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"AGEING OF CENTRIFUGAL COMPRESSORS"

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ABSTRACT

Centrifugal compressors operating in hydrocarbon service are increasingly required to function beyond their nominal design life. While thermodynamic performance degradation can be quantified through conventional analysis, integrity degradation associated with corrosion, fatigue, and geometric modification of pressure-retaining components requires more structured evaluation. This paper investigates ageing-related integrity risks in centrifugal compressor casings, with emphasis on corrosion-induced material loss and its influence on stress redistribution in critical regions such as shear-ring grooves. A combined inspection-based and analytical approach is presented. Field observations from ageing offshore compressors are integrated with established degradation mechanisms, including corrosion, erosion, fatigue, and sulphide stress cracking. Finite Element Analysis (FEA) is employed to evaluate stress amplification resulting from corrosion depths within typical corrosion allowance limits. Results indicate that moderate geometric loss (<3 mm) may increase peak local stresses by approximately 20%, with implications for fatigue margin and structural reliability. A structured lifecycle integrity framework is proposed, incorporating risk-based inspection, degradation assessment, maintenance strategy review, and verification of material properties in accordance with fitness-for-service principles. The findings support a transition from experience-based ageing management toward analytically supported integrity verification for extended operation of centrifugal compressors.

KEYWORDS: Centrifugal compressor; ageing equipment; life extension; casing integrity; corrosion–fatigue interaction; finite element analysis; fitness-for-service; risk-based inspection; pressure boundary assessment.

1. INTRODUCTION

Centrifugal compressors are critical assets in the petroleum, chemical, and gas processing industries, where continuous operation and containment integrity are essential for safe production. Over extended service periods, compressor performance degradation is typically quantified through thermodynamic analysis and efficiency tracking. Performance losses due to fouling, seal wear, and internal clearance changes can often be restored through overhaul and component replacement, consistent with design and maintenance guidance provided in API Standard 617 (1).

However, while performance degradation is measurable and recoverable, structural integrity degradation associated with ageing remains significantly more complex. Ageing effects represent the cumulative interaction between material properties, cyclic stresses, environmental exposure, corrosion mechanisms, maintenance practices, and operational history. Unlike thermodynamic deterioration, integrity degradation cannot be assessed solely through performance metrics and requires a multidisciplinary evaluation approach incorporating inspection, materials assessment, and structural verification.

API 617 specifies minimum design requirements for centrifugal compressors and historically references a nominal design life often interpreted in industry practice as approximately 20 years (1). It is important to recognize that this period represents a design basis rather than a strict end-of-life limit. Beyond this timeframe, continued operation must be justified through structured integrity verification rather than assumed safe by default. Although standards such as API 579-1/ASME FFS-1 provide methodologies for fitness-for-service assessments (2), and API RP 580 establishes principles for risk-based inspection (3), there remains limited integrated discussion specifically addressing ageing effects in compressor pressure-containing casings.

The Energy Institute has published guidelines for the life extension of ageing rotating equipment in offshore petroleum installations, including centrifugal compressors (4). These guidelines emphasize systematic review of degradation mechanisms, maintenance history, and operational changes. Nevertheless, practical implementation often relies heavily on experiential judgement rather than analytical validation of stress redistribution caused by corrosion, wear, or geometric modification in highly stressed regions.

Operating a centrifugal compressor beyond its nominal design life does not inherently imply that the equipment is unfit for service. Numerous offshore and onshore installations demonstrate extended operational periods exceeding original design assumptions. However, safe life extension requires verification that degradation mechanisms such as corrosion (including CO_2 corrosion), sulphide stress cracking (SSC), fatigue accumulation, and stress concentration effects have not compromised structural margins (5)– (7).

In particular, corrosion within allowable limits can alter local stress fields, especially in geometrically sensitive regions such as shear-ring grooves and flange interfaces. Stress amplification in these areas may reduce fatigue life or increase susceptibility to environmentally assisted cracking. Therefore, ageing must be considered as a coupled degradation–stress interaction problem rather than as a simple function of service duration.

In addition, changes in process gas composition, pressure conditions, temperature, or operating envelope may invalidate original material selection assumptions. Sour service environments require compliance with ISO 15156/NACE MR0175 to mitigate hydrogen-induced cracking and sulphide stress cracking risks (5). Similarly, increased CO_2 content and moisture presence may accelerate carbonic acid corrosion mechanisms (6). These factors necessitate periodic reassessment of material suitability and structural reliability during life extension evaluations.

1.1. Research Gap and Contribution

While industry standards provide design requirements, fitness-for-service methodologies, and risk-based inspection frameworks, there remains limited published analysis quantifying how ageing-related geometric loss in compressor casings influences stress distribution and structural integrity. Most available literature focuses on performance restoration or general ageing management rather than on the detailed structural implications of corrosion in highly stressed casing regions.

This paper addresses that gap by developing an integrity-focused assessment framework for ageing centrifugal compressors and analytically evaluating stress amplification in corroded shear-ring regions using finite element modelling. The study further links inspection findings to structural reliability considerations and proposes a risk-informed lifecycle verification approach to support safe operation beyond nominal design life.

The objective is not to redefine design standards, but to strengthen evidence-based decision-making for operators managing ageing compressor assets in high-consequence environments.

Figure 1 conceptually summarizes the principal ageing considerations influencing integrity management.

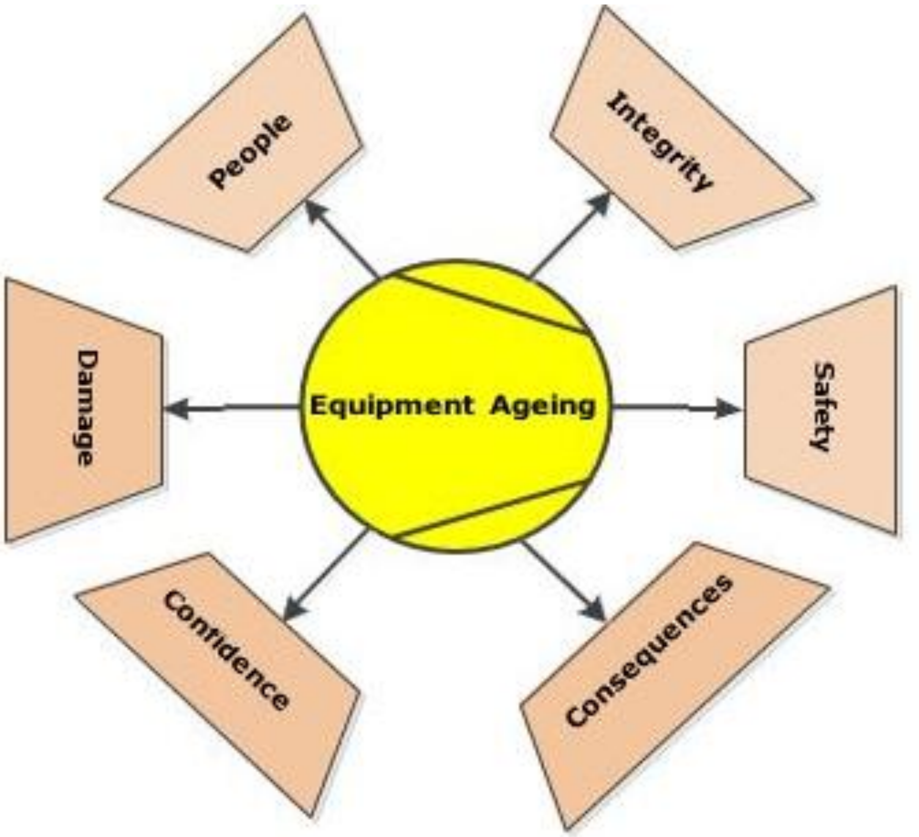

Figure 1: Factors to consider when equipment is ageing

2. MANAGING EQUIPMENT LIFE CYCLE

2.1. Degradation rate and the accumulation of damage

Rotating equipment operating in hydrocarbon service is subjected to multiple time-dependent degradation mechanisms, including corrosion, erosion, cyclic fatigue, creep (where applicable), and environmentally assisted cracking. Unlike performance degradation, which can often be restored through overhaul, structural degradation accumulates irreversibly and progressively alters the component's mechanical response.

The concept of accumulated damage is well established in fatigue and structural reliability theory. Under cyclic loading, cumulative damage may be described using Miner's rule, in which failure is assumed to occur when the summation of cycle damage fractions reaches unity (8). However, in ageing compressors, degradation is rarely fatigue-driven alone. Corrosion-induced wall thinning and localized pitting increase stress concentration factors, thereby accelerating fatigue crack initiation and propagation (9), (10).

The interaction between corrosion and mechanical loading is particularly critical in pressure-retaining casings. Local material loss reduces load-carrying cross-section and modifies stress distribution. Even modest geometric changes in highly stressed regions, such as shear-ring grooves or flange interfaces, can significantly amplify local stresses. According to stress concentration theory (11), small geometric discontinuities may elevate peak stresses beyond nominal design values, reducing fatigue margin and increasing susceptibility to crack growth under cyclic pressure loading (12).

From a lifecycle perspective, degradation rate is not constant but depends strongly on operating environment, fluid composition, temperature, stress level, and maintenance quality. In CO_2-containing environments with moisture presence, carbonic acid corrosion may occur, resulting in uniform or localized material loss (13). In sour service environments containing H_2S, sulphide stress cracking risks become dominant if material hardness and stress thresholds exceed ISO 15156 limits (5).

Figure 2 presents a conceptual representation of accumulated damage progression during equipment service life. Degradation may initially develop gradually during early operation, followed by progressive acceleration in later years due to corrosion–fatigue interaction and stress redistribution effects. The lifecycle stage boundaries are indicative rather than absolute and should be supplemented by condition-based assessment rather than fixed time thresholds.

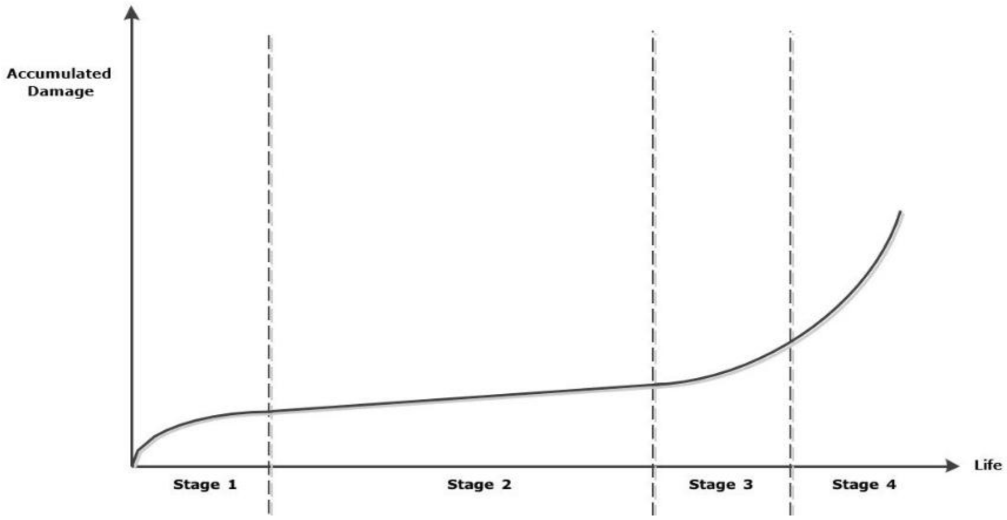

Figure 2: Accumulated damage during pressure equipment service (14)

Inspection data from the Health and Safety Executive indicate that the frequency of detected defects in pressure equipment increases with service age (14). Although much of the published data relates to static equipment, the underlying principle of cumulative deterioration with increasing uncertainty over time is consistent with broader asset integrity and lifecycle management frameworks (15), (16). Figure 3 presents the reported increase in detected defects with equipment age as observed in the HSE survey (14). While the dataset primarily reflects static pressure equipment, the trend of rising defect frequency with increasing service duration provides empirical support for the conceptual degradation behaviour illustrated in Figure 2.

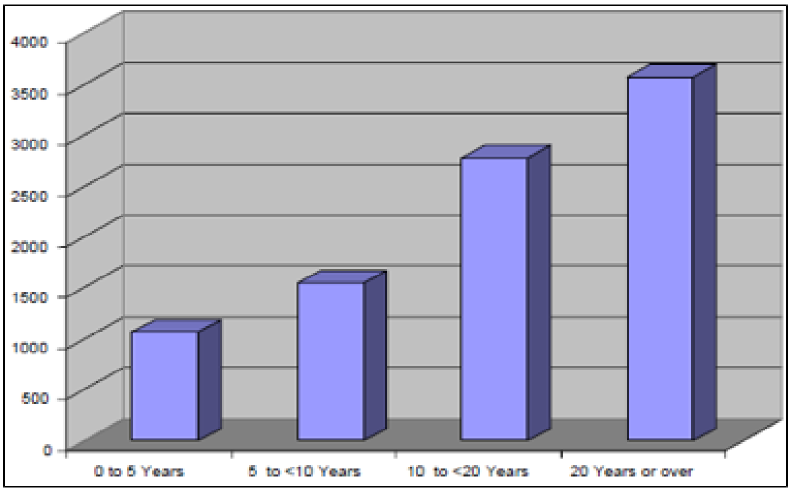

Figure 3: Number of defects versus age of equipment (14)

From a risk-based perspective, lifecycle integrity may be expressed as:

$$Risk = P_f \times C_f$$

Where P_f represents the probability of failure, and C_f represents the associated consequence in terms of safety, environmental impact, and economic loss. As degradation accumulates and inspection intervals extend, P_f increases unless mitigated through appropriate inspection and maintenance strategies (17), (18). Risk-based inspection methodologies therefore emphasize integration of degradation modelling, inspection effectiveness, and consequence assessment rather than reliance solely on elapsed service time.

2.2. *Management of Ageing and Component Criticality*

Effective management of ageing equipment requires identification of components whose failure would result in significant safety or environmental consequences. In centrifugal compressors, internal rotating elements such as impellers, shafts, and seals are typically removed during overhauls and subjected to detailed inspection and periodic replacement. These components, therefore, benefit from direct condition monitoring throughout the operational life of the machine.

In contrast, the pressure-containing casing and associated structural attachments often receive comparatively limited intrusive inspection during routine maintenance. The casing is typically cleaned and visually examined prior to installation of refurbished rotating assemblies; however, localized corrosion, geometric distortion, weld degradation, or stress concentration effects may remain undetected without targeted non-destructive examination and dimensional verification.

From an integrity standpoint, the casing represents the highest-consequence component because it forms the primary pressure boundary. Failure of this component may result in hydrocarbon release, posing immediate safety and environmental risk. According to fitness-for-service principles (2), pressure-retaining components must satisfy minimum thickness, stress, and fracture resistance criteria under prevailing operating conditions.

In offshore environments, atmospheric corrosion, salt exposure, and variability in process gas composition may accelerate degradation relative to original design assumptions. Furthermore, repeated maintenance activities may introduce cumulative mechanical damage at flange faces, threaded connections, and shear-ring grooves, contributing to localized stress intensification.

Given that the casing constitutes the primary pressure-retaining boundary and represents the highest-consequence failure scenario, detailed inspection and structural evaluation of this component form the central focus of the present study. The following section, therefore, outlines a structured casing inspection and verification methodology aligned with fitness-for-service principles.

3. CASING INSPECTION METHODOLOGY AND STRUCTURAL VERIFICATION

3.1. Integrity-Oriented Inspection Philosophy

The inspection methodology presented in this section is structured around integrity verification rather than routine maintenance activity. The objective is not merely to document observable deterioration, but to determine whether ageing-related degradation has reduced the structural safety margin of pressure-retaining components below acceptable limits defined by design codes and fitness-for-service (FFS) criteria (2).

For centrifugal compressors operating beyond nominal design life defined in API 617 (1), inspection must focus on regions where stress concentration, corrosion interaction, and load transfer mechanisms are most critical. These areas include shear-ring grooves, flange interfaces, threaded connections, and sealing surfaces. Degradation in such regions may amplify local stresses and influence both static and fatigue performance.

Figure 4 identifies the primary pressure-containing components considered in this assessment.

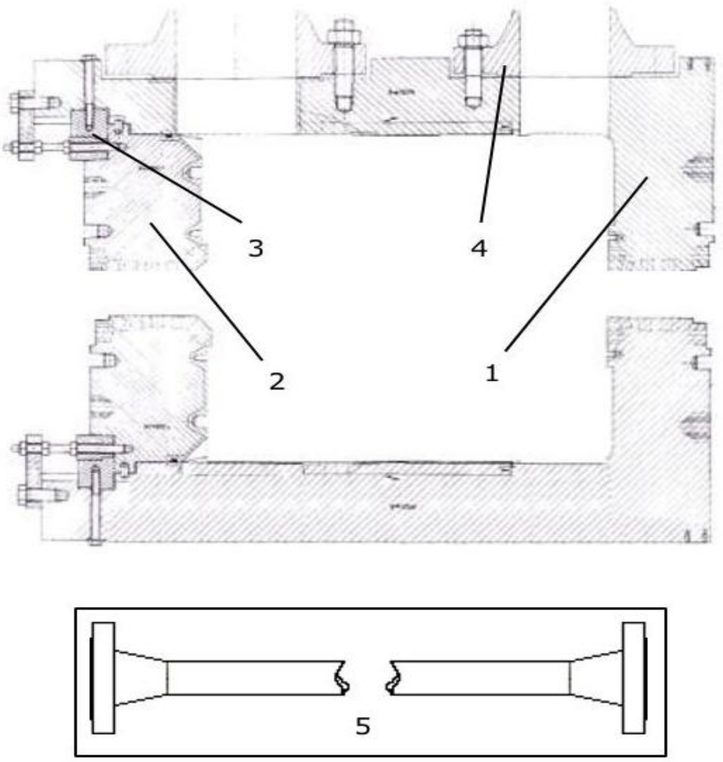

Figure 4: Pressure-containing parts – casing assembly

3.2. *Scope of Casing Integrity Assessment*

The casing represents the primary pressure boundary of the compressor and therefore constitutes the highest-consequence component in the event of failure. The inspection process is intended to verify preservation of minimum required wall thickness, absence of cracking in stress-critical regions, integrity of shear-ring load transfer interfaces, dimensional stability, including ovality or distortion, and retention of acceptable material mechanical properties.

Where feasible, removal of the casing from the baseplate and inspection in a controlled facility is recommended to enable comprehensive non-destructive examination (NDE). When multiple identical machines exist, detailed inspection of one representative unit may be used to inform a risk-based inspection strategy for the remaining units, provided results are satisfactory (3).

Pipework alignment should be verified before casing removal, as degradation or settlement of pipe supports may introduce external bending stresses that alter casing stress distribution. External piping loads are recognised contributors to nozzle and flange stress concentration in pressure equipment (19).

3.3. *Casing Inspection Activities*

Inspection of the casing should focus on regions susceptible to corrosion–stress interaction and stress concentration. Auxiliary components such as drain valves, pressure tappings, and studs should be removed to ensure full surface accessibility. Corrosion depth should be measured dimensionally, and the remaining wall thickness verified against corrosion allowance or acceptable limits defined by fitness-for-service assessment procedures (2).

Internally threaded holes require examination for corrosion or distortion, as localised degradation may influence stress distribution and joint integrity. Mounting welds and attachments should be subjected to dye penetrant testing to identify surface-breaking cracks, and hardness testing should be performed in welded and highly stressed regions to verify retention of acceptable material properties.

Particular attention shall be given to shear-ring grooves, which represent critical load-transfer interfaces and typically constitute the most highly stressed regions of the casing assembly. Localised corrosion at the base of the groove may increase effective radial clearance and modify contact stress distribution, thereby influencing fatigue performance.

Dimensional verification of casing bore ovality is also required, as excessive distortion may affect rotor alignment and alter stress distribution under internal pressure loading.

3.4. *Cover (Head) and Shear Ring Inspection*

The cover and associated shear-ring locking components are subjected to similar degradation mechanisms and should therefore be evaluated using comparable integrity criteria. Inspection should include dimensional measurement of corrosion depth and comparison with allowable limits, verification of shear-ring seating integrity, confirmation of O-ring seating geometry, crack detection at welded blanking plugs, and examination of threaded holes and internal drillings for corrosion or breakthrough.

Localised corrosion at sealing interfaces may compromise pressure containment even when global wall thickness remains within acceptable limits. Figures 5–7 illustrate representative corrosion damage observed during field inspections and demonstrate the tendency for material loss to concentrate at geometric discontinuities.

Figure 5: Corrosion of the shear ring groove

Figure 6: Corrosion of the cover seal location

Figure 7: Corrosion of the inner face of the cover

These examples demonstrate that material loss frequently concentrates at geometric discontinuities, reinforcing the need for dimensional measurement rather than reliance on visual inspection alone.

3.5. Finite Element Evaluation of Corrosion Effects

Many legacy compressors were originally designed using explicit stress calculation methods rather than detailed numerical simulation. While conservative design practices often provided adequate margin in as-new condition, ageing introduces geometric modification and potential material degradation that may invalidate original assumptions.

To evaluate the structural implications of corrosion at a shear-ring interface, a two-dimensional finite element model of the casing cross-section was developed. Linear elastic material behaviour was assumed, and no plasticity or material degradation effects were included in the model. Internal design pressure was applied uniformly to internal surfaces, and symmetry boundary conditions were imposed along the axial plane. Contact interaction between the shear ring and casing was defined to simulate load transfer.

Corrosion was represented by increasing the radial clearance at the groove base from 0.5 mm to 2.5 mm and by reducing the effective axial contact width between the shear ring and casing. Both the as-new and corroded geometries were analysed under identical loading and boundary conditions to isolate the influence of geometric modification.

Results are presented in Figure 8.

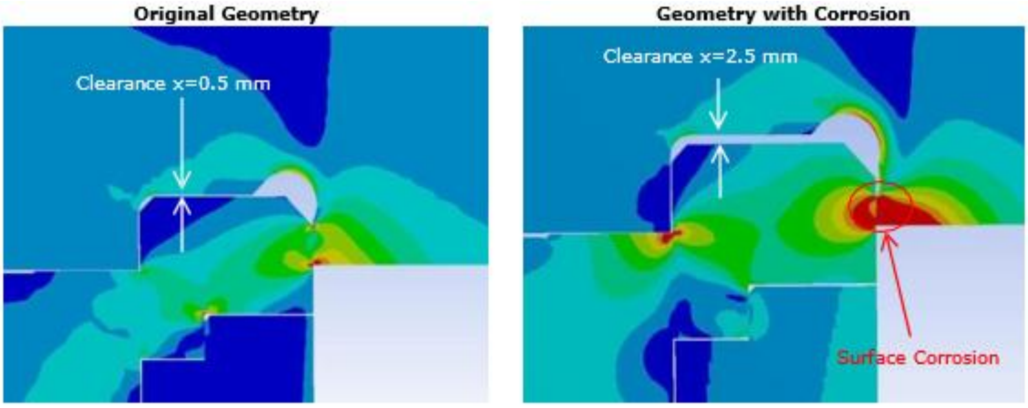

Figure 8: Stress increases due to corrosion

Maximum stresses occur at the shear-ring contact interface in both configurations. The corroded geometry exhibited an approximate 20% increase in peak stress compared with the as-new condition.

Although this example represents a simplified 2D model, the result illustrates that corrosion depth below the typical global corrosion allowance (3–5 mm) may significantly affect local stress concentration. In fatigue-sensitive regions, such stress amplification may reduce life expectancy in accordance with fatigue design principles (8), (16).

It should be noted that the analysis does not account for material property degradation, residual stresses, or three-dimensional geometric effects. Nevertheless, it demonstrates the sensitivity of stress-critical interfaces to geometric modification and supports the integration of analytical verification into life-extension assessments.

4. ROUTINE CASING INTEGRITY VERIFICATION

Routine casing inspection forms part of ongoing integrity management and complements the detailed off-line inspection described in Section 3. The purpose of routine inspection is early detection of leakage, corrosion progression, or seal degradation that may develop between major overhauls.

It is recommended that routine casing inspections be performed during scheduled or unscheduled shutdowns, with intervals not exceeding six months unless justified by a formal risk-based assessment (3). The inspection frequency should consider operating pressure, gas composition, corrosion susceptibility, and historical defect trends.

4.1. Leak Detection Under Pressurised Conditions

With the compressor shut down but maintained under residual operating pressure, verification of containment integrity should be performed. Leak testing under pressurised conditions is essential because minor O-ring or flange imperfections may not be detectable once the system is depressurised.

Assessment should focus on the head-to-casing joint (using a calibrated gas detector equipped with a probe, see Figure 9), balance lines and associated pressure tappings, dry gas seal console and interconnecting tubing, main process connection flanges, and pressure instrumentation connections, including impulse tubing. These locations represent typical leakage pathways due to sealing degradation, joint relaxation, or corrosion-induced surface irregularities.

Manufacturers utilise varying sealing configurations at the head-to-casing interface. In some designs, dual O-rings with an intermediate pressure tapping are installed to facilitate leakage monitoring. Figure 9 illustrates a representative arrangement; however, manufacturer-specific documentation should be consulted to ensure inspection alignment with the original design configuration.

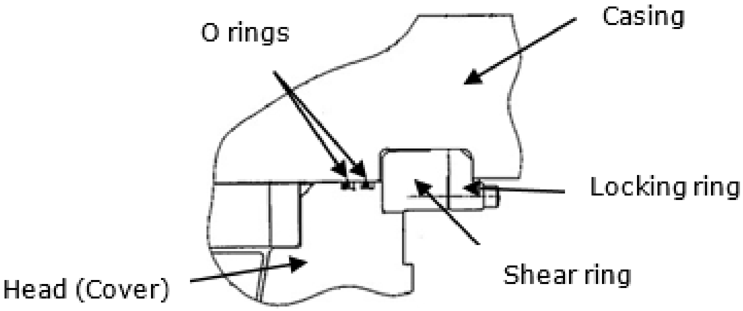

Figure 9: Typical head O-ring arrangement

4.2. Visual and Surface Condition Assessment

In addition to leak detection, the external surfaces of the casing and head should be assessed for evidence of corrosion, coating degradation, mechanical damage, and localized pitting near flange or sealing interfaces. Particular attention should be given to areas exposed to marine or chemically aggressive environments, as coating failure may accelerate corrosion progression.

Although visual inspection alone cannot quantify structural integrity, it provides an early indication of environmental exposure and surface deterioration that may influence long-term degradation behaviour.

4.3. Documentation and Lifecycle Traceability

A detailed inspection report shall be generated following each routine inspection. The documentation should record leak detection results, measured corrosion observations, corrective actions undertaken, and photographic evidence where applicable. These records form part of the lifecycle integrity documentation and provide traceability for future fitness-for-service evaluations (2).

Systematic trend analysis of repeated inspection findings supports identification of progressive degradation patterns and assists in refining inspection intervals within a risk-based inspection framework (3).

5. REVIEW OF EXISTING COMPRESSOR MAINTENANCE STRATEGY

Operation beyond nominal design life requires a systematic reassessment of the existing maintenance strategy to ensure continued alignment between degradation behaviour and inspection practices. Although many compressor maintenance programs are condition-based rather than strictly time-based, ageing introduces additional uncertainty in corrosion progression, fatigue accumulation, and sealing performance that may not have been fully considered in the original strategy.

A structured review should therefore evaluate whether current maintenance activities adequately address the evolving degradation profile of the pressure-retaining components. Particular attention should be given to corrosion development in stress-critical regions, fatigue-sensitive geometries such as shear-ring interfaces, degradation of sealing locations, and potential material property changes in highly stressed areas. The suitability of inspection intervals should be examined in light of observed corrosion rates, historical defect trends, and operating environment variability.

Within a risk-based inspection framework (3), maintenance frequency should reflect both the probability and consequence of failure rather than elapsed service time alone. Therefore, continuation of existing intervals is acceptable only where inspection data demonstrate stable degradation rates and sufficient structural margin. Where uncertainty exists, a conservative adjustment to inspection frequency or additional verification activities may be warranted.

In practice, experience indicates that intrusive maintenance intervals may not require substantial modification provided that condition monitoring and inspection regimes have been consistently implemented. However, operation beyond nominal design life necessitates enhanced documentation and traceability. Ageing-related inspection results, corrosion assessments, non-destructive examination findings, and any analytical evaluations, such as fitness-for-service assessments (2) or stress analysis, should be consolidated within a structured integrity dossier.

The purpose of this review is not to increase maintenance burden unnecessarily, but to formally recognise ageing as a risk modifier and ensure that integrity management decisions remain technically justified, auditable, and aligned with applicable design standards (1).

6. LIFE EXTENSION STRATEGY AND OPERABILITY ASSESSMENT

Extension of compressor service life beyond nominal design limits requires a structured technical evaluation rather than reliance on elapsed operating time alone. Life extension decisions must integrate degradation behaviour, operational conditions, maintenance history, and structural verification results presented in earlier sections.

The feasibility of continued operation depends on three primary factors:

1. The current structural condition of pressure-retaining components
2. The degradation rate under prevailing process conditions
3. The adequacy of monitoring and maintenance controls

A systematic life-extension assessment, therefore, involves evaluation of deterioration mechanisms, review of historical performance data, and analytical verification of remaining structural margin.

6.1. Quality of historical data records

Reliable historical operating data form the foundation of any life-extension decision. Continuous monitoring of pressure, temperature, vibration, and gas composition enables identification of abnormal trends and correlation with degradation behaviour.

Where high-resolution operational data (e.g., hourly logging) is available, fatigue cycle estimation and thermal loading assessment may be performed with greater confidence. However, in many ageing installations, maintenance records and inspection documentation are incomplete or inconsistent, particularly following ownership transfer.

In such cases, uncertainty in degradation history must be acknowledged explicitly in the life-extension evaluation. Conservative assumptions may be required when estimating remaining fatigue life or corrosion progression in accordance with established fatigue design methodologies (8), (16).

6.2. Influence of Process Fluid Changes

Changes in gas composition represent one of the most critical life-limiting factors in ageing compressors. Increased concentrations of CO_2 or H_2S can significantly accelerate corrosion rates and introduce additional failure mechanisms not considered in the original design specification.

Regular gas analysis is therefore essential to confirm that operating conditions remain within the material compatibility envelope defined during design. Where original material selection did not fully comply with sour service requirements, evaluation against ISO 15156 criteria becomes necessary (5).

Factors that may adversely affect equipment life include elevated CO_2 or H_2S content, multiphase flow conditions, increased operating temperature, and solid particle entrainment. Each of these influences either the corrosion rate, the erosion rate, or the combined corrosion–erosion interaction.

Figure 10 illustrates corrosion–erosion damage associated with wet CO_2 exposure in a rotor not originally designed for such conditions.

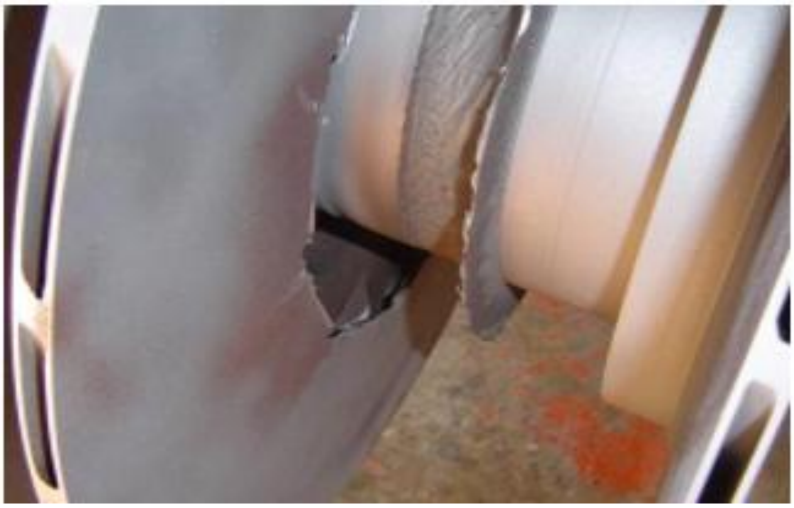

Figure 10: Factors to consider when equipment is ageing

6.3. Wet CO_2 Corrosion Mechanism

The combined presence of CO_2 and liquid water under pressure leads to the formation of carbonic acid:

$$CO_2 + H_2O \rightarrow H_2CO_3$$

Carbonic acid reacts with carbon steel, resulting in the formation of iron carbonate ($FeCO_3$), commonly referred to as siderite (13). While protective $FeCO_3$ films may form under certain conditions, fluctuating temperature, turbulence, or erosion may destabilise this layer, leading to continued metal loss.

In compression systems, incomplete liquid separation at suction or condensation within pipework can introduce water droplets into the gas stream. Localised corrosion may then occur at stress-concentration sites, potentially influencing the structural margin as demonstrated in Section 3.

In addition to wall thinning, corrosion products may contribute to fouling or erosion within internal flow passages, affecting aerodynamic performance and mechanical reliability.

6.4. Sulphide Stress Corrosion (SSC)

In environments containing H_2S and water, sulphide stress cracking may occur when material hardness and applied stress exceed threshold limits (5). SSC is a hydrogen-assisted cracking mechanism in which atomic hydrogen generated during corrosion diffuses into the steel microstructure, reducing ductility and promoting brittle fracture under tensile stress.

Crack morphology is typically characterised by fine branching cracks with limited macroscopic plastic deformation. Localised pitting often acts as a stress concentrator, initiating crack propagation.

Prevention of SSC relies primarily on material selection and hardness control. Industry practice commonly limits hardness to approximately 22 HRC in sour service applications, particularly in weld heat-affected zones. Where ageing equipment was not originally specified for sour environments, verification of material hardness and susceptibility becomes essential during life-extension assessment.

6.5. Remaining Fatigue Life Considerations

Where operational data permit, estimation of remaining fatigue life should be performed using cumulative damage principles and stress concentration effects described previously (8), (16). Corrosion-induced geometric modification may reduce fatigue life significantly even where global wall thickness remains within allowable limits.

Life-extension decisions should therefore consider not only wall-thickness measurements but also local stress amplification effects and fatigue accumulation history. Where uncertainty in loading history exists, conservative life estimates or additional monitoring may be warranted.

6.6. Integrated Life-Extension Decision Framework

Life extension should not be approached as a simple binary decision based solely on elapsed operating time, but rather as a structured technical evaluation that integrates inspection findings, projected corrosion rates, analytical stress verification, material compatibility assessment, and maintenance performance history. These elements must be considered collectively to establish whether an adequate structural margin remains for continued safe operation under foreseeable operating conditions.

The assessment should demonstrate that active degradation mechanisms are either stabilised or progressing at predictable and manageable rates, and that stress levels within critical regions remain within acceptable limits. Particular attention should be given to the interaction between corrosion-induced geometric modification and fatigue-sensitive stress concentration zones identified in earlier sections. Where uncertainty exists regarding remaining life or structural adequacy, conservative assumptions or additional monitoring may be required.

Formal fitness-for-service evaluation in accordance with API 579-1/ASME FFS-1 (2) may provide a structured and defensible basis for demonstrating continued operability. Such an approach ensures that life-extension decisions are supported by quantitative analysis rather than subjective judgment, and that operational risk remains aligned with recognised engineering standards.

7. DISCUSSION

This study has examined the integrity implications of operating centrifugal compressors beyond their nominal design life, with particular emphasis on pressure-retaining casings. Ageing should not be interpreted solely as performance degradation, which can be assessed through thermodynamic evaluation, but rather as cumulative structural damage resulting from corrosion, fatigue, geometric modification, and maintenance-induced wear. Such degradation mechanisms are well established in structural integrity literature and fatigue design frameworks (8), (16), and their interaction becomes increasingly significant as assets exceed original design assumptions.

Inspection data reported in prior studies (14) demonstrate that defect frequency increases with equipment age, particularly beyond nominal design life. Similar age-related degradation trends have been reported in offshore structural reassessment methodologies, where continued operation beyond original design life requires explicit verification of structural margin rather than reliance on historical performance (20). The present work highlights that degradation does not manifest uniformly across compressor components. Internal rotating elements are routinely removed and inspected during overhaul cycles, whereas casings, despite forming the primary pressure boundary, often receive comparatively limited intrusive evaluation. This imbalance in inspection emphasis represents a potential integrity vulnerability.

The finite element analysis conducted in this study demonstrates that localized corrosion at shear-ring interfaces can produce stress amplification of approximately 20%, even when material loss remains within conventional corrosion allowance limits. From a structural mechanic's perspective, such amplification is consistent with classical stress concentration theory (11) and established finite element modelling principles (21), (22). In fatigue-sensitive regions, local stress increases of this magnitude may substantially reduce remaining life in accordance with fatigue design guidance (8), (16). Furthermore, fracture assessment methodologies such as BS 7910 recognise that local stress intensification and geometric discontinuities can significantly influence crack driving force and structural reliability (23). The implication is that global wall-thickness criteria alone may be insufficient indicators of remaining structural margin in ageing equipment.

The interaction between corrosion and fatigue is particularly critical in compressors exposed to CO_2 or H_2S environments. Wet CO_2 corrosion mechanisms, including carbonic acid formation and iron carbonate film development (13), may be further quantified using established corrosion rate prediction models such as NORSOK M-506 (24). In sour service environments, sulphide stress cracking susceptibility governed by material hardness and hydrogen embrittlement mechanisms remains a significant concern (5). Where process composition evolves, reassessment of material compatibility and stress exposure becomes essential to maintain compliance with industry standards and fitness-for-service criteria (2).

Beyond technical degradation mechanisms, lifecycle integrity management must account for operational and organisational influences. Asset management standards emphasise the importance of structured documentation, traceability, and risk-informed decision-making in ageing infrastructure (15). Machinery reliability literature similarly recognises that extended service life demands disciplined maintenance planning and systematic condition monitoring to prevent latent defect escalation (25). While extended intervals between intrusive inspections do not inherently imply increased failure probability, such decisions must be justified within a risk-based inspection framework (3), (18) and supported by demonstrable structural margin.

A principal contribution of this work is the integration of field inspection observations with analytical stress modelling to establish a mechanistic link between corrosion-induced geometric modification and potential reduction in fatigue margin. While the FEA presented is simplified and based on linear elastic assumptions, the modelling approach is consistent with established computational structural mechanics methodologies (21), (22). The results demonstrate that corrosion effects below nominal corrosion allowance can nonetheless influence stress distribution in critical load-transfer regions, reinforcing the need for analytical verification during life-extension assessments.

It is important to acknowledge limitations. The case study FEA represents a two-dimensional approximation and does not capture three-dimensional stress gradients, residual stresses, or progressive material embrittlement effects. Additionally, corrosion rate estimation and fatigue accumulation depend heavily on the quality of historical operating data. Where uncertainty exists in degradation history, conservative assumptions or additional monitoring may be required to ensure structural reliability remains within acceptable bounds.

Finally, although this paper focuses primarily on compressor casings due to their role as primary pressure boundaries and the associated risk of hydrocarbon release, the principles discussed are equally applicable to adjacent process equipment, including piping systems, scrubbers, and coolers. System-level reassessment consistent with offshore structural integrity philosophy (20) and asset management principles (15) is necessary to ensure that life-extension decisions remain technically justified and aligned with recognised engineering standards.

Future research should extend the present work through three-dimensional modelling of casing geometries to capture complex stress gradients and contact behaviour more accurately. In addition, coupled corrosion–fatigue interaction modelling would improve prediction of remaining life under variable operating conditions. Probabilistic assessment approaches that incorporate uncertainty in degradation history and inspection effectiveness may further enhance risk-informed decision-making. Development of industry-specific guidance addressing ageing rotating pressure equipment would also support consistent application of integrity verification methodologies.

8. CONCLUSIONS

The effective age of a centrifugal compressor cannot be defined solely by calendar service life, but must be interpreted in relation to accumulated degradation, operating environment, maintenance quality, and structural loading history. This study demonstrates that ageing in centrifugal compressors is fundamentally an integrity-driven phenomenon rather than merely a performance-related issue.

Inspection findings indicate that pressure-retaining casings may experience progressive corrosion, stress concentration amplification, and corrosion–fatigue interaction, even when global corrosion allowance limits have not been exceeded. The finite element evaluation presented shows that moderate geometric loss at shear-ring interfaces can produce approximately 20% local stress amplification, highlighting the sensitivity of highly stressed regions to corrosion-induced modification.

Safe and reliable operation beyond the nominal design life defined in API 617 is achievable, provided that inspection strategies are integrity-focused and supported by risk-based and fitness-for-service methodologies. Integration of dimensional verification, corrosion assessment, fatigue considerations, and analytical stress modelling provides a defensible framework for life-extension decisions.

Ageing management should therefore transition from time-based maintenance philosophy toward structured, condition-based and analytically verified integrity assessment to ensure continued operational safety and environmental protection.

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