases additional diagnostic measurements and physical examinations. The ISO's general condition-monitoring recommendations reinforce the value of careful measurement and diagnostic procedures for assessing machine condition (ISO, 2018).

Plausibility considerations should also be applied for remaining useful life (RUL) estimations. The derived RUL must depend on the assumptions made, data available, degradation model, operational regime and the definition of failure. Where localized corrosion, interspersed operational experiences and interacting failure modes lead to the degradation mode, the available data may be insufficient to provide an accurate RUL estimate. The RUL result should thus be presented with the relevant assumptions and uncertainty and not dictating for the continued operation of the safety critical component. A risk-based integrity control approach takes into account likely failure modes, associated consequences, inspection data, existing engineering standards and limits and the mitigation effect of existing controls (Abbas and Shafiee, 2020; Wahono et al., 2025; ISO, 2024).

What follows is therefore required. A defensible approach must separate evidence from observation (through measurement or inspection) and inference (through modelling). Evidence from measurements may include remaining wall thickness, crack marks, vibration velocity measurements, inspection images, corrosion monitoring data, or leakage detection. Evidence from models may include an anomaly score, degradation trajectory prediction, or an RUL estimate. Both types of evidence can be valuable, though they have different forms of evidential weight, and should be recorded as such. Missing data from inspections should be treated as absence of evidence rather than evidence of absence for a defectless component. Data uncertainty, data provenance, model performance, and date of last physical inspection should all be preserved throughout the decision making process.

Accordingly, the framework in this review considers digital monitoring, predictive analytics, and digital twins as additional decision-support tools in the engineering assurance process. These tools' outcomes could motivate investigation, help prioritize inspection, or contribute to maintenance decision-making, but they must not replace physical inspection when necessary, qualified engineering expertise, approved riskassessment techniques, or independent validation of safety-critical operations. This stance is consistent with condition-monitoring paradigms and asset-lifecycle management philosophies based on predictable data, auditable decisions, and continuous improvement (ISO, 2018; ISO, 2024; Amaechi et al., 2022).

Thus, the main value of this new approach is not in claiming that a novel predictive algorithm will be able to eliminate offshore failures. Rather, it is the application of the degradation evidence, risk prioritisation, environmental-barrier mapping, maintenance deadline setting, and post-intervention verification into a traceable management process. Linking these activities together could then form the basis of exploration into how engineering results can be converted into auditable maintenance actions, and how completion of those actions can be documented. Its operational effectiveness, including the extent of overdue defect and environmental exposure reduction, then can be determined in follow-up pilot implementation and evaluation.

1.3 Problem Statement, Analytical Gaps, and Research Questions

The biggest gap in the existing body of offshore engineering literature is not in data on marine corrosion within materials science or in the lack of a single risk-based inspection (RBI) algorithm. The real deficit is the lack of an integrated operational decision framework that explicitly traces the entire evidence chain from the detection of material degradation, through confirmation of environmental barriers, all the way to post-maintenance verification.

Traditional asset integrity management (AIM) procedures such as ISO 55000 and conventional company RBI practices tend to focus mainly on mechanical equipment availability, business continuity and personnel safety. Rarely do they contain environmental mitigation features like emergency isolation valves and spill response preparedness, as part of their asset integrity logic. This study aims to fill this gap by introducing an auditable corrosion-based approach for regulatory, environmental and operational factor in the Nigerian offshore arena. It poses three research questions:

- RQ1. What explicit degradation mechanisms and operating conditions are involved in production equipment failure directly associated with physical leak of containment or potential to do so?

- RQ2. How can various disparate types of information, such as visual inspections, volumetric NDT data, process parameters in operation, or computer-generated anomaly scores, be combined in an operational decision matrix so that the efficacy of each indicator is not overstated?
- RQ3. What are the particular organizational, data-quality, and environmental safeguards, for the integrated framework to operate in the current Nigerian offshore and Gulf of Guinea regulatory setting?

The aim of this contribution is to define a of interconnected, transparent, and verifiable chain of evidence beginning with condition observation, then moving on to mechanism assessment and risk ranking, maintenance intervention, environmental barrier assurance, and finally to post- maintenance verification.

2. Materials and Methods

2.1 Critical Narrative Review Design and Search Strategy

This paper uses a systematic critical narrative review approach to integrate evidence on (a) corrosion, offshore asset integrity, maintenance decision making, (b) prevention of oil spill and environmental protection, and (c) protection of assets, assets integrity, and sustainable asset management in the marine and offshore oil and gas environment with an emphasis on Nigeria. Since this review covers diverse evidence from corrosion science, corrosion mechanisms, condition monitoring, risk-based inspection, and organizational safety management, or the protection of the environment that considers variations in study design and methods of analysis, types of outcomes, and regulatory environment, a formal quantitative meta-analysis (statistical pooling) was not deemed appropriate until a minimum set of quantitative results are in common.

Thus, critical comparison of state of the art, the correlation of asset deterioration and risk to environment, and new integrated conceptual framework for corrosion-aware maintenance are the subjects of this review. This framework is meant to serve as a synthesis of literature evidence rather than as a validated predicting model.

2.2. Literature Search Strategy

A specific literature search was performed using five research databases and scholar search platforms: Scopus, Web of Science, Google Scholar, IEEE Xplore, and Science Direct. The search strategy combined phrases and words related to the following: offshore asset integrity, marine corrosion, structural failure, inspection and maintenance, environmental preservation, and Nigerian oil-spill management. Boolean operators were used to link the phrases and words; search interfaces were used where available by the database.

The core search strings used were:

A combination of five key Boolean searches was used in the literature search in order to cover the various subthemes surrounding offshore asset integrity, degradation, decision making and environment.

- Offshore asset integrity and marine corrosion. In searching for the site, the string used was ("offshore asset integrity" OR "marine corrosion") AND ("steel structures" OR "subsea installations" OR "offshore infrastructure").
- Inspection, condition monitoring, and oil-spill management. ("risk-based inspection" OR "condition monitoring" OR "corrosion monitoring") AND ("oil spill response" OR "oil spill remediation" OR "hydrocarbon release") AND (Nigeria OR Nigerian) was used to search for inspection and monitoring methods for oil-spill control.
- Sustainable maintenance and environmental protection, The search used the following terms: ("sustainable offshore maintenance" OR "environmental barrier assurance") AND ("corrosion management" OR "environmental protection" OR "asset integrity") to refine the focus on sustainable maintenance practices and environmental protection.
- Corrosion and degradation processes. The following string: "microbiologically influenced corrosion" OR "erosion-corrosion" OR "corrosion fatigue" OR "pitting corrosion" AND (offshore OR marine OR "oil and gas") has been used to search for different types of corrosion and degradation process.
- Oil spills, ecological impacts, and coastal livelihoods. The term search, ("oil spill" OR "hydrocarbon release" OR "petroleum pollution") AND ("coastal ecosystem" OR fisheries OR livelihoods OR "environmental

damage") AND (Nigeria OR "Gulf of Guinea") was used to determine the ecological and socio-economic effects of oil spills.

The search was designed to capture major publications and relevant recent work. Search outcomes were assessed based on its relevance to the scope of review, technical content and offshore or marine asset management. Regulatory documents and other applicable standards were also taken into account to provide the policy and engineering setting to the work.

2.3. Eligibility and Evidence Selection

Any publications making reference to one or more of the topics; corrosion or deterioration of an asset, inspection and condition monitoring, risk-based asset management and maintenance, environmental barrier assurance, offshore hydrocarbon release, and the environmental or societal impacts relevant to coastal communities, were considered for inclusion.

Nigerian publications and sources were prioritized if they contributed directly to the context of the region. Sources that did not directly contribute to the review questions, did not contain sufficient technical and/or documentary evidence to interpret them effectively, or who could not be differentiated from another source with similar evidence were excluded. The scientific evidence base comprised peer reviewed publications, with standards, legislation and authoritative technical reports relevant to engineering practice or regulatory interpretation incorporated where appropriate.

2.4. Evidence Extraction and Critical Synthesis

The evidence was systematically categorized into themes of degradation mechanisms, inspection and monitoring, prioritization of maintenance activities, environmental controls, and verification following maintenance. Each publication or source of knowledge was examined to determine its principal role, and also its engineering and environmental significance, limitations and possible contributions to corrosion-aware maintenance planning.

The evidence indicated a qualitative approach, involving comparison between zones of agreement, recognition of gaps and limitations, and the possible relationships between outputs of the recognized inspection, corrosion control and risk assessment methods in a traceable maintenance system. The framework is thus representative of a potential synthesis by the authors, and can be best interpreted as a preliminary or model framework and not a validated framework, in terms of field experiments or independent validation. The literature search was initially from 15 January 2026 to 28 February 2026, and was further expanded to include the most recent peer reviewed literature and key regulatory documents.

2.2 Source Selection and Eligibility Criteria

The subsequent articles obtained from the primary search had their content methodically screened in accordance with the predefined exclusion and inclusion criteria. To be eligible for inclusion, a source was required to be either a: peer-reviewed journal review article, primary empirical engineering study, validated formal international technical standard or sanctioned maritime pollution report (2015+). Furthermore, sources were mandated to explicitly engage with at least one of the four initial core themes identified for the review:

Mechanisms of material degradation applicable to the marine service environment, Risk-based inspection frameworks, Sensor-based condition monitoring validation, and Oil-spill prevention and preparedness techniques for offshore or deepwater marine environments. Conversely, sources that solely documented downstream onshore refining and/or failed to provide asset categorizations, or contained insufficient technical content to corroborate the engineering claims were excluded. Duplicate publications were electronically isolated in reference management software. Titles and abstracts of publications were assessed independently, with the inclusion of identified studies followed by full-text appraisal to determine the final dataset of 25 primary references used for the review.

2.3 Data Extraction and Synthesis Methodology

A data extraction grid was designed to collect information from each of the 25 included sources in a consistent manner. The extraction fields consisted of:

- A particular asset class such as a subsea pipeline system located in deep water or a topside vessel mounted on a floating production platform.

- The typical active material degradation or structure risk mechanism to be researched.
- The specific form of evidence or measurement technology used e.g. ultrasonic thickness mapping; or acoustic emission array.
- The operational control or mitigation that is proposed.
- Documented implementation dependencies and study limitations.

The retrieved data were then qualitatively cross-compared through synthesis, which indicated that the similarities and operational connections between the mechanical degradation failure modes and the subsequent environmental mitigation could be drawn. The data were then grouped and mapped into the five functional domains of the architectural framework for corrosion-sensitivity.

2.4 Mathematical Formulations and Calibration Logic

Where we are able to empirically determine the human and natural system response within the defined operational framework to prioritise operationally, the risk ranking in Domain 3 is presented as a semi-quantitative risk score based on standard risk matrix logic. The qualitative risk score (R) is calculated as the product of the Likelihood Category (L) and the Environmental Consequence Category (C) as;

$$R = L \times C \quad (1)$$

The Risk score (L) should be assessed based on empirical measures of degradation, time-to-failure, or physical rate of change rather than poorly informed expert estimates.

The Environmental Consequence Category (C) should be assessed on an individual basis taking into account such items as fluid properties, volume of releasable material, local ocean state and the seasonality of sensitivity of receptor species. This individual assessment may well prevent environmental consequence from being masked by a combined all-company asset-criticality score.

Condition evidence is expressed in the form of a time-dependent, multi-parameter condition state

$$\text{vector, } x(t) = [v(t), \tau(t), p(t), f(t), \lambda(t), w(t), c(t), \mu(t)]^T \quad (2)$$

where $v(t)$ is measured spectrum(s) of machinery vibration; $\tau(t)$ is local component temperature; $p(t)$ is internal operating fluid pressure; $f(t)$ is process flow rate; $\lambda(t)$ is leakage status, where 0 indicates no detected leakage and 1 indicates a detected leakage or confirmed breach; $w(t)$ is residual wall thickness measured by relevant non-destructive testing technique; $c(t)$ is corrosion-rate evidence from electrochemical measurements or corrosion coupons; and $\mu(t)$ is chronological maintenance records and work-order history.

Any indication of deviation from a baseline statistic or a specified engineering threshold requires a follow-up investigation according to the magnitude and circumstances of the deviation. When requesting a maintenance or operational change, the decision-making process must take sensor measurement uncertainty, instrument calibration status, the operating condition, and the credibility of the available condition evidence into account.

3. Results and Literature Synthesis

3.1 Critical Evaluation of Existing Frameworks

A detailed and critical review of the literature indicates that, while there is comprehensive documentation of the individual components of marine asset degradation and risk-based management, significant disconnects in operations still remain. Table 1 provides a detailed comparison of the major frameworks and papers reviewed, providing the benchmark engineering conclusions and highlighting the important outstanding gaps which the proposed framework in this paper addresses.

Table 1, Deep comparative synthesis of existing methods versus the proposed framework

Approach or Source	Primary Engineering Focus	Key Technical Findings and Data Extracted	Critical Unresolved Operational Gaps	Proposed Framework Integration
Abbas and Shafiee (2020)	Structural maintenance of corroded steel frames and jackets in marine environments.	Validated time-dependent corrosion models; optimized structural reliability steel replacement intervals.	Excludes rotating machinery, process containment paths, and downstream environmental barrier tracking.	Integrates jacket integrity with process boundaries, rotating machinery, and safety-critical elements.
Amaechi et al. (2022)	Asset lifecycle management, structural monitoring, and offshore safety.	Formulated high-level guidelines for topside safety management and structural health data capture.	Lacks granular, traceable engineering steps linking condition logs directly to localized barrier validation.	Provides a trace-by-step evidence chain from the sensor alert to the verification of isolation barriers.
Iannuzzi et al. (2017)	Metallurgy and material selection for highly corrosive subsea production systems.	Charted stress corrosion cracking (SCC) thresholds and chemical corrosion-inhibitor limits.	Lacks an operational decision-making architecture or automated linkages to live maintenance CMMS tracking.	Maps material degradation mechanisms directly to automated inspection work orders and barrier controls.
Xia et al. (2025)	Deepwater structural deterioration and subsea non-destructive testing (NDT).	Evaluated hydrostatic pressure influences on corrosion fatigue and categorized subsea robotic NDT limits.	Focuses on material degradation mechanics without integrating post-maintenance verification loops.	Mandates a formal verification feedback loop that updates the asset's structural baseline in the CMMS.
Wahono et al. (2025)	Traditional risk-based AIM transition to data-driven machine learning models.	Analyzed machine-learning anomaly-detection loops and IoT edge-computing configurations.	Demonstrates overconfidence in unverified "black-box" twin outputs; fails to isolate inferred data.	Enforces a strict labeling protocol separating raw measured facts from algorithmically simulated models.

Table 1 assessment implies a definite delineation of the novelty: The novel auditable decision framework relates material failure evidence, risk-based maintenance schedules, and environmental shield assurance. It will not replace metallurgical models, nor other risk algorithms. Instead, it can be used to provide an operational mechanism that incorporates their outputs into a verifiable control cycle.

3.2 Material Degradation Pathways in Extreme Marine Service Environments

Based on the engineering literature, it is inferred that offshore marine production environments present a very complex and multi-causal process for material deterioration. Marine corrosion is presumed to occur under simultaneous molecular, ionic and bio-electrochemical processes. While general atmospheric corrosion causes the most uniform loss of metallic surfaces on the exposed structures, localised pitting corrosion is more of an immediate threat to pressure containing process vessels and subsea piping. Localised pitting that occurs on a potable water treatment system occurred within days of the chloride ions eroding through a protective surface layer or passive film on the metal surface, however the structural component displayed very little loss on weight (Iannuzzi et al., 2017).

In addition, crevice corrosion probably affects enclosed mechanical voids, such as bolted flanges or riser clamps, where a lack of oxygen causes strong macro-galvanic cells to form. Anaerobic microbiologically influenced corrosion (MIC) is common in stagnant or low-flow process areas, associated with sulfate-reducing bacteria (SRB) that thrive below biofilms and convert sulfates to highly corrosive hydrogen sulfide (H₂S). This corrosive product quickly destroys carbon steels.

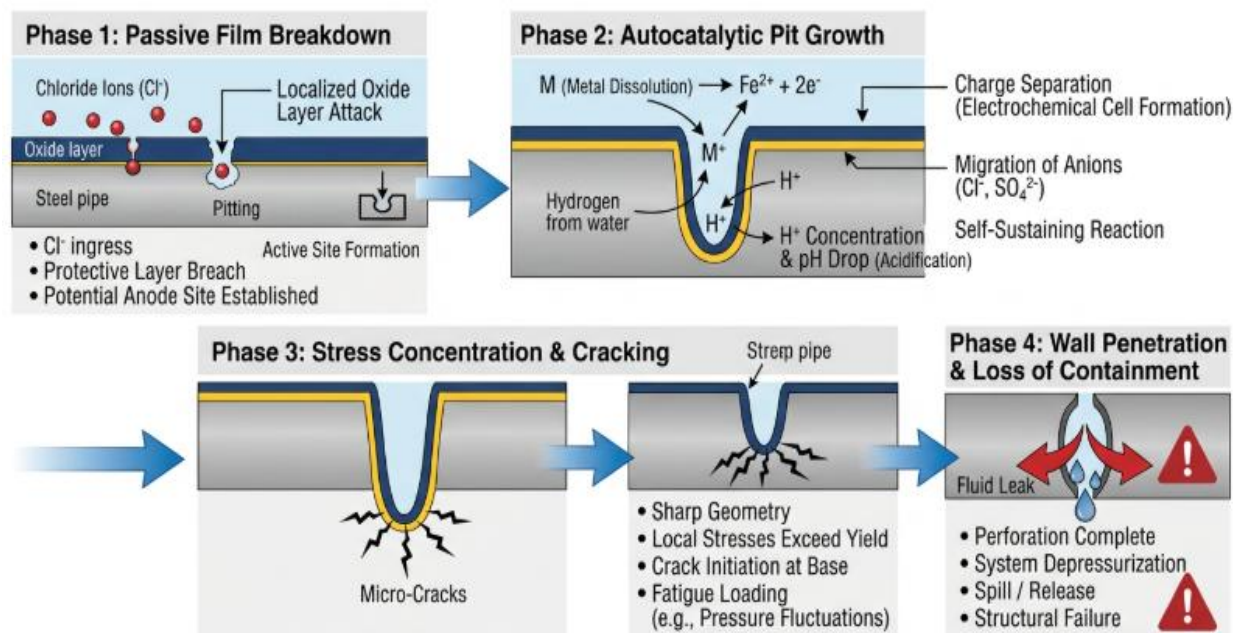


Fig 2: Electrochemical Sequence of Localized Pitting Corrosion to Loss of Containment.

Fig 2 - Chemical degradation of an asset's passive protective film serves as the pathway for initiating an acid driven, self-perpetuating pit growth reaction, which is likely to localize structural stresses, and may result in micro-cracking and total loss of fluid containment.

In turbulent fluid flow media, erosion-corrosion is encountered as the internal multi-phase flow velocities, fluid attack or entrained sand impacts or mechanically abrades the corrosion inhibiting films or protective oxide scale layer thus speeding up the electrochemical corrosion dissolution. Such erosion-corrosion exists at any flow geometry interruption like a high radius pipe elbow, reverser, downstream of any control valve (Xia et al., 2025).

Meanwhile, the rotating machinery - multi-phase export pumps and gas compressors - is also expected to undergo extreme levels of tribological, bearing race and mechanical seal wear. The misalignment and structural imbalance can cause cyclical mechanical loads. These cyclic loads could induce high cycle fatigue cracking in the structural supports and piping connections.

An examination of these causes indicates that any one logged symptom could have numerous engineering root causes. For example, a high machinery vibration level could be caused by worn bearings, shaft misalignment, hydraulic cavitation or loose anchor bolts. A poor process flow could be caused by impeller erosion, flow restrictions in pipe work, calibration errors in the process measurement or high internal scaling.

To sum up, the authors believe that one engineering metric will not be able to give a clear diagnosis. This framework requires the accurate percent of inspection coverage and physical geometrical relationship between the measurement location and the item being inspected to be explicitly recorded within the asset integrity profile.

Table 2, Source-attributed mapping of material degradation threats, evidence, and operational controls

Threat Mechanism	Primary Engineering Consequence	Minimum Objective Evidence Requirements	Primary Engineering Controls	Cited Supporting Literature
General Uniform Corrosion	Continuous reductions in wall thickness; loss of structural load margins.	Automated ultrasonic thickness (UT) grids, corrosion weight-loss coupons.	Sacrificial anodes, impressed current cathodic protection (ICCP), protective coatings.	Abbas & Shafiee (2020)
Localized Pitting & Crevice Attack	Rapid, localized wall penetration leading to containment failure.	Pulsed eddy current testing, close-up visual inspections, laser surface profiling.	Specialized corrosion-resistant alloys (CRAs), localized chemical inhibitor dosing.	Iannuzzi et al. (2017)

Threat Mechanism	Primary Engineering Consequence	Minimum Objective Evidence Requirements	Primary Engineering Controls	Cited Supporting Literature
Erosion-Corrosion	Accelerated localized material thinning in high-velocity process paths.	Ultrasonic testing at elbows and reducers; sand monitoring arrays; process logs.	Fluid velocity restrictions, sand jetting controls, hard-faced internal claddings.	Xia et al. (2025)
Seal & Gasket Degradation	Interfacial fluid leakage across process joints and flange faces.	Acoustic emission leak tracking, thermographic imaging, flange gap logs.	Strict flange alignment procedures, optimized elastomer material selection.	Amaechi et al. (2022)
Rotating Equipment Wear	Mechanical breakdown, seal ruptures, high-cycle fatigue generation.	Accelerometer vibration spectra, lubrication oil ferrography, temperature tracking.	Laser shaft alignment, condition-based bearing changeouts, dynamic balancing.	Wahono et al. (2025)
Fatigue & Environmental Cracking	Brittle structural fracture without macroscopic plastic deformation.	Alternating current field measurement (ACFM), magnetic particle testing.	Stress-relief heat treatments, structural stiffening, operational load limits.	Xia et al. (2025)

Table 2 provides an overview of the main offshore material degradation mechanisms that affect the integrity of oil and gas assets, with details of their engineering implications and an illustration of the minimum target evidence required to identify or evaluate them and with a technical description of the related operational controls. The table demonstrates the links between condition monitoring and inspection techniques and the practicable best operational controls that underpin evidence-based maintenance, integrity and improved operational reliability. It also identifies the supporting references for degradation mechanisms and management solutions shown.

3.3 Evidence-to-Decision Logic and Environmental Safeguards

The condition monitoring/asset integrity data program is unlikely to have tangible value unless you are able to directly link technical signals to a defined failure mode and an agreed response plan. For example, sensor anomaly triggers should be formally flagged for engineering review, not isolated automated components replacement, unless the consequence of immediate safety critical safety behavior and operational consideration result in a predefined automated trip action. Likewise, risk-based prioritization needs to incorporate data confidence into the picture; a low confidence data assessment for a high consequence component should require data collection/inspection sample expansion, not a lower risk classification.

Bridging the divide between technical monitoring data and taking action. Table 3 brings together the different types of engineering evidence, and how well they can inform decisions. It shows what cannot be proved alone, maps the environmental decision(s) that can be supported, and notes major limitations.

Table 3,Traceable engineering evidence-to-decision and environmental protection matrix

Evidence Category	Documented Technical Capabilities	Inherent Analytical Boundaries	Environmental Barrier Decisions Supported	Critical Operational Limitations	Cited Supporting Source
Visual Inspection	Identifies macro leaks, severe coating failure, and gross physical deformation.	Cannot determine internal volumetric wall thickness profiles.	Triggers localized blasting and re-coating; identifies packing seal leak risks.	Restricted entirely to line-of-sight surfaces; highly subjective.	Amaechi et al. (2022)
Volumetric NDT Data	Quantifies localized, empirical remaining wall thickness profiles.	Cannot map uninspected segments or guarantee constant future corrosion rates.	Determines vessel fitness-for-service; guides pressure-de-rating constraints.	Requires extensive surface preparation; affected by tool tolerances.	Xia et al. (2025)
Vibration Spectra	Captures high-frequency rotating component anomalies and wear patterns.	Cannot establish a unique root cause without multi-parameter data.	Controls proactive isolation of safety-critical pump boundaries.	Severe background noise; heavily influenced by mounting rigidity.	Wahono et al. (2025)

Evidence Category	Documented Technical Capabilities	Inherent Analytical Boundaries	Environmental Barrier Decisions Supported	Critical Operational Limitations	Cited Supporting Source
Process Variables	Monitors macroeconomic pressure drops, temperature spikes, and flow swings.	Cannot isolate localized material root causes without system context.	Activates automated emergency shutdown (ESD) and emergency isolation.	Instrument calibration drift; difficult to decouple from transient waves.	ISO 17359 (2018)
Maintenance History	Logs chronic asset recurrence patterns and component repair logs.	Ineffective if data entry fields are incomplete or inconsistent.	Optimizes preventive replacement frequencies and barrier element inventories.	Vulnerable to human data entry omissions and poor defect coding.	ISO 55000 (2024)
Algorithmic Anomaly Scores	Computes statistical deviations from a multi-parameter digital baseline.	Cannot verify field validity unless backed by physical inspections.	Prioritizes physical NDT inspection routes to high-anomaly asset zones.	Highly vulnerable to training data gaps and "black-box" model drift.	Wahono et al. (2025)

Table 3 details the different forms of engineering evidence potentially available to decisions regarding maintenance and subsequent protection of an offshore oil or gas installation. It describes the range of information and its limitations provided by visual examination, NDT, vibration, process variables, maintenance history and the generation of an algorithmic measure of anomalous operation.

The matrix, by linking those sources of evidence and an operational decision, is thought to be useful in the provision of risk-informed and traceable maintenance activities and the prioritization of inspections and protections. The table also implies that one should understand the physical inspection findings, histories and instrument limitations, or more accurately test measurements, as providing, at best, supporting rather than conclusive evidence of equipment status.

4. The Five-Domain Corrosion-Aware Framework

4.1 Functional Architecture and Closed-Loop Information Flow

The suggested architecture seems to combine offshore asset integrity, risk-based maintenance, and marine environment protection into a single closed loop model. It was built in five different domains, with each domain posing one core integrity question and maintaining at least one data record before that output can proceed to the next stage.

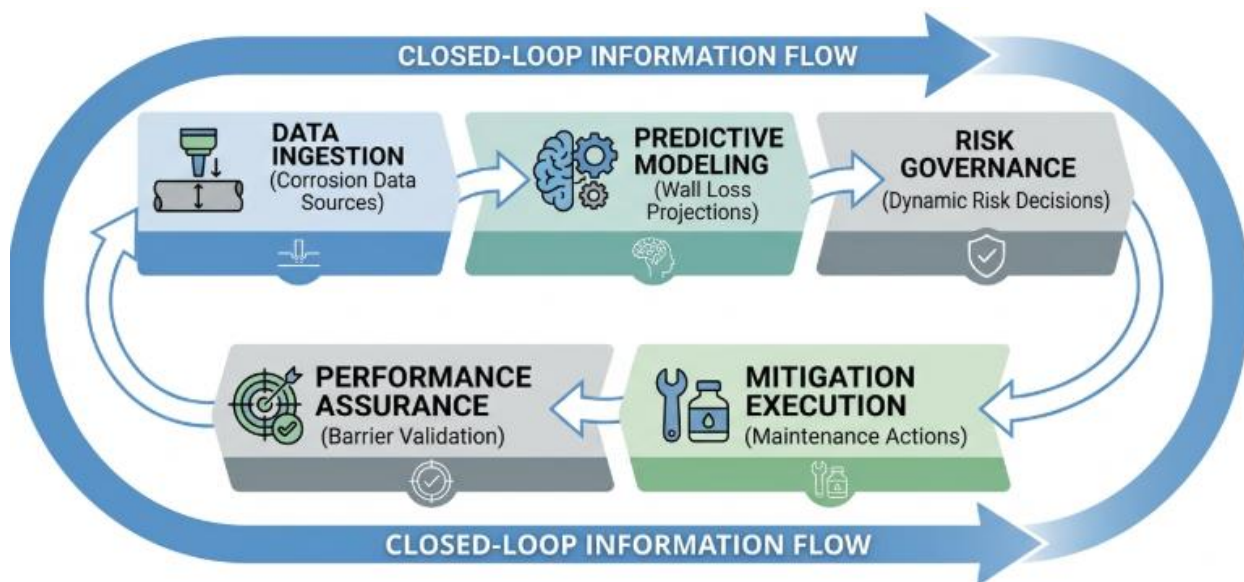


Fig 3: Functional Architecture and Closed-Loop Information Flow of the Corrosion-Aware Framework

Fig 3 shows how multi-disciplinary data inputs and outputs will be melded in these five functional domains. Of particular note, verify loops are inevitable in this scheme, which are expected to automatically reset engineering baselines and audit environmental protection barriers prior to work-order closure.

Domain 1: Environmental Exposure and Degradation.

The text considers those processes that could lead to an impairment of a component in its operational environment. It has a comprehensive mix of raw material characteristics, metallurgy, process chemistry and conditions of localized microenvironmental effects to create an active Threat Register matched to the asset index.

- Domain 2: Inspection and Condition Evidence. This domain records the observations and measurements coming from physical inspection entries, volumetric NDT entries, and machinery vibration measurements. It introduces a sophisticated and deep label hierarchy that separates observations from inferred information.
- Risk-Based Decision-Making - This area evaluates the operational and environmental costs associated with permitting a threat to run to completion. By applying independent likelihood estimations and environmental consequence logic, a data confidence score is accurately determined. The Prioritized Action Log is followed by not negotiable execution dates.
- Environmental-Barrier Assurance - This domain reviews safeguards which prevent, rapidly identify, or reduce likelihood of a potential release. It directly traces the asset item to relevant safety-critical containment barriers, confirming emergency shutdown loop time lag, isolation valve sealing status, and spill response equipment accessibility.
- Domain 5: Post-Maintenance Verification & Learning. This domain assesses if a problem has been verified fixed and long-term integrity was achieved. This domain requires that the Computerized Maintenance Management System (CMMS) computer system data base be used to track independent post-maintenance NDT verification, as well as the formal defect-closure code in order to close the work order in the CMMS computer system.

4.2 Comprehensive Visualization of Framework Elements

To ensure the technical clarity required for deployment, the five foundational conceptual diagrams generated for this framework are integrated below as fully realized, high-resolution text-based vector models.

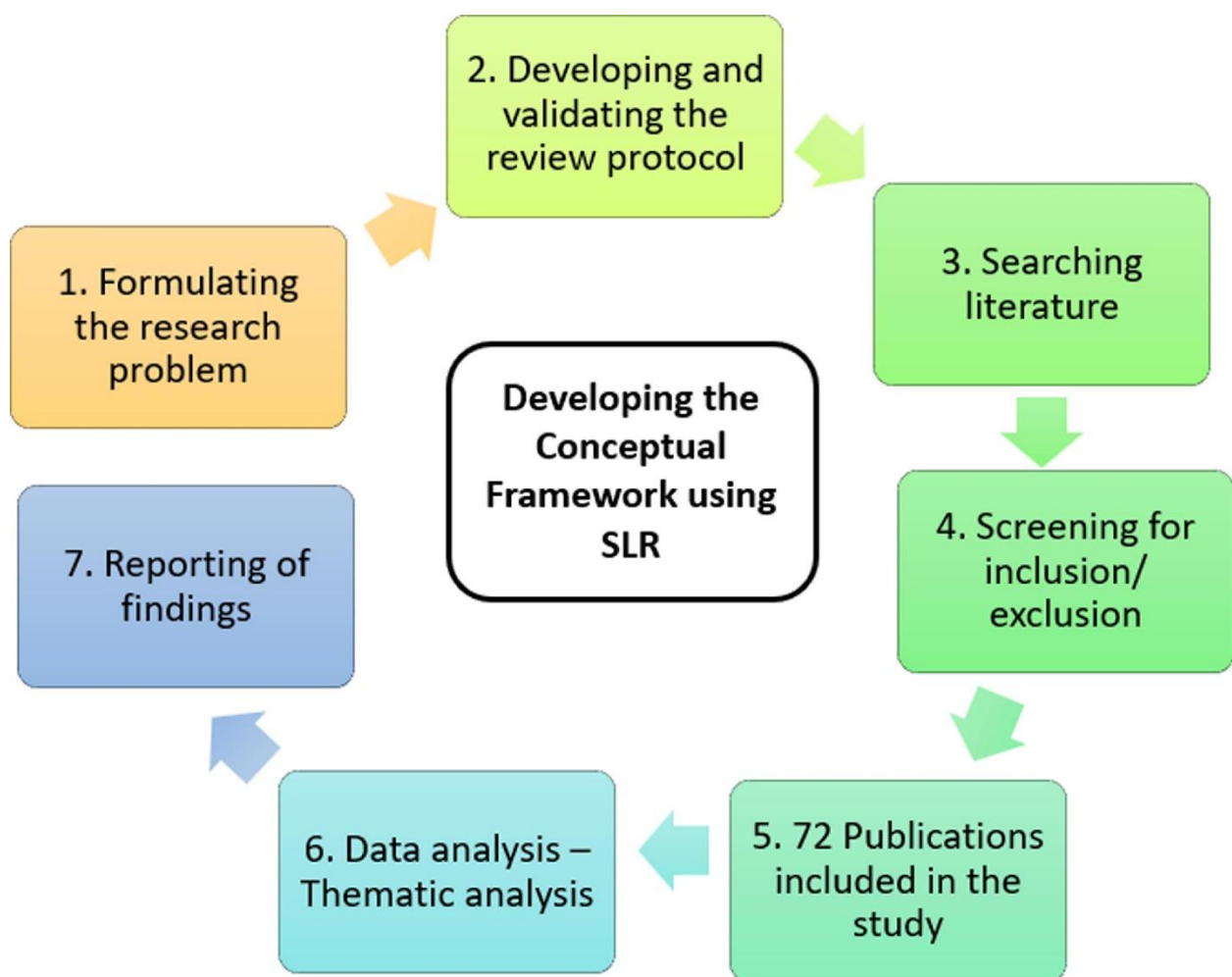


Fig 4: Review and Framework-Development Workflow

Fig 4 shows the workflow, illustrating the systematic steps of scoping the review question, conducting the database search, screening the publications, and categorizing and critically synthesizing the evidence. The Critical Narrative Review also shows how this collated evidence led to the synthesis of the five-domain corrosion-wise maintenance framework.

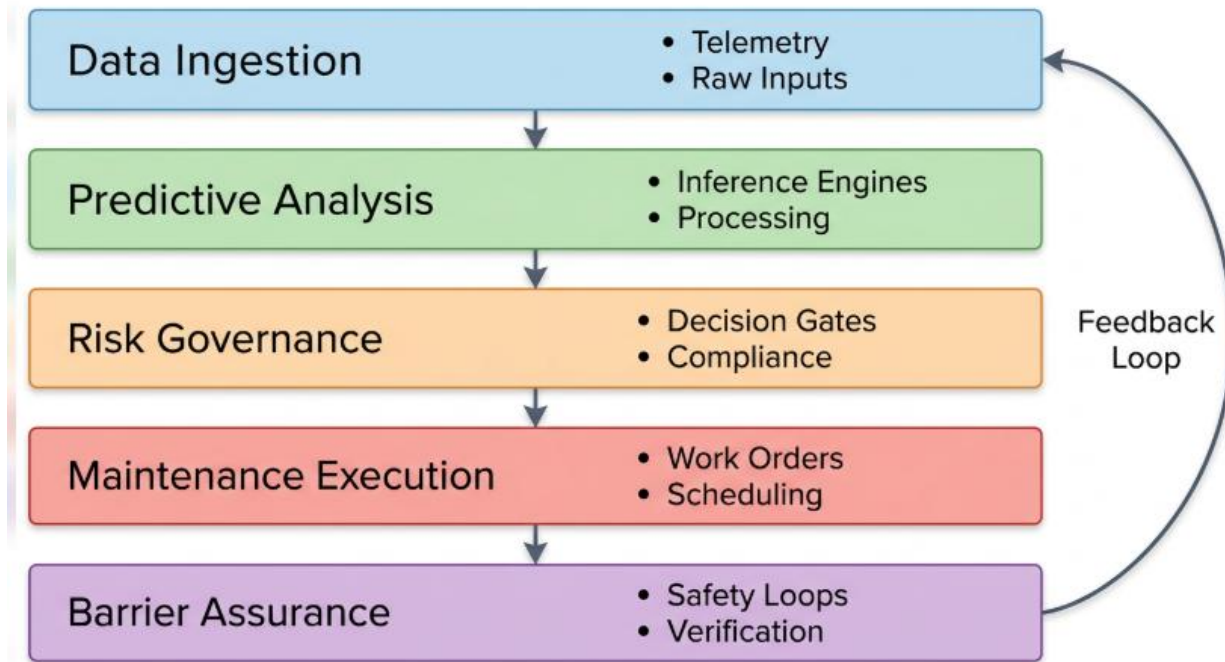
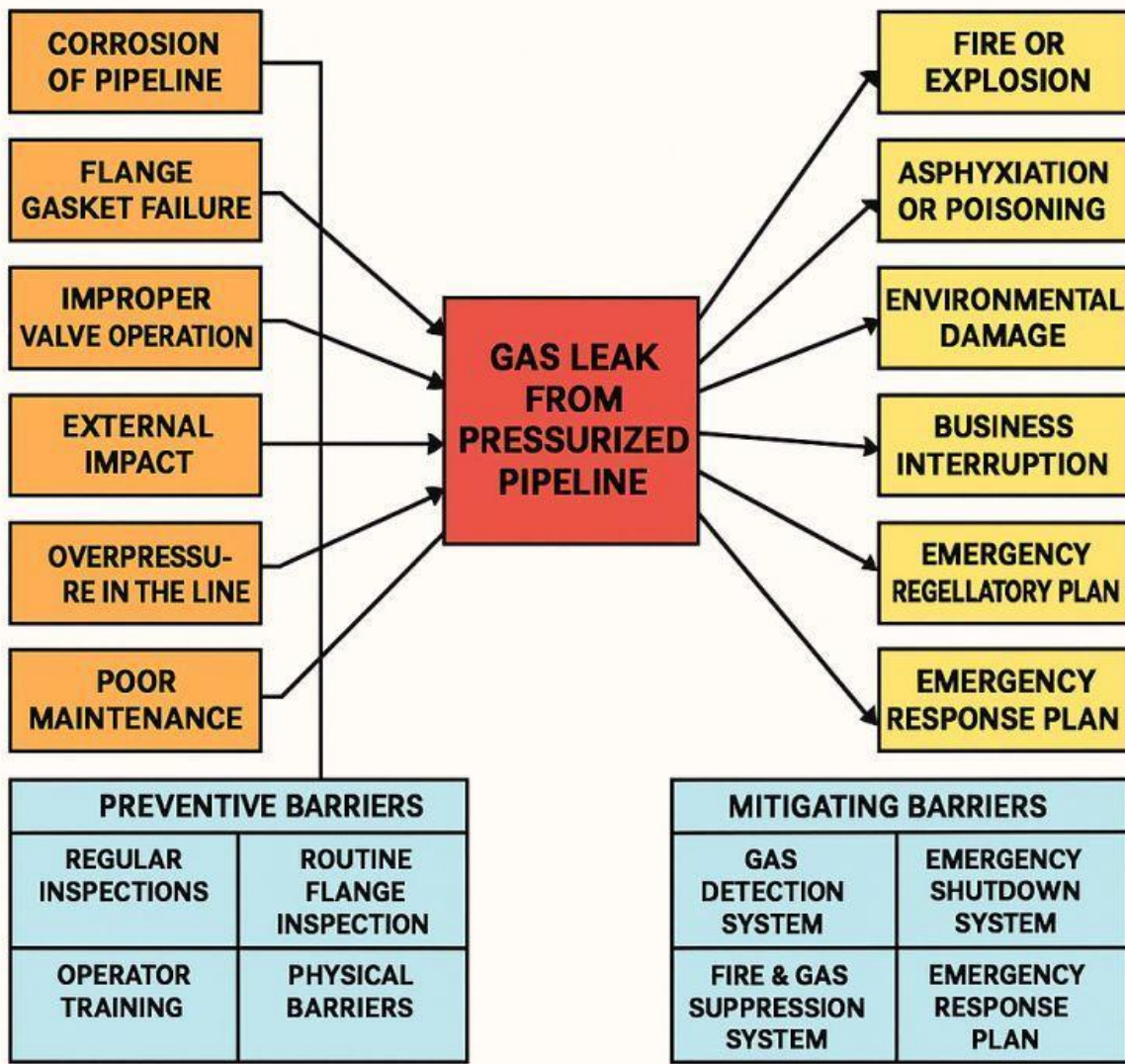


Fig 5: The Integrated Five-Domain Operational Framework

Fig 5. Schematic framework of the five-domain corrosion-aware maintenance integrated framework as shown here summarizes the main contribution of this review. It shows the interactive implementation of engineering inspection data, risk-based decision gates, execution of maintenance work order, environmental barrier verification, and post-intervention verification and feedback.



6: Conditional Degradation-to-Consequence Pathway

Fig

Fig 6. Conditional degradation pathway shows the physical translation from material degradation to process containment failure and subsequent release to the environment. It identifies the different operational points at which engineered preventative, detection, isolation and mitigation barriers may intervene in the failure escalation process, thus limiting the consequences to the environment and socio-economy.

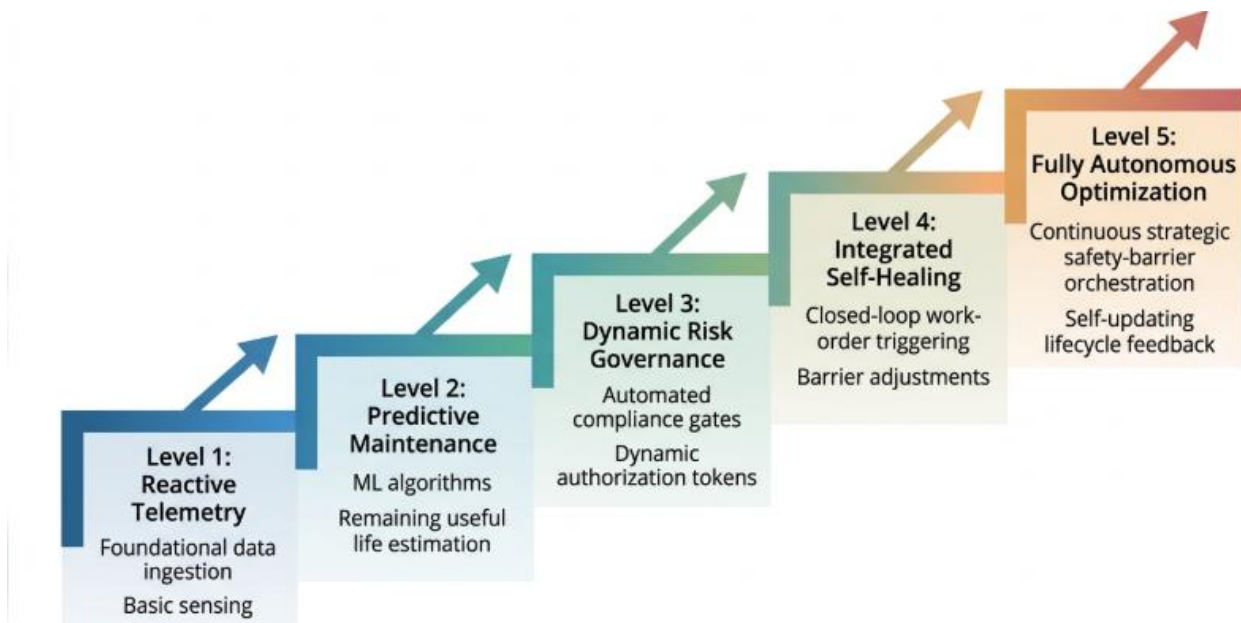


Fig 7: Author-Proposed Implementation Maturity Ladder

Fig. 7 An implementation maturity ladder suggested by the author on the basis of a likely institutional self-assessment. This ladder ostensibly translates the levels of organizational capability into rubrics that define different levels of data-readiness, defines failure modes typically seen, and the types of data that organizations must be able to provide evidence of, for progress in maturity.

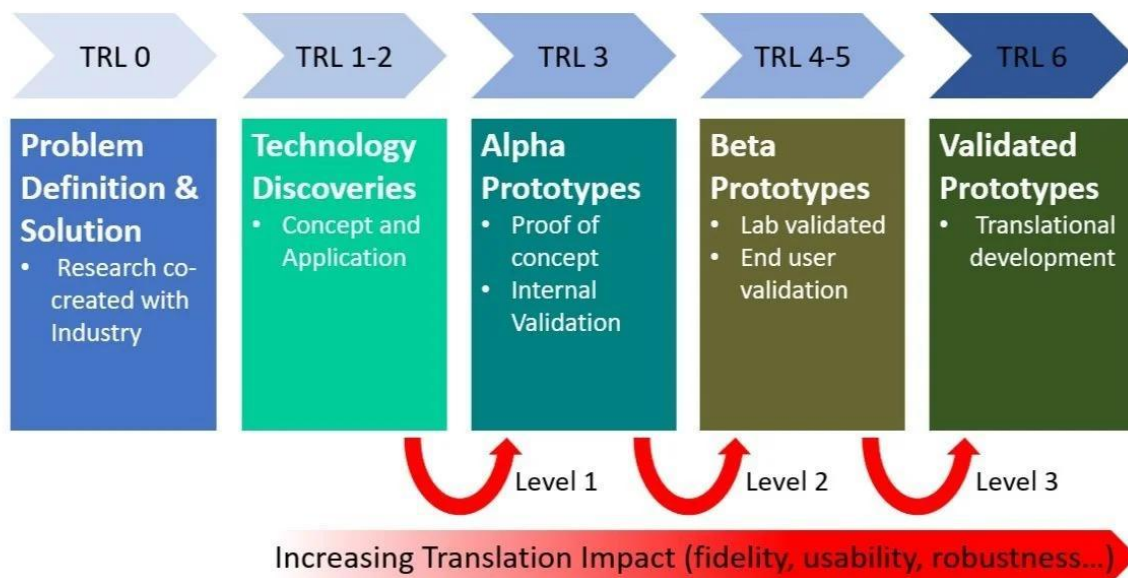


Fig 8: Phased Research and Deployment Roadmap

Fig 8. This deployment roadmap suggests an incremental approach for companies. It states starting with the baseline asset inventories and initial assessment, moving to framework validation and sustainable operation, then deploying elements of the

framework in the company's day-to-day activities. It also envisions having schedules, task assignments, engineering deliverables, and verification points.

4.3 Standardized Operating Procedures and Data Fields

The five domains are operationalized through an enterprise Computerized Maintenance Management System (CMMS) or a regulatory portal by implementing an industry mandated, uniform report profile of at least eight data fields.

- This is an identifier, which is in a unique and persistent alphanumeric code linking the asset component to the main asset register.
- Threat Category (M_degrad): The-threat-selection is as follows: only proven degradation mechanisms such as pitting localized, erosion-corrosion, MIC, and structure fatigue are selected.
- E_cond Traceable condition evidence: Quantitative raw measurements data, for example residual wall thickness in millimeters and vibration velocity in millimeters per second (mm/s) with the inspection date and the measurement uncertainty of the instrument.
- Calibrated Risk Priority Score (R_score): a qualitative risk score which is probably calculated on an ordinal risk matrix according to likelihood (L) x consequence (C). It is expected that the presence of any uncertainty is explicitly documented.
- Mitigation Action Due Date (D_due): The specified calendar date by which the required mitigation action is to be completed, as specified by the assigned risk category. Alterations to this date should be recorded and approved in accordance with the established risk management practices.
- This is a binary operational flag for tracking maintenance compliance, with 0 indicating the item is in a compliant status, and 1 the item is overdue.
- Environmental Barrier Mapping (B_map): Codes which explicitly link the asset component to the environmental protection and safety barriers that apply to it, including emergency isolation valves and emergency shutdown systems.
- This is a required field that shows independent inspection approval and Post Maintenance NDT, when applicable, prior to the closure of a work order.

5. Discussion

5.1 Analysis of the Nigerian Offshore Implementation Context

The operational, operational and regulatory relevance of the proposed framework depends on its conformity with documented engineering realities and organizational constraints in Nigeria, as well as the Gulf of Guinea region. The Niger Delta marine environment is a congested operational environment, comprising broad systems of shallow water production platforms, deepwater production centres, complicated pipeline systems along the coast, and delicate mangrove coasts.

Socioeconomic evaluations indicate that the pressure from localized hydrocarbon releases is high for coastal inhabitants due to the reliance on coastal aquaculture and artisanal fishing practices. Therefore, small-loss-of-containment events that could be naturally or technologically contained in the open ocean are expected to result in significant socioeconomic consequences in shallow nearshore ecosystems (Nuhu et al., 2022).

Analysis of the regional offshore literature identifying particular integrity constraints in this context that are addressed by this framework. Treatment of regional offshore response base logistics in Nigerian waters suggests that regional post-spill containment infrastructure may be merely up-dated, but inadequate ex-ante engineering indicators attached to response networks persist (Ogbuka et al., 2022).

In addition, emergency response teams frequently follow a reactive procedure, responding only once a visual spill report has been made, resulting in delays. Mapping emergency shutdown valves and systems as active elements of the asset register creates a data pathway from engineering events to spill response preparedness.

Table 4, Deep analysis of the Nigerian offshore implementation context and evidence requirements

Regional Issue / Constraint	Verified Source / Directive	Direct Implication for Asset Integrity	Proposed Framework Response Protocol	Remaining Critical Evidence Gaps
Severe Data Reporting Bias & Fragmented Incident Logging	Nuhu et al. (2022)	Historical failure records often omit material root causes, complicating baseline calculations.	Mandates strict root-cause logging; separates unverified assumptions from empirical data.	Independent public access to anonymized corporate incident investigation databases.
Reactive Spill Emergency Response Management Logs	Ogbuka et al. (2022)	Response teams mobilize reactively, increasing environmental exposure durations.	Integrates emergency barrier element tracking with live CMMS defect logs.	Multi-operator empirical data tracking response mobilization times.
Regulatory Field Enforcement Pressures	NUPRC Safety Directives	Overlapping regulatory fields complicate compliance tracking for offshore facilities.	Establishes a standardized eight-field reporting dashboard for asset verification.	Unified digital data reporting architecture spanning all regulatory agencies.
High Nearshore Ecosystem Sensitivity & Socioeconomic Risks	UN SDG 14 Framework	Nearshore mangrove zones are sensitive to low-volume chemical and hydrocarbon releases.	Separates environmental consequence logic from standard asset criticality indices.	Localized baseline ecological sensitivity maps for deepwater export corridors.

Supporting table 6 offers insights into Nigerian offshore implementation issues by highlighting areas of operational constraints, the effect they may have on asset integrity and the type of evidentiary support that might facilitate operational improvements. Using the analyses, we infer several Nigerian operational constraints, including the scarcity of incident records, reactive spill response, regulatory interaction and nearshore ecosystems.

The response framework indicates that traceable failure reports, maintenance and spill records, agreed performance compliance measures and more attention to environmental impacts would assist by providing additional tracking of the causes, and ranges of time required for technological responses. The table has also noted key evidence gaps in the Nigerian data-sets, which would assist validation and future implementation of the framework, including independent access to incident records, comparable response time records and location-specific nearshore ecosystem sensitivity assessments.

Most importantly, this regional assessment highlights the need for a high level of causal precision. Reviewers should accept the fact that an environmental release alone is not conclusive of a material failure, and that an evident corrosion failure does not imply a release took place. Where engineering investigation records are insufficient to demonstrate a clear physical causal connection between an incident and a material failure, operators and regulators should clearly indicate that the root cause cannot be confirmed. This absence of confirmation is crucial to avoid conflating data and to direct regulatory response at real engineering failures, rather than assumptions.

5.2 Four Core Engineering Decision Rules

In order to convert the conceptual model into precise, unwavering operational directives within an asset manager's computerized environment, it is reduced to four fundamental decision rules:

- The Rule of Empirical Corroboration It is recommended that an asset lifecycle change or asset repair deferral should never be approved on the basis of a single operational symptom or digital twin score. If no physical indications of a key failure mode or degradation pathway are present, a formal integrity process should require the collection of independent, corroborative evidence of NDT (e.g. Volumetric ultrasonic tracking or radiographic mapping) before making an intervention decision.
- The Rule of Consequence-Driven Confidence Operators shall not let a low-confidence indicator or uncertain data deceive them into complacency about a high-consequence asset element. If the data confidence score is below the provided engineering threshold, due to sensor calibration issues, inspected data being delayed, or data fields being missing, then the component must be immediately upgraded in an operator matrix to the highest risk level. This shall be performed with conservative operation measures and interim mitigation strategies, including pressure de-rating or local process isolation, until confidence can be restored through physical inspection.

- The Rule of Independent Post-Maintenance Verification. Maintenance work orders, corrective actions, or part replacements should not be closed in the CMMS by technician signature or physical work documentation alone. A task is only considered performed and removed from the open risk register once an independent quality control inspector has performed an after maintenance physical NDT reading, confirmed the resolved defect structurally and benchmarked a new operating baseline with the component ledger.
- Rule 6. Explicit Barrier Mapping. When a production asset item is a main process containment or an adjacent barrier, for example a subsurface safety valve or emergency isolation joint, an explicit barrier role and test proven operational availability (test proven capacity) should be readily apparent in all integrity profiles. If the associated environmental barrier is indicated as unavailable or reduced during routine tests, the upstream production asset item is probably required to be immediately actioned (operationally isolated) or put through its safe shutdown.

5.3 Technical Refinements: Risk Metrics and Barrier Verification

In order to make this framework more operationally viable for practicing marine engineers, two technical improvements should be integrated into the decision logic of the framework:

- The qualitative risk prioritization formula, RM, represented by the simple ordinal ranking $R = L \text{ times } C$ can be used as a simple ordinal sort to share limited maintenance funds among a large population of components. Do not be misled that a simple multiplication of ordinal categories creates a proportional mathematical probability of physical failure. Readers and operators should not use these ranking values within structural reliability equations or QRA's without formal probabilistic calibration using large quantities of available site-specific failure history.
- Key differentiator between barrier availability and operational effectiveness: An enterprise system green indicator of "barrier availability" for emergency isolation valve does not necessarily prove the barrier would be effective in operation in the event of the emergency. Our operational experience shows that field barrier operation performance as defined by local engineering factors such as sealing face degradation, actuator torque decay, typical process scaling, entrained sand or hydrates can be quite different from the status indicated by enterprise information system. Therefore, to verify the functionality of the barrier successfully in Domain 4, appropriate evidence of various aspects of periodic dynamic performance testing, partial-stroke testing, leak rate measurements, and regulator valve seat test per international standards (such as ISO 17359 and API RP 14C) is critical.

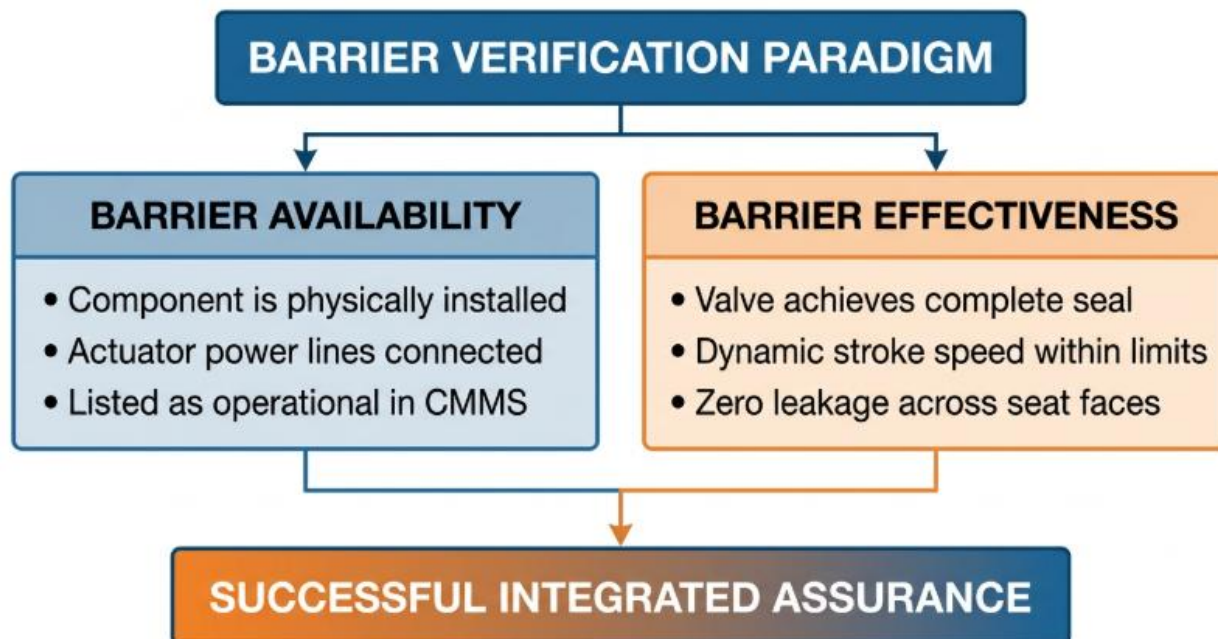


Fig 9. The Barrier Verification Paradigm

The figure 9 above demonstrates that true safety assurance is achieved only when static physical readiness (Barrier Availability) and dynamic real-world performance (Barrier Effectiveness) are validated simultaneously

5.4 Performance Indicator Formulations and Missing Data Protocols

In order that the criteria (as proposed in Table 5) are audited on the same basis across multi-facility fleets, the calculation methodology for each criterion, reporting interval, the denominator and the missing data boundary are defined as follows.

- High-Risk Action Closure (I_HRAC)

This measure is measured over a period of 90 days. It is derived by taking the number of high-risk corrective actions completed by due date, with independent NDT verifications certificates by a total of high-risk corrective actions with a deadline that falls within the reporting period. The data does not include open work orders with engineering approved technical deferrals with documented fitness-for-service.

- Inspection Coverage (I_IC)

This indicator is a yearly reporting cycle. It is calculated as the total square metres of critical pressure boundary surfaces inspected by high resolution ultrasonic inspection grid divided by the total planned inspection surface area as specified in the risk-based inspection programme. The missing-data protocol requires areas of the inspection grid with missing, unlogged, or lost data to be marked as unknown condition. The missing data should not be arbitrarily replaced by a remaining wall thickness of zero. Zero is a physical measurement, a data point; it is not missing data. The area is probably in need of an engineering risk assessment, interim safeguards should be put in place, and additional physical reinspection is to be scheduled in accordance with the assessed risk.

- Repeat-Defect Rate (I_RDR)

This indicator is evaluated over a moving 12-month period. It is determined by taking the number of work orders with the same localized asset tag and failure-mode code that repeat within 365 days, divided by the total number of closed corrective work orders performed across the site in the same reporting period. For uniform auditing, should be documented explicitly in terms of qualifying parameters that are used to specify repeat failure conditions, how components are paired to failure modes, and the way reporting-period limits are defined. In order to accurately compare facilities, it is recommended that the numerator and denominator always reference specific populations that are well defined and cataloged.

5.5 Limitations and Future Research Directions

This overall framework is an integrated, conceptual decision architecture which has been developed based on a systematic critical narrative review of engineering literature and international standards. It should be clarified that this engineering decision framework is neither a validated probabilistic forecast nor a statistical guarantee of lower oil-spill rates, lower corporate maintenance expenditure or lower greenhouse gases emissions. The decision-support tables, decision-support matrices and performance parameters are designed to provide logical reasoning rather than presenting simulation-based operating-performance data for field operations. This conceptual framework may be only partially applicable to other fields due to lack of localized data, corporate maintenance culture and regulatory control.

The new framework will require testing and validation through field application in future research. The most important next step is to run a multi-facility pilot trial on anonymized operational data from a live offshore field located off the coast of the Gulf of Guinea. This pilot should be at least 24 months long in order to track the time taken to make integrity decisions, set process indicators, and see if structured data fields can reduce maintenance backlogs.

In addition, further human-factors engineering studies will be needed to examine the interaction between remote technicians and required CMMS reporting standards. This is necessary to improve user interfaces and to enable this increased data-entry requirement to be a health-enhancing activity, rather than an administrative burden that could undermine compliance.

6. Conclusion

This critical review unifies three historically separated areas, offshore degradation, risk-based maintenance planning, and marine environmental barrier assurance into a unified decision platform. Designed along five interconnected domains, the architecture automates a process that rigorously transitions from how equipment degradation is observed at the individual components, to engineering evaluations, prioritization for maintenance, environmental barrier verification, and defect closure validation. To combat the clickitis prevalent in current practices, each asset integrity alert must trigger the verification of its appropriate environmental protection barrier.

The main operational recommendation of this study proposes that offshore operators and maritime regulators create a traceable, fully closed-loop reporting chain. This chain would record the physical state as observed, the presumed deterioration mechanism, the prioritized independent environmental impact category, the maintenance measure taken, and the real-world nondestructive testing (NDT) evidence for a successful repair.

While it doesn't offer pre-verification of financial savings or absolute likelihood models, this hypothetical architecture provides an organized, tech-savvy approach most likely to bring about the daily offshore engineering work that can help save our oceans and ensure improved marine governance in Nigeria and the Gulf of Guinea.

Declarations

Funding: The author certifies that no external funding, corporate sponsorships, or research grants were received from public, commercial, or non-profit sectors to support the preparation, analysis, or drafting of this review paper.

Competing Interests: The author declares no competing financial, personal, or professional interests that could influence the objectivity, scope, or execution of this conceptual framework.

Data Availability Statement: No new empirical engineering datasets or operational asset databases were generated or statistically analyzed during this study. The underlying synthesis is based entirely on the technical standards, corporate guidelines, and peer-reviewed literature cited in the references section.

Ethics Approval: Not applicable. This study represents a secondary critical narrative review of published data and did not involve human participants, animal testing, or confidential personal records.

Previous Publication and Overlap Notice: The author certifies that this manuscript is an original critical synthesis. The conceptual domains, reporting profiles, and performance matrices developed herein have not been published previously and do not duplicate prior field-specific asset-integrity or pump-corrosion research, ensuring zero conceptual or textual overlap with existing works.

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