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ENHANCING RELIABILITY AND OPERATIONAL INTEGRITY OF HYDROGEN COMPRESSION SYSTEMS SUPPORTING THE US ENERGY TRANSITION

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ABSTRACT
Hydrogen compression systems are essential to the production, storage, transportation, and dispensing infrastructure required for the United States energy transition. However, high operating pressures, cyclic loading, hydrogen embrittlement, seal degradation, leakage, thermal instability, and component fatigue can undermine equipment reliability, safety, and operational continuity. This study proposes an integrated reliability and operational integrity framework for hydrogen compressors combining condition monitoring, digital twins, physics-informed artificial intelligence, prognostics, and risk-based maintenance. The framework captures real-time vibration, pressure, temperature, acoustic, and leakage data to identify developing faults, estimate remaining useful life, and support timely maintenance decisions. It also links material degradation, operating severity, failure probability, and consequence assessment to improve asset prioritisation. The proposed approach is applicable to reciprocating, diaphragm, centrifugal, and electrochemical compressors deployed across hydrogen production facilities, pipeline networks, storage terminals, industrial hubs, and refuelling stations. By enabling earlier fault detection, reducing unplanned downtime, improving maintenance efficiency, and strengthening safety assurance, the framework supports dependable hydrogen infrastructure expansion and contributes to a resilient, scalable, and lower-carbon future United States energy system.

Keywords:
Hydrogen compression systems; Operational integrity; Predictive maintenance; U.S. energy transition

1. INTRODUCTION

1.1 Hydrogen Compression as a Critical Enabler of the U.S. Energy Transition

Hydrogen has emerged as a strategic energy carrier supporting the decarbonisation of the United States energy sector through its ability to reduce greenhouse gas emissions across transportation, industrial manufacturing, electricity generation, and heavy-duty mobility [1]. National initiatives promoting the hydrogen economy have accelerated investments in clean hydrogen production, storage, transportation, and utilisation as part of broader efforts to achieve long-term energy security and carbon neutrality [2]. The U.S. Clean Hydrogen Strategy has further stimulated the deployment of low-carbon hydrogen technologies by encouraging innovation in production pathways, infrastructure development, and end-use applications that strengthen domestic energy resilience [3].

Hydrogen production is increasingly classified into green hydrogen, generated through renewable-powered electrolysis, and blue hydrogen, produced from natural gas with carbon capture and storage technologies [4]. Regardless of production pathway, efficient transportation and storage remain fundamental requirements for establishing a reliable hydrogen supply chain. Because hydrogen possesses a very low volumetric energy density under ambient conditions, compression is essential for economical storage, pipeline transmission, industrial processing, and high-pressure refuelling applications [5].

Hydrogen compression systems therefore serve as critical infrastructure connecting production facilities with storage terminals, distribution pipelines, refuelling stations, chemical processing plants, and emerging hydrogen hubs. Reliable compressor performance directly influences system efficiency, operational safety, hydrogen availability, and infrastructure economics [6]. Consequently, improving the reliability and operational integrity of hydrogen compression systems has become a priority for supporting large-scale hydrogen deployment and ensuring the successful transition towards a resilient, low-carbon United States energy economy [7].

1.2 Engineering Challenges in Hydrogen Compression Systems

Hydrogen compression systems operate under demanding mechanical and environmental conditions that significantly influence equipment reliability, operational efficiency, and long-term service life [8]. Compressors frequently operate at pressures exceeding several hundred bar to support hydrogen storage, pipeline transportation, and vehicle refuelling applications. Such extreme operating conditions expose compressor components to

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complex stress cycles, elevated temperatures, and repeated pressure fluctuations that accelerate material degradation and increase maintenance requirements [1].

One of the most significant engineering challenges is hydrogen embrittlement, a degradation mechanism in which hydrogen atoms diffuse into metallic materials, reducing ductility, fracture toughness, and fatigue resistance [5]. Prolonged exposure may initiate microscopic cracks that progressively propagate under cyclic loading, ultimately leading to structural failure. Seal degradation presents another critical concern because hydrogen molecules are exceptionally small and readily permeate conventional sealing materials, increasing leakage risks and reducing compressor efficiency [9].

Repeated compression cycles also induce mechanical fatigue within pistons, valves, bearings, diaphragms, connecting rods, and pressure vessels, particularly under variable operating conditions [3]. Thermal effects arising from adiabatic compression further increase mechanical stresses by generating substantial temperature gradients that influence lubrication performance, seal integrity, and material behaviour. Combined with hydrogen leakage, these degradation mechanisms can result in unplanned compressor downtime, increased maintenance costs, reduced operational availability, and heightened safety risks [6].

Maintaining high levels of operational safety and asset reliability therefore requires continuous monitoring of equipment condition, early fault detection, accurate degradation assessment, and proactive maintenance strategies capable of preventing catastrophic failures before they compromise hydrogen infrastructure operations [2].

1.3 Research Gap, Objectives and Contributions

Current maintenance strategies for hydrogen compression systems continue to rely predominantly on preventive maintenance schedules and periodic inspections that often fail to account for the dynamic operating conditions experienced by compressor assets [4]. Although preventive maintenance reduces the likelihood of unexpected failures, fixed maintenance intervals may result in unnecessary servicing of healthy equipment or delayed intervention for rapidly degrading components. Consequently, maintenance decisions frequently lack the flexibility required for highly demanding hydrogen operating environments [8].

Existing integrity management practices are similarly fragmented, with condition monitoring, structural assessment, degradation analysis, reliability evaluation, and maintenance planning commonly implemented as independent activities rather than integrated operational processes [1]. Furthermore, many current approaches inadequately exploit real-time operational data generated by modern sensors, limiting their ability to anticipate equipment degradation before failures occur. Despite recent advances in artificial intelligence, Digital Twins, and prognostic health management, relatively few integrated frameworks combine these technologies to provide comprehensive predictive reliability management for hydrogen compression systems [7].

This study addresses these limitations by proposing an intelligent framework that integrates Digital Twin technology, artificial intelligence, condition monitoring, degradation modelling, reliability engineering, and predictive maintenance into a unified operational integrity platform [5]. The objectives are to improve fault detection, estimate remaining useful life, optimise maintenance scheduling, and enhance compressor reliability under demanding hydrogen operating conditions. The study further contributes novel mathematical models for degradation assessment, integrity evaluation, maintenance optimisation, and recovery analysis, providing a quantitative foundation for intelligent reliability management. Collectively, the proposed framework supports safer hydrogen infrastructure, reduced operational downtime, improved asset utilisation, and a more resilient United States hydrogen energy ecosystem [9].

2. RELIABILITY ENGINEERING AND INTELLIGENT INTEGRITY MANAGEMENT OF HYDROGEN COMPRESSION SYSTEMS

2.1 Evolution of Hydrogen Compression Technologies

Hydrogen compression technologies have evolved considerably in response to increasing demands for higher operating pressures, improved energy efficiency, enhanced safety, and long-term operational reliability within hydrogen production, transportation, and storage infrastructures [7]. Early hydrogen applications primarily relied on reciprocating compressors because of their ability to achieve extremely high discharge pressures suitable for industrial gas processing and pipeline transmission. These positive displacement machines remain widely used owing to their mature design, relatively high compression ratios, and adaptability across a broad range of hydrogen flow rates [8]. However, their numerous moving components increase maintenance requirements and expose critical parts to cyclic mechanical loading.

Diaphragm compressors were subsequently developed to eliminate direct contact between hydrogen and lubricated mechanical components. By separating the compression chamber using flexible metallic diaphragms, these compressors significantly reduce contamination risks while providing excellent leak-tight performance for

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high-purity hydrogen applications such as fuel cell production, semiconductor manufacturing, and laboratory systems [9]. Nevertheless, diaphragm fatigue and membrane replacement remain important operational considerations.

Centrifugal compressors are generally employed where large hydrogen flow rates are required, particularly in refinery operations and large-scale chemical processing. Their continuous-flow configuration offers smooth operation, lower vibration levels, and reduced maintenance compared with reciprocating machines, although they are less effective at achieving extremely high compression ratios without multiple stages [10].

Recent technological developments have introduced electrochemical compressors, which compress hydrogen through proton exchange mechanisms without conventional mechanical pistons, thereby reducing mechanical wear and operational noise [11]. Ionic compressors further represent an emerging technology that utilises ionic liquids to achieve compression with reduced leakage and improved thermal management. Collectively, these compressor technologies support diverse industrial applications, each providing unique performance characteristics suited to specific operational requirements while driving continued innovation in hydrogen infrastructure reliability [12].

2.2 Failure Mechanisms in Hydrogen Compression Systems

Hydrogen compression systems operate under severe mechanical, thermal, and chemical conditions that accelerate degradation of critical components throughout their operational lifetime [13]. Unlike conventional gas compression systems, hydrogen compressors are subjected to unique degradation mechanisms associated with hydrogen diffusion, elevated operating pressures, cyclic loading, and continuous thermal fluctuations. These mechanisms directly influence compressor reliability, operational integrity, maintenance frequency, and equipment lifespan.

Hydrogen embrittlement remains one of the most critical degradation processes affecting metallic pressure-containing components. Hydrogen atoms diffuse into metallic microstructures, reducing ductility, fracture toughness, and resistance to crack propagation, thereby increasing the likelihood of structural failure under repeated loading conditions [14]. Fatigue crack growth further accelerates degradation as cyclic pressure variations induce progressive crack initiation and propagation within pistons, connecting rods, pressure vessels, diaphragms, valves, and compressor casings.

Seal wear constitutes another significant reliability concern because the extremely small molecular size of hydrogen promotes permeation through sealing materials, increasing leakage and reducing compression efficiency [15]. Bearing degradation may arise from excessive loading, lubrication contamination, vibration, and misalignment, while rotor imbalance introduces abnormal dynamic forces that accelerate component wear and reduce operational stability. Inadequate lubrication further increases friction, heat generation, and mechanical wear, contributing to premature component failure.

Corrosion mechanisms associated with aggressive operating environments may additionally weaken compressor materials, particularly when contaminants are present. Elevated operating temperatures generated during high-pressure compression accelerate material ageing, lubricant degradation, and seal deterioration, while persistent hydrogen leakage introduces both operational inefficiencies and significant safety hazards.

The cumulative degradation process can be represented using the following degradation function:

$$D(t) = D_0 + \int_0^t \phi\,(\sigma, T, P, H)\,dt$$

where:

- $D(t)$= degradation state at time t;
- D_0= initial degradation;
- σ= mechanical stress;
- T= operating temperature;
- P= operating pressure;
- H= hydrogen concentration;
- $\phi(\cdot)$= degradation rate function.

This formulation recognises degradation as a cumulative process governed by interacting mechanical, thermal, pressure, and hydrogen-related effects, providing a quantitative foundation for predictive reliability assessment and integrity management [8].

2.3 Intelligent Monitoring Technologies

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Recent advances in sensing technologies, artificial intelligence, and digital engineering have transformed the monitoring of hydrogen compression systems from periodic inspection towards continuous condition assessment and predictive diagnostics [9]. Intelligent monitoring enables operators to identify degradation mechanisms at an early stage, thereby reducing unexpected failures and improving operational safety. Modern hydrogen compressor installations increasingly integrate multiple sensing modalities to provide comprehensive information regarding equipment condition and operational performance.

Vibration monitoring remains one of the most widely adopted techniques for detecting rotor imbalance, bearing degradation, shaft misalignment, looseness, and mechanical faults. Changes in vibration signatures often provide early indications of component deterioration before catastrophic failure occurs [10]. Acoustic emission monitoring complements vibration analysis by detecting high-frequency elastic waves generated during crack initiation, material fracture, seal leakage, and frictional contact between moving components.

Pressure monitoring continuously evaluates compressor operating conditions, enabling early identification of valve malfunction, internal leakage, and abnormal compression cycles. Temperature sensing provides additional diagnostic information by detecting excessive friction, inadequate lubrication, thermal overload, and abnormal heat generation. Fibre optic sensing technologies have recently attracted significant interest because of their immunity to electromagnetic interference, high measurement accuracy, and ability to monitor distributed temperature and strain across extensive compressor installations [11].

The rapid expansion of the Internet of Things (IoT) has enabled continuous collection of operational data from distributed sensor networks, while Edge Artificial Intelligence allows real-time analysis of these data streams close to the equipment, thereby reducing communication delays and cloud dependency. Digital Twin technology further integrates sensor information with virtual compressor models to simulate equipment behaviour under changing operating conditions and evaluate maintenance strategies before implementation [12]. Emerging physics-informed machine learning approaches combine engineering knowledge with data-driven algorithms, improving fault diagnosis, degradation prediction, and Remaining Useful Life estimation while enhancing the reliability of intelligent integrity management systems [13].

2.4 Reliability Engineering and Prognostics Theory

Reliability engineering provides the theoretical foundation for evaluating the probability that engineering systems perform their intended functions without failure over specified operating periods [14]. Within hydrogen compression systems, reliability engineering supports maintenance planning, component design, operational risk assessment, and lifecycle optimisation by quantifying equipment performance under uncertain operating conditions. Traditional reliability approaches have gradually evolved from statistical failure analysis towards intelligent prognostic frameworks capable of predicting future equipment health.

Prognostics and Health Management (PHM) extends conventional reliability engineering by integrating continuous condition monitoring, degradation modelling, fault diagnosis, and predictive analytics into unified maintenance strategies. PHM enables maintenance interventions to be scheduled according to actual equipment condition rather than predetermined maintenance intervals, thereby improving operational efficiency and reducing unnecessary servicing [15].

Fault diagnosis represents another essential component of reliability engineering by identifying the root causes of abnormal operating behaviour using sensor measurements, signal processing techniques, and artificial intelligence algorithms. Remaining Useful Life (RUL) estimation subsequently predicts the time remaining before equipment reaches unacceptable performance or failure thresholds, enabling operators to optimise maintenance schedules and minimise operational disruption.

Bayesian reliability models provide probabilistic estimates of equipment health by continuously updating failure probabilities as new operational information becomes available. Similarly, Weibull analysis remains one of the most widely adopted statistical techniques for modelling failure distributions, estimating component lifetimes, and identifying dominant degradation mechanisms across engineering systems [7]. Digital Twin theory further enhances reliability engineering by establishing continuously synchronised virtual representations of physical compressor assets capable of simulating degradation processes, evaluating maintenance scenarios, and supporting operational decision-making. Collectively, systems reliability theory integrates these analytical approaches into comprehensive frameworks capable of improving fault detection, maintenance optimisation, operational safety, and long-term integrity management for hydrogen compression systems [11].

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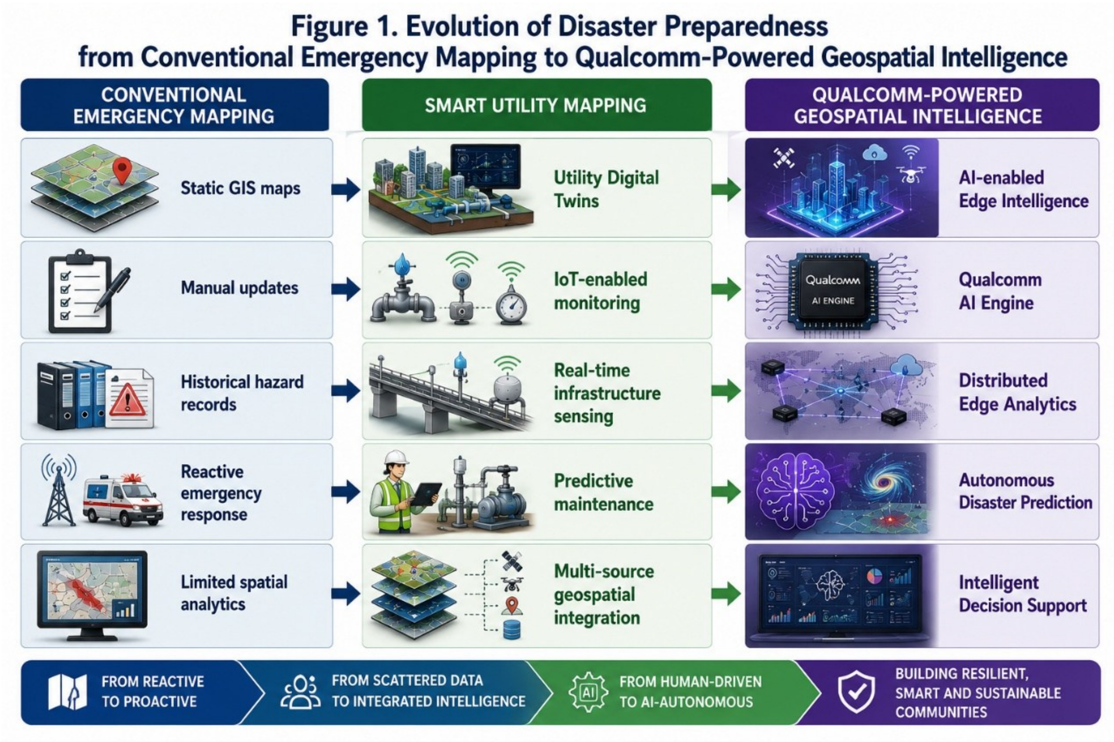

Figure 1. Evolution of Hydrogen Compression System Reliability from Conventional Maintenance to Intelligent Prognostics

Table 1. Comparison of Conventional Maintenance, Condition-Based Maintenance, Predictive Maintenance and Intelligent Integrity Management

Attribute	Conventional Maintenance	Condition-Based Maintenance	Predictive Maintenance	Intelligent Integrity Management
Maintenance strategy	Fixed schedule	Condition-triggered	Failure prediction	Autonomous optimisation
Data source	Manual inspection	Sensor measurements	AI-driven diagnostics	Digital Twin and Edge AI
Fault detection	After degradation	Early detection	Predictive detection	Continuous intelligent assessment
Remaining Useful Life	Not available	Limited	Estimated	Dynamically updated
Decision support	Operator judgement	Maintenance alerts	Predictive recommendations	Autonomous decision intelligence
Downtime	High	Moderate	Reduced	Minimal
Asset utilisation	Moderate	Improved	High	Optimised
Operational safety	Moderate	Improved	High	Very high

3. INTELLIGENT RELIABILITY AND OPERATIONAL INTEGRITY FRAMEWORK

3.1 Design Philosophy and Engineering Objectives

The proposed Intelligent Reliability and Operational Integrity Framework is designed to improve the reliability, safety, and long-term performance of hydrogen compression systems operating under demanding industrial conditions [13]. The framework adopts a reliability-centred philosophy in which maintenance and operational decisions are driven by continuously assessed equipment condition rather than predetermined maintenance schedules. This approach enables operators to minimise unexpected failures while improving asset availability and extending equipment service life [14].

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Operational safety represents a fundamental design objective because hydrogen compressors operate under high pressures and are susceptible to leakage, material degradation, and mechanical failure. Continuous integrity assessment allows emerging faults to be identified before they develop into hazardous operating conditions. Sustainability is also embedded within the framework by reducing unnecessary maintenance activities, improving energy utilisation, extending component lifespan, and minimising material waste throughout the equipment lifecycle [15].

Digital Twin technology serves as the central intelligence platform by maintaining synchronised virtual representations of physical compressor assets using continuously acquired operational data. These virtual models support real-time simulation, degradation forecasting, and performance evaluation under changing operating conditions. Risk-informed maintenance further prioritises maintenance interventions according to equipment health, operational criticality, and predicted failure probability, thereby improving maintenance efficiency, operational continuity, and overall system resilience while supporting dependable hydrogen infrastructure deployment [16].

3.2 Multi-Layer Intelligent Integrity Architecture

The proposed architecture adopts a hierarchical multi-layer design that integrates sensing technologies, artificial intelligence, Digital Twins, and predictive reliability engineering into a unified operational integrity framework [17]. Each layer performs specialised analytical functions while exchanging information continuously to provide accurate assessment of compressor condition and operational risk.

The Hydrogen Compression Layer represents the physical infrastructure comprising reciprocating, diaphragm, centrifugal, electrochemical, and ionic compressors together with associated valves, seals, bearings, piping systems, and pressure vessels. Operational data generated at this level provide the foundation for reliability assessment.

The Sensor Layer continuously acquires vibration, pressure, temperature, acoustic emission, hydrogen leakage, lubricant condition, and structural strain measurements using distributed sensing technologies. These observations provide comprehensive visibility of equipment health under changing operating conditions [18].

The Condition Monitoring Layer processes raw sensor information using advanced signal processing techniques to identify abnormal operating behaviour, extract diagnostic features, and detect early degradation mechanisms affecting compressor components. Continuous monitoring significantly improves fault detection accuracy while reducing reliance on periodic manual inspections.

The Digital Twin Layer maintains a continuously synchronised virtual representation of the physical compressor by integrating engineering models with real-time operational measurements. This layer supports simulation, degradation forecasting, and evaluation of alternative maintenance strategies before implementation [19].

The AI Prognostics Layer applies machine learning and physics-informed artificial intelligence to estimate degradation trends, predict remaining useful life, and forecast future operating performance. Outputs from this layer are evaluated by the Integrity Assessment Layer, which quantifies structural integrity, operational risk, and equipment reliability.

The Maintenance Decision Layer determines optimal maintenance interventions based on predicted equipment condition, operational priorities, and available resources. Finally, the Operational Control Layer implements maintenance decisions, updates Digital Twin models, and continuously optimises compressor operation through adaptive feedback, ensuring long-term reliability and operational continuity [20].

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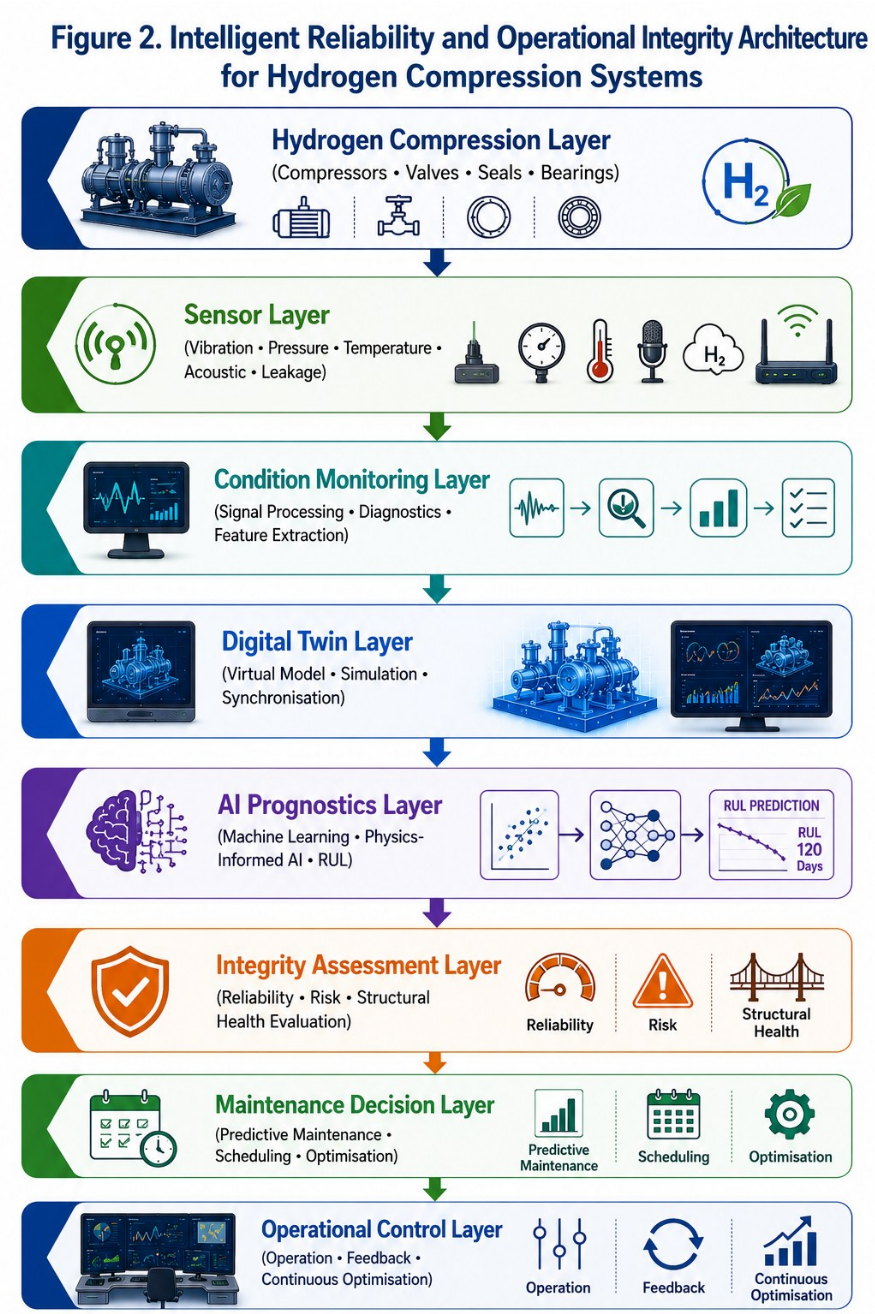

Figure 2. Intelligent Reliability and Operational Integrity Architecture for Hydrogen Compression Systems

3.3 Intelligent Condition Monitoring and Data Fusion

Continuous condition monitoring forms the analytical foundation of the proposed framework by transforming heterogeneous sensor observations into reliable indicators of compressor health and operational integrity [18]. Unlike conventional monitoring approaches that evaluate individual sensor measurements independently, the proposed framework integrates multiple sensing modalities to provide a comprehensive representation of equipment condition under dynamic operating environments.

Sensor fusion combines vibration, pressure, temperature, acoustic emission, hydrogen leakage, lubricant condition, and structural response measurements into unified health indicators capable of detecting subtle degradation mechanisms that may remain undetected using isolated monitoring techniques. Vibration analysis identifies rotor imbalance, bearing degradation, shaft misalignment, looseness, and mechanical wear through changes in frequency characteristics and vibration amplitudes [19]. Pressure dynamics reveal abnormal

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compression behaviour associated with valve malfunction, internal leakage, or compression inefficiencies, while thermal behaviour provides valuable information regarding excessive friction, lubrication degradation, and overheating.

Acoustic emission monitoring complements these techniques by detecting high-frequency stress waves generated during crack initiation, material fracture, seal deterioration, and frictional contact between moving components. Physics-informed artificial intelligence enhances diagnostic performance by integrating engineering principles with data-driven learning, enabling physically consistent interpretation of complex operational behaviour [20]. Feature extraction algorithms subsequently transform raw sensor measurements into informative diagnostic variables suitable for fault classification, degradation assessment, and Remaining Useful Life prediction.

The adaptive sensor fusion process is expressed as

$$F(t) = \sum_{i=1}^{n} \omega_i\,(t) S_i(t)$$

where:

- $F(t)$= fused equipment health information;
- $S_i(t)$= measurement obtained from sensor i;
- $\omega_i(t)$= adaptive weighting coefficient representing sensor reliability and relevance;
- n= total number of sensing sources.

This adaptive formulation continuously adjusts sensor importance according to operating conditions, improving diagnostic robustness and prediction accuracy under varying compressor environments [21].

3.4 Digital Twin-Based Integrity Prediction Engine

The Digital Twin-Based Integrity Prediction Engine constitutes the predictive intelligence component of the proposed framework by maintaining continuous synchronisation between physical hydrogen compression equipment and virtual engineering models [22]. Operational measurements obtained from distributed sensors are continuously transmitted to the Digital Twin, enabling the virtual model to accurately represent the evolving condition of compressor components throughout their operational lifecycle.

Physics-informed artificial intelligence combines engineering knowledge with real-time operational data to simulate degradation processes while preserving consistency with established physical laws governing compressor behaviour. Unlike purely data-driven models, this hybrid approach improves prediction accuracy even under limited failure data by incorporating knowledge of material degradation, thermodynamics, structural mechanics, and hydrogen behaviour. Consequently, degradation forecasts remain physically meaningful across diverse operating conditions.

The prediction engine continuously evaluates crack evolution within pressure-containing components by analysing stress histories, cyclic loading, vibration characteristics, and material degradation trends. Seal degradation is simultaneously monitored using pressure loss, leakage measurements, temperature behaviour, and operational efficiency indicators to estimate future sealing performance and maintenance requirements. Leakage prediction further identifies progressive deterioration before significant hydrogen loss or hazardous operating conditions develop.

Dynamic simulation enables the Digital Twin to evaluate multiple operating scenarios, maintenance strategies, and loading conditions without interrupting physical compressor operation. These simulations provide operators with valuable insight into future equipment behaviour while supporting optimisation of maintenance schedules and operational planning. Operational forecasting further estimates future reliability, equipment availability, degradation progression, and Remaining Useful Life, enabling proactive maintenance decisions that minimise unexpected failures, reduce downtime, improve operational safety, and maximise lifecycle performance across hydrogen compression systems [16].

3.5 Intelligent Reliability Decision Workflow

The proposed Intelligent Reliability Decision Workflow establishes a systematic process that transforms continuously acquired operational data into proactive maintenance decisions supporting long-term compressor reliability and operational integrity [17]. The workflow begins with sensor acquisition, where distributed monitoring devices continuously collect vibration, pressure, temperature, acoustic emission, hydrogen leakage, lubricant condition, and structural response information from compressor components operating under varying environmental conditions.

The collected information is subsequently processed through feature extraction, where advanced signal processing and machine learning algorithms identify informative characteristics representing equipment behaviour while

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reducing data dimensionality. These extracted features are then analysed during the fault diagnosis stage to detect abnormal operating conditions, classify fault types, and determine their probable causes using artificial intelligence and engineering knowledge [18].
Following fault diagnosis, the integrity prediction stage evaluates degradation progression, structural health, and operational risk by integrating Digital Twin simulations, physics-informed artificial intelligence, and historical operational information. Based on predicted degradation trends, the framework performs Remaining Useful Life (RUL) estimation, enabling maintenance planners to determine the expected operational lifetime of critical compressor components before unacceptable performance degradation occurs.
The subsequent maintenance optimisation stage evaluates alternative intervention strategies according to equipment criticality, predicted failure probability, maintenance resources, and operational priorities. Optimal maintenance schedules are then implemented through the operational feedback stage, where maintenance outcomes and updated equipment conditions are continuously incorporated into the Digital Twin and prognostic models. Finally, continuous learning enables artificial intelligence algorithms to refine prediction accuracy by incorporating newly acquired operational experience, thereby continuously improving fault diagnosis, degradation prediction, maintenance effectiveness, and long-term operational reliability throughout the compressor lifecycle [22].

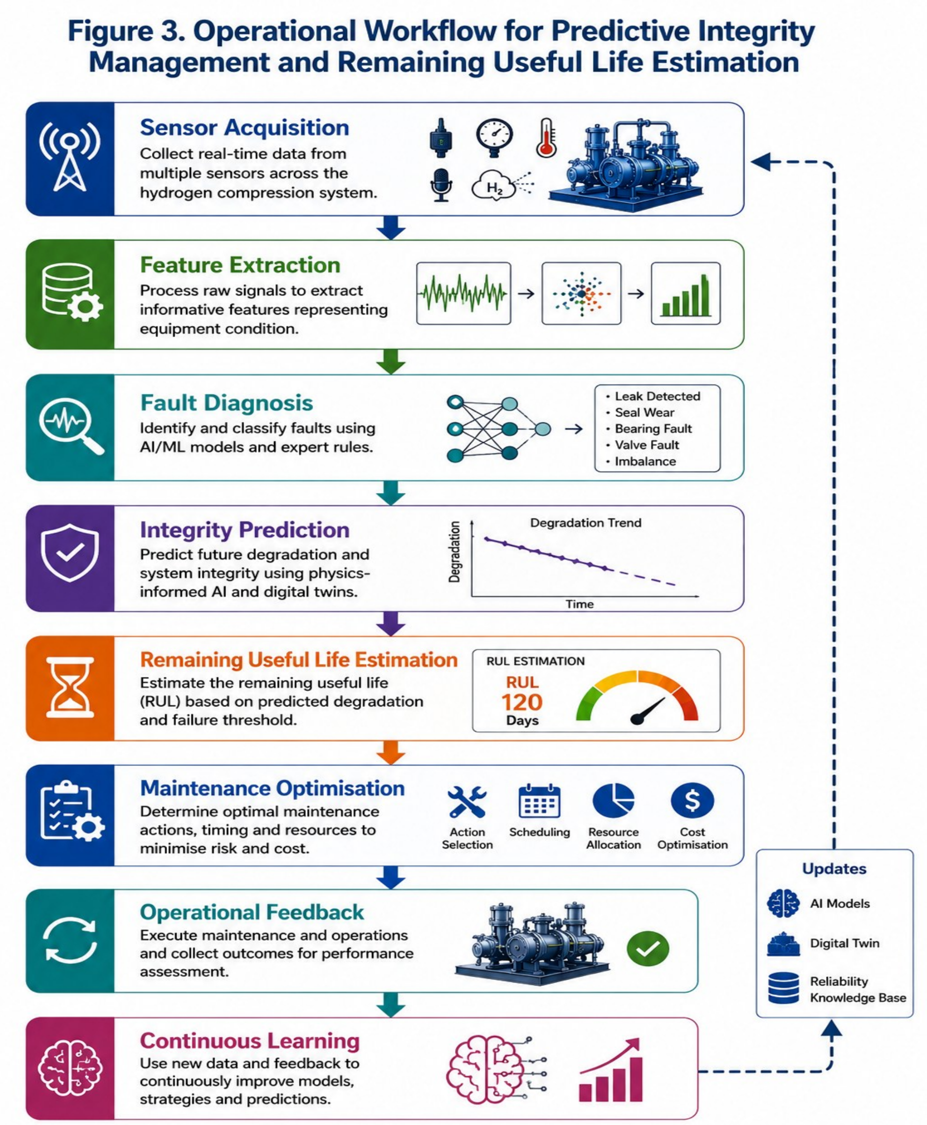

Figure 3. Operational Workflow for Predictive Integrity Management and Remaining Useful Life Estimation

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4. MATHEMATICAL FRAMEWORK FOR RELIABILITY AND OPERATIONAL INTEGRITY OPTIMISATION

4.1 Hydrogen Compressor Degradation Function (HCDF)

Hydrogen compression systems experience progressive degradation resulting from the interaction of mechanical loading, thermal stress, hydrogen diffusion, and material ageing throughout their operational lifecycle [20]. Conventional degradation models frequently consider these factors independently, limiting their ability to represent the coupled deterioration mechanisms that occur in high-pressure hydrogen environments. To address this limitation, the proposed Hydrogen Compressor Degradation Function (HCDF) integrates the dominant physical variables influencing compressor deterioration into a unified mathematical formulation suitable for predictive integrity assessment.

The proposed degradation model is expressed as

$$D_c(t) = \left(\frac{P^{\alpha} T^{\beta} \sigma^{\gamma} H^{\delta}}{M^{\eta}}\right) e^{\lambda t}$$

where

- $D_c(t)$= compressor degradation state at time t;
- P= operating pressure;
- T= operating temperature;
- σ= mechanical stress;
- H= hydrogen concentration;
- M= material resistance against degradation;
- $\alpha, \beta, \gamma, \delta, \eta$= sensitivity coefficients;
- λ= degradation growth constant.

The exponential component represents cumulative deterioration over prolonged operation, while the denominator reflects the protective influence of material resistance. Increasing pressure, temperature, stress, or hydrogen exposure accelerates degradation, whereas improved material properties reduce degradation progression. The HCDF therefore provides a quantitative basis for forecasting compressor health, supporting Digital Twin simulations, and enabling predictive maintenance planning under dynamic operating conditions [21].

4.2 Leakage Propagation Reliability Model (LPRM)

Hydrogen leakage represents one of the most significant operational and safety concerns in hydrogen compression systems because leakage may progressively propagate through interconnected components before becoming detectable by conventional inspection methods [22]. Localised degradation of seals, valves, joints, pressure vessels, or pipe connections can influence neighbouring components through pressure redistribution, vibration transmission, and thermal interactions. Consequently, leakage should be modelled as a dynamic network phenomenon rather than an isolated event.

The proposed Leakage Propagation Reliability Model (LPRM) is defined as

$$L(t+1) = L(t) + \sum_{i} \omega_i P_i L_i$$

where

- $L(t)$= leakage state at the current operating interval;
- $L(t+1)$= predicted future leakage state;
- L_i= leakage contribution of component i;
- P_i= propagation influence associated with component i;
- ω_i= weighting coefficient representing component connectivity and operational significance.

The weighted summation models the cumulative influence of interconnected compressor components on future leakage development. Components exhibiting stronger physical interactions or higher operational criticality receive greater weighting during prediction. The model therefore enables early identification of leakage propagation pathways, supports proactive intervention before extensive hydrogen loss occurs, and improves overall system reliability by incorporating component interdependence into predictive integrity management [23].

4.3 Operational Integrity Index (OII)

Reliable operation of hydrogen compression systems depends not only on equipment reliability but also on structural integrity, inspection quality, and maintenance effectiveness throughout the asset lifecycle [24]. Existing

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assessment methods frequently evaluate these factors separately, making it difficult to obtain a comprehensive measure of operational readiness. The proposed Operational Integrity Index (OII) integrates these critical dimensions into a single quantitative indicator for evaluating overall compressor health and supporting operational decision-making.

The proposed index is formulated as

$$OII = \left(R^{\alpha} S^{\beta} I^{\gamma} M^{\delta}\right)^{\frac{1}{\alpha+\beta+\gamma+\delta}}$$

where

- R= reliability;
- S= structural integrity;
- I= inspection confidence;
- M= maintenance effectiveness;
- $\alpha, \beta, \gamma, \delta$= weighting coefficients representing the relative importance of each factor.

The weighted geometric mean ensures that poor performance in any individual dimension proportionally reduces the overall integrity score, preventing exceptionally high values in one attribute from masking weaknesses elsewhere. Higher OII values indicate improved operational resilience, stronger structural health, and greater confidence in maintenance performance. The index may be continuously updated using Digital Twin outputs and real-time sensor information to support intelligent operational control, maintenance prioritisation, and long-term integrity evaluation [25].

4.4 Remaining Useful Life Prediction Model (RULPM)

Remaining Useful Life (RUL) estimation enables maintenance planners to predict the operational lifetime of compressor components before unacceptable degradation or failure occurs [26]. Accurate RUL prediction supports proactive maintenance scheduling, reduces unexpected equipment failures, and improves operational continuity across hydrogen infrastructure. Since degradation progresses continuously under varying operating conditions, RUL estimation should account for both the current degradation state and the ongoing degradation rate.

The proposed Remaining Useful Life Prediction Model (RULPM) is expressed as

$$RUL = \frac{C_f - D_c(t)}{\dot{D}_c}$$

where

- RUL= Remaining Useful Life;
- C_f= degradation threshold corresponding to failure;
- $D_c(t)$= current degradation estimated using the HCDF;
- $\dot{D}_c$= instantaneous degradation rate.

The numerator represents the remaining degradation capacity before failure, while the denominator measures the speed at which degradation progresses under prevailing operating conditions. Higher degradation rates produce shorter predicted operational lifetimes, whereas slower deterioration extends service duration. By continuously updating degradation estimates using Digital Twin synchronisation and intelligent monitoring technologies, the model provides dynamic RUL forecasts that support maintenance optimisation, spare-part planning, and operational scheduling while reducing lifecycle costs and improving compressor availability [27].

4.5 Risk-Informed Maintenance Priority Function (RIMPF)

Maintenance resources within hydrogen infrastructure are often limited, requiring maintenance activities to be prioritised according to equipment condition, operational importance, and failure consequences rather than maintenance intervals alone [28]. The proposed Risk-Informed Maintenance Priority Function (RIMPF) provides a quantitative mechanism for ranking maintenance interventions according to overall operational risk.

The proposed Maintenance Priority Index is defined as

$$MPI = \frac{D_c R_c C_s}{L_r}$$

where

- D_c= degradation level;
- R_c= risk consequence;
- C_s= system criticality;

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- L_r= remaining operational life.

Higher degradation, greater operational consequences, and increased system criticality produce higher maintenance priority values, while longer remaining operational life reduces maintenance urgency. This prioritisation approach enables maintenance resources to be allocated where they produce the greatest improvement in operational integrity, equipment reliability, and safety performance, thereby supporting risk-based asset management and predictive maintenance strategies across hydrogen compression facilities [29].

4.6 Reliability Resilience Metric (RRM)

Modern hydrogen compression systems require evaluation metrics that consider not only reliability but also the ability of equipment to recover rapidly from disturbances while maintaining safe operation [30]. Conventional reliability measures often neglect predictive performance and post-failure recovery capabilities. The proposed Reliability Resilience Metric (RRM) therefore combines operational availability, prediction accuracy, recovery efficiency, failure occurrence, and downtime into a unified resilience indicator.

The proposed metric is expressed as

$$RRM = \frac{APR}{FD}$$

where

- A= operational availability;
- P= prediction accuracy;
- R= recovery efficiency;
- F= failure frequency;
- D= operational downtime.

Higher values indicate systems capable of maintaining availability, accurately predicting failures, and rapidly recovering following maintenance interventions. Conversely, increased failure frequency or prolonged downtime reduces resilience. The RRM therefore provides a comprehensive measure of operational robustness and supports benchmarking of intelligent integrity management strategies implemented across hydrogen compression infrastructure using Digital Twin-enabled predictive maintenance frameworks [31].

4.7 Multi-Objective Operational Optimisation

Hydrogen compressor operation requires simultaneous optimisation of multiple, often conflicting, engineering objectives including reliability, safety, maintenance expenditure, energy efficiency, and hydrogen containment [32]. Rather than optimising individual performance measures independently, the proposed framework adopts a multi-objective optimisation strategy that balances operational performance across the entire compressor lifecycle.

The optimisation problem is formulated as

$$\min \begin{cases} \text{Failure Risk} \\ \text{Downtime} \\ \text{Maintenance Cost} \\ \text{Energy Consumption} \\ \text{Leakage} \end{cases}$$

Subject to:

- pressure limits;
- safety constraints;
- maintenance resource availability;
- operational demand;
- compressor capacity.

Candidate solutions are generated using Non-dominated Sorting Genetic Algorithm II (NSGA-II) to identify Pareto-optimal operating strategies. Bayesian optimisation improves parameter selection under uncertainty, while Deep Reinforcement Learning continuously adapts operational policies according to changing compressor conditions. Together, these optimisation techniques enable intelligent decision-making that simultaneously improves reliability, reduces lifecycle costs, enhances energy efficiency, minimises hydrogen leakage, and strengthens long-term operational integrity.

Theorem 1: Stability of Degradation Prediction

Statement

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If degradation rates remain bounded and monitoring observations satisfy persistent excitation, the Hydrogen Compressor Degradation Function converges to a bounded degradation estimate, ensuring reliable long-term integrity prediction.

Justification

Because the degradation variables (pressure, temperature, mechanical stress, and hydrogen concentration) remain bounded within operational limits, the HCDF evolves continuously without divergence. Persistent excitation supplied by continuous sensor measurements ensures sufficient information is available to update the degradation estimate accurately over time. Consequently, the prediction error remains bounded, enabling stable long-term estimation of compressor degradation and supporting reliable integrity forecasting through Digital Twin synchronisation and adaptive monitoring.

Theorem 2: Optimality of Risk-Informed Maintenance

Statement

Under finite maintenance resources and bounded operational constraints, the Risk-Informed Maintenance Priority Function produces an optimal maintenance schedule that maximises operational integrity while minimising system failure probability.

Justification

The RIMPF ranks maintenance interventions according to degradation severity, failure consequence, system criticality, and remaining operational life. Given finite maintenance resources and operational constraints, allocating maintenance activities according to the highest priority indices produces the greatest reduction in cumulative operational risk. Therefore, the optimization framework maximizes overall system integrity while minimizing the probability of compressor failure and inefficient maintenance allocation.

5. INDUSTRIAL DEPLOYMENT, CHALLENGES AND FUTURE RESEARCH

5.1 Practical Deployment Across the U.S. Hydrogen Infrastructure

The proposed Intelligent Reliability and Operational Integrity Framework is designed to support deployment across the expanding United States hydrogen value chain, where dependable compression systems are essential for maintaining safe and continuous hydrogen delivery [31]. At hydrogen production facilities, including both green hydrogen electrolysis plants and blue hydrogen production sites, intelligent integrity management enables continuous monitoring of compressor health, improving equipment availability while reducing production interruptions. By integrating Digital Twins with real-time operational data, plant operators can identify degradation at an early stage and schedule maintenance before failures affect hydrogen output [32].

Pipeline compressor stations can benefit from continuous integrity assessment through distributed sensor networks and predictive analytics that monitor pressure fluctuations, vibration signatures, leakage behaviour, and structural health. Such capabilities improve operational reliability while supporting long-distance hydrogen transportation across interconnected pipeline networks [33]. Hydrogen refuelling infrastructure similarly requires highly reliable compression systems to maintain rapid dispensing, minimise downtime, and ensure safe high-pressure operation for fuel-cell vehicles.

Large industrial hydrogen hubs, where production, storage, distribution, and end-use facilities operate within integrated ecosystems, provide ideal environments for deploying Digital Twin-enabled operational management. Edge-cloud integration allows computationally intensive analytics to be shared between local edge devices and cloud platforms, supporting real-time decision-making without compromising response speed [34]. Successful implementation will also depend upon workforce readiness through multidisciplinary training in hydrogen engineering, artificial intelligence, Digital Twin technologies, data analytics, and reliability engineering, ensuring that operators possess the technical competencies required to manage increasingly intelligent hydrogen infrastructure [35].

5.2 Technical, Safety and Regulatory Challenges

Despite significant technological progress, several engineering and regulatory challenges must be addressed before intelligent reliability management can be widely deployed across hydrogen compression infrastructure [36]. Hydrogen safety remains the foremost consideration because of hydrogen's low ignition energy, wide flammability range, and high diffusivity. Consequently, predictive integrity systems must reliably identify degradation and leakage before hazardous operating conditions develop.

The growing integration of Digital Twins, Industrial Internet of Things devices, and cloud-based analytics also increases cybersecurity risks. Protecting operational technology networks against unauthorised access, data manipulation, and cyberattacks is essential for maintaining the integrity of predictive maintenance systems. Sensor reliability presents an additional challenge, as inaccurate or degraded sensor measurements may reduce diagnostic

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accuracy and compromise Remaining Useful Life predictions. Robust sensor validation and redundancy strategies are therefore necessary to ensure dependable monitoring performance [37].

Artificial intelligence explainability is increasingly important within safety-critical industrial environments because maintenance engineers must understand the reasoning underlying automated maintenance recommendations. Compliance with recognised engineering standards, including ASME B31.12 for hydrogen piping systems, relevant API standards for compressor equipment, and ISO 19880 governing hydrogen refuelling infrastructure, provides essential guidance for safe system design and operation [38]. Future deployment will also require reliability certification frameworks capable of validating Digital Twin models, AI algorithms, and predictive maintenance systems before widespread industrial adoption [39].

5.3 Future Research Directions

Future research should focus on advancing hydrogen compression systems from predictive maintenance towards fully autonomous reliability management capable of continuously adapting to changing operating environments [40]. Autonomous compressors equipped with self-optimising control algorithms could automatically adjust operating parameters according to degradation trends, hydrogen demand, and environmental conditions, thereby improving efficiency while reducing operator intervention.

The development of self-healing machinery represents another promising research direction in which intelligent materials, adaptive lubrication technologies, and automated repair mechanisms collectively reduce the impact of component degradation and extend equipment service life. Physics-informed foundation models trained using large-scale engineering datasets may further improve degradation prediction by combining physical principles with advanced artificial intelligence, enabling more accurate fault diagnosis under previously unseen operating conditions.

Federated Digital Twins offer an emerging architecture in which geographically distributed compressor assets collaboratively improve predictive models while preserving data ownership and cybersecurity. Such collaborative intelligence could substantially strengthen the resilience of regional hydrogen infrastructure through shared operational learning across production facilities, compressor stations, and industrial hydrogen hubs. Ultimately, integrating these technologies will contribute to highly resilient, carbon-neutral industrial systems capable of supporting the long-term expansion of the United States hydrogen economy while maintaining exceptional standards of operational safety, reliability, and sustainability.

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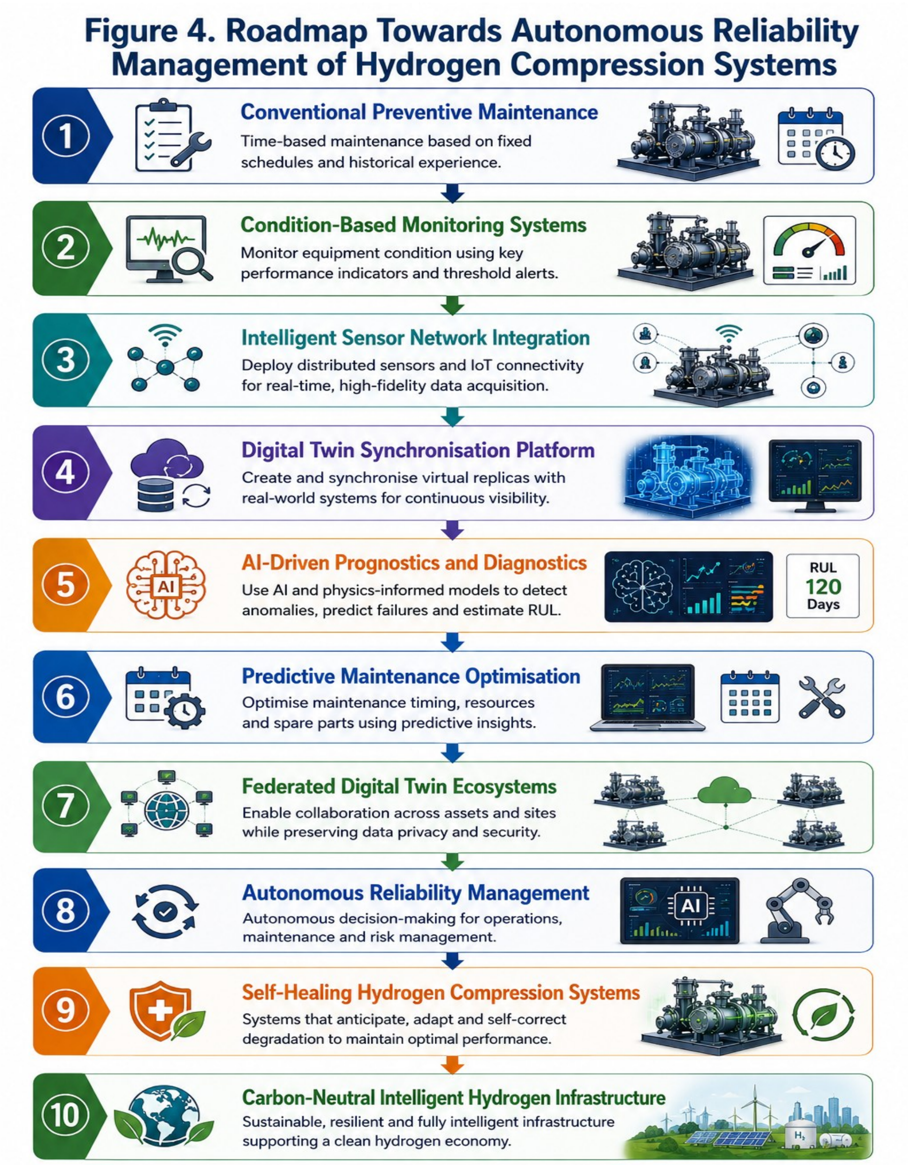

Figure 4. Roadmap Towards Autonomous Reliability Management of Hydrogen Compression Systems

Table 2. Operational Challenges, Integrity Enhancement Strategies and Future Research Opportunities

Operational Challenge	**Integrity Enhancement Strategy**	**Future Research Opportunity**
Hydrogen embrittlement	Advanced materials and continuous degradation monitoring	Self-healing materials for hydrogen service
Hydrogen leakage	Intelligent leakage detection and Digital Twin prediction	Autonomous leak localisation and mitigation
High-pressure operation	Adaptive pressure monitoring and predictive control	AI-enabled autonomous compressor optimisation
Sensor degradation	Sensor validation, redundancy and calibration	Self-calibrating intelligent sensor networks
Maintenance scheduling	Risk-informed predictive maintenance	Reinforcement learning for autonomous maintenance planning

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Operational Challenge	Integrity Enhancement Strategy	Future Research Opportunity
Cybersecurity threats	Secure edge-cloud architecture and encrypted communications	Cyber-resilient Digital Twin ecosystems
Limited operational visibility	Multi-source sensor fusion and real-time analytics	Physics-informed foundation models
Distributed hydrogen assets	Federated Digital Twin collaboration	National intelligent hydrogen infrastructure networks

6. CONCLUSION

This study proposed an Intelligent Reliability and Operational Integrity Framework for hydrogen compression systems that integrates Digital Twins, intelligent condition monitoring, prognostics, and physics-informed artificial intelligence into a unified asset management approach. By combining continuous sensor monitoring with predictive analytics and virtual asset 49ynchronization, the framework enables early fault detection, degradation forecasting, remaining useful life estimation, and risk-informed maintenance decision-making. The study further introduced a suite of novel mathematical models, including the Hydrogen Compressor Degradation Function (HCDF), Leakage Propagation Reliability Model (LPRM), Operational Integrity Index (OII), Remaining Useful Life Prediction Model (RULPM), Risk-Informed Maintenance Priority Function (RIMPF), Reliability Resilience Metric (RRM), and a multi-objective operational optimisation framework that collectively provide quantitative support for intelligent integrity management. The proposed framework enhances operational safety, equipment reliability, maintenance effectiveness, and operational continuity, thereby supporting dependable hydrogen compression infrastructure. Its implementation provides a pathway towards scalable, resilient, and low-carbon hydrogen systems that will underpin the continued expansion of the United States hydrogen economy.

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