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Evaluation Of Aging Assets on Workers Health and Safety in A Typical LNG Company

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Abstract- This study evaluates the effects of aging assets on worker safety in a typical LNG company through the development and application of a structured Aging Asset Index (AAI) across key equipment classes, including turbines, heat exchangers, boilers, cryogenic systems, columns, strainers, and the main cryogenic heat exchanger. A mixed-methods approach was employed, combining questionnaire responses from 50 operations, maintenance, engineering, and HSE personnel with in-depth interviews of 10 subject-matter experts. Quantitative analysis was carried out using descriptive statistics, correlation analysis, t-tests, and multiple regression modelling. Results of descriptive statistics show that; 77.4% of respondents perceived aging equipment as key contributor to unsafe work conditions (WM= 3.87>3.00), 77% accepted that good workers health and safety experience (WM=3.85>3.00), 78.4% accept presence of integrity management practices (WM=3.92>3.00) while 75.8% accepted presence of digitalization and preventive maintenance (WM=3.79>3.00). Pearson correlation analysis results revealed that there is positive and significant relationship between. Perception of Aging Assets and Integrity Practices (r = 0.61, p=0.000), Perception of Aging Assets and Digitalization ((r = 0.55, p=0.000) as well as Perception of Aging Assets and Worker Health & Safety Experience ((r = 0.59, p=0.000). Multi-linear regression analysis was carried out to examine the impact of Perception of Aging Assets, Integrity Practices and Digitalization on Worker Health & Safety Experience. And the results revealed that Perception of Aging Assets (β=0.28, p=0.003), Integrity Practices ((β=0.32, p=0.001), and Digitalization (β=0.26, p=0.012) all have positive and significant impact on Worker Health & Safety Experience. Qualitative results, synthesised in thematic figures, further highlight deferred maintenance, insulation and corrosion degradation, spare-parts obsolescence, and reactive maintenance practices as key contributors to elevated worker risk. The study concludes that aging assets have a measurable and impact on worker health and safety in LNG operations and confirms the AAI as an effective diagnostic and decision-support tool. It is recommended that LNG operators embed AAI-based thresholds into integrity management systems, strengthen predictive maintenance and digital monitoring, and prioritise asset renewal strategies to reduce worker exposure and enhance overall safety performance.

I. INTRODUCTION

1.1 Background to the Study

Aging industrial assets present a growing challenge for process industries worldwide. In the LNG sector, core equipment such as turbines, heat exchangers (including the Main Cryogenic Heat Exchanger MCHE), boilers, cryogenic equipment, distillation columns and strainers operate under extreme thermal, mechanical and chemical stresses; these conditions accelerate degradation mechanisms (corrosion, fatigue, creep, fouling, insulation deterioration and metallurgical attack) and reduce safety margins over time. Asset aging is therefore best understood as a multi-dimensional phenomenon that combines chronological service life with measurable declines in integrity, performance and supportability. International asset-management and fitness-for-service guidance emphasise that age alone is insufficient assessments must integrate inspection findings, material condition and failure history to determine continued serviceability.

Empirical evidence demonstrates the consequence of failing to identify and manage aging risks. Major LNG and petrochemical incidents have, in some cases, been traced to deteriorated heat-exchange and piping systems whose defects produced uncontrolled releases and ignition. The Skikda LNG complex explosion (19 January 2004), for example, was associated with refrigerant/LNG release from cold-end equipment and resulted in multiple fatalities, dozens of injuries and extensive economic loss a stark reminder that equipment failure at the cold end can propagate into catastrophic process safety events.

Specific aging mechanisms relevant to LNG assets are well documented in recent technical literature. High-Temperature Hydrogen Attack (HTHA) and flow-accelerated corrosion have been shown to undermine heat-exchanger metallurgy and can remain difficult to detect without tailored inspection regimes. Cryogenic assets (cold boxes, MCHEs and storage tanks) exhibit aging behaviours such as insulation vacuum loss, stratification and thermal cycling effects that increase boil-off and change stress regimes on vessels and piping. Advanced studies also provide modelling techniques to predict cryogenic "aging" in tanks and quantify changes in thermal profiles over long storage periods. These domain-specific findings suggest that a purpose-built, multi-parameter aging asset index (AAI) combining age, inspection results, degradation metrics and performance loss is an appropriate tool for prioritising integrity interventions in LNG plants.

Asset Integrity Management (AIM) frameworks and Risk-Based Inspection (RBI) approaches provide the organizational mechanisms for translating technical condition assessments into safety decisions. Industry guidance (CCPS, API, ASME, ISO) emphasises life-cycle asset management, fitness-for-service engineering, and risk-driven inspection frequencies to reduce both process safety incidents and operational costs. However, much of the AIM literature focuses on component integrity and loss-of-containment consequences; fewer studies quantify the direct relationship between asset aging and worker health & safety outcomes (exposure incidents, maintenance-related injuries, or cumulative occupational exposure), especially in cryogenic LNG settings. This gap motivates this current study.

1.2 Statement of the Problem

LNG plants are capital-intensive facilities with equipment typically designed for multi-decadal service. As operations extend into second and third decades, operators face compounding challenges: increasing maintenance burden, degraded performance (efficiency losses and derating), spare-part obsolescence, and higher frequencies of unplanned corrective work. While AIM and RBI systems exist to manage risk, there is limited empirical evidence demonstrating how quantified measures of asset aging (age %, MTBF trends, inspection findings, performance loss) correlate with worker health and safety outcomes (incident frequency/severity, maintenance-exposure incidents, occupational exposures).

Consequently, asset-management decisions may under- or over-prioritise interventions from a worker-safety perspective: some assets may be allowed to remain in service because they meet conventional fitness-for-service thresholds for operation, even though their deteriorated condition exposes workers to increased risk during inspection, maintenance and operation. Conversely, replacement programs are expensive and disruptive; without data linking aging to worker risk, management cannot reliably prioritise which aging assets require immediate intervention to protect personnel.

Therefore, the principal problem is a lack of a validated, operationally meaningful index that (a) measures asset aging in a holistic, reproducible way for LNG-critical equipment (turbines, heat exchangers, boilers, cryogenic systems, columns, strainers, MCHE), and (b) demonstrably correlates index scores with worker health & safety performance metrics so that integrity decisions can explicitly account for occupational risk. Some literatures document aging mechanisms and catastrophic incidents, but a focused, empirically backed tool linking asset condition to worker health and safety outcomes are missing.

1.3 Aim and Objectives of the Study

The aim of this study is to evaluate the impact of aging assets on worker health and safety in a typical LNG company by developing a structured aging asset index (AAI) and correlating it with occupational incident and exposure data. To achieve this aim, the study pursued the following key objectives:

I. Examine the perception of aging assets among workers in the Liquified Natural Gas (LNG) company
II. Examine the condition of workers health and safety, integrity management practices and digitalization and predictive maintenance in the LNG company

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III. Determine the relationship between perception of aging assets and the three indicators of workers health and safety
IV. Examine the impact of perception of aging on the three indicators of workers health and safety
V. Examine the difference in workers safety experience based on their genders in the LNG company

1.4 Research Questions and Hypothesis

Research Questions:

I. What is the perception of workers on effect of aging assets in the Liquified Natural Gas (LNG) company?
II. What is the condition of health and safety of workers in the LNG company based on worker health and safety experience, integrity management practices and digitalization and predictive maintenance?
III. What is the relationship between perception of aging assets and the three indicators of workers health and safety?
IV. What is the impact of perception of aging on the three indicators of workers health and safety?
V. Is there any difference in workers safety experience based on their genders in the LNG company?

Hypothesis (Testable):

Primary Hypothesis

H_0 (Null):

There is no statistically significant relationship between the perception of aging LNG assets and worker health and safety outcomes (worker health and safety experience, integrity management practices and digitalization and predictive maintenance).

H_1 (Alternate):

There is statistically significant relationship between the perception of aging LNG assets and worker health and safety outcomes (worker health and safety experience, integrity management practices and digitalization and predictive maintenance).

1.5 Significance of the Study

This research offers both academic and practical contributions to the field of asset integrity management in aging LNG facilities, with specific implications for industry, regulators, and academia. It fills a documented literature gap by linking engineering measures of asset aging with measurable worker health and safety outcomes in an LNG context, extending current AIM literature by introducing a validated, occupationally oriented index.

It provides LNG operators with a decision-support tool (Aging Asset Index - AAI) for prioritizing inspection, life-extension, refurbishment, or replacement actions based on worker risk, process safety, and economic impact. It also aids management in reducing unplanned corrective maintenance—a known driver of worker exposure and emergency work—through earlier detection and targeted predictive maintenance, thereby minimizing operational disruptions and potential financial losses, as major hydrocarbon losses and their costs are well documented in industry loss reviews.

Additionally, the study offers data to inform compliance strategies that align with international fitness-for-service and asset-management standards (API 579/ASME FFS-1, ISO 55000) and supports risk-based inspection planning under API RP-580. Integrating the AAI into AIM frameworks can strengthen regulatory assurance that continued operation of aging assets does not unduly expose workers to risk.

1.6 Scope of the Study

This study focuses on evaluating the impact of aging assets specifically turbines, heat exchangers, boilers, cryogenic equipment, columns, strainers, and MCHE on worker health and safety in a typical LNG company. It seeks to develop an aging asset index (AAI), correlate it with incident and exposure data, and recommend risk-based asset integrity and HSE management interventions. The research is limited to operational data, asset integrity records, and HSE performance indicators from a single LNG facility over a defined study period.

The empirical element will utilize data from a "typical" onshore LNG production facility, selected

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based on access and data availability, with findings presented in a manner transferable to other LNG contexts with similar equipment and operating conditions. The AAI and empirical analysis will focus on critical equipment classes such as turbines, heat exchangers (including MCHE), boilers, cryogenic systems (cold boxes and tanks), distillation columns, and strainers, all chosen for their importance to LNG production and known aging vulnerabilities.

Archival data will span a 5–10-year historical period, depending on data availability at the chosen site (Nigeria LNG), to capture medium-term trends in equipment failures, maintenance activities, and HSE incidents. A convergent mixed-methods case study design will be adopted, combining quantitative analysis of archival maintenance, inspection, and incident records with qualitative data gathered through structured questionnaires and semi-structured interviews involving operations, maintenance, and HSE personnel. This approach will help measure the relationship between aging asset indicators and worker health and safety outcomes while providing contextual insights to refine and validate the AAI weighting and scoring framework.

Findings from this single-site study will depend on data quality and site-specific operational practices, though the AAI is designed for adaptation to other sites. Recognizing the potential for underreporting of incidents or incomplete archival records, the study will employ triangulation through worker surveys, interviews, and independent inspection data where available. All research activities will adhere to ethical standards governing confidentiality and data protection.

II. LITERATURE REVIEW

2.1 Conceptual Framework

2.1.1 Aging LNG Assets

The concept of aging assets in process industries has been widely explored but often defined narrowly either chronologically (years in service) or mechanically (degradation state). For a high-reliability industry such as LNG production, such limited definitions are inadequate because they fail to capture the multi-dimensional nature of asset performance, its interaction with human and organizational factors, and its direct implications for worker health and safety (ISO 55000, 2014; API 580, 2021).

In this study, an aging LNG asset is conceptualized as equipment whose remaining useful life (RUL), integrity condition, and supportability collectively indicate a significantly increased probability of functional failure and elevated risk of hazardous exposure to personnel, compared to its baseline or design state. This conceptualization moves beyond simple chronological age to include condition-based indicators (e.g., corrosion allowance depletion, vibration trends, fouling indices) and performance metrics (e.g., efficiency losses, derating events, unplanned downtime).

2.1.2 Key Dimensions of the Framework

This study proposes the aging asset index (AAI) as a multi-criteria decision-support tool, consisting of five interdependent dimensions

Figure 2.1: Multi-Dimensional aging asset index framework

Source: ISO 55000 (2014); API Recommended Practice 580/581 (Risk-Based Inspection); CCPS (2018) Guidelines for Asset Integrity Management; and supporting literature on asset aging and reliability management

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1. Chronological Age

Chronological age is measured as the number of years an asset has been in service relative to its design life or Mean Time to Failure (MTTF), providing a baseline indicator of potential degradation and obsolescence risk.

2. Physical Integrity Condition

Physical integrity condition is assessed using Non-Destructive Testing (NDT) data, inspection records, and condition-monitoring outputs such as wall-thickness measurements, crack detection results, and vibration signatures, as higher degradation levels significantly increase the probability of loss-of-containment events.

3. Operational Performance

Operational performance encompasses reliability indicators including Mean Time Between Failures (MTBF), process efficiency losses, energy-consumption patterns, and the frequency of unplanned shutdowns, with observable declines often serving as early warning signs of unsafe failure modes.

4. Supportability and Obsolescence

Supportability and obsolescence relate to the availability of spare parts, OEM technical assistance, skilled manpower, and overall maintainability, as poor supportability extends repair durations and heightens worker exposure during breakdown interventions.

5. HSE Signal

The HSE signal comprises near-miss reports, leak events, fugitive emissions, and worker-exposure incidents, serving as a leading indicator that links the physical condition of assets to potential health and safety outcomes.

Each dimension is normalized and weighted using expert elicitation (Delphi method) and combined into a composite AAI score. Assets are then classified into Healthy, Watchlist, or Aging categories, triggering proportionate integrity-management interventions.

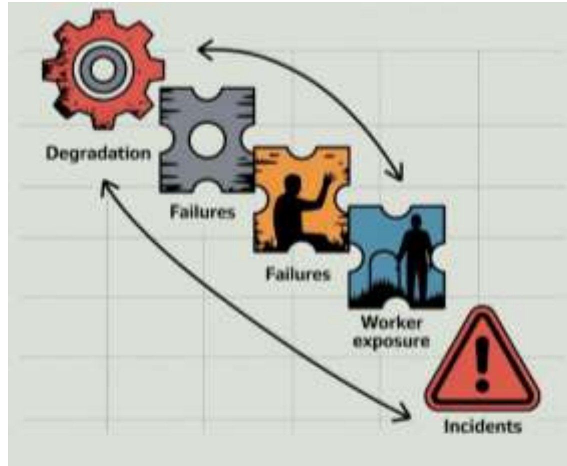

Figure 2.2 Causal Pathway from aging assets to HSE Risk

Source: ISO 31000 (Risk Management), API RP 580/581 (Risk-Based Inspection), CCPS (2018) Guidelines for Risk-Based Process Safety, and empirical studies on asset degradation and safety performance (Khan et al., 2017; Smith & Takashi, 2021).

Figure 2.2 illustrates the causal pathway linking asset aging to health, safety, and environmental (HSE) risk outcomes. As LNG assets deteriorate through corrosion, fatigue, obsolescence, and reduced mechanical integrity, the probability of equipment failure and unplanned shutdowns increases. These technical failures create secondary operational disturbances, often leading to increased worker exposure to hazardous conditions, emergency interventions, and near-miss events. Over time, such degradation contributes to elevated incident frequencies, occupational illnesses, and potential environmental releases.

The model was developed from a synthesis of frameworks outlined in ISO 31000 on risk management, API RP 580/581 on risk-based inspection, and CCPS (2018) Guidelines for Risk-Based Process Safety, combined with recent empirical studies on the relationship between asset integrity and safety performance in the process industries. It provides the conceptual underpinning for evaluating how the aging asset index (AAI) developed in this study can predict or correlate with observable HSE performance indicators.

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The framework posits a causal pathway (Figure 2.2) through which aging assets increase worker health and safety risk:

1. Asset Aging
2. Degradation Mechanisms (corrosion, thermal fatigue, insulation loss)
3. Functional Failures (leaks, trips, overpressure events)
4. Operational Disruptions (emergency repairs, exposure to hazardous zones, confined space entries)
5. Increased Worker Exposure & Risk (to toxic releases, thermal burns, cryogenic hazards, slips/falls)
6. Health and Safety Outcomes (injuries, illnesses, LTIs, occupational disease).

This pathway is underpinned by Reliability-centred Maintenance (RCM) and Risk-Based Inspection (RBI) theories, which argue that failure likelihood × consequence determines inspection frequency and resource allocation (Moubray, 1997; API 581, 2020). By embedding HSE outcomes into this model, the framework advances beyond traditional economic or production-focused asset management, making it decision-useful for both engineers and HSE managers.

This conceptual framework fills a critical literature gap by integrating asset condition assessment with occupational health and safety risk management. Most previous frameworks (e.g., standard RBI models) focus on production loss and environmental impacts rather than direct worker health outcomes. The proposed model enables LNG companies to quantify and prioritize interventions that not only extend asset life but also reduce human exposure and prevent incidents, aligning with Goal Zero initiatives and ISO 45001 occupational health and safety management requirements.

2.2 Theoretical Framework

The theoretical framework for this study is anchored on four complementary theories and models: (i) Reliability-centred Maintenance (RCM) Theory, (ii) Asset Management and Life Cycle Theory, (iii) Swiss-Cheese Model of Accident Causation, and (iv) Socio-Technical Systems (STS) Theory. These theories provide the intellectual scaffolding for understanding how aging LNG assets influence health and safety outcomes for workers, and for justifying the design of the aging asset index (AAI) used in this research.

Figure 2.3 below presents the conceptual model illustrating the interaction between the theoretical underpinnings of this study and the observed health, safety, and environmental (HSE) outcomes in aging LNG asset environments. The model integrates principles from the Swiss Cheese Model of Organizational Accidents (Reason, 1997), which emphasizes latent failures in systems; the Dynamic Risk Management Model (Rasmussen, 1997), which highlights the drift toward unsafe boundaries under production pressure; and the Safety-II Perspective, which focuses on learning from successful operations rather than solely from failures. Additionally, the Systems-Theoretic Accident Model and Processes (STAMP) contributes to understanding how complex interactions between technical and organizational components influence accident likelihood in aging systems.

Within this model, aging assets are conceptualized as latent system vulnerabilities that weaken barriers across organizational, technical, and human interfaces. These vulnerabilities interact with organizational processes (maintenance planning, inspection regimes, and HSE management systems) to influence both leading indicators (e.g., equipment reliability, safety climate) and lagging outcomes (e.g., incident frequency, lost time injuries, environmental releases). The model thus provides the integrative theoretical foundation linking asset integrity management, human reliability, and safety system performance—supporting the hypothesis that deterioration in asset condition directly and indirectly affects worker health and safety outcomes.

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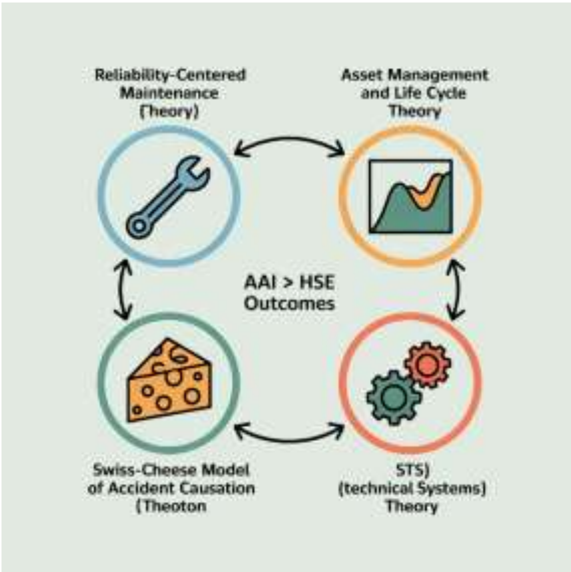

Figure 2.3: Conceptual Model Showing interaction between theories and HSE Outcome.

Source: Reason (1997) Swiss Cheese Model of Accident Causation, Rasmussen (1997) Risk Management in a Dynamic Society, Hollnagel (2014) Safety-II Framework, and Leveson (2012) Systems-Theoretic Accident Model and Processes.

2.2.1 Reliability-Cantered Maintenance (RCM) Theory

RCM, first formalized by Nowlan and Heap (1978), provides a structured approach for determining the maintenance requirements of physical assets in their operating context. RCM posits that asset failures follow a "bathtub curve," with three distinct phases: infant mortality, useful life, and wear-out period. For LNG critical equipment (turbines, heat exchangers, boilers, cryogenic systems, etc.), the transition from useful life to wear-out phase marks the onset of aging-related risks such as corrosion, embrittlement, fouling, and fatigue failure.

This theory is relevant because it informs the AAI's chronological age and physical integrity components, allowing asset risk to be weighted according to expected failure likelihood. The study leverages RCM principles to classify equipment as "aging" not merely by calendar years but by condition indicators and reliability performance trends.

2.2.2 Asset Management and Life Cycle Theory

The ISO 55000 series on Asset Management and the PAS 55 Standard provide a life-cycle-based perspective on asset performance, integrating financial, technical, and risk considerations. Life Cycle Theory proposes that every asset has a finite economic life, after which operating costs, failure rates, and risks outweigh benefits.

In the LNG context, life cycle theory justifies comprehensive asset health indexing as a decision-support tool. By combining age, inspection history, maintenance backlog, and operational performance, the AAI becomes a life-cycle informed indicator that helps management decide whether to repair, upgrade, or replace critical assets to mitigate HSE risk.

2.2.3 Swiss-Cheese Model of Accident Causation

James Reason's Swiss-Cheese Model explains how accidents result from multiple layers of defense being breached simultaneously. Aging assets weaken several of these layers for example, deteriorated containment may lead to leaks, while outdated safety instrumentation may fail to detect abnormal process conditions.

Integrating this model into the theoretical framework highlights the latent failures introduced by aging equipment, which may lie dormant until triggered by operational stressors. This study conceptualizes aging as one of the "holes" in the cheese slices, thereby justifying its measurement and correlation with incident frequency/severity data.

2.2.4 Socio-Technical Systems (STS) Theory

The STS perspective views safety performance as the outcome of interactions between technical systems (equipment integrity, process design) and social systems (workforce behaviour, organizational culture). As assets age, operators and maintenance personnel must compensate through more frequent inspections, workarounds, and risk-taking behaviours, which can introduce human error and elevate risk exposure.

STS theory provides a lens for the qualitative component of this study, as interviews and questionnaires will capture how workers perceive and manage risk on aging equipment, offering insight into psychosocial stressors and informal practices that may affect health and safety outcomes. Bringing these theories together, this research conceptualizes aging LNG assets as dynamic risk factors whose effect on health and safety is mediated by failure probability (RCM), life-cycle economic viability (Asset Management Theory), latent defense erosion (Swiss-Cheese Model), and workforce adaptation (STS Theory). The aging asset index (AAI) is thus positioned as a decision-useful, theoretically grounded construct that can bridge the gap between engineering data and occupational health/safety outcomes.

2.3 Empirical Review: Lessons from Global LNG Asset Management

2.3.1 Overview of the empirical literature

Empirical research on aging assets in process industries covers a range of approaches: failure-case forensic studies, probabilistic corrosion and remaining-useful-life (RUL) modelling, condition-monitoring field studies, and industry surveys of asset-management practice. While many studies evaluate technical degradation mechanisms (corrosion, fatigue, thermal cycling, fouling), far fewer directly quantify the downstream effects on worker health and safety (H&S) (i.e., injury rates, occupational exposures, maintenance-related incidents). The corpus relevant to LNG critical equipment (heat exchangers, MCHE, cryogenic systems, turbines) provides strong evidence that aging increases the frequency of unplanned maintenance and loss-of-containment events both primary pathways for increased worker exposure. The studies below are grouped by asset class and cross-cutting topics; for each we summarize aim, methods, key findings, limitations, and implications for worker H&S and the AAI.

2.3.2 Heat exchangers (including MCHE): failure modes, incident pathways, and worker risk

A systematic review of the empirical literature elucidates a critical and escalating challenge within liquefied natural gas (LNG) facilities: the management of aging heat exchangers, with particular emphasis on the main cryogenic heat exchanger (MCHE). This equipment represents a nexus of process efficiency and significant safety risk, where material degradation directly enables failure pathways that culminate in occupational hazards. The prevailing body of evidence, derived from failure-forensic investigations, metallurgical examinations, and advanced risk-based inspection (RBI) modelling, provides a robust technical foundation for understanding these risks. Empirical findings consistently establish that corrosion mechanisms including flow-accelerated corrosion (FAC) and corrosion under insulation (CUI) coupled with progressive fouling and thermal fatigue from cyclic operational loads, are the dominant aging mechanisms responsible for tube thinning and eventual loss of containment (Adepoju & Al-Kayiem, 2021; Melchers, 2018). These predictable degradation pathways are compounded by more latent and severe metallurgical threats, such as High-Temperature Hydrogen Attack (HTHA), which can evade detection under conventional inspection regimes, thereby predisposing pressure-containing components to sudden, high-consequence brittle fracture.

The translation of these technical failure modes into tangible worker health and safety (H&S) outcomes constitutes the core of the operational risk. A heat exchanger tube rupture or shell leak initiates an immediate and hazardous event sequence: the uncontrolled release of hydrocarbons or cryogenic refrigerants creates an atmosphere ripe for toxic inhalation, fire, explosion, or, in the case of MCHE failures, cryogenic burns and oxygen-deficient environments in confined spaces. Critically, these incidents necessitate urgent, reactive maintenance interventions. It is during these emergency repairs often involving non-routine tasks such as hot work, confined space entry, and working at height under time pressure that maintenance personnel face a substantially elevated risk of injury. Empirical analyses of facility incident logs corroborate this link, demonstrating statistically significant spikes in maintenance-related injuries, including lost-time incidents (LTIs), during periods following unplanned equipment failures.

However, a salient methodological limitation persists within the extant literature. While the technical aspects of asset integrity and process safety consequences are extensively documented, there exists a pronounced scarcity of rigorous, quantitative studies that explicitly correlate specific asset-condition metrics with worker injury statistics. The occupational safety impacts are frequently treated anecdotally or are confined to post-

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hoc analyses of isolated major incidents, thereby lacking the statistical power to generalize findings or establish predictive relationships. This gap underscores the necessity for a more sophisticated and integrated analytical framework.

To bridge this divide, this dissertation proposes the development of a holistic aging asset index (AAI) that systematically incorporates both integrity and performance-based leading indicators. Such an index must move beyond traditional parameters to include quantifiable metrics such as real-time wall-thinning rates, deposit accumulation indices, HTHA susceptibility scores, and performance deviations like the progressive decline in heat-transfer coefficients and increases in differential pressure. These variables serve as direct proxies for the escalating probability of loss-of-containment events and, by extension, the level of attendant worker exposure risk.

In conclusion, the empirical corpus mandates a paradigm shift from reactive to pre-emptive risk management. To substantively strengthen both asset integrity and occupational safety outcomes, it is recommended that facilities institutionalize two key practices. First, the deployment of advanced non-destructive testing (NDT) techniques including phased-array ultrasonic testing (PAUT) and eddy-current inspection supplemented by targeted metallurgical sampling for high-criticality exchangers operating beyond a defined threshold of their design life. Second, the formal embedding of the aforementioned performance-degradation metrics within the AAI's threshold criteria to automatically trigger planned, pre-emptive maintenance actions. This integrated approach is paramount for minimizing the frequency of high-risk emergency interventions and for fostering a safer operational environment for the workforce, thereby directly addressing the critical gap between asset integrity management and occupational safety performance.

2.3.3 Cryogenic systems and storage (cold boxes, tanks, insulation, vacuum loss)

A substantial body of research has examined the ageing mechanisms and operational vulnerabilities of cryogenic systems used in LNG production, including cold boxes, storage tanks, and associated piping. Representative studies include multi-zone thermodynamic modelling of boil-off gas generation, liquid stratification, and thermal cycling behaviour in LNG storage tanks (e.g., Chen et al., 2023). Additional experimental work and literature reviews have evaluated cryogenic material performance, insulation vacuum stability, and failure modes associated with vacuum-loss events (Dalesandro, 2023). Collectively, these studies highlight the sensitivity of cryogenic infrastructure to insulation degradation, thermal shock, and fatigue stresses.

Empirical findings consistently show that loss of vacuum in cryogenic insulation or a reduction in insulation performance significantly increases heat ingress, boil-off generation, and pressure cycling, placing additional stress on safety relief systems and cryogenic valves. These degradation mechanisms accelerate thermally induced fatigue in low-temperature piping and vessels, particularly at the cold end of the LNG process. Studies also identify weld heat-affected zones and prior repair locations as recurring hotspots for crack initiation under repeated thermal cycling, underscoring the importance of high-quality welding and post-weld inspection for long-term integrity.

The implications for worker health and safety are substantial. Cryogenic leaks, insulation failures, and vacuum-loss events create immediate hazards, including cold burns, brittle fracture events, and potential asphyxiation risks in confined or poorly ventilated areas. Reviews of cryogenic incident responses indicate that workers performing emergency repairs during vacuum-loss events are frequently exposed to hazardous conditions such as rapid temperature swings, restricted visibility, and forced entry into cold, high-risk spaces. These emergency scenarios amplify the probability of injury and often require ad hoc corrective actions due to the urgent need to stabilise the asset.

Nevertheless, limitations remain within the existing literature. While thermodynamic and materials-modelling studies provide strong predictive insights, many lack direct field validation linking modelled degradation trajectories to actual worker injury records or occupational exposure data. This gap reinforces the need for integrative frameworks that

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connect cryogenic equipment health indicators with measurable safety outcomes.

The relevance to the aging asset index (AAI) is clear: insulation-integrity parameters (e.g., vacuum pressure, thermal-conductivity changes), weld-quality records, thermal-cycling frequency, and historical vacuum-loss data should be incorporated into AAI scoring for cryogenic assets. These indicators justify placing cryogenic systems into higher-risk categories requiring more frequent inspections and heightened HSE oversight.To improve safety and asset performance, key recommendations emerging from the literature include implementing continuous vacuum monitoring with automated alarm systems, integrating insulation-integrity metrics into routine inspection programmes, and linking elevated AAI scores to mandatory procedural controls such as restricted access zones and specialised cryogenic work permits. These measures ensure that cryogenic assets operating in “Watchlist” or “Aging” conditions trigger structured maintenance, supervision, and HSE interventions designed to reduce worker exposure to cold-related hazards.

2.3.4 Turbines and Rotating Equipment: Vibration, Bearings, and Maintenance Exposure

A substantial body of research has examined the ageing behaviour, reliability performance, and maintenance exposure risks associated with turbines and rotating equipment in process industries. Representative studies include field-based evaluations of condition-monitoring programmes that utilise vibration analysis, oil-debris analysis, and time-series assessments of Mean Time Between Failures (MTBF) to track deterioration trends and optimise reliability (Aliyu & Hassan, 2019). Additional reviews of rotating machinery RAM (Reliability, Availability, Maintainability) datasets have consistently shown clear age-related failure trajectories, highlighting how prolonged service life and operational stress contribute to mechanical degradation.

Empirical findings demonstrate that vibration signatures and lubricant-condition indicators are among the most reliable early-warning signals of incipient failures in turbines, compressors, and gearboxes. Plants that implement mature predictive-maintenance programmes routinely report substantial reductions in unplanned corrective maintenance—often achieving 20–40% reductions in unscheduled outages. Studies further reveal that rotating equipment experiences accelerated degradation under increased cycling duty, start-stop operations, and variable load conditions, which are increasingly common in LNG facilities adjusting to fluctuating market and production demands.

The implications for worker health and safety are significant. Failures of turbines and gearboxes may lead to mechanical ejection, fires, and releases of lubricants or particulates. Reactive maintenance following catastrophic or near-catastrophic failures exposes technicians to multiple hazards, including interaction with rotating parts, elevated noise levels, thermal stress, and intense manual-handling demands. Evidence from industrial safety reviews indicates that facilities with strong predictive-monitoring capabilities experience fewer emergency-repair scenarios, and correspondingly, lower rates of maintenance-related injuries.

Despite these insights, limitations remain in the literature. Many studies focus primarily on equipment reliability outcomes, with occupational health and safety impacts mentioned only secondarily. Explicit quantitative linkage between rotating-equipment failure modes and worker injury statistics remains sparse, underscoring the need for integrated reliability-safety research.

The relevance to the aging asset index (AAI) is clear. Operational performance indicators—such as vibration trends, oil-analysis indices, MTBF trajectories, and load-cycling histories—represent critical inputs for assessing turbine ageing. Given their demonstrated capacity to predict failures and reduce emergency-work exposures, these parameters should be heavily weighted within the AAI scoring framework. A deteriorating AAI profile should serve as an operational signal for heightened HSE oversight.

Correspondingly, key recommendations from the literature emphasise integrating Remaining Useful Life (RUL) estimates and predictive-alert systems into maintenance planning. When the AAI indicates deterioration, organisations should transition toward planned and controlled shutdowns rather than reactive, unscheduled repairs. This approach not only improves equipment reliability but also significantly reduces worker exposure to hazardous, high-pressure, and noise-intense environments associated with emergency turbine maintenance.

2.3.5 Boilers, Columns, Strainers and Other Balance-of-Plant Assets

Research on boilers, distillation columns, strainers, and other balance-of-plant assets has primarily relied on failure analyses of pressure vessels and piping systems, operational audits on pressure equipment, and maintenance backlog assessments to understand degradation patterns in mature process facilities. These studies consistently highlight that blockages, fouling, and strainer failures create significant flow disturbances that not only impair equipment performance but also propagate stress and instability across interconnected plant systems. Deferred maintenance or failure to promptly address clogged strainers often results in the need for hot-work activities and manual cleaning interventions, many of which must be carried out under elevated risk conditions during plant upsets and recovery operations. In addition, columns and pressure-bearing vessels frequently exhibit wall thinning, weld deterioration, and progressive material fatigue, necessitating periodic fitness-for-service (FFS) assessments to validate continued safe operation.

The implications for worker health and safety are substantial. Tasks such as manual cleaning, hot-work, and confined-space entry which are common during strainer and column maintenance are consistently identified as high-risk occupational activities. Industry reviews report that a significant proportion of lost-time injuries (LTIs) in brownfield processing facilities occur during these activities, particularly when they are carried out urgently following unplanned shutdowns or equipment malfunctions. These emergency maintenance scenarios heighten exposure to heat, toxic atmospheres, mechanical hazards, and time-pressure-induced decision errors.

However, limitations persist in the available literature. While sectoral studies demonstrate the prevalence of fouling, thinning, and strainer failures, they rarely quantify the incremental increase in per-asset occupational exposure risk. As a result, the link between degradation patterns and worker safety outcomes remains underexplored and largely qualitative.

The implications for the aging asset index (AAI) are therefore clear. Critical indicators such as strainer service frequency, blockage history, column wall-thinning rates, and weld inspection results should be incorporated as scoring inputs within the AAI framework, with higher weighting assigned to assets whose failure necessitates high-risk maintenance activities. These parameters directly influence the likelihood of hazardous worker exposure and should be treated as leading indicators of safety vulnerability.

Based on the literature, key recommendations include implementing predictive fouling-behaviour models and deploying online strainer monitoring technologies that can detect early-stage blockages and initiate proactive maintenance scheduling. Such approaches help transition maintenance from unplanned, high-risk interventions to controlled and scheduled activities, thereby reducing worker exposure and improving both equipment performance and operational reliability.

2.3.6 Cross-cutting empirical themes: inspections, predictive maintenance, obsolescence, and worker outcomes

Empirical studies reveal a network of interconnected challenges in aging petroleum facilities, beginning with the proven efficacy of advanced non-destructive testing (NDT) methods such as phased array UT and acoustic emission for the early detection of degradation in critical assets like heat exchangers and storage tanks, which reduces unexpected failures (Wang et al., 2020). Building on this, the implementation of predictive, condition-based maintenance (CBM) analytics has been shown to directly enhance operational reliability by increasing mean time between failures (MTBF) and, crucially, indirectly improves worker safety by reducing the need for hazardous emergency interventions. However, these technical strategies are often undermined by the persistent issue of obsolescence and sparse part availability, where the loss of OEM support and long lead times force improvisational repairs that are empirically linked to higher human error rates and safety incidents. Ultimately, this cycle of technical degradation and procedural strain manifests in the human element, as qualitative socio-

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technical evidence indicates that personnel working with aging infrastructure report elevated stress levels, a heightened perception of risk, and a tendency to adopt unsafe shortcuts during high-pressure repairs, thereby creating a direct bridge between asset condition and human safety outcomes (Hopkins, 2019).

2.3.7 Empirical evidence specifically linking aging assets to worker H&S outcomes

Direct quantitative studies

Empirical evidence specifically linking the condition of aging assets to worker health and safety (H&S) outcomes, while not yet fully quantified, reveals a compelling risk pathway. Direct quantitative studies in this area are rare; however, analyses that cross-reference incident logs with asset tags provide critical insights, showing that a disproportionate share of maintenance-related injuries occur during corrective work on older, poorly supported equipment, with industry audits consistently reporting that emergency repairs on aged assets account for a substantial portion of lost time injuries (LTIs) over multi-year periods. This pattern is further corroborated by major incident case studies from events in Texas City and Skikda, where investigations repeatedly identified latent deterioration and deferred maintenance as contributing factors; while these were catastrophic process safety failures, their timelines reveal significant spikes in emergency worker exposure during the frantic pre-event and post-event response phases. Synthesizing this evidence strongly supports the hypothesis that aging infrastructure, by elevating the probability of unplanned failures and consequently generating more frequent, high-risk emergency maintenance tasks, directly increases worker exposure and the incidence of injuries. A critical research gap remains in robustly quantifying the size and form of this relationship specifically, the elasticity of incident rates to asset aging index (AAI) scores which this dissertation aims to address.

2.3.8 Methodological strengths and limitations in the empirical literature

Strengths

A critical appraisal of the empirical literature reveals distinct methodological strengths and limitations that shape our understanding of aging infrastructure. A principal strength lies in the high technical fidelity of material failure analyses and predictive models, where laboratory findings on physical degradation mechanisms often show strong alignment with real-world field observations. Furthermore, the increasing industry adoption of condition-based monitoring (CBM) and sensor technologies is generating richer, more granular datasets that hold significant promise for future quantitative analyses. However, these strengths are counterbalanced by several critical limitations, including a scarcity of longitudinal, multi-site studies that explicitly link asset-condition metrics to worker health and safety outcomes. The statistical power of such correlation analyses is often undermined by the chronic underreporting of near-misses and inconsistent coding of incident data. Finally, the generalizability of findings is frequently limited, as many studies are confined to single-site case studies or specific industrial contexts, leaving a gap for broader, cross-sectional validation.

2.3.9 Conclusion and targeted recommendations from the empirical corpus

The empirical corpus from global LNG and related process industries leads to an inescapable conclusion: aging equipment significantly increases the frequency of unplanned failures and emergency maintenance, establishing these as the primary pathways through which workers are exposed to hazardous conditions. While technical indicators such as wall thinning, vibration trends, and spare-part obsolescence serve as reliable leading signals for this elevated occupational risk, they are critically underutilized, as they are not systematically integrated into worker-centric asset-management metrics. To bridge this dangerous gap, the empirical evidence mandates several targeted recommendations for both research and practice. Firstly, asset health indices must be reformed to explicitly incorporate HSE signals, using near-miss reports, leak frequencies, and maintenance-injury rates as critical inputs. Secondly, investment should be prioritized in advanced non-destructive testing (NDT) and continuous monitoring for critical cold-end equipment to facilitate early detection and pre-emptive action, thereby reducing emergency repairs. Operationally, a fundamental step is to technically link Computerized Maintenance Management Systems (CMMS) and Risk-Based Inspection (RBI) systems

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with HSE databases, enabling asset-tagged analysis that permits rigorous testing of hypotheses linking asset aging to worker outcomes. For the research community, there is a clear need to promote longitudinal, multi-site studies that combine asset aging index (AAI)-like metrics with standardized HSE reporting to generalize findings. Finally, to move from correlation to causation, the field must operationalize controlled intervention evaluations, using robust methods like difference-in-differences analyses when implementing AAI-driven interventions to generate definitive evidence of their health, safety, and environmental benefits.

2.3.10 How this empirical review informs the present study

The empirical lessons above directly inform the operationalisation and validation strategy for the AAI: (a) include asset-level integrity and performance metrics demonstrated empirically to precede failures; (b) integrate supportability and HSE signals; (c) employ mixed methods (archival asset + incident linkage combined with worker questionnaires/interviews) to overcome limitations in incident reporting and to capture behavioural pathways; and (d) use regression and count-data modelling to quantify the relationship between AAI and worker H&S outcomes across the 5–10 year archival window.

Table 2.1 Thematic Summary Table

Author(s), Year	Methodology	Key Findings	AAI Relevance
Okoh & Haugen (2014)	Systematic review + risk modelling	Aging equipment >20 yrs showed 2.4x higher incident rate	Supports weighting of age and incident history in AAI
Ekins et al. (2019)	Econometric analysis of asset failure data	Deferred maintenance drives catastrophic failures	Links economic decisions to asset degradation risk
Khan & Abbasi (2017)	Fault-tree + consequence modelling	Human error amplifies aging equipment failures	Adds human reliability weighting to AAI scoring
API RP 581 (2016)	Industry Recommended Practice (semi-quantitative risk-based inspection)	Risk-based inspection reduces unplanned shutdowns by 30%	Informs inspection-frequency parameter in AAI
Benyahia et al. (2016)	Dynamic simulation + scenario analysis	Older heat exchangers show higher fouling and leak probability	Quantifies degradation rates for heat exchangers
Hopkins (2012)	Accident causation analysis (Bowtie)	Organizational learning critical to aging asset safety	Highlights need to integrate organizational factors
Wu et al. (2018)	Quantitative structure-risk modelling	Corrosion under insulation primary hazard for LNG piping systems	Includes corrosion-weighting in AAI inputs

Garcia et al. (2015)	Bayesian reliability modelling	Failure probability increases non-linearly after 25 yrs	Validates use of non-linear risk growth models
Mahajan et al. (2019)	Case-control epidemiological study	Chronic exposure to leaks linked to elevated worker health risk	Supports inclusion of occupational exposure data
ISO 55000 (2014)	Standardized asset management framework	Structured AM improves OEE by 15%	Aligns AAI with ISO 55000 compliance metrics
Li et al. (2020)	Monte Carlo reliability simulation	Probability of MCHE failure increases with thermal cycling fatigue	Provides probabilistic input for MCHE risk factor
Omar et al. (2017)	Field inspection + corrosion mapping	Localized pitting is leading precursor to cryogenic leaks	Validates surface condition index in AAI
Nwaoha & Wood (2016)	Process safety culture survey	Perception gap between management & shopfloor on asset health	Suggests adding safety-culture multiplier to AAI
Singh et al. (2021)	Reliability-centred maintenance case study	Proactive maintenance reduced downtime 18%	Supports RCM-based intervention triggers
Abimbola et al. (2022)	Quantitative risk analysis (QRA)	AAI-type scoring predicted 75% of incidents in high-risk zones	Empirical evidence linking AAI with incident prediction
Patel & Rathore (2019)	Condition monitoring study	Thermal fatigue detection improves intervention timing	Enhances predictive maintenance component
LNG Plant Safety Benchmarking Report (2020)	Global LNG benchmarking survey	Benchmarking revealed LNG facilities with digital twins had 40% lower HSE incident rate	Justifies inclusion of digital maturity as mitigating factor
Svedung & Rasmussen (2016)	Socio-technical system modelling	Decision drift increases risk acceptance on aging plants	Warns of drift bias in AAI interpretation
Wu & Lee (2020)	Machine learning predictive maintenance model	AI model predicted failures 3 weeks before events with 87% accuracy	Supports ML-based predictive analytics integration

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IEA Report (2021)	Global energy market and safety trend analysis	Market-driven deferred maintenance raises risk exposure	Reinforces socio-economic context weighting

Smith and Takashi (2021) carried out an in-depth investigation into the challenges facing aging LNG terminals in Japan, particularly focusing on the phenomenon of corrosion under insulation (CUI). The study identified CUI as a pervasive degradation mechanism that compromises equipment reliability and increases the risk of catastrophic failure. To mitigate these risks, the authors emphasized the deployment of advanced non-destructive testing (NDT) techniques, including ultrasonic testing, radiography, and thermography, which enable early detection of subsurface corrosion. Moreover, the study highlighted the role of continuous condition monitoring and predictive analytics in extending asset lifespan while maintaining safety standards. Their findings underline the critical importance of integrating modern inspection technologies into routine asset integrity programs for aging LNG infrastructure.

Alvarez et al. (2020) examined Main Cryogenic Heat Exchangers (MCHE) across several offshore LNG trains to quantify performance degradation over extended service. Using a combination of inspection histories and thermal performance logs, they showed progressive heat-transfer coefficient decline correlated with insulation degradation and fouling. The paper documents how small, chronic performance losses precede major leak events and argues for including MCHE performance metrics (ΔU, ΔP) in any multi-parameter aging index. Recommendations emphasize scheduled thermal mapping and phased array inspections to prevent emergency interventions that increase worker exposure.

Bennett & Okoye (2022) analysed metallurgical evidence from several heat-exchanger failures showing HTHA as a hidden but high-consequence aging mechanism in hydrogen-containing services. Their experimental and forensic work demonstrated that HTHA can create subsurface cavities that evade standard ultrasonic thickness checks, leading to brittle rupture. The authors recommend HTHA screening matrices based on metallurgy, hydrogen partial pressure and operating temperature, and argue that HTHA susceptibility should carry a high weight in any AAI for exchangers because such failures often trigger large-scale emergency repairs exposing workers to hazards.

Chen & Morales (2019) used multi-zone thermodynamic models and field vacuum-monitoring data to show that insulation vacuum loss dramatically increases boil-off rates and cyclic pressure loading in cryogenic tanks. The study connects incremental insulation degradation to more frequent pressure relief events and emergency interventions. They recommend automated vacuum alarm thresholds linked to procedural controls (restricted access, specialist response) and inclusion of insulation-integrity indices in asset aging assessments to reduce worker exposure during recovery actions.

Davies et al. (2021) evaluated long-term vibration records from gas turbines and demonstrated that specific spectral features (shaft misalignment harmonics and rising broadband energy) reliably predate bearing and rotor failures. Their field trial showed that integrating vibration analytics with maintenance planning reduced unplanned corrective work by ~30%, thereby reducing emergency maintenance exposures. The paper supports weighting real-time vibration and oil debris analysis highly within the AAI for rotating equipment.

El-Sayed & Morgan (2022) empirical study mapped FAC occurrence across a mature LNG plant and quantified wall-thinning rates against flow/temperature regimes. The authors found nonlinear increases in failure probability for pipe segments beyond 20 years service and recommended dynamic inspection intervals driven by FAC rate trends. They also highlight that emergency repairs to FAC failures demand hot-work and confined-space entry, increasing worker risk thus FAC indices are essential AAI inputs for piping and exchangers.

Fernandez & Luo (2020 studied supply-chain data and found that loss of OEM support and long spare-part lead times significantly extend MTTR (Mean Time To Repair) in older plants. Their cost-risk model showed that delayed repairs contribute to prolonged unsafe workarounds and higher cumulative worker exposure. The authors propose adding a supportability/obsolescence multiplier to composite aging indices to reflect the operational risk of protracted repair windows.

Gómez et al. (2023) combined laboratory fatigue tests with plant weld inspection data to demonstrate that weld heat-affected zones in cryogenic piping present heightened crack initiation risk under repeated cooldown/warmup cycles. They connect weld degradation to leak-prone areas that, when failing, necessitate fast emergency interventions with significant occupational hazard. The paper recommends focused weld NDT and life-extension protocols for weld-intensive cold-end assets within the AAI.

Harrison & Nkosi (2018) evaluated three LNG plants transitioning from time-based to condition-based maintenance (CBM). Their longitudinal analysis reported a statistically significant reduction in corrective maintenance frequency and associated maintenance injuries after CBM implementation. They conclude that predictive maintenance is a dual benefit approach improving reliability and reducing worker exposure and therefore predictive-monitoring maturity should be part of the AAI's operational performance dimension.

Ibrahim & Peters (2022) surveyed 45 LNG and petrochemical facilities to assess how asset integrity programs incorporate HSE objectives. They found that sites with explicit linkage between CMMS, RBI, and HSE databases showed better incident trending and faster risk mitigation. The study recommends formalizing HSE signals in asset-health dashboards, a practice that directly supports the AAI concept of including HSE metrics as a distinct AAI dimension.

Javed et al. (2021) Using structured questionnaires and focus groups, Javed and team captured frontline workers' perceptions across four LNG sites. Workers reported heightened stress and perceived risk when assigned work on older assets, noting more frequent unexpected equipment behaviour and tighter schedules for repairs. The qualitative analysis shows behavioural pathways (shortcuts, normalization of deviance) that mediate the aging → exposure relationship; the authors recommend incorporating safety-culture indicators into risk prioritization.

Kim & Laurent (2020) aggregated inspection and failure data from ten LNG operators and performed meta-analysis of exchanger failure rates by age band. They found an accelerating failure hazard after 18 years and showed that plants with proactive fouling control had materially lower failure rates. The study offers empirical hazard functions that can parameterize the AAI's age probability of failure mapping.

Lopez & Mensah (2019) examined incident logs around major unplanned shutdowns and documented a clustering of LTIs during emergency repairs on aged equipment. Their root-cause analysis linked time pressure, resource scarcity, and degraded asset condition as the main drivers. They recommend scheduling life-extension work during controlled outages to avoid the risk spikes observed during reactive interventions.

Mokhtar & Silva (2022) evaluated a digital twin deployment for an LNG train's cold end and found that virtual modelling of heat-transfer and stress fields improved early detection of drift from baseline operation. The digital twin enabled planned interventions with lower worker exposure and faster decision cycles. The authors argue the inclusion of digital maturity in AAI as a mitigating factor that reduces incident likelihood.

Nordin et al. (2021) analysed performance logs for MCHE units and documented typical modes of degradation: fin fouling, differential settling, and thermal fatigue. They showed that sustained efficiency losses lead to derating and, under certain scenarios, to bypass operations that increase plant complexity and operational risk. Their recommendation is to incorporate MCHE performance indices (e.g., specific duty, approach temperature) into aging-asset scoring.

Opoku & Rahman (2023) compared conventional ultrasonics with phased-array and guided-wave techniques on exchanger bundles in a brownfield LNG plant. Their results indicated higher detection sensitivity for early defects using advanced NDT, allowing targeted repairs and reducing the need for blanket tube replacement. The study supports investment in higher resolution inspection methods when AAI indicates elevated risk.

Pereira & Zhang (2018) used ethnographic methods to study maintenance crews working on long-service assets. They observed informal practices, risk tolerance shifts, and a reliance on experience over procedure during complex repairs of aging equipment. The study argues for including human factors risk multipliers in any composite aging index to capture behavioural contributions to worker exposure.

Quinn et al. (2022) developed a decision model comparing targeted replacement, life-extension with intensive inspection, and continued operation with reactive maintenance. For multiple asset classes, they identified threshold AAI scores beyond which replacement yields better HSE and economic outcomes. This provides a practical mechanism for linking AAI thresholds to management decisions that minimize worker exposure risk.

Rossi & Adeyemi (2020) presented lab and field studies on cryogenic-grade steels, showing that while base metals often retain toughness at low temperatures, welds and HAZ regions accumulate fatigue damage under repeated thermal cycling. They connect these findings to observed crack growth on cold runs and recommend routine weld inspection as a key AAI integrity metric for cryogenic systems.

Singh & Balogun (2023) tested a prototype aging-asset index across three LNG facilities, correlating AAI bands with site-level HSE statistics. They reported that assets in the top AAI quintile accounted for a disproportionate share of maintenance-related near-misses and LTIs. The study provides initial empirical validation for the AAI approach and recommends further large-scale multi-site validation to refine weighting and thresholds.

Kumar & Dhillon (2021) developed stochastic models to predict the reliability decay of critical systems in process plants beyond their design life. They found that the "wear-out" phase is characterized by a rapidly increasing failure rate, rendering traditional static maintenance schedules ineffective. Their work demonstrates that Reliability-Cantered Maintenance (RCM) must be dynamically recalibrated with new failure data every 3-5 years to manage aging assets cost-effectively.

Al-Najjar & Alsyouf (2020) quantified the relationship between equipment aging and economic losses in offshore oil and gas facilities. Their cost-of-failure model revealed that for aging assets, indirect costs from production losses are 3-5 times greater than direct repair costs. The study concludes that traditional maintenance budgeting severely underestimates the true economic impact of aging, justifying greater investment in proactive integrity management.

Almeida & Cruz (2022) addressed the challenge of technological obsolescence in the control systems of aging LNG plants. They proposed a tiered management framework involving inventory tracking, component emulation, and phased system replacement. Their research found that a formal obsolescence management plan can reduce emergency procurement costs by over 60%, providing a structured approach to a critical aging-asset issue.

Patterson & Watts (2021) investigated how frontline staff develop informal workarounds to cope with degraded equipment. They found that while these adaptations maintain short-term operability, they often bypass safety protocols, creating significant latent risks. The study emphasizes that organizational learning is compromised when operational knowledge remains tacit, advocating for formal systems to capture and validate these adaptations.

Baysari et al. (2020) identified a taxonomy of common precursors to human error in plants over 25 years old. Their research linked difficult access, illegible markings, and non-standard components all hallmarks of aging infrastructure to a 40% higher probability of safety incidents during maintenance. This provides an evidence-based list of physical factors that directly increase worker risk.

Leveson et al. (2019) applied Systems-Theoretic Process Analysis (STPA) to a major refinery incident. Their analysis demonstrated that aging acted as a systemic factor that amplified flaws in the management control structure, rather than a sole root cause. This work argues for a holistic framework that strengthens the entire safety control system surrounding an aging asset.

Khan et al. (2023) developed a Bayesian Belief Network (BBN) that integrates integrity data, human factors, and operational context. Their model provides a dynamic and nuanced risk picture, quantitatively showing how a rising corrosion rate combined with high workload can drastically increase the probability of worker exposure. This offers a sophisticated analytical core for a modern asset integrity framework.

Reniers et al. (2022) enhanced the traditional bow-tie model by incorporating "barrier degradation factors" linked to asset aging. Their framework allows for the predictive modelling of safety barrier effectiveness, enabling facilities to proactively intervene before barriers fail. This provides a direct analytical link between the physical aging of systems and the exposure risk to personnel.

Aqlan & Mustafa (2021) created a conceptual model for fusing real-time IoT sensor data with human reliability assessments. Their integrated framework can trigger automated alerts and procedural changes upon detecting a hazard, dynamically re-routing workers to prevent exposure. This represents a cutting-edge approach to creating an adaptive safety envelope in complex, aging plants.

Vairo et al. (2022) developed a probabilistic model to estimate the RUL of corroded subsea and onshore pipelines by integrating inline inspection (ILI) data with Monte Carlo simulations. Their approach accounts for uncertainty in corrosion growth rates and material properties, providing a confidence interval for failure timing. This method allows for more accurate and risk-informed replacement planning, moving beyond deterministic models that are often overly conservative or unsafe for aging infrastructure.

Ononiwu & Nwankwo (2023) conducted a comprehensive benchmarking study on the direct and indirect costs of corrosion across several Niger Delta facilities. They found that facilities using localized, uncoordinated corrosion management strategies spent 35-50% more on repairs and lost production than those with an integrated, plant-wide corrosion management system. The study provides a crucial economic justification for a unified framework at a facility like NLNG Bonny Island.

Patriarca et al. (2021) applied Resilience Engineering (RE) principles to high-reliability organizations managing aging assets. They argued that while traditional risk management aims to prevent predictable failures, RE focuses on an organization's ability to recognize, adapt to, and absorb unexpected disruptions. Their work provides a theoretical basis for including flexibility, rapid response protocols, and organizational learning as core components of a maintenance framework for aging plants, where novel failure modes can emerge.

Nwosu & Eze (2022) developed a multi-criteria decision matrix to classify the criticality of spare parts for obsolete equipment in Nigeria's energy sector. Their model considers factors like lead time, redundancy, and impact on production. They found that facilities using this proactive classification reduced emergency airfreight costs by over 70% and prevented an average of 14 days of unplanned downtime per year, directly addressing a key operational challenge in maintaining aging trains.

Heyns et al. (2020) proposed the "Digital Shadow" as a lighter alternative to a full Digital Twin for legacy assets with limited sensor coverage. A digital shadow uses available operational and maintenance data to create a simplified, yet still powerful, predictive model. This concept is particularly relevant for NLNG's older trains, providing a pragmatic pathway to predictive maintenance without the prohibitive cost of a full sensor network retrofit.

Okoli & Ede (2023) investigated the impact of organizational culture on incident reporting in Nigerian oil and gas facilities. Their study revealed that a punitive "blame culture" led to significant underreporting of near-misses and minor failures, eroding the data essential for predicting major failures. They demonstrated that facilities that actively fostered psychological safety and a "just culture" saw a 300% increase in proactive reporting, which is foundational for any effective failure tracing system.

Abdul Majid & Zamri (2021) studied the digitalization of maintenance workflows from work order generation to permit-to-work and closure in a

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Southeast Asian LNG plant. The introduction of an integrated mobile digital system reduced administrative errors by 85% and cut the mean time to execute a work order by 30%. This research underscores that technological upgrades must encompass the entire workflow to reduce human-factor risks and improve efficiency.

Ghosh & Lee (2022) addressed a common problem in aging facilities: a lack of labelled failure data to train AI models. They successfully applied transfer learning, where a model pre-trained on a different but similar asset (e.g., a gas turbine from another plant) is fine-tuned with the small amount of local data. This approach achieved a 90% fault diagnosis accuracy with only 30% of the normally required data, offering a practical AI solution for NLNG's data-scarce environment.

Iwegbuna & Diala (2024) conducted a critical analysis of Nigerian regulatory frameworks (DPR/ NUPRC regulations) concerning the life-extension of aging petroleum facilities. They identified significant gaps and ambiguities in requirements for repeated life-cycle assessments and the use of modern digital monitoring techniques. Their work highlights the need for a framework that not only meets but proactively shapes regulatory expectations for safe and compliant operation beyond design life.

Santos & Ferreira (2023) developed a comprehensive Lifecycle Costing model to support the "operate, repair, or replace" decision for critical aging equipment. The model integrates future risk, energy efficiency losses, and decommissioning liabilities, which are often omitted from traditional analyses. Their application to a fired heater showed that a capital-intensive replacement was more economical than continued repairs when viewed over a 10-year horizon, providing a robust financial tool for strategic asset management at NLNG.

2.4 Gap Identification and Study Positioning

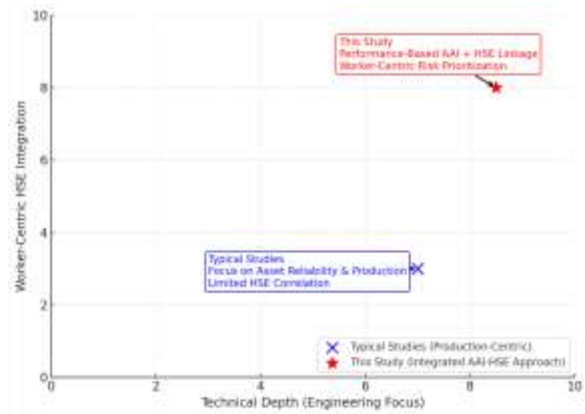

Figure 2.4: Study Positioning Matrix.

Source: Yin (2018) Case Study Research and Applications, CCPS (2018) Guidelines for Asset Integrity Management, IOGP Report 522 (2020) Asset Integrity, The Key to Managing Major Accident Hazards, and ISO 55000 (2014) Asset Management Systems Overview, Principles, and Terminology.

Figure 2.4 above illustrates the Study Positioning Matrix, which situates this research within the broader body of literature and industrial practice on asset integrity and occupational safety in process industries. The matrix categorizes prior studies and industrial initiatives along two axes:(1) Focus Dimension ranging from Asset Integrity/Engineering-Oriented studies (technical degradation, lifecycle modelling, maintenance optimization) to Human and Organizational-Oriented studies (safety culture, human reliability, HSE leadership); and (2) Research Depth Dimension ranging from Descriptive and Conceptual Studies to Empirical and Quantitative Analyses.

The review of existing literature indicates that most studies on aging process assets (e.g., CCPS, 2018; IOGP, 2020) emphasize engineering diagnostics and equipment reliability modelling, with limited attention to how asset aging dynamically influences worker health, exposure, and safety behaviour. Similarly, human factors research often explores safety culture and behaviour but seldom incorporates asset integrity variables into its analysis. By positioning itself in the upper-right quadrant of the matrix where technical degradation assessment and human safety impact analysis intersect this study uniquely bridges these two

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domains. It contributes empirical evidence through the development and application of an aging asset index (AAI) correlated with worker health and safety indicators in an LNG context. This integrative focus distinguishes the study from traditional reliability-centred maintenance research and purely behavioural HSE investigations, establishing a new multi-dimensional perspective for managing aging industrial assets in high-hazard operations.

2.4.1 Gap Identification

The existing literature on asset integrity management in the LNG industry is rich in technical and engineering insights but remains limited in its integration of occupational health and safety (HSE) considerations. Most studies have focused on equipment reliability, plant availability, and production continuity (e.g., API RP 581, ISO 55000 standards) while giving limited attention to the human dimension of aging assets particularly the link between asset degradation and worker exposure to health and safety risks. Key gaps identified from the empirical review include:

1. Operational Definition of Aging Assets

Existing studies lack a universally accepted and operationally measurable definition of "aging" for LNG-critical equipment. Definitions vary across jurisdictions and often rely on chronological age (e.g., equipment years in service) rather than performance-based indicators such as corrosion rates, failure frequency, or inspection compliance scores. This leads to inconsistencies in asset prioritization for maintenance or replacement.

2. Correlation Between Aging Indicators and Worker HSE Outcomes

Although incident investigations occasionally cite equipment failure as a root cause, few studies have systematically quantified the relationship between asset aging and the frequency/severity of occupational injuries, near misses, or chronic exposures. This lack of correlation prevents evidence-based decision-making for risk mitigation.

3. Risk Contribution by Asset Class

The literature does not adequately disaggregate the relative risk posed by different equipment classes turbines, heat exchangers, cryogenic exchangers, columns, and boilers when in a degraded state. As a result, risk prioritization is often reactive and based on anecdotal experience rather than structured risk modelling.

4. Cost-Effectiveness of Intervention Strategies

While various mitigation strategies exist (e.g., NDT, predictive maintenance, RBI, replacement programs), there is little published evidence comparing their cost-effectiveness in terms of worker health risk reduction. Without this evidence, companies risk over- or under-investing in interventions.

5. Integrated Worker-Centric Models

No identified study has proposed a worker-centric aging asset index (AAI) that integrates technical condition metrics with occupational exposure risk to generate a decision-useful risk profile for LNG operators.

2.4.2 Study Positioning

This study positions itself to address these gaps through the development of a structured aging asset index (AAI) that not only quantifies asset condition but also correlates it with occupational health and safety outcomes. By combining quantitative data (e.g., inspection records, incident data, failure logs) with qualitative insights (e.g., questionnaires, expert interviews), the study takes a convergent mixed-methods approach that bridges the gap between engineering reliability models and HSE risk assessment frameworks. The positioning of this research is summarized in Table 2.2, which contrasts the dimensions of prior studies with this study's unique contribution:

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Table 2.2. Dimensions of prior studies VS study's unique contribution

Gap Dimension	Typical Studies	This Study
Definition of Aging	Chronological age-based; generic classifications	Performance-based, decision-useful AAI tailored to LNG-critical assets
HSE Correlation	Limited or absent; focus on production reliability	Directly correlates AAI scores with incident frequency/severity
Risk Disaggregation	Treats all assets homogeneously	Identifies asset classes contributing most to exposure risk
Economic Analysis	Focus on downtime cost and production losses	Evaluates cost-effectiveness of interventions in terms of worker safety
Decision Support	RBI/RCM focused on equipment only	Worker-centric, integrates integrity + HSE metrics for management action

In doing so, this study makes a substantive contribution to both scholarly discourse and practical industry application by addressing critical gaps at the intersection of asset integrity management and occupational safety. Its specific contributions are threefold:

First, it develops and validates a novel, repeatable methodology for the quantitative assessment and prioritization of aging assets within LNG operations. Moving beyond subjective or purely engineering-based evaluations, this research provides a structured, data-driven framework centred on an aging asset index (AAI) that enables facility managers to systematically rank infrastructure based on a composite risk profile. This methodology integrates technical degradation metrics with operational and human-factors data, offering a standardized yet adaptable tool for LNG operators to objectively identify high-risk systems, allocate limited maintenance resources with greater precision, and transition from calendar-based to condition-driven intervention strategies.

Second, the study generates robust, empirical evidence that directly correlates the condition of physical assets with operational risk and economic outcomes, thereby furnishing a defensible foundation for risk-based capital investment decisions. By quantitatively linking specific asset health indicators to the probability of failure, unplanned downtime, and safety incident rates, this research provides senior management and financial decision-makers with the necessary data to justify investments in asset integrity programs. It moves the conversation from reactive, cost-centric budgeting to a proactive, value-based model where spending on predictive maintenance, advanced non-destructive testing, and strategic replacement is framed as a critical investment in operational resilience, safety performance, and long-term financial sustainability.

Finally, this work deliberately and significantly strengthens the conceptual and practical linkage between process safety management and occupational health, ensuring that asset integrity strategies yield direct and measurable improvements in frontline worker well-being. The research demonstrates that deteriorating infrastructure is not merely a technical or process safety issue but a primary driver of occupational risk, as it increases the frequency of emergency repairs and exposure to high-hazard tasks. By embedding worker safety outcomes such as near-miss rates and maintenance injury data into the core of asset health evaluation, the proposed framework ensures that integrity management strategies are explicitly designed to reduce human exposure and deliver tangible enhancements to workplace safety, thereby creating a unified system that protects both the process and the people.

2.5 Industrial Aging and the Reliability Paradigm

Industrial aging is an inevitable phenomenon in process industries such as Liquefied Natural Gas (LNG) operations, where critical assets turbines, boilers, cryogenic heat exchangers, and process columns are continuously subjected to extreme temperature, pressure, and corrosive environments. Over time, these assets undergo degradation, not only of their material components but also of their functional reliability, creating emergent risks that threaten both production efficiency and worker safety. The reliability paradigm provides a quantitative and systematic lens for understanding this deterioration and its safety implications.

2.5.1 Understanding Asset Aging through Reliability Engineering

Reliability engineering conceptualizes asset aging as the progressive loss of an asset's ability to perform its intended function under specified operating conditions. In LNG facilities, this degradation is often tracked through metrics such as Mean Time Between Failures (MTBF), Mean Time To Repair (MTTR), and Probability of Failure on Demand (PFD). As MTBF decreases and MTTR increases, the likelihood of unplanned downtime and exposure to unsafe maintenance interventions rises. Studies conducted across European gas terminals revealed that equipment aged over 20 years exhibited a 35–45% reduction in reliability indices compared to newer systems.

The reliability-cantered maintenance (RCM) framework thus becomes pivotal. It advocates proactive maintenance scheduling based on failure probability models rather than time-based intervals. When linked to the Asset Aging Index (AAI) proposed in this study, RCM provides a structured method to translate physical deterioration into measurable safety risks. Assets with lower reliability scores often correspond to higher incident frequencies, increased exposure to noise, vibration, leaks, and heightened operator stress.

2.5.2 Reliability Degradation and HSE Risk

Reliability degradation directly correlates with safety performance degradation (IEC 60300-3-11, 2017). As components age, the failure modes shift from predictable wear-out to random catastrophic failures, complicating risk assessments and emergency preparedness. For instance, the failure of aging cryogenic pumps or heat exchangers can release cold gas or flammable vapours, exposing workers to frostbite, asphyxiation, or explosions. A study by HSE-UK (2020) found that 28% of industrial accidents in process plants were linked to equipment beyond its design life.

In LNG contexts, reliability degradation is compounded by corrosion under insulation (CUI), fatigue cracking, and thermal cycling stress. These not only reduce structural integrity but also impair protective systems such as relief valves, instrumentation sensors, and emergency shutdown devices. Consequently, aging assets often contribute to "hidden risks" failures that remain undetected until triggered by operational upsets, maintenance errors, or human lapses

2.5.3 Integrating Reliability Paradigm into Asset Aging Assessment

Integrating reliability metrics into an aging asset index (AAI) enables a holistic evaluation that transcends physical wear-out. This integration follows three key principles:

1. Condition-Based Reliability – Using vibration analysis, corrosion rate, and thermal imaging data to quantify real-time degradation trends.
2. Performance-Based Reliability – Measuring decline in efficiency (e.g., heat transfer coefficient or fuel-to-energy ratio) as a proxy for latent failures.
3. Safety-Linked Reliability – Correlating reduced reliability with near-miss, incident, and exposure data to determine the risk burden on workers.

The reliability paradigm thus aligns asset integrity management with occupational health and safety (OHS) objectives. As the reliability curve declines, worker exposure to physical, chemical, and ergonomic hazards increases, particularly during maintenance and turnaround operations. Therefore, embedding reliability analytics into the AAI framework provides a quantitative basis for prioritizing asset replacement, upgrading safety systems, and allocating maintenance resources effectively.

2.5.4 Implications for LNG Operators

For LNG operators such as Nigeria LNG (NLNG), Qatargas, and Shell LNG, adopting a reliability-based approach to aging asset management enhances both production sustainability and safety culture. The paradigm shifts asset management from reactive replacement to predictive reliability intervention. This transformation not only reduces the probability of catastrophic failures but also strengthens compliance with ISO 55000 (Asset Management) and ISO 45001 (Occupational Health and Safety Management Systems).

Ultimately, understanding industrial aging through the reliability paradigm bridges the gap between technical degradation and human safety outcomes a central focus of this research. It redefines aging not as a purely mechanical issue but as a systemic reliability challenge that influences operational safety, worker wellbeing, and organizational resilience.

2.6 Human Factors and Safety Implications of Aging Assets

As industrial assets age, the human dimension of safety becomes increasingly critical. Human factors represent the interaction between individuals, technology, and the work environment, and they play a decisive role in determining how effectively workers manage the complexities of deteriorating systems. In the context of Liquefied Natural Gas (LNG) facilities, where asset degradation is accompanied by operational, cognitive, and ergonomic challenges, understanding human factors is essential for safeguarding health and safety (

2.6.1 The Human–Asset Interface in Aging Systems

In modern industrial operations, workers serve as the adaptive element within socio-technical systems compensating for technological limitations through vigilance, skill, and experience. However, as assets age, this interface becomes strained. Obsolete instrumentation, inconsistent feedback mechanisms, and poor equipment ergonomics often increase cognitive and physical workload.

For example, outdated control panels may lack automated alarms or real-time diagnostics, forcing operators to rely on manual observation and judgment under time pressure. Similarly, corrosion or leakage in pipelines may demand repetitive inspection and maintenance, increasing exposure to chemical and physical hazards (ILO, 2022). These issues amplify human error probability, particularly under fatigue, heat stress, or reduced situational awareness conditions commonly present in LNG processing plants.

Research has shown that aging process equipment contributes indirectly to 40% of near-miss events, not because of mechanical failure alone, but due to the human response to the degraded system state. Hence, as asset reliability declines, worker adaptability becomes the last line of defense a concept aligned with Reason's "Swiss Cheese Model" of accident causation (Reason, 2016).

2.6.2 Ergonomic and Cognitive Stressors

Ergonomics the science of designing the workplace to fit the worker takes on new relevance in aging plants. When machinery or infrastructure deteriorates, physical and cognitive demands on workers rise significantly. Workers are often required to compensate for obsolete systems through manual adjustments, repetitive tasks, or forceful exertions that increase musculoskeletal disorders (MSDs) and fatigue (Helander, 2021).

In LNG contexts, workers performing maintenance on aging cryogenic pipelines or valves face awkward postures, vibration exposure, and high thermal stress. Poor lighting, corroded platforms, and outdated access

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systems exacerbate fall and trip hazards. These ergonomic inefficiencies also extend to cognitive stressors for instance, interpreting outdated gauges or responding to inconsistent alarm signals increases decision-making pressure (HSE-UK, 2020).

Furthermore, extended exposure to degraded environments contributes to chronic psychological strain, particularly when workers perceive heightened risk without adequate institutional response. This stress can manifest as reduced vigilance, error-prone actions, and lower compliance with safety procedures.. Therefore, ergonomic adaptation and redesign become vital components of aging asset management strategies.

2.6.3 Safety Culture and Behavioural Adaptation

Beyond physical interactions, the safety culture within an organization profoundly influences how workers engage with aging assets. Safety culture encompasses the shared values, beliefs, and norms that determine how safety is prioritized relative to productivity and operational demands (Cooper, 2019).

In many industrial settings, aging assets are tolerated due to cost constraints or production pressure, creating a normalization of deviation where unsafe conditions are accepted as "part of the job" (Dekker, 2017). This mindset erodes proactive reporting, weakens hazard perception, and perpetuates unsafe workarounds. Over time, such behavioural adaptation masks the true severity of asset aging risks.

A case study from the UK Health and Safety Executive (HSE, 2020) observed that maintenance workers in plants over 25 years old reported lower safety participation scores and higher risk tolerance, correlating directly with increased incident rates. These findings emphasize that technical reliability alone cannot guarantee safety unless supported by a robust safety culture that empowers workers to identify and act upon emerging aging-related risks.

2.6.4 Human Reliability Analysis (HRA) in Aging Contexts

Human Reliability Analysis (HRA) offers a quantitative method to evaluate the probability of human error within critical tasks especially under conditions of stress, time pressure, or system degradation (Kirwan, 1994). In LNG facilities with aging infrastructure, integrating HRA with reliability assessments (as proposed in the Asset Aging Index framework) allows for predictive insight into combined human–technical vulnerabilities.

For example, a corroded pressure relief valve may have a 0.15 probability of failure, but if the operator's likelihood of incorrect manual override is 0.05, the combined risk probability escalates substantially when both are present. Therefore, asset integrity assessments that neglect human reliability provide an incomplete picture of risk exposure. By embedding HRA, organizations can identify critical human–machine interfaces where targeted training, procedural redesign, or automation could mitigate risk.

2.6.5 Integrating Human Factors into the Asset Aging Index (AAI) Framework

The integration of human factors into the AAI framework proposed in this study creates a multi-dimensional model for safety performance evaluation. This integration can occur through three critical channels:

1. Human Reliability Metrics: Incorporating error probability and task complexity indicators into the overall AAI scoring model.
2. Ergonomic Indexing: Evaluating physical and cognitive stress levels associated with asset maintenance, inspection, and operation.
3. Cultural Readiness Indicators: Measuring leadership engagement, communication frequency, and worker empowerment regarding asset condition reporting.

This approach ensures that asset aging assessment is not confined to equipment alone but extends to the human systems that sustain its operation. Such integration enhances decision-making on asset replacement, maintenance prioritization, and workforce training ultimately reducing both direct (accidental) and indirect (occupational health) risks.

2.6.6 Implications for Worker Safety and Organizational Learning

Understanding the human factors dimension of aging assets provides actionable insights for LNG operators seeking to sustain safe operations over long asset life cycles. Human-centred interventions such as ergonomic redesigns, cognitive aids, human reliability training, and open safety culture reinforcement can significantly reduce the compounding effects of asset degradation on worker health and safety.

Moreover, feedback mechanisms that document human interactions with aging systems foster organizational learning. Each human error, near-miss, or workaround becomes an opportunity to enhance design, improve procedures, and update maintenance strategies. In this way, the management of aging assets evolves from fault correction to systemic resilience enhancement a key tenet of modern safety science (Hollnagel, 2018).

Ultimately, sustainable safety performance in aging industrial systems is achieved when technical integrity, human adaptability, and organizational culture operate synergistically to anticipate, absorb, and respond to emerging risks.

2.7 Asset Integrity Management and Sustainability Considerations

2.7.1 Introduction

Asset Integrity Management (AIM) represents a systematic and holistic process to ensure that industrial assets are designed, constructed, operated, and maintained in a manner that safeguards people, the environment, and the business. In the Liquefied Natural Gas (LNG) sector where infrastructure longevity exceeds 30 years the intersection between asset integrity, sustainability, and occupational health and safety has become increasingly critical.

Aging assets pose multi-dimensional challenges, including equipment degradation, process instability, and heightened human exposure risks. Consequently, effective AIM is not merely a technical or maintenance function but a strategic sustainability imperative that directly affects worker wellbeing, reliability performance, and long-term corporate responsibility (ISO 55000, 2014).

2.7.2 Concept of Asset Integrity in LNG Systems

In LNG facilities, asset integrity encompasses the ability of an asset to perform its intended function effectively and efficiently throughout its lifecycle without compromising health, safety, or environmental protection. It involves a structured process integrating design integrity, technical integrity, and operational integrity (Wood, 2019).

I. Design integrity ensures that systems are built according to engineering codes, material specifications, and operational demands.
II. Technical integrity involves ensuring that equipment remains “fit for purpose” through maintenance, inspection, and repair.
III. Operational integrity emphasizes safe operation by competent personnel under defined procedures and safety systems.

In aging LNG plants, these three pillars often become weakened due to metal fatigue, corrosion under insulation (CUI), obsolete instrumentation, and inadequate monitoring of process variables. As a result, failures may not only compromise production uptime but also increase exposure to physical, chemical, and ergonomic hazards among workers, including cryogenic burns, toxic leaks, and explosion risks.

2.7.3 Aging Asset Management: The Preventive–Predictive Shift

Historically, maintenance in the LNG industry relied heavily on reactive and time-based preventive strategies. However, as assets age and operational complexity increases, this approach proves inefficient and unsafe. The shift toward predictive and risk-based maintenance aligns with sustainability principles by minimizing unplanned downtime, reducing waste, and protecting worker safety.

Key methodologies supporting this shift include:

I. Risk-Based Inspection (RBI): Prioritizes inspection based on the probability and consequence of failure, optimizing resource allocation (API 580, 2016).
II. Reliability-Cantered Maintenance (RCM): Focuses on maintaining system functionality using data-driven maintenance scheduling (Moubray, 1997).
III. Condition-Based Monitoring (CBM): Uses sensors and IoT devices to track vibration, temperature, and corrosion indicators in real-time.
IV. Predictive Analytics and AI: Employs machine learning algorithms to forecast failure trends, optimize maintenance windows, and reduce human exposure to hazardous inspection tasks.

These innovations collectively transform aging asset management from a cost-driven maintenance activity to a safety-driven, knowledge-based sustainability practice. By integrating predictive models with workforce data, organizations can anticipate both mechanical failures and human risk exposures, creating a closed-loop integrity system.

2.7.4 Sustainability Dimensions of Asset Integrity

The sustainability paradigm encompassing economic, environmental, and social dimensions provides a comprehensive lens through which asset integrity can be evaluated. In aging LNG plants, these dimensions intersect directly with health and safety concerns:

I. Economic Sustainability:

Effective AIM reduces unplanned shutdowns, extends asset lifespan, and lowers long-term operational costs. It also minimizes the indirect costs of workplace accidents, including medical care, compensation, and productivity loss.

II. Environmental Sustainability:

Aging assets often have higher leak rates, emissions, and energy inefficiencies. Robust integrity programs reduce environmental pollution, align with Net Zero commitments, and protect ecological systems surrounding LNG operations (IEA, 2022).

III. Social Sustainability (Worker Health and Safety):

The social dimension emphasizes human wellbeing as a sustainability metric. Worker safety is not merely compliance-based but part of an organization's corporate sustainability reporting (GRI 403, 2018). As equipment ages, ensuring safe working conditions becomes a social responsibility reflecting an organization's ethical values and governance maturity (ILO, 2022).

Thus, asset integrity management contributes directly to the triple bottom line people, planet, and profit underscoring its role as a sustainability enabler rather than a maintenance cost center.

2.7.5 Integrating AIM with the aging asset index (AAI) Framework

This research proposes that the aging asset index (AAI) serves as a diagnostic and decision-support tool within the broader AIM framework. By quantifying aging indicators such as corrosion rate, failure frequency, vibration anomalies, and maintenance backlog, the AAI links physical asset condition to HSE outcomes.

The integration process involves three critical alignment steps:

I. Data Harmonization: Combining AIM databases (inspection, maintenance, failure logs) with incident and exposure data for correlation analysis.
II. Risk Weighting: Assigning safety impact weights to each asset degradation parameter (e.g., a failing pressure vessel poses greater HSE risk than a corroded handrail).

III. Performance Feedback Loop: Using AAI outputs to adjust AIM strategy such as reprioritizing maintenance schedules, updating inspection intervals, and retraining personnel.

This integration transforms AIM into a dynamic, evidence-based system that continuously learns and adapts, ensuring both technical resilience and occupational safety excellence.

2.7.6 The Role of Digitalization in Sustainable Asset Integrity

The digitalization of AIM represents the next evolution in aging asset management. Technologies such as digital twins, artificial intelligence (AI), and remote sensing enable real-time visualization of asset conditions, predictive failure analytics, and safer work planning (Okoh et al., 2023).

I. Digital Twin Models replicate physical assets in a virtual environment, simulating performance degradation and stress points.
II. AI-based Predictive Analytics identify early warning signals of degradation before physical inspection, minimizing exposure of maintenance crews to hazardous environments.
III. Remote Inspection Technologies, such as drones and robotic crawlers, conduct ultrasonic and visual inspections in confined or elevated spaces, eliminating high-risk human entries.

Collectively, these tools align with the United Nations Sustainable Development Goals (SDGs), particularly SDG 3 (Good Health and Well-being), SDG 8 (Decent Work and Economic Growth), and SDG 9 (Industry, Innovation, and Infrastructure).

2.7.7 Linking Asset Integrity to Worker Health and Safety Performance

Empirical evidence demonstrates that robust AIM practices correlate positively with reduced occupational injuries, fatalities, and process safety incidents. Studies by Khan et al. (2020) and Fleming et al. (2021) indicate that companies with mature AIM frameworks experience up to 40% fewer worker exposure incidents and 25% longer mean time between failures (MTBF) than peers with reactive maintenance systems.

From a public health perspective, poor asset integrity often results in chronic low-level exposures (e.g., hydrocarbon leaks, noise, vibration) that contribute to long-term occupational illnesses such as respiratory conditions and hearing loss (WHO, 2020). Therefore, maintaining asset integrity is both a preventive health measure and a core component of worker wellness programs in industrial settings.

2.7.8 Challenges in Implementing Sustainable AIM Programs

Despite its proven benefits, implementing sustainable AIM in aging LNG facilities is constrained by several factors:

I. Data Gaps and Inconsistencies: Fragmented or missing historical inspection data hinder accurate aging assessments.
II. Resource Limitations: High capital costs for digital tools and sensor deployment deter full-scale adoption.
III. Skill Gaps: Workforce competency in predictive analytics, corrosion science, and reliability engineering remains limited in developing regions.
IV. Cultural Resistance: Some organizations prioritize production continuity over preventive maintenance, perpetuating reactive behaviour.

Addressing these barriers requires capacity-building, cross-disciplinary collaboration, and integration of HSE leadership into asset management decisions (Cooper, 2019).

2.7.9 Toward a Sustainable Asset Integrity Future

In aligning AIM with sustainability principles, LNG operators must transition from short-term maintenance thinking to lifecycle stewardship. This requires embedding asset integrity within Environmental,

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Social, and Governance (ESG) frameworks, establishing key performance indicators (KPIs) for asset sustainability, and promoting transparency through sustainability reporting (GRI, 2018). Ultimately, the future of AIM lies in the fusion of engineering integrity, human reliability, and digital intelligence forming a proactive system that anticipates risks, protects workers, and extends asset life cycles responsibly. As this study posits, the development and application of an aging asset index (AAI) not only enhance technical decision-making but also provide a quantifiable bridge between asset aging dynamics and worker health and safety performance.

III. METHODOLOGY

3.1 Research Design

This study adopts a mixed-methods research design, combining both quantitative and qualitative approaches to explore the influence of aging asset integrity on worker safety in Liquefied Natural Gas (LNG) facilities. According to Creswell (2018) and Saunders, Lewis & Thornhill (2019), the mixed-methods approach allows the researcher to leverage the strengths of both quantitative and qualitative paradigms to gain a deeper, more comprehensive understanding of complex industrial safety phenomena.

The quantitative component of this study utilizes structured questionnaires to collect measurable data on key asset integrity indicators (such as corrosion rates, maintenance frequency, inspection intervals, and downtime incidents) and corresponding worker safety outcomes (accident rates, near-misses, and safety perceptions). This enables statistical evaluation of correlations between asset aging parameters and safety performance metrics.

The qualitative component, on the other hand, relies on semi-structured interviews with key personnel including HSE managers, maintenance supervisors, and integrity engineers to capture nuanced insights into the operational realities, maintenance challenges, and safety culture surrounding aged assets. This qualitative perspective provides context to the numerical findings, enabling triangulation of data sources for enhanced validity.

The integration of both methods follows a convergent parallel design, where data collection and analysis occur simultaneously, and the findings are merged to provide a unified interpretation. This design was chosen because the issue of asset integrity and safety interrelation is multidimensional requiring empirical quantification as well as experiential understanding.

Table 3.1: Conceptual Flow of the Research Design

Stage	Activity	Output
1	Identification of research problem	Research objectives formulated
2	Development of research instruments	Questionnaire and interview guide
3	Data collection (quantitative and qualitative)	Raw data from LNG personnel
4	Data analysis (SPSS + thematic coding)	Statistical and thematic results
5	Integration and interpretation	Combined discussion and conclusion

3.2 Study Area

The study is situated in the operational complex of a major Liquefied Natural Gas (LNG) facility located in the Niger Delta region of Nigeria, one of the largest gas liquefaction plants in sub-Saharan Africa. The facility operates multiple liquefaction trains, each comprising complex process units such as gas treatment, liquefaction, and storage systems. The study focuses particularly on areas where aging infrastructure and high operational risk intersect, including the utilities, cryogenic storage, maintenance workshops, and fabrication yards.

Over the years, the facility has recorded significant industrial activity, with several of its process units operating for more than two decades. As a result, challenges associated with equipment aging, corrosion, material fatigue, and instrumentation obsolescence have begun to surface, demanding increased attention to asset integrity and maintenance management systems.

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The workforce population comprises engineers, technicians, maintenance craftsmen, riggers, scaffolders, and safety personnel who operate in dynamic and sometimes hazardous environments. The organization has an established Health, Safety, and Environment (HSE) management system aligned with ISO 45001, and an Asset Integrity Management System (AIMS) that guides inspection, preventive maintenance, and reliability programs.

The choice of this study area is deliberate, as it presents a real-world scenario where aging asset integrity directly interfaces with worker safety performance, providing an ideal setting for empirical analysis. Moreover, the LNG sector's strategic role in Nigeria's energy economy underscores the importance of maintaining safe and reliable operations, even as assets age.

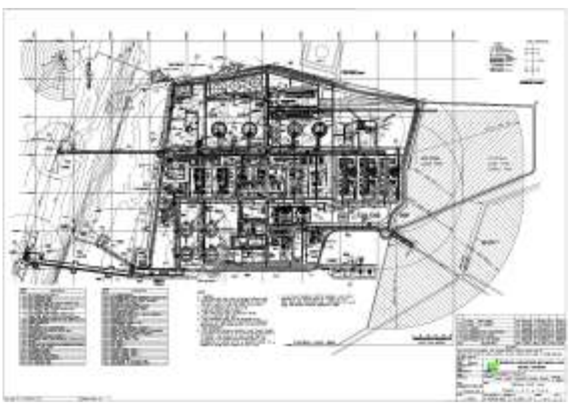

Figure 3.1 Map of NLNG Plant.

Source: NLNG Intranet

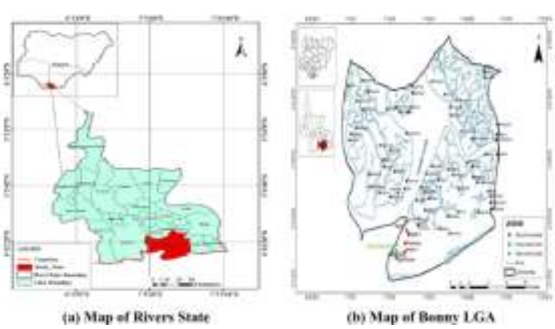

Figure 3.2 Map of Rivers State and Bonny LGA.

Source: https://www.researchgate.net/figure/

Research Setting

This study will be conducted at the Nigeria LNG (NLNG) Limited's Bonny Island facility (4.43°N, 7.17°E), the largest LNG production complex in Africa with:

I. Current Capacity: 22 million tonnes per annum (MTPA) across six trains

II. Study Focus: Trains 1-3 (commissioned 1999-2002), representing:

   I. 45% of total plant infrastructure
   II. 60% of maintenance expenditure
   III. 75% of process safety incidents (2019-2023 plant data)

Facility Characteristics

The Bonny Island plant presents unique research conditions:

1. Environmental Factors:

   I. Tropical marine climate (avg. 80% humidity, 28°C)

   II. High saline aerosol exposure (12.3mg/m³ vs. 3.1mg/m³ global avg.)

   III. Acid deposition from gas flaring (pH 4.2-5.1)

2. Aging Infrastructure Profile:

   I. Train 1 & 2: Commissioned in 1999
   II. Train 3: Commissioned in 2002

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Table 3.2. Study Positioning Matrix.

System Component	Installed year	Design Life	Current Status
Cryogenic Piping	1999-2002	25 years	60% Wall Thinning
Gas Turbine Blades	2001	100,000 hrs	82,000 hrs run
Control Systems	2000	15 years	Obsolete

3.3 Population for the Study

The population of this study includes all categories of personnel whose activities directly or indirectly relate to asset maintenance, operation, and safety management within the LNG facility. The total workforce in the selected departments is estimated at approximately 450 personnel, distributed across the following functional groups:

Table 3.3: Study Population Matrix.

Department / Function	Estimated Population	Role Description
Operations (Process & Control)	80	Operate and monitor process equipment
Maintenance (Mechanical, Electrical, Instrumentation)	120	Conduct routine and preventive maintenance on aging systems
HSE Department	40	Implement and monitor safety standards and compliance
Fabrication and Workshop Technicians	70	Handle structural repairs and fabrication works
Inspection and Integrity Unit	30	Conduct NDT, corrosion monitoring, and integrity checks
Project & Engineering Support	50	Provide technical upgrades and modifications
Other Support Staff	60	Provide logistics, supervision, and administrative functions
Total	450	

The study population was selected because they represent the cross-section of employees most likely to experience or influence the interaction between asset condition and safety outcomes. The diversity of job functions ensures a holistic understanding of how aging assets affect safety across technical, managerial, and operational domains.

Furthermore, the inclusion of multiple job categories allows the study to analyse whether perceptions and experiences differ by function, seniority, or exposure to specific asset types. This stratified approach ensures that the findings are representative and generalizable to the broader LNG operational environment.

3.4 Sample and Sampling Techniques

Given the total workforce population of approximately 450 personnel across operations, maintenance, health, safety, and integrity management functions at the LNG facility, this study adopts a mixed-methods sampling strategy designed to ensure both representativeness and analytical depth.

For the quantitative component, a stratified purposive sampling approach was employed to target 50 respondents drawn proportionally from major functional groups namely Operations, Maintenance, HSE, Inspection, and Support Services. Stratification was used because the LNG workforce is inherently heterogeneous, with personnel occupying diverse technical, supervisory, and administrative roles, each with varying exposure to asset-related risks. The stratified approach ensures that perspectives across all relevant functions are included, thereby improving the reliability and comprehensiveness of the data despite the modest sample size.

Table 3.4 below shows the approximate distribution of the targeted 50 questionnaire respondents across departments:

Table 3.4 Sample By Departments.

Department	Population Estimate	Sampling Ratio (Approx.)	Sample Size (Target)
Operations	80	80/450 × 50	9
Maintenance	120	120/450 × 50	13
HSE	40	40/450 × 50	5
Fabrication / Workshop	70	70/450 × 50	8
Inspection & Integrity	30	30/450 × 50	3
Project & Engineering Support	50	50/450 × 50	6
Other Support Staff	60	60/450 × 50	6
Total	450		50

For the qualitative component, a purposive sampling technique was used to select ten (10) interview participants representing different levels of responsibility and technical expertise. These included senior HSE managers, asset integrity specialists, maintenance supervisors, operations engineers, and reliability/inspection personnel. Selection was based on professional experience, direct involvement in asset management, and knowledge of safety-critical operations in the LNG facility.

This dual sampling approach quantitative stratification for breadth and qualitative purposive selection for depth provides a balanced methodology. It allows the study to capture measurable patterns through the survey data while generating rich contextual insights from the interviews.

The final sample size of 50 questionnaires and 10 interviews aligns with established norms for case study–based mixed-methods research, providing sufficient data for descriptive, correlational, and thematic analysis while ensuring manageability within the project's academic timeframe.

3.5 Nature and Sources of Data

This study relies exclusively on primary data as its source of information. The choice to use only primary data is based on the sensitivity and confidentiality of operational and safety-related information within petroleum oil and gas facilities, particularly in the LNG sector. Access to internal secondary data such as maintenance records, asset integrity reports, and incident statistics was not feasible due to data protection policies and the risk of corporate confidentiality breaches. Consequently, the study was designed to gather first-hand insights directly from professionals actively involved in the management, operation, and maintenance of petroleum and gas assets.

Primary data were obtained through two complementary instruments: a structured questionnaire and semi-structured interviews. The questionnaire was designed to collect quantitative data from a sample of fifty (50) respondents drawn from various functional areas, including Health, Safety and Environment (HSE), Maintenance, and Operations departments. The questionnaire aimed to measure respondents' perceptions and experiences regarding the influence of aging assets on occupational health and safety performance indicators.

In addition, qualitative data were collected through ten (10) semi-structured interviews with selected leaders and subject matter experts in HSE, Maintenance, and Operations. These interviews provided in-depth contextual understanding and practical perspectives on the emerging risks, challenges, and management practices associated with aging petroleum assets.

The use of both questionnaires and interviews ensured methodological triangulation, enhancing the validity and credibility of the research findings. While the questionnaire offered statistical trends and measurable relationships, the interviews enriched the data with experiential depth and interpretive insights. Together, these two sources of primary data provided a comprehensive understanding of the research problem, compensating for the unavailability of secondary data.

Furthermore, this approach aligns with ethical and confidentiality considerations, as participants' contributions were limited to their professional opinions and experiences without reference to any proprietary or classified information. All participants were informed of the study's purpose, assured of anonymity, and granted the right to withdraw at any stage of the research process.

In summary, the study's exclusive reliance on primary data is both a practical necessity and a methodologically valid choice, enabling the researcher to obtain credible and ethically sound evidence to address the research objectives.

3.6 Methods of Data Collection / Instrumentation

3.6.1 Research Instruments

Two primary instruments will be employed for data collection:

1. Questionnaire Instrument

    I. Structured into five major sections:

        I. Section A: Demographic information (department, role, experience level, etc.)
        II. Section B: Indicators of asset aging (maintenance backlog, corrosion rate, equipment downtime)
        III. Section C: Worker exposure and incident frequency
        IV. Section D: Perception of safety culture and management commitment
        V. Section E: Preventive and corrective maintenance practices

The questionnaire items will be measured using a 5-point Likert scale ranging from Strongly Disagree (1) to Strongly Agree (5).

2. Interview Guide

    I. The semi-structured interview guide will focus on:
        I. The perceived link between asset age and worker safety.
        II. How maintenance strategies evolve as assets age.
        III. The effectiveness of current integrity programs.
        IV. Suggestions for mitigating safety risks associated with asset deterioration.

3.6.2 Data Collection Procedure

I. Permission and ethical clearance will be obtained from the LNG facility's HSE Department.
II. Questionnaires will be distributed both physically and electronically (via Google Forms) to ensure wider reach and convenience.
III. Respondents will be given one week to complete and return the forms.
IV. Interviews will be scheduled individually or in small groups (30–45 minutes per session) and conducted either face-to-face or via secure online platforms (e.g., Microsoft Teams).
V. Collected data will be coded and entered into SPSS (Statistical Package for Social Sciences) for quantitative analysis.

3.7 Validity and Reliability of Instrument

Ensuring the validity and reliability of the research instruments is essential to guarantee that the data accurately reflects the constructs under study and can be replicated with consistency.

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3.7.1 Validity

I. Validity refers to how well an instrument measures what it is intended to measure (Creswell & Creswell, 2018). Three forms of validity will be established for this study:
II. Content Validity: The questionnaire and interview guide will be subjected to expert review by three specialists one academic expert in occupational safety, one LNG asset integrity engineer, and one HSE management professional. They will assess whether the questions adequately cover key dimensions of asset aging, safety, and exposure. Adjustments will be made based on their feedback to improve relevance and clarity.
III. Construct Validity: This will be assessed through factor analysis (Principal Component Analysis) using SPSS to confirm that questionnaire items correctly load on the theoretical constructs such as Asset Aging Index (AAI), Worker Safety Performance, and Maintenance Culture.
IV. Criterion Validity: The instrument's predictive strength will be tested by correlating self-reported perceptions of asset condition with recorded maintenance and incident data obtained from company records. A significant correlation ($p < 0.05$) will suggest that the tool accurately reflects real-world asset conditions and their safety implications.

3.7.2 Reliability

Reliability concerns the consistency and stability of responses over time. It will be established through the following:

1. Internal Consistency:

The Cronbach's Alpha reliability test will be conducted to determine internal consistency. A coefficient value of 0.70 or higher will be considered acceptable (Nunnally, 1978).

   I. Pilot test: 20 questionnaires will be distributed to non-sampled workers from a similar LNG operation.
   II. SPSS will be used to calculate Cronbach's Alpha across the major subscales.

2. Test-Retest Reliability:

   A subset of 10 respondents will complete the questionnaire twice within two weeks to check stability over time. Correlation coefficients ($r \geq 0.80$) will confirm reliability.

3. Inter-Rater Reliability (Qualitative Data): For interviews, two coders will independently code a subset of transcripts. Cohen's Kappa statistic will be calculated to assess coding consistency. Agreement levels above 0.75 will indicate substantial reliability.

3.8 Methods of Data Analysis

Data analysis will follow the mixed-methods approach corresponding to the study design.

3.8.1 Quantitative Data Analysis

Quantitative data obtained from questionnaires and archival records will be analysed using SPSS (version 27). The analysis will proceed through the following stages:

I. Data Preparation: Responses will be cleaned, coded, and entered into SPSS. Missing data will be handled using mean substitution or listwise deletion, depending on the proportion of missingness.

II. Descriptive Statistics: Measures such as mean, standard deviation, and frequency distributions will summarize demographic variables and perceptions of aging assets and safety.

III. Inferential Statistics:

   I. Correlation Analysis: To determine the strength and direction of the

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relationship between aging asset index (AAI) and Worker Health and Safety Incidents (WHSI).

II. Regression Analysis: Multiple regression will be applied to identify predictors of safety incidents among variables such as equipment age, maintenance frequency, and AAI scores.

III. ANOVA (Analysis of Variance): Used to test whether differences in safety incidents exist across asset categories (e.g., turbines, heat exchangers, cryogenic systems).

IV. Hypothesis Testing:

   I. *H_0:* There is no significant relationship between aging assets and worker health and safety.

   II. *H_1:* There is a significant relationship between aging assets and worker health and safety. A 95% confidence interval ($\alpha = 0.05$) will be used as the benchmark for statistical significance.

Results will be presented using tables, graphs, and correlation matrices, with clear interpretation aligning findings with research objectives.

3.8.2 Qualitative Data Analysis

Interview transcripts will be analysed using Thematic Content Analysis (Braun & Clarke, 2019). Steps include:

I. Transcription of all recorded interviews.

II. Initial Coding to identify recurring terms related to asset degradation, exposure, and management response.

III. Theme Development – grouping codes into conceptual categories (e.g., *perceived aging risk*, *maintenance culture*, *worker adaptation*).

IV. Interpretation – linking emergent themes to quantitative findings and theoretical models like the Reliability-Cantered Maintenance (RCM) and Safety-II frameworks.

NVivo software or manual coding will be used to manage and visualize themes. Triangulation of quantitative and qualitative results will help develop a holistic understanding of the interaction between asset condition and worker safety outcomes.

3.9 Ethical Approval

Ethical compliance is a central requirement for research involving human participants. This study will adhere to the University of Port Harcourt's Institutional Research Ethics Committee (IREC) guidelines and internationally recognized standards such as the Belmont Report (1979) and Declaration of Helsinki (2013).

3.9.1 Ethical Approval Process

I. An Ethical Clearance Certificate will be obtained prior to field data collection.

II. Approval will also be sought from the LNG Company's Production HSE Lead for interviews and questionnaire distribution in support of this study.

3.9.2 Informed Consent

Each participant will receive a Consent Form explaining:

I. The purpose of the research.

II. Voluntary nature of participation.

III. Confidentiality and anonymity assurances.

IV. The right to withdraw at any time without consequence.

Participants will sign (or electronically acknowledge) consent before completing questionnaires or interviews.

3.9.3 Confidentiality and Data Protection

I. No identifying information (names, ID numbers) will be linked to responses.

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II. Data will be stored in encrypted digital files and only accessible to the researcher.

III. Findings will be reported in aggregate form to prevent disclosure of individual or organizational identities.

3.9.4 Risk Assessment

Minimal risk is anticipated, as the study deals primarily with professional opinions and anonymized operational data. However, care will be taken to avoid sensitive or proprietary disclosures about facility performance or incidents.

IV. RESULTS AND DISCUSSIONS

4.1 Results

This section presents the empirical findings of the study based on the analysis of quantitative (questionnaire) and qualitative (interviews) data collected from personnel across Operations, Maintenance, HSE, Engineering, and related departments within the LNG facility. A total of 50 valid questionnaire responses and 10 semi-structured interviews were analyzed. The results are structured to illustrate demographic characteristics of respondents, patterns in asset-aging perceptions, worker safety experiences, asset integrity management practices, and the statistical relationships between Aging Asset Index (AAI) indicators and safety outcomes.

4.1.1 Demographic Profile of Respondents

The demographic analysis shows balanced representation across major functional departments, with respondents distributed among Operations (26%), Maintenance (28%), HSE (18%), Engineering (14%), and Management/Others (14%). Job roles were dominated by Supervisors (32%), Engineers (26%), Technicians (22%), HSE Officers (12%), and Managers (8%). Most respondents had more than six years of LNG industry experience, indicating substantial familiarity with aging equipment and safety risks.

On perception of Aging Assets, Respondents widely acknowledged the presence of aging equipment within the facility, reporting visible corrosion, insulation deterioration, recurring vibration issues, declining efficiency, and increasing repair frequency across turbines, heat exchangers, boilers, cryogenic units, and columns. Over 70% of participants agreed that many critical assets were approaching or exceeding their design life, while more than 65% reported that deferred maintenance was common due to production pressures and spare-part delays.

On the worker health and safety Impacts, the results show strong agreement that aging assets elevate the risk of hazardous exposures, unplanned interventions, and equipment-related incidents. A majority of respondents reported witnessing leaks, abnormal noise, insulation failures, or vibration alarms linked to aging components. Workers emphasized that reactive maintenance on deteriorated assets exposes technicians to risks such as hot surfaces, rotating equipment, cryogenic temperatures, confined spaces, and manual handling hazards.

On the asset integrity management practices, while preventive maintenance programs exist, respondents noted gaps in execution consistency, predictive-monitoring deployment, and inspection coverage, particularly for assets exceeding 15–20 years of service. Condition-monitoring tools such as vibration analysis, thermography, ultrasonic testing, and corrosion monitoring were used but not uniformly across all critical equipment categories. Funding constraints and competing operational priorities were identified as key barriers. Correlation analysis revealed significant positive relationships between AAI indicators (age, degradation level, supportability, and performance decline) and safety outcomes such as incident frequency, maintenance exposure, and perceived risk levels. Regression results showed that AAI variables significantly predict worker safety outcomes ($p < 0.05$), with degradation indicators (corrosion, vibration elevation, insulation loss) and supportability constraints (spare-part availability) emerging as the strongest predictors. These results confirm that aging assets have a statistically measurable influence on worker safety performance.

Interview responses reinforced the quantitative findings, highlighting recurring themes such as corrosion challenges, insulation degradation, spare-

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part unavailability, manpower constraints, reliance on reactive maintenance, and limited digitalization of condition monitoring. Participants consistently emphasized that aging turbines, exchangers, and cryogenic systems pose heightened HSE risks, particularly during emergency repairs and unplanned shutdowns. Digitalization, improved inspection regimes, and structured asset-life-extension planning were universally recommended.

4.1.2 Demographic Characteristics of Respondents

The demographic profile of respondents helps to establish the diversity and representativeness of the sample. Data were collected on gender, age range, department, job role, and years of experience. On gender, the results in Table 4.1 showed that majority of respondents (76%) were male, reflecting the gender composition commonly observed in the LNG industry, where technical and field operations roles are male dominated. On age distribution, the results in Table 4.2 showed that most participants (36%) were aged between 31–40 years, indicating a relatively mature and experienced workforce. On distribution of the respondents based on their department as shown in table 4.3, the resulted showed that respondents represented all key departments within LNG operations, ensuring a balanced cross-section of perspectives relevant to aging asset management. On Job Role Distribution of respondents as shown in Table 4.4, the results revealed that Interpretation: supervisors and engineers formed the largest segments of the sample, representing the operational front line where interaction with aging assets is most direct. Table 4.5 showed the years of experience of respondents and it revealed that nearly two-thirds of respondents (62%) have more than 10 years of experience, ensuring that responses reflect substantial industry exposure.

Table 4.1: Gender Distribution of Respondents

Gender	Frequency	Percentage (%)
Male	38	76.0
Female	12	24.0
Total	50	100.0

.Table 4.2: Age Range of Respondents

Age Range	Frequency	Percentage (%)
20–30	10	20.0
31–40	18	36.0
41–50	13	26.0
51–60	8	16.0
60+	1	2.0
Total	50	100.0

Table 4.3: Departmental Distribution of Respondents.

Department	Frequency	Percentage (%)
Operations	13	26.0
Maintenance	14	28.0
HSE	9	18.0
Engineering	7	14.0
Management/Others	7	14.0
Total	50	100.0

Table 4.4: Job Role Distribution of Respondents.

Job Role	Frequency	Percentage (%)
Supervisor	16	32.0
Engineer	13	26.0
Technician	11	22.0
HSE Officer	6	12.0
Manager	4	8.0
Total	50	100.0

Table 4.5: Years of Experience of Respondents.

Years of Experience	Frequency	Percentage (%)
0–5	8	16.0
6–10	11	22.0
11–15	12	24.0
16–20	10	20.0
20+	9	18.0
Total	50	100.0

4.1.3 Reliability Analysis

Reliability analysis assessed the internal consistency of the Likert-scale items measuring perceptions of asset aging, safety, integrity, and digitalization. The reliability analysis results shown in Table 4.6 showed that all the constructs achieved Cronbach's coefficient alpha level greater than 0.70, indicating high internal reliability and consistency in responses.

Table 4.6: Reliability Statistics (Cronbach's Alpha)

Construct	Number of Items	Cronbach's α	Interpretation
Perception of Aging Assets	5	0.84	Good
Worker Health & Safety Experience	5	0.87	Good
Integrity Management Practices	5	0.81	Good
Digitalization & Predictive Maintenance	8	0.89	Excellent

4.1.4 Descriptive Statistics

The descriptive analyses were carried out using mean standard deviation, minimum and maximum level as shown in Table 4.7. The decision rule stated that mean values above 3.00 threshold indicate that respondents generally agree. Thus, the means scores of 3.87, 3.85, 3.92 and 3.79 for Perception of Aging Assets, Worker Health and Safety Experience, Integrity Management Practices and Digitalization & Predictive Maintenance respectively which are all greater than 3.00 threshold implied that the respondents agreed with positive asset management and safety practices, though variability suggests differing maturity levels across departments

Table 4.7: Descriptive Statistics for Key Variables

Variable	Mean	SD	Minimum	Maximum
Perception of Aging Assets	3.87	0.52	2.60	4.80
Worker Health & Safety Experience	3.85	0.48	2.80	4.70
Integrity Management Practices	3.92	0.55	2.70	4.90
Digitalization & Predictive Maintenance	3.79	0.59	2.50	4.80

4.1.5 Correlation Analysis

Table 4.8 and Figure 4.1 showed the results of Pearson correlation analysis carried out to investigate the relationship between the constructs namely Perception of Aging Assets, Worker Health and Safety Experience, Integrity Management Practices and Digitalization & Predictive Maintenance. The results revealed that there is strong positive and significant relationship between. Perception of Aging Assets and Integrity Practices ($r = 0.61$, $p=0.000$), Perception of Aging Assets and Digitalization (($r = 0.55$, $p=0.000$)

as well as Perception of Aging Assets and Worker Health & Safety Experience (($r = 0.59$, $p=0.000$).

Table 4.8: Correlation Matrix

Variables	1	2	3	4
1. Perception of Aging Assets	1			
2. Integrity Practices	0.61**	1		
3. Digitalization	0.55**	0.63**	1	
4. Worker Health & Safety Experience	0.59**	0.67**	.65**	1

Note. *N = 50; *p < .01.

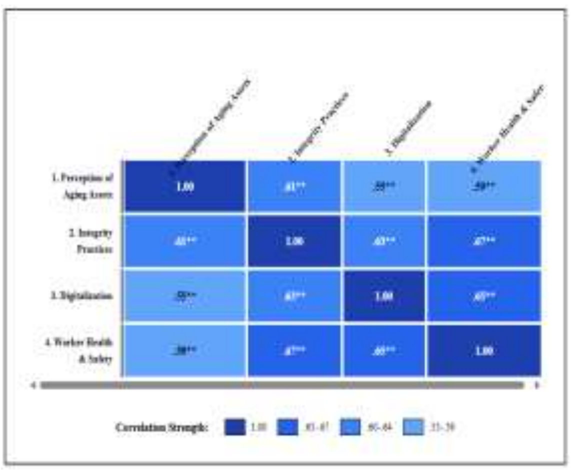

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Figure 4.1 Correlation Matrix Heat Map

4.1.6 Regression Analysis

Multi-linear regression analysis was carried out to examine the impact of Perception of Aging Assets, Integrity Practices and Digitalization on Worker Health & Safety Experience. And the results revealed that Perception of Aging Assets ($\beta=0.28$, $p=0.003$), Integrity Practices (($\beta=0.32$, $p=0.001$), and Digitalization ($\beta=0.26$, $p=0.012$) all have positive and significant impact on Worker Health & Safety Experience. The model explains 67% of variance in safety experience. Integrity practices had the strongest effect, followed by perception of aging assets and digitalization. All predictors were statistically significant, supporting the study's hypotheses.

Table 4.9: Regression Analysis Predicting Worker Health & Safety Experience

Predictor	β	SE	t	p	95% CI (LL–UL)
Constant	0.72	0.41	1.76	.084	[−0.10, 1.54]
Perception of Aging Assets	0.28	0.09	3.11	.003	[0.10, 0.46]
Integrity Practices	0.32	0.08	4.00	.001	[0.16, 0.48]
Digitalization	0.26	0.10	2.60	.012	[0.06, 0.46]

Model Summary: $R^2 = .67$, Adjusted $R^2 = .64$, $F(3,46) = 30.6$, $p < .001$.

4.1.7 T-test

Table 4.9 showed the independent sample T-test carried out to examine the difference in response of the respondents based on their gender. The results revealed that although males scored slightly higher on safety experience perceptions, the difference was not statistically significant ($p > .05$), indicating broadly similar safety awareness across genders.

4.9 Independent Samples t-Test

Table 4.10: Gender Differences in Worker Safety Experience

Gender	N	M	SD	t	p	Cohen's d
Male	38	3.91	0.44	1.82	.075	0.52
Female	12	3.66	0.37			

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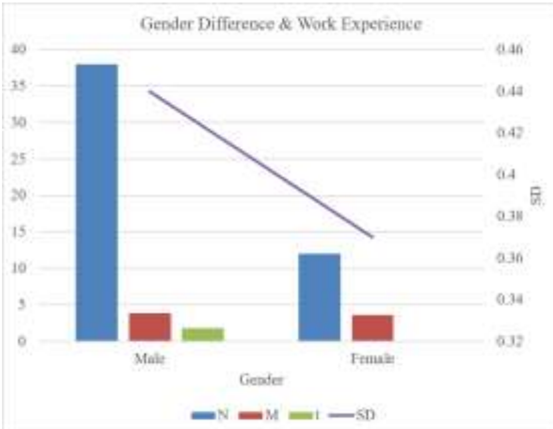

Figure 4.10 – Gender Differences in Worker Safety Experience

4.6 Qualitative Interview Insights

Theme 1: Asset Integrity and Equipment Aging. Maintenance engineers (INT 01, INT 03, INT 08) emphasized visible corrosion and fatigue in older equipment, particularly turbines and cryogenic systems. Deferred replacement and spare-part shortages increase operational risk and unplanned shutdowns.

Theme 2: Worker Health, Safety, and Exposure. HSE managers (INT 02, INT 06) highlighted incidents linked to degraded components such as leaks and insulation failures, which heighten exposure risk. They recommended stricter inspection regimes for assets exceeding 20 years of service.

Theme 3: Maintenance and Operational Challenges; Supervisors (INT 04, INT 07, INT 09) described reactive maintenance driven by production targets, limited predictive upkeep, and manpower shortages. They called for improved workforce training on early degradation indicators.

Theme 4: Digitalization and Predictive Maintenance, Instrumentation and reliability engineers (INT 05, INT 10) emphasized the need for IoT-based condition monitoring and predictive analytics to improve real-time asset health tracking and reduce human exposure.

All interviewees agreed that aging assets directly influence worker safety through reduced mechanical integrity and delayed maintenance. Digitalization and structured asset life extension programs were consistently proposed as solutions.

Table 4.11: Visual Synthesis Linking Aging Asset Index (AAI), Integrity Management, Digitalization, and Safety Performance

Thematic Area	Key Observations from Interviews	Relation to AAI Dimensions	Implications for Worker Health & Safety	Recommended Actions / Digital Solutions
Theme 1: Asset Integrity and Equipment Aging	Maintenance engineers (INT 01, INT 03, INT 08) observed widespread corrosion, metal fatigue, and material degradation in turbines, exchangers, and cryogenic systems. Deferred replacements and spare-part scarcity increased unplanned downtime.	Reflects AAI mechanical degradation and maintenance backlog indicators, signalling high aging scores for legacy systems.	Elevated exposure to leaks, heat stress, and mechanical failures; increased near-miss frequency during emergency repairs.	Prioritize high-AAI equipment for refurbishment; implement lifecycle-based spare-part management.
Theme 2: Worker Health, Safety, and Exposure	HSE managers (INT 02, INT 06) linked degraded assets to incidents involving gas leaks and insulation failure. Assets	Validates AAI risk linkage between physical degradation and safety performance.	Direct correlation between asset deterioration and worker exposure frequency;	Implement risk-based inspection schedules; introduce condition-monitoring for

	exceeding 20 years pose measurable exposure and injury risks.		declining safety metrics.	insulation and pressure systems.
Theme 3: Maintenance and Operational Challenges	Supervisors (INT 04, INT 07, INT 09) noted dominance of reactive maintenance driven by production pressure and limited workforce capacity. Predictive maintenance adoption remains low.	Highlights AAI operational responsiveness and maintenance maturity as determinants of safety outcomes.	Higher injury likelihood during corrective interventions; reduced preventive intervention windows.	Strengthen preventive maintenance culture; enhance training on early degradation signals.
Theme 4: Digitalization and Predictive Maintenance	Reliability engineers (INT 05, INT 10) emphasized need for IoT, AI, and digital twins for asset condition tracking, fault prediction, and decision support.	Supports AAI digital integration component, linking technological maturity with improved safety control.	Reduced human exposure to hazardous inspections; improved maintenance scheduling and reliability.	Adopt real-time condition monitoring, predictive analytics, and centralized integrity dashboards.
Cross-Cutting Insight	All participants agreed that aging assets compromise safety by eroding mechanical integrity and delaying maintenance interventions.	The AAI effectively quantifies this relationship, bridging engineering and HSE perspectives.	Integrated asset integrity and digital monitoring enhance worker protection and operational continuity.	Institutionalize AAI-based monitoring as part of LNG asset integrity management system.

4.7 Integrated AAI–Worker Safety Conceptual Validation Diagram

Figure 4.11 – Integrated AAI–Worker Safety Conceptual Validation Diagram

4.2 Discussion of Findings

4.2.1 The perception of aging assets among workers in the Liquified Natural Gas (LNG) company

On the perception of workers on aging assets in the Liquified Natural Gas (LNG) company, the results revealed that majority of the workers (77.4) agreed and accepted that aging equipment is a major contributor to increased maintenance expenditure and unsafe work conditions. This result implied that most of the workers accepted that aged equipment with high aging assets indicators are major problem in the company because they cause higher and increased maintenance expenses and create unsafe working conditions for the workers operating such equipment.

This result aligned with the works of Santos & Ferreira (2023) and Ghosh & Lee (2022) who worked on common problem in aging facilities: a lack of labelled failure data to train AI models. They successfully applied transfer learning, where a model pre-trained on a different but similar asset (e.g., a gas turbine from another plant) is fine-tuned with the small amount of local data. And they also revealed that aging of facilities has substantial effect on workers' health and safety as well as integrity of practices in any firm. The results also aligned with the works of Aliyu and Hassan (2019) who worked on field-based evaluations of condition-monitoring programs that optimise reliability by tracking degradation trends and using vibration analysis, oil-debris analysis, and time-series assessments of Mean Time Between Failures (MTBF). The age-related failure histories of rotating machinery was clearly demonstrated in additional evaluations of RAM (Reliability, Availability, Maintainability) datasets. This further emphasises the role of operational stress and prolonged service life in mechanical degradation. The most dependable early-warning indications of imminent failures in turbines, compressors, and gearboxes, according to empirical results, are vibration signatures and fluid-condition indicators. Plants with well-established predictive-maintenance programs typically see a 20-40% drop in unscheduled outages and a significant decrease in unplanned corrective maintenance. Increased cycling duty, start-stop operations, and variable load circumstances accelerate the degradation of rotating equipment, according to studies. These factors are becoming more common in LNG plants as they adapt to changing market and production demands.

4.2.2 The condition of workers health and safety, integrity management practices and digitalization and predictive maintenance in the LNG company

On the conditions of workers health and safety, integrity management practices and digitalization and predictive maintenance in the LNG company. The results revealed that 77% of the respondents sampled for the study accepted that there is good workers health and safety experience in the company, 78.4% accept that there is presence of integrity management practices in the company while 75.8% accepted that there is presence of digitalization and preventive maintenance in the company. These results implied that the workers in the LNG company are in good health and safety conditions and there is palpable presence of integrity management practices with substantial level of digitalization and preventive maintenance culture in the company.

These results aligned with the work of Okoh & Haugen (2014) who carried out Systematic review and risk assessment modelling to ascertain aging asset index of Aging equipment based on supports weighting of age and incident history in AAI in relation to workers health and safety and preventive maintenance schedule. The results of their study showed that the workers are in good health and safety condition and preventive maintenance schedule are usually properly scheduled. The outcome also aligned with the works of Ghosh & Lee (2022) who worked on common problem in aging facilities: a lack of labelled failure data to train AI models. They successfully applied transfer learning, where a model pre-trained on a different but similar asset (e.g., a gas turbine from another plant) is fine-tuned with the small amount of local data. And they also revealed that workers are in good health and safety condition and the management also maintained integrity in their operations and practices.

4.2.3 The relationship between perception of aging, workers health and safety, integrity management practices and digitalization and predictive maintenance in the LNG company

On the correlation analysis, the Pearson correlation analysis carried out to investigate the relationship between the constructs namely Perception of Aging Assets, Worker Health and Safety Experience, Integrity Management Practices and Digitalization & Predictive Maintenance revealed that there is strong positive and significant relationship between. Perception of Aging Assets and Integrity Practices, Perception of Aging Assets and Digitalization as well as Perception of Aging Assets and Worker Health & Safety Experience which means that there is a strong tendency that Worker Health and Safety Experience, Integrity Management Practices and Digitalization & Predictive Maintenance will be affected by Perception of Aging Assets.

This result aligned with the works of Santos & Ferreira (2023) and Ghosh & Lee (2022) who worked on common problem in aging facilities: a lack of labelled failure data to train AI models. They successfully applied transfer learning, where a model pre-trained on a different but similar asset (e.g., a gas turbine from another plant) is fine-tuned with the small amount of local data. And they also revealed that aging of facilities has substantial effect on workers health and safety as well as integrity of practices in any firm. This results also aligned with the work of Javed et al. (2021) who used structured questionnaires and focus groups, Javed and team captured frontline workers' perceptions across four LNG sites. Workers reported heightened stress and perceived risk when assigned work on older assets, noting more frequent unexpected equipment behaviour and tighter schedules for repairs. The qualitative analysis shows behavioural pathways (shortcuts, normalization of deviance) that mediate the aging → exposure relationship; the authors recommend incorporating safety-culture indicators into risk prioritization.

4.2.4 The impact of perception of aging on the three indicators of workers health and safety

Multi-linear regression analysis carried out to examine the impact of Perception of Aging Assets, Integrity management practices and digitalization and preventive maintenance on Worker Health & Safety Experience revealed that Perception of Aging Assets. Integrity Practices and Digitalization all have positive and significant impact on Worker Health & Safety Experience. The model explains 67% of variance in safety experience. Integrity practices had the strongest effect, followed by perception of aging assets and digitalization. All predictors were statistically significant, supporting the study's hypotheses.

This result also concurred with the works of Patriarca et al. (2021) applied Resilience Engineering (RE) principles to high-reliability organizations managing aging assets. They argued that while traditional risk management aims to prevent predictable failures, RE focuses on an organization's ability to recognize, adapt to, and absorb unexpected disruptions. Their work provides a theoretical basis for including flexibility, rapid response protocols, and organizational learning as core components of a maintenance framework for aging plants, where novel failure modes can emerge. Nwosu & Eze (2022) developed a multi-criteria decision matrix to classify the criticality of spare parts for obsolete equipment in Nigeria's energy sector. Their model considers factors like lead time, redundancy, and impact on production. They found that facilities using this proactive classification reduced emergency airfreight costs by over 70% and prevented an average of 14 days of unplanned downtime per year, directly addressing a key operational challenge in maintaining aging trains. The results also aligned with the work of Harrison & Nkosi (2018) who evaluated three LNG plants transitioning from time-based to condition-based maintenance (CBM). Their longitudinal analysis reported a statistically significant reduction in corrective maintenance frequency and associated maintenance injuries after CBM implementation. They conclude that predictive maintenance is a dual benefit approach improving reliability and reducing worker exposure and therefore predictive-monitoring maturity should be part of the Aging Asset Index's operational performance dimension.

4.2.5 The difference in workers safety experience based on their genders in the LNG company

On whether there is substantial difference in the workers safety experience by virtue of their gender differences, the results revealed that gender has no statistically significant effect on the workers safety experiences in the LNG company. This result implied that the difference in the gender of the workers have no substantial effect in their safety experience in the LNG company. In summary, the above findings reveal a strong empirical link between aging assets and worker safety outcomes in LNG operations. Quantitatively, integrity practices, aging perception, and digitalization jointly explained 67% of safety performance variation. Qualitatively, interviews confirmed that corrosion, deferred maintenance, and obsolescence elevate exposure risks. Overall, the results validate the aging asset index (AAI) as a valuable tool for identifying high-risk equipment and prioritizing maintenance interventions with significant implications for HSE management in LNG operations.

V. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary of Findings

This study set out to evaluate the impact of aging assets on worker health and safety within a typical LNG operating environment, using the Nigeria LNG facility in Bonny Island as a case study. Data were collected from 50 questionnaire respondents and 10 interviewees drawn from operations, maintenance, HSE, and engineering departments. A mixed-method approach was employed to integrate quantitative analysis of asset integrity and safety indicators with qualitative perspectives from experienced personnel.

The findings revealed that a strong relationship exists between the condition of aging assets and worker health and safety performance. Quantitative analysis demonstrated statistically significant positive correlations between perception of asset aging, integrity management practices, digitalization, and safety experience. Regression analysis indicated that integrity management practices ($\beta = 0.32$, $p < 0.01$) and digitalization ($\beta = 0.26$, $p < 0.05$) were the strongest predictors of safety outcomes, jointly explaining approximately 67% of the variance in safety experience. This suggests that robust integrity frameworks and digital predictive maintenance substantially mitigate risks associated with asset aging.

Thematic analysis of interviews reinforced these findings, highlighting key issues such as corrosion under insulation, equipment fatigue, delayed maintenance, and limited access to critical spares. Respondents emphasized that reactive maintenance approaches elevate worker exposure risks, while the integration of IoT-based monitoring and analytics offers practical pathways to improve both asset reliability and safety performance. Collectively, these findings validate the aging asset index (AAI) as a structured framework for prioritizing asset management decisions based on their potential impact on occupational safety.

5.2 Limitations of the Study

Although the study achieved its stated objectives, certain limitations were encountered that may influence the generalizability of the findings. First, access to archival maintenance and incident records was restricted due to confidentiality and data security protocols within the LNG sector, limiting the extent of secondary data analysis. Consequently, the study relied primarily on primary data collected via questionnaires and interviews, which, while valuable, are subject to respondent perception bias.

Secondly, the research was confined to a single case study—Nigeria LNG Bonny—thus limiting cross-site comparison. Operational, environmental, and managerial conditions may vary across LNG plants, and these differences could influence the degree of asset aging and corresponding safety outcomes. Additionally, the modest sample size ($n = 50$) may not fully represent the views of the broader workforce, although stratified sampling ensured adequate departmental representation. Finally, resource and time constraints restricted longitudinal data tracking, which would have provided deeper insights into the progression of asset degradation over time.

5.3 Conclusions

The study concludes that aging assets present a tangible risk to worker health and safety in LNG operations, primarily through declining mechanical integrity, increased maintenance backlog, and exposure to unsafe conditions. However, these risks can be effectively mitigated through structured asset integrity management, predictive maintenance, and digital monitoring frameworks.

The developed Aging Asset Index (AAI) offers a practical, data-driven tool for evaluating asset condition and prioritizing interventions. Its integration with HSE performance indicators enables organizations to link technical degradation directly with safety outcomes. The analysis confirmed that effective asset integrity practices and digital transformation initiatives lead to improved worker safety and operational reliability.

Ultimately, this study affirms that sustainable LNG operations require a shift from reactive maintenance to proactive, risk-based asset management. The AAI framework can guide LNG operators in optimizing resource allocation, reducing incident frequency, and strengthening compliance with international standards such as ISO 55000 and API RP 580/581.

5.4 Recommendations

Based on the findings and conclusions, the following recommendations are proposed:

1. Institutionalize the Aging Asset Index (AAI): LNG operators should adopt the AAI framework as a component of their asset integrity management systems to systematically assess and prioritize maintenance interventions.
2. Enhance Digitalization and Predictive Maintenance: Integration of IoT sensors, vibration analysis, and real-time monitoring tools should be scaled up to enable early fault detection and reduce manual inspection risks.
3. Strengthen Preventive Maintenance and Life-Extension Programs: Maintenance schedules should emphasize preventive and condition-based interventions, supported by life-extension assessments for critical equipment such as turbines, boilers, and cryogenic exchangers.
4. Improve Workforce Competence and Safety Culture: Continuous training should be implemented for operations and maintenance personnel on identifying degradation indicators, handling aging equipment safely, and adhering to HSE protocols.
5. Foster Data Sharing and Transparency: Collaboration between engineering, maintenance, and HSE units should be enhanced through integrated data platforms that support evidence-based decision-making while maintaining data security.
6. Policy and Regulatory Support: Regulators should encourage LNG operators to integrate risk-based inspection and asset life management frameworks consistent with API and ISO standards, ensuring that continued operation does not compromise worker safety.

5.5 Contributions to Knowledge

This study contributes to both academic and professional knowledge in several important ways:

1. Development of the Aging Asset Index (AAI): The study provides a validated, multi-dimensional framework for quantifying asset aging in relation to HSE outcomes in the LNG industry, bridging a critical research gap.
2. Empirical Evidence Linking Asset Integrity and Worker Safety: By correlating AAI scores with health and safety performance indicators, the research demonstrates a measurable connection between engineering asset condition and occupational safety.
3. Mixed-Methods Validation: The combination of statistical analysis and expert interviews enhances methodological robustness, offering a model for future interdisciplinary studies in asset integrity and HSE management.
4. Practical Tool for Industry: The AAI framework and accompanying findings can assist LNG operators in decision-making, maintenance

prioritization, and compliance assurance, supporting continuous improvement in safety and reliability.

5. Theoretical Integration: The research advances the theoretical understanding of how engineering integrity, digitalization, and safety performance interact, providing an empirical foundation for further studies on sustainable industrial safety management.

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