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# Accelerated Internal Corrosion in a Fresh Water Carbon Steel Pipeline Due to Intermittent Seawater Intrusion: Failure Analysis and Integrity Implications

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## Abstract:

Internal corrosion in carbon steel fresh water distribution systems is generally limited under chemically stable operating conditions. However, operational deviations can significantly alter electrochemical behavior and accelerate localized degradation. This study investigates severe internal corrosion identified in a carbon steel pipeline nominally designated for fresh water service onboard an oil tanker during dry docking.

Operational records indicated intermittent short-term seawater use through a secondary bypass line during periods of fresh water generation (FWG) unit breakdown. These contingency operations introduced saline water into sections of the fresh water distribution network not designed for chloride exposure. Macroscopic examination revealed extensive tuberculation, severe hydraulic restriction, and deep under-deposit pitting concentrated at flange interfaces and low-flow regions. Cross-sectional evaluation confirmed substantial reduction of effective flow area and localized wall penetration beneath consolidated corrosion products.

The degradation morphology is attributed to chloride-assisted destabilization of corrosion product films, differential aeration beneath deposits, and potential microbiologically influenced corrosion following marine contamination.

The findings demonstrate that intermittent saline use in fresh water systems during operational contingency events can produce corrosion severity substantially exceeding that expected under stable fresh water conditions. A risk-based integrity management framework is proposed, emphasizing operational segregation, post-event chemical stabilization, targeted inspection of high-risk regions, and evaluation of appropriate internal protection strategies.

***Keywords:*** Intermittent seawater exposure; Chloride-assisted corrosion; Fresh water utility systems; Marine microbiological corrosion; Differential aeration; Tuberculation; Oil tanker pipeline integrity; Asset life management

## Introduction

Carbon steel piping systems remain extensively utilized in marine vessels for fresh water distribution due to their structural strength, cost efficiency, and ease of fabrication. Under controlled conditions, internal corrosion in fresh water systems is typically moderate, primarily governed by dissolved oxygen concentration, pH, alkalinity, and flow regime. In contrast to seawater service, the relatively low chloride content in fresh water reduces the risk of aggressive pitting corrosion when chemical stability is maintained. However, deviations from designed operating conditions can significantly alter corrosion behavior and accelerate degradation mechanisms.

Onboard oil tankers, fresh water systems are commonly supplied through evaporators or reverse osmosis units. During operational disruptions such as fresh water generator breakdowns, temporary bypass arrangements may be implemented to maintain essential services. In some cases, seawater may be introduced into pipelines originally designed exclusively for fresh water service. Although such exposure may be short in duration, the introduction of chloride ions, dissolved salts, and marine microorganisms can fundamentally destabilize the corrosion equilibrium of carbon steel surfaces.

Chloride ions are particularly detrimental because they interfere with the formation and stability of protective iron oxide films. In oxygenated environments, carbon steel corrosion proceeds through anodic iron dissolution coupled with cathodic oxygen reduction. Under stable fresh water conditions, corrosion products may form semi-protective layers that limit further attack. However, chloride contamination disrupts passive film integrity, increases electrolyte conductivity, and promotes localized breakdown of oxide layers, facilitating pitting and under-deposit corrosion. When cyclic exposure occurs alternating between saline and non-saline conditions the electrochemical environment becomes unstable, further accelerating localized corrosion processes.

Additionally, seawater introduces diverse microbial populations, including sulfate-reducing bacteria (SRB), iron-oxidizing bacteria, and biofilm-forming microorganisms. Once established within a pipeline, these organisms can persist even after reversion to fresh water service. Microbiologically influenced corrosion (MIC) may then develop through biofilm formation, differential aeration cell creation, localized acid production, and sulfide generation. The interaction between chloride-assisted electrochemical corrosion and microbial activity creates a synergistic degradation mechanism capable of producing corrosion rates significantly higher than those expected under controlled fresh water conditions.

Flow characteristics further influence corrosion severity. Low-velocity regions, dead legs, and geometric discontinuities such as flange connections promote sediment accumulation and oxygen concentration gradients. These conditions favor tuberculation a corrosion morphology characterized by mound-like rust deposits with active anodic pits beneath. Tuberculation not only accelerates localized metal loss but also progressively reduces hydraulic diameter, increasing pressure drop and altering flow profiles. The resulting turbulence at constricted sections can exacerbate localized attack and further destabilize corrosion product layers.

Marine utility systems are often overlooked in structured corrosion management programs compared to cargo tanks, ballast systems, or seawater lines. However, extended vessel service life, operational modifications, and emergency system cross-connections can introduce unanticipated corrosion risks. The cumulative effect of intermittent seawater exposure over a prolonged operational period may therefore result in severe internal degradation even in systems nominally designated for fresh water service.

The present study investigates severe internal corrosion observed in a carbon steel fresh water pipeline onboard a 16-year-old oil tanker during scheduled dry docking. While the vessel had been in extended service, the installation date of the examined pipeline segment could not be conclusively verified. Therefore, the analysis focuses on corrosion morphology, operational exposure history, and mechanistic interpretation rather than service-life assumptions.

The objectives of this research are:

1. To characterize the corrosion morphology and extent of internal degradation.
2. To identify the dominant electrochemical and microbiological mechanisms involved.
3. To evaluate the influence of intermittent seawater exposure on corrosion acceleration.
4. To assess structural and hydraulic implications.
5. To develop a technically justified integrity management framework applicable to marine fresh water systems subject to operational deviations.

By correlating documented operational practices with corrosion morphology and electrochemical principles, this work provides a mechanistic explanation for accelerated degradation in a nominal fresh water pipeline and highlights the importance of strict operational segregation and post-exposure stabilization measures in marine utility systems.

## 2. Materials and Methods

### 2.1 Component Description

The examined component was a flanged carbon steel spool section removed from the vessel's fresh water distribution system during scheduled dry docking. The pipeline was intended for fresh water service under normal operating conditions.

Operational records indicated that, during periods of fresh water generation plant failure, the line was intermittently supplied with seawater via a temporary bypass arrangement. These exposures were limited in duration but introduced saline conditions into the system.

The pipe material was identified through visual assessment as standard carbon steel utility piping typical of marine installations. No internal lining, coating system, or corrosion protection measures were present within the bore at the time of inspection. No evidence of internal cathodic protection was observed.

The investigation was conducted through direct macroscopic examination of the removed spool section, with emphasis on correlating observed degradation features with documented service conditions.

**Table X. Nominal Chemical Composition of Marine-Grade Carbon Steel Used in the Investigated Pipeline (wt.%)**

| **Element** | **C** | **Mn** | **Si** | **P** | **S** | **Fe (Balance)** |
|---|---|---|---|---|---|---|
| wt.% | 0.18-0.25 | 0.60-1.20 | 0.10-0.35 | ≤ 0.035 | ≤ 0.035 | Remainder |

### Technical Verification of Iron Balance

Based on the nominal composition ranges provided in Table X, the maximum specified alloying content can be estimated using the upper limits:

C = 0.25 wt.%
Mn = 1.20 wt.%
Si = 0.35 wt.%
P = 0.035 wt.%
S = 0.035 wt.%

Total maximum alloying content:

$$0.25 + 1.20 + 0.35 + 0.035 + 0.035 = 1.87\%$$

Therefore, the minimum iron content (Fe balance) can be conservatively calculated as:

$$Fe_{min} = 100\% - 1.87\% = 98.13\%$$

This confirms that the investigated material consists of greater than 98 wt.% iron, consistent with ferritic low-carbon structural steel typically used in marine utility piping.

## 2.2 Macroscopic Examination

Following removal during dry docking, the flanged spool section was subjected to systematic macroscopic examination to characterize the extent, morphology, and spatial distribution of internal corrosion damage. The initial inspection was conducted in the as-received condition without disturbance of corrosion products in order to preserve deposit structure and morphological integrity.

External examination revealed minor atmospheric oxidation but no evidence of through-wall leakage or significant external corrosion attack. The degradation was therefore determined to be internally driven.

Internal bore inspection revealed extensive tuberculation and severe obstruction of the flow passage. Large nodular corrosion products projecting inward from the pipe wall were observed, resulting in substantial reduction of the effective hydraulic diameter, as shown in **Figure 1**. The corrosion morphology exhibited a layered and porous structure typical of oxygen-driven corrosion under deposit conditions.

Localized concentration of attack was observed at flange bore interfaces and circumferential regions adjacent to gasket seating areas **Figure 2**. These regions displayed irregular penetration geometry consistent with crevice-enhanced corrosion and differential aeration cell development.

To facilitate complete evaluation, the spool was longitudinally sectioned into two symmetrical halves using mechanical cutting. The cross-sectional exposure revealed extensive corrosion product accumulation occupying a major portion of the internal volume, as presented in **Figure 3**. The corrosion scale exhibited heterogeneous coloration, ranging from dark magnetite-like regions to voluminous orange-brown oxide deposits, indicating variable oxygen availability during formation.

Partial removal of corrosion products in selected zones exposed deep under-deposit pitting with sharp cavity profiles and localized wall penetration, as illustrated in **Figure 4**. The pit morphology confirms concentrated anodic dissolution beneath stabilized tubercles, characteristic of differential aeration and microbiologically influenced corrosion mechanisms.

The macroscopic findings clearly demonstrate severe localized internal degradation with significant hydraulic restriction and structural wall thinning.

**Figure 1.** Internal bore condition showing extensive tuberculation and severe reduction of effective flow diameter due to corrosion product accumulation.

**Figure 2.** Flange bore region exhibiting localized penetration and circumferential corrosion consistent with crevice-enhanced attack.

**Figure 3.** Longitudinally sectioned spool revealing massive internal oxide buildup and cross-sectional obstruction.

**Figure 4.** Under-deposit pitting morphology exposed after partial removal of corrosion products.

## 3. Results

### 3.1 Corrosion Morphology Characterization

Macroscopic examination revealed that corrosion damage was highly localized and non-uniform along the internal bore. The degradation was dominated by tuberculation characterized by voluminous, nodular corrosion products firmly adhered to the internal pipe surface.

The tubercles exhibited heterogeneous morphology, with outer porous orange-brown oxide layers and darker inner regions suggestive of partially reduced iron oxides. This layered structure is consistent with oxygen concentration gradients during deposit formation. The morphology indicates sustained electrochemical activity beneath stabilized corrosion products.

Corrosion was most severe at flange bore interfaces and geometric discontinuities, where flow separation and stagnation likely occurred. These regions exhibited concentrated penetration and irregular pit cavities, supporting the presence of differential aeration cells and crevice-enhanced attack.

The cross-sectional analysis confirmed that corrosion products occupied a substantial portion of the internal flow area. In several regions, deposit thickness approached or exceeded 50% of the original wall thickness.

### 3.2 Hydraulic Restriction and Flow Impairment

Macroscopic cross-sectional examination of the longitudinally sectioned spool (Figure 3) demonstrated severe internal obstruction due to consolidated tuberculation. Measurement of the remaining open passage indicated that the effective hydraulic diameter was reduced to approximately 0.30-0.50 of the nominal internal diameter.

For a circular pipe, the internal cross-sectional area is:

$$A = \frac{\pi D^2}{4}$$

Thus, the fractional reduction in flow area resulting from diameter reduction can be expressed as:

$$\frac{A_{residual}}{A_{original}} = \left(\frac{D_{residual}}{D_{original}}\right)^2$$

Accordingly, the percentage area loss is:

$$\text{Area Loss (\%)} = \left[1 - \left(\frac{D_{residual}}{D_{original}}\right)^2\right] \times 100$$

For the observed diameter range:

If $D_{residual} = 0.50 D_{original}$:

$$\text{Area Loss} = [1 - (0.50)^2] \times 100 = 75\%$$

If $D_{residual} = 0.30 D_{original}$:

$$\text{Area Loss} = [1 - (0.30)^2] \times 100 = 91\%$$

Therefore, the effective hydraulic area was reduced by approximately **75-91%**, confirming a critically restricted flow condition.

**Velocity Amplification**

From the continuity equation:

$$Q = AV$$

For constant volumetric flow rate, velocity is inversely proportional to area:

$$\frac{V_{residual}}{V_{original}} = \frac{A_{original}}{A_{residual}} = \left(\frac{D_{original}}{D_{residual}}\right)^2$$

Thus:

For $D_{residual} = 0.50 D_{original}$:

$$V_{residual} = 4\, V_{original}$$

For $D_{residual} = 0.30D_{original}$:

$$V_{residual} \approx 11.1\,V_{original}$$

This indicates that local velocity within the remaining open passage may have increased between **4 and 11 times** the nominal design velocity.

**Pressure Drop Implication**

For turbulent internal flow, pressure drop is governed by the Darcy-Weisbach equation:

$$\Delta P = f\frac{L}{D}\frac{\rho V^2}{2}$$

Where:

- $f$= friction factor
- $L$= pipe length
- $D$= hydraulic diameter
- $\rho$= fluid density
- $V$= mean velocity

Since pressure drop varies approximately with $V^2$, velocity amplification of 4-11 times results in theoretical local pressure gradient increases of approximately **16-123 times**, neglecting secondary losses due to geometry. Such hydraulic intensification results in:

- Elevated wall shear stress
- Local turbulence amplification
- Increased oxygen transport to exposed metal
- Mechanical destabilization of corrosion products
- Acceleration of under-deposit corrosion kinetics

**Engineering Significance**

The observed obstruction represents a critically degraded hydraulic condition. Beyond supply inefficiency, the amplified velocity and turbulence create a feedback mechanism whereby localized metal exposure and oxygen availability are enhanced, promoting continued localized penetration.

The interaction between hydraulic restriction and electrochemical activity therefore contributes directly to the severity of internal corrosion observed in this system.

### 3.3 Flange Region Degradation

Corrosion severity was markedly intensified at flange bore interfaces and adjacent gasket seating regions. Macroscopic examination revealed preferential metal loss in these geometrically discontinuous zones relative to straight pipe sections. The degradation exhibited circumferential concentration around the internal flange bore, with corrosion products densely accumulated at the pipe
flange transition. Upon partial removal of deposits, deep localized penetration was observed beneath consolidated corrosion products. The morphology was irregular and crevice-like, characterized by sharply defined pit boundaries and directional propagation along the flange interface.

Such degradation is consistent with stagnant flow development and restricted mass transport conditions inherent to flanged geometries. Gasket compression and micro-crevice formation at the bore interface promote the establishment of differential aeration cells. Oxygen concentration gradients between exposed bore surfaces and shielded crevice regions generate localized anodic activity within occluded zones. Intermittent seawater exposure likely introduced chlorides and marine microorganisms into these partially shielded regions, where chloride accumulation lowered local pH and destabilized semi-protective oxide films. Once corrosion deposits formed within the crevice, they stabilized the oxygen gradient and sustained under-deposit corrosion kinetics. The flange region therefore acted as a preferential corrosion initiation site due to the combined influence of geometric discontinuity, reduced local flow velocity, oxygen concentration cell formation, chloride entrapment, and deposit stabilization.

### 3.4 Mechanical Integrity Context

Although mechanical testing was not conducted as part of the present investigation, the chemical composition and service application identified in Section 2 indicate that the pipeline material corresponds to low-carbon ferritic steel typically used in marine utility systems, such as ASTM A106 Grade B or ASTM A53 Grade B. These steels are characterized by classical ductile behavior under tensile loading, with a linear elastic region governed by a Young's modulus of approximately 200 GPa, followed by yielding in the range of 235-275 MPa and strain hardening to ultimate tensile strengths commonly between 415 and 480 MPa prior to necking and ductile fracture.

A representative schematic engineering stress-strain response for marine carbon steel is shown in Figure 5. The schematic illustrates the expected elastic–plastic transition, strain hardening behavior, and ductile failure mode consistent with ferritic microstructures.

Examination of the removed spool revealed no evidence of brittle fracture, cleavage facets, or crack branching associated with metallurgical embrittlement. Instead, degradation was confined to localized wall thinning and under-deposit penetration. The structural condition of the component is therefore governed by minimum remaining ligament thickness rather than deterioration of intrinsic bulk mechanical properties. The failure mechanism is interpreted as electrochemically driven metal loss rather than material strength degradation.

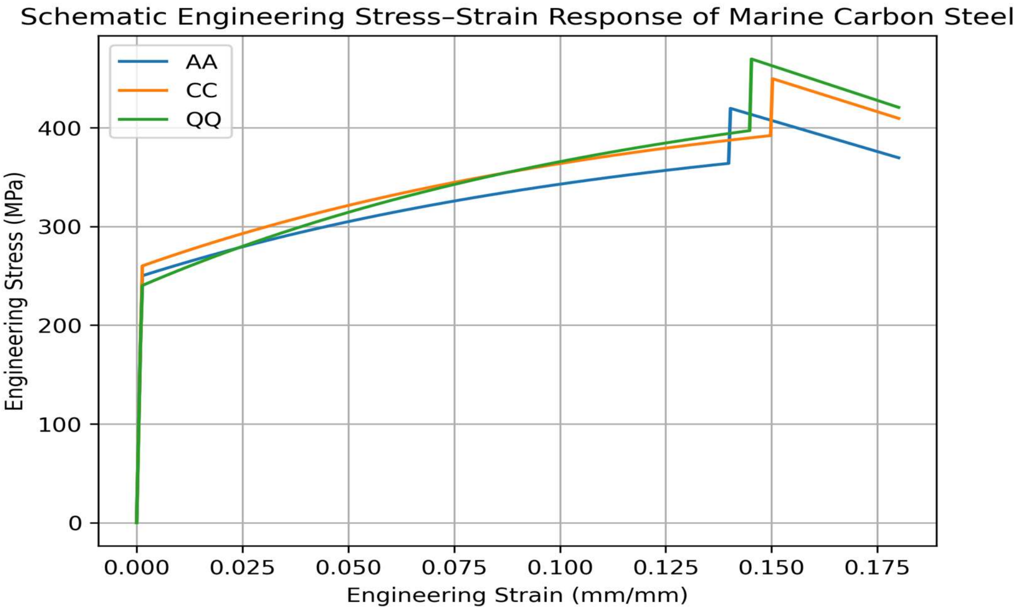

Figure 5. Schematic engineering stress–strain response representative of low-carbon ferritic steel used in marine piping systems. Curves illustrate typical yield strength and ultimate tensile strength ranges for ASTM carbon steel grades. (Included for mechanical context; no tensile testing was conducted in this investigation.)

### 3.5 Under-Deposit Pitting

Following controlled partial removal of corrosion products, pronounced localized penetration was observed beneath consolidated tubercular deposits. The exposed metal surface revealed discrete pit cavities distributed non-uniformly across the internal bore. The pit morphology was characterized by irregular cavity geometry, sharply defined boundaries, and localized depth progression relative to adjacent areas. The base of several pits exhibited directional growth consistent with sustained anodic dissolution under occluded conditions. No evidence of uniform surface thinning was observed in these regions; degradation was confined to localized attack beneath stabilized deposits.

This morphology is characteristic of under-deposit corrosion driven by differential aeration effects. Accumulation of corrosion products creates a partially shielded microenvironment in which oxygen concentration beneath the deposit becomes depleted relative to surrounding exposed surfaces. This establishes an oxygen concentration cell in which the occluded region functions as the anodic site while adjacent oxygen-rich surfaces act as cathodic regions. Intermittent seawater exposure likely intensified this mechanism through chloride ingress into the deposit structure. Chloride ions penetrate and destabilize iron oxide films, promote localized breakdown of semi-protective layers, and sustain active dissolution. Within the confined deposit region, restricted mass transport facilitates acidification and metal ion accumulation, further accelerating pit propagation. The observed penetration depth and localization are therefore consistent with the combined action of differential aeration, chloride-assisted oxide destabilization, restricted electrolyte renewal, and deposit-stabilized electrochemical gradients.

## 4. Mechanistic Interpretation

### 4.1 Oxygen Reduction-Controlled Corrosion

The degradation observed is attributed to the interaction of electrochemical, hydraulic, and microbiological processes rather than a single dominant mechanism.

Under stable fresh water conditions, corrosion of carbon steel is governed by anodic iron dissolution coupled with cathodic oxygen reduction. Semi-stable iron oxide and hydroxide layers may develop, providing limited diffusion resistance under chemically stable environments.

Intermittent seawater exposure introduces elevated chloride concentration and increases electrolyte conductivity. Chloride ions penetrate porous corrosion products, destabilize oxide films, and promote localized anodic activation. Accumulation of chloride within occluded regions enhances pit stabilization and prevents effective repassivation.

Simultaneously, corrosion product deposition and stagnation promote differential aeration. Oxygen-depleted regions beneath deposits act as anodic sites, while adjacent oxygen-rich surfaces act as cathodic regions. Restricted mass transport conditions facilitate localized acidification through hydrolysis of dissolved ferrous species, sustaining pit propagation.

Marine microbial contamination introduced during saline exposure may further modify localized chemistry through biofilm formation and oxygen depletion. Although direct microbiological testing was not performed, the morphology is consistent with deposit-stabilized localized corrosion potentially enhanced by microbial activity.

Progressive tuberculation reduces hydraulic diameter, increasing local velocity and turbulence within the remaining flow passage. Elevated shear stresses may intermittently destabilize deposits and expose fresh metal surface, reinforcing localized corrosion processes.

The combined effect of chloride-assisted film destabilization, differential aeration, hydraulic intensification, and potential microbial contribution explains the severity and localization of penetration observed in the present system.

### 4.2 Chloride-Assisted Film Breakdown and Differential Aeration

The transition from moderate corrosion under stable fresh water service to severe localized penetration in the investigated system is attributed to chloride-induced destabilization of corrosion products combined with differential aeration effects. Intermittent seawater exposure introduced elevated chloride concentrations into a system originally designed for low-salinity operation. Chloride ions, due to their high mobility and small ionic radius, readily penetrate the porous corrosion product layers formed on carbon steel during fresh water service.

Unlike the relatively stable passive films formed on stainless steels, corrosion product layers on carbon steel consist of porous iron oxyhydroxides and magnetite phases that are susceptible to chemical destabilization in chloride-bearing environments.

Chloride adsorption at the metal-oxide interface increases the solubility of iron hydroxides, interferes with film adherence, and promotes localized anodic activation. Once chloride accumulation occurs beneath deposits or within geometric discontinuities such as flange bores, localized electrochemical gradients develop. Under tubercular deposits, restricted oxygen diffusion establishes an occluded microenvironment in which oxygen concentration beneath the deposit becomes lower than that of adjacent exposed surfaces. This differential in oxygen availability produces a concentration cell in which the oxygen-depleted region functions as the anodic site while the surrounding oxygen-rich surface acts as the cathodic region. The resulting potential difference sustains localized anodic dissolution beneath the deposit.

Simultaneously, hydrolysis of dissolved ferrous ions within the confined region contributes to localized acidification according to:

$Fe^{2+} + 2H_2O \rightarrow Fe(OH)_2 + 2H^+$

The generation of hydrogen ions decreases local pH and further accelerates metal dissolution within the occluded zone. Elevated electrolyte conductivity associated with saline intrusion increases corrosion current density relative to stable fresh water conditions, thereby intensifying localized attack. Repeated cycling between low-salinity and high-salinity environments prevents stabilization of corrosion products and promotes recurring film breakdown events. The combined effects of chloride-assisted film destabilization, oxygen concentration cell formation, localized acidification, and restricted mass transport account for the deep under-deposit pitting and localized penetration observed in the present system.

### Figure 6 & 7 Cross-Sectional Morphology of Tuberculated Region (Optical Macrograph)

Figure 6 presents the cross-sectional morphology of the tuberculated internal surface following longitudinal sectioning of the removed spool. The image corresponds to the as-sectioned condition prior to aggressive cleaning, thereby preserving the in-situ architecture of corrosion products and the underlying metal interface.

The macrograph reveals extensive volumetric corrosion product accumulation occupying a substantial portion of the original internal diameter. The deposits exhibit a stratified structure with distinct outer and inner layers. The outer regions appear relatively porous and heterogeneous, while darker internal zones are consistent with magnetite-rich phases and lighter brown or orange regions are indicative of hydrated iron oxyhydroxides (FeOOH phases). Beneath consolidated deposits, irregular cavities extend into the steel substrate, demonstrating localized penetration rather than uniform wall thinning.

The corrosion product mass appears porous and discontinuous, capable of retaining electrolyte within occluded regions. In several locations, deposit thickness is comparable to or exceeds the remaining intact metal ligament, indicating advanced localized degradation and substantial loss of effective wall thickness. The interface between corrosion products and base metal is irregular, with penetration concentrated beneath stabilized tubercles rather than distributed evenly across the bore.

**Figure 6.Flange bore cross-section showing localized attack.** Severe non-uniform metal loss is concentrated at the internal bore. Attack is confined to occluded regions and is consistent with differential aeration and chloride-assisted under-deposit corrosion.

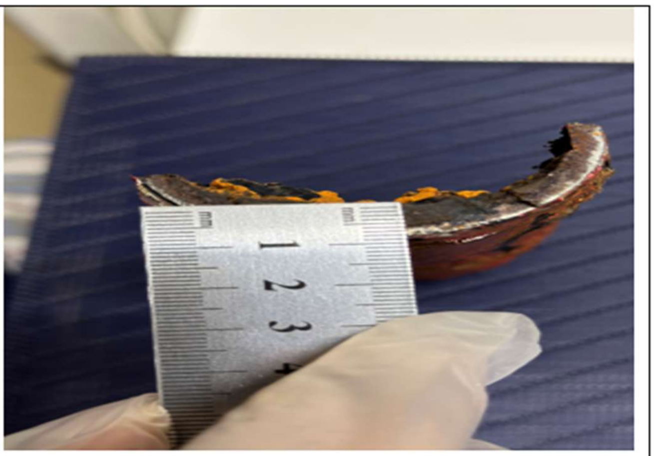

**Figure 7. Longitudinal section of carbon steel spool .** Heavy corrosion product buildup significantly reduces the original internal diameter. Stratified deposits with porous outer FeOOH layers and darker inner magnetite-rich regions are observed. Localized cavities beneath tubercles indicate under-deposit penetration rather than uniform wall thinning.

The observed cross-sectional morphology is consistent with differential aeration beneath deposits, localized acidification within occluded electrolyte volumes, chloride retention within porous corrosion products, and sustained pit propagation. The evidence confirms that metal loss occurred predominantly beneath consolidated tubercles rather than through generalized corrosion across the internal surface.

### 4.3 Effect of Intermittent Seawater Exposure

Intermittent exposure of a carbon steel fresh water pipeline to seawater produces a substantial shift in electrochemical boundary conditions. In contrast to treated fresh water, which typically exhibits moderate conductivity and low chloride concentration, seawater is characterized by high ionic strength, elevated dissolved salt content, and aggressive anion activity. Chloride concentrations in seawater are on the order of 19,000 ppm, and electrical conductivity commonly ranges between 30 and 50 mS/cm. In addition to increased ionic strength, seawater introduces magnesium and calcium species as well as marine microbial populations capable of colonizing internal surfaces.

The primary electrochemical consequence of chloride ingress is destabilization of corrosion product films formed under fresh water service. In oxygenated neutral environments, carbon steel corrosion produces iron oxyhydroxides and magnetite (FeOOH and $Fe_3O_4$ phases). Although these corrosion products are not fully protective, they may provide limited diffusion resistance to oxygen and moderately reduce uniform corrosion rates under chemically stable conditions. However, chloride ions readily penetrate porous oxide layers and disrupt their stability. Chloride adsorption at the metal–oxide interface increases the solubility of iron oxides and hydroxides, promotes localized film breakdown, facilitates anodic activation, and contributes to localized acidification within occluded regions.

Chloride accumulation within corrosion deposits enhances electrolyte conductivity beneath tubercles and promotes formation of localized electrochemical cells. Once film breakdown occurs at discrete sites, pit initiation is favored due to the high mobility of chloride ions and their ability to stabilize soluble ferrous chloride complexes. These processes inhibit effective repassivation and sustain localized metal dissolution.

When seawater exposure is followed by a return to fresh water service, the system undergoes chemical cycling. This transition produces transient chloride concentration gradients, fluctuating oxygen solubility and diffusion conditions, repeated oxide formation and destabilization, and overall instability of semi-protective corrosion product layers. Such cyclic exposure is particularly aggressive because it prevents establishment of steady-state corrosion behavior. Previously activated anodic sites remain electrochemically unstable, and incomplete repassivation promotes repeated depassivation events. The resulting instability accelerates localized penetration relative to continuous fresh water operation.

From a mechanistic standpoint, intermittent saline exposure may be more damaging than continuous fresh water service because it combines periods of high-conductivity chloride attack with repeated electrochemical destabilization. In the investigated pipeline, this cyclic chemical disturbance is interpreted as a principal accelerating factor contributing to severe tuberculation, sustained under-deposit corrosion, and deep localized penetration.

### 4.4 Tuberculation Development

Tuberculation represents a progressive, multi-stage corrosion phenomenon arising from localized electrochemical instability and subsequent deposit accumulation. The process is typically initiated by discrete pit formation at sites of oxide film breakdown. Once localized anodic dissolution begins, ferrous ions released into the electrolyte undergo hydrolysis and oxidation, resulting in precipitation of iron hydroxides and oxyhydroxides at or near the corrosion site. These corrosion products accumulate over the active region and progressively consolidate into mound-like deposits.

As corrosion products thicken, mass transport within the occluded region becomes increasingly restricted. Oxygen diffusion beneath the deposit decreases relative to adjacent exposed surfaces, establishing an oxygen concentration gradient. This differential aeration condition transforms the occluded region into a sustained anodic site while the surrounding oxygen-rich surface functions as the cathodic region. The resulting electrochemical cell reinforces localized dissolution beneath the deposit.

With continued exposure, chloride ions and other dissolved species become concentrated within the deposit structure, further enhancing electrolyte conductivity and inhibiting repassivation. Hydrolysis of ferrous ions within the confined microenvironment leads to localized acidification, which accelerates anodic metal dissolution and stabilizes pit growth. The external deposit may continue to thicken while active penetration progresses beneath it, producing the characteristic morphology of tuberculated corrosion in which substantial internal metal loss occurs below apparently stable corrosion product accumulations.

This self-sustaining electrochemical configuration promotes progressive localized penetration and explains the severe under-deposit damage observed in the investigated pipeline. The presence of intermittent seawater exposure likely intensified this process by increasing chloride availability and facilitating rapid stabilization of the tubercular structure once initiated.

### 4.5 Integrated Corrosion Mechanism Model

The degradation observed in the investigated pipeline is interpreted as the consequence of interacting electrochemical, hydraulic, and microbiological processes rather than a single dominant corrosion mechanism. The corrosion morphology and documented operational history indicate a synergistic system driven by intermittent seawater exposure within a pipeline nominally designated for fresh water service.

Under stable fresh water conditions, corrosion of carbon steel is governed primarily by oxygen reduction-controlled anodic dissolution. In neutral aqueous environments, iron oxyhydroxide and magnetite layers may develop on the steel surface. Although these corrosion products are not fully protective, they may provide limited diffusion resistance to oxygen and ionic transport, thereby moderating uniform corrosion rates under chemically stable conditions.

Intermittent seawater intrusion introduces elevated chloride concentration and significantly increases electrolyte conductivity. Chloride ions penetrate porous corrosion product layers and destabilize oxide films by enhancing solubility at the metal-oxide interface and promoting localized anodic activation. This destabilization is particularly pronounced in occluded or low-flow regions where chloride accumulation can occur and mass transport is restricted.

Concurrently, corrosion product deposition and sediment accumulation promote the establishment of differential aeration cells. Beneath tubercles and consolidated deposits, oxygen concentration becomes depleted relative to adjacent exposed surfaces. The oxygen-deficient regions function as anodic sites, while better-aerated surfaces act as cathodic regions. This spatial separation of electrochemical reactions sustains localized dissolution beneath deposits. The porous structure of corrosion products intensifies this effect by retaining chloride-rich electrolyte within occluded volumes, restricting oxygen diffusion gradients, and facilitating localized acidification through hydrolysis reactions. These conditions preserve electrochemical heterogeneity and inhibit effective repassivation.

Intermittent seawater exposure may also introduce marine microorganisms capable of colonizing internal surfaces. Biofilm development within deposit-stabilized regions can generate microenvironments characterized by oxygen depletion, altered pH, and accumulation of metabolic by-products. Although microbiological sampling was not performed, the observed morphology is consistent with corrosion processes potentially enhanced by biofilm-mediated electrochemical gradients.

Hydraulic restriction resulting from progressive tuberculation further amplifies the degradation process. As internal flow area decreases, local velocity increases within the remaining open passage for a constant volumetric flow rate. Elevated shear stresses and localized turbulence enhance oxygen transport and may intermittently destabilize corrosion products, exposing fresh metal surface to aggressive electrolyte conditions. This establishes a feedback mechanism in which corrosion-induced hydraulic impairment contributes to continued localized attack.

The combined action of chloride-assisted film destabilization, differential aeration beneath deposits, potential biofilm-mediated effects, and hydraulic intensification produces corrosion severity significantly greater than that expected under continuous fresh water operation. The deep under-deposit penetration and preferential degradation at flange interfaces observed in the present investigation are consistent with this integrated mechanistic model.

## 5. Corrosion Rate Considerations

The observed degradation was dominated by localized under-deposit penetration rather than uniform wall thinning. Consequently, integrity assessment is governed by minimum remaining ligament thickness rather than average wall loss.

Because the installation date of the spool section could not be confirmed, quantitative corrosion rates cannot be assigned with certainty. However, the measured penetration depths are significantly greater than typically expected under stable fresh water conditions, suggesting accelerated localized corrosion during periods of chemical instability.

For engineering assessment purposes, localized penetration rate may be conservatively estimated as:

$$CR = \frac{d_{max}}{t_{eff}}$$

where $d_{max}$is the maximum observed penetration depth and $t_{eff}$is the effective duration of corrosive exposure. Bounding interpretations may be applied using vessel service duration and estimated cumulative saline exposure periods.

Structural integrity under internal pressure is governed by hoop stress:

$$\sigma_h = \frac{PD}{2t_{min}}$$

where $t_{min}$represents the minimum remaining wall thickness. Localized wall thinning therefore directly increases stress concentration and reduces allowable pressure margin.

### 5.2 Localized Corrosion Rate

The localized corrosion rate was estimated using maximum penetration depth over an effective exposure duration:

$T$= exposure time (years)

$$CR = \frac{d_{max}}{T} \text{(mm/year)}$$

Because the installation date of the spool is unknown, $T$cannot be stated as a confirmed service time. Two bounding interpretations are therefore used:

**Upper-bound duration**: $T$taken as vessel service period (gives a minimum average rate).

**Effective corrosive duration**: $T$taken as cumulative periods when saline cycling occurred (gives a higher, more realistic localized rate during active damage periods).

This approach avoids overstating certainty while still providing engineering-useful rate bounds.

### 5.3 Effect of Wall Thinning on Hoop Stress

For a thin-walled pipe under internal pressure:

- $P$= internal pressure (MPa)
- $D_i$= internal diameter (mm)
- $t$= local remaining thickness (mm)

$$\sigma_h = \frac{P\,D_i}{2t}$$

Therefore, the stress increase factor due to localized wall thinning from $t_0$to $t_{min}$is:

$$\frac{\sigma_{h,min}}{\sigma_{h,0}} = \frac{t_0}{t_{min}}$$

This shows that hoop stress rises in direct proportion to thickness loss. In localized pitting, the effective risk is further elevated by geometric stress concentration at pit bases, so the minimum remaining ligament thickness governs integrity.

### 5.4 Remaining Life Expression

Remaining life is governed by the margin between the minimum remaining thickness and the minimum allowable thickness:

- $t_{allow}$= minimum allowable thickness (mm), per applicable design code

$$RL = \frac{t_{min} - t_{allow}}{CR} \text{ (years)}$$

Where localized corrosion is active, $CR$should be taken as the localized penetration rate (Section 5.2), not an average uniform corrosion rate.

## 6. Mitigation and Integrity Management Framework

### 6.1 Immediate Corrective Actions

Given the severity of localized penetration and hydraulic restriction, affected pipe spools should be replaced rather than repaired where deep under-deposit pitting is present. Replacement sections should be inspected prior to installation to confirm internal cleanliness, flange condition, and gasket seating integrity.

Following replacement, the affected network should be flushed and cleaned to remove residual deposits, corrosion products, and potential microbial contamination introduced during seawater intrusion. Where practical, high-velocity flushing followed by controlled chemical cleaning should be applied to remove adherent tubercles and sediment from adjacent piping runs.

### 6.2 Operational Control to Prevent Seawater Intrusion

The primary mitigation requirement is prevention of future saline exposure within fresh water networks. Positive segregation between seawater and fresh water systems should be ensured through physical isolation measures such as blind spades or spool removal where bypass arrangements exist. Non-return valves and verified isolation valves should be installed to prevent backflow during freshwater generator outages. A formal operational procedure must define permitted emergency use, duration limits, and mandatory flushing requirements following any seawater exposure event. All seawater intrusion events should be logged with documentation of date, duration, and affected line sections to maintain traceability. Where emergency seawater use is unavoidable, the system should be returned to stable chemistry through immediate flushing and chemical reconditioning to restore chloride concentration to baseline fresh water levels prior to continued service.

### 6.3 Water Chemistry Management and Chemical Treatment

Control of oxygen concentration and microbiological activity is essential in fresh water systems, particularly in stagnation-prone segments. Dissolved oxygen should be maintained at the lowest practicable level consistent with operational constraints. Periodic biocide treatment may be required to control biofilm formation, especially following confirmed seawater intrusion events. Corrosion inhibitors compatible with potable or utility water requirements may be considered to reduce electrochemical activity. Chloride concentration should be monitored after flushing to confirm complete removal of saline contamination, and defined acceptance thresholds should be established prior to return to service.

### 6.4 Design Improvements to Minimize Stagnation and Crevice Effects

The concentration of localized degradation observed at flange interfaces indicates that geometric discontinuities and stagnation-prone regions play a significant role in corrosion initiation and propagation. Design optimization should therefore prioritize minimization of stagnant flow zones and reduction of crevice-susceptible configurations within fresh water distribution systems.

Dead legs and low-flow branches should be eliminated wherever practicable, as these regions promote restricted mass transport, oxygen gradients, and sediment accumulation. Piping layouts should be configured to facilitate complete drainage and to avoid low points where suspended solids or corrosion products can accumulate. Improved hydraulic continuity reduces the likelihood of localized oxygen depletion and differential aeration cell formation.

Where operational constraints permit, replacement of flanged spool sections in permanently stagnant or low-flow service with welded joints should be considered. Welded configurations reduce the number of crevice interfaces and eliminate gasket-sealed boundaries that may serve as initiation sites for localized corrosion. When flanged connections are required for maintenance or accessibility reasons, attention should be given to gasket material selection and flange face condition to minimize micro-crevice formation and electrolyte retention at the bore interface. Proper surface finish, controlled bolt tightening, and compatible gasket materials can reduce occluded electrolyte entrapment and limit crevice corrosion susceptibility.

In systems where flanged connections cannot be avoided, these regions should be assigned elevated inspection priority within integrity management programs. Targeted monitoring of flange bores and gasket seating regions is recommended due to their demonstrated susceptibility to differential aeration, chloride accumulation, and deposit-stabilized corrosion processes.

### 6.5 Internal Protection Systems

Where operational segregation of seawater and fresh water systems cannot be fully guaranteed, implementation of internal corrosion protection measures should be evaluated, particularly in low-flow or stagnation-prone segments of the distribution network.

### 6.5.1 Internal Lining Systems

Application of organic internal lining systems provides a barrier-based corrosion control strategy by isolating the carbon steel substrate from the electrolyte and thereby interrupting the electrochemical corrosion circuit. For fresh water distribution service, particularly where the system may supply potable or domestic water onboard, lining materials must comply with applicable drinking water approval standards such as NSF/ANSI 61 (or equivalent regional certification).

High-build, solvent-free epoxy systems specifically formulated and certified for potable water immersion service are generally preferred. These systems combine low permeability, strong adhesion to properly prepared carbon steel, and verified compliance with potable water contact requirements. Selection of lining systems should therefore prioritize products that are NSF-approved (or certified under equivalent regulatory schemes) for continuous immersion in fresh water service.

Epoxy phenolic systems are typically used in chemically aggressive industrial immersion environments and may offer enhanced resistance to hydrocarbons or elevated temperatures; however, their use in fresh water distribution systems must be limited to formulations that carry verified potable water approval. In the absence of such certification, epoxy phenolic coatings should not be specified for drinking water service. Where enhanced diffusion resistance is required under intermittent saline exposure conditions, glass-flake reinforced epoxy systems may be considered, provided that the specific product is certified for potable or utility water immersion.

Surface preparation prior to lining application remains critical to long-term performance. Internal steel surfaces should be abrasive blast cleaned to a minimum of Sa 2½ in accordance with ISO 8501-1 or SSPC-SP 10 where access permits. The anchor profile should be compatible with the selected coating system, typically within 50-75 µm depending on manufacturer requirements. Soluble salt contamination must be measured following blasting, particularly where prior seawater exposure has occurred. Surface chloride levels should be reduced below manufacturer-specified acceptance limits to prevent osmotic blistering and premature coating failure.

Dry film thickness (DFT) should be selected based on immersion severity and coating permeability characteristics, commonly within the range of 300-600 µm for high-build immersion-grade epoxy systems. Application must follow manufacturer-defined recoat intervals and curing conditions to ensure full polymerization and intercoat adhesion. After curing, holiday detection should be performed in accordance with NACE SP0188 (or equivalent) to identify discontinuities. Cure verification testing should be conducted prior to commissioning to confirm suitability for service.

Properly selected and certified organic lining systems can significantly reduce corrosion risk in fresh water networks where operational segregation from seawater cannot be absolutely guaranteed.

### 6.5.2 Cement Mortar Lining (CML)

For larger diameter fresh water distribution systems, cement mortar lining (CML) may provide corrosion mitigation through alkaline passivation of the steel substrate. Hydration of Portland cement generates calcium hydroxide and related alkaline phases, producing pore solution pH values typically exceeding 12.5. Under these conditions, carbon steel develops a passive oxide film, significantly reducing corrosion kinetics under stable fresh water service.

The primary protective mechanism of CML is chemical passivation rather than impermeable barrier protection. The mortar matrix provides a moderately resistive diffusion path to oxygen and ionic species; however, it remains porous and permeable to chloride ions over time. In continuous low-chloride fresh water environments, this alkaline buffering capacity can maintain passive conditions for extended service periods.

Under intermittent saline exposure, chloride ingress through the mortar matrix may accumulate at the steel interface. Once local chloride concentration exceeds the passive stability threshold, depassivation and localized corrosion may occur beneath the lining. Performance may also be affected by cracking resulting from thermal cycling, hydraulic loading, or structural movement, which can create preferential pathways for electrolyte penetration and oxygen access.

Accordingly, CML is generally more suitable for stable continuous fresh water service than for systems subject to repeated chloride cycling. Where saline intrusion cannot be reliably eliminated, lining systems with lower chloride permeability and higher adhesion integrity may provide more predictable long-term corrosion control.

### 6.5.3 Material Upgrades for High-Risk Segments

Complete replacement of utility fresh water piping with corrosion-resistant alloys (CRAs) is generally not economically justified in marine distribution systems. However, selective material upgrades may be appropriate in localized high-risk zones where geometric configuration, hydraulic stagnation, or repeated saline intrusion increases corrosion susceptibility. Such zones may include flange spool sections exposed to persistent low-flow conditions, bypass segments subject to intermittent seawater exposure, and low-point regions prone to sediment accumulation and differential aeration.

In these locations, alternative materials such as duplex stainless steels or internally clad carbon steel may be evaluated to improve localized corrosion resistance. Duplex stainless steels offer enhanced resistance to chloride-induced pitting and crevice corrosion due to their higher chromium, molybdenum, and nitrogen content, resulting in elevated pitting resistance equivalent numbers (PREN) relative to austenitic grades.

However, material selection must consider the expected chloride concentration, temperature, dissolved oxygen content, and potential for microbiological activity.

Where dissimilar metals are introduced into predominantly carbon steel systems, galvanic compatibility must be carefully assessed. The electrochemical potential difference between stainless steel and carbon steel in aerated fresh water environments can result in galvanic acceleration of the carbon steel component if the area ratio is unfavorable. Design measures such as electrical isolation, use of insulating gaskets and sleeves, or controlled area ratio management may be necessary to mitigate galvanic effects.

Internally clad carbon steel, whether through metallurgical bonding or weld overlay, may provide localized corrosion resistance while maintaining structural compatibility with adjacent carbon steel piping. Cladding systems should be evaluated for bond integrity, thermal expansion compatibility, and susceptibility to crevice formation at clad terminations.

Selective material upgrading should therefore be based on a risk-based assessment incorporating corrosion mechanism severity, hydraulic conditions, inspection accessibility, and life-cycle cost considerations. Proper evaluation of galvanic interaction and water chemistry compatibility is essential to ensure that localized upgrades do not introduce secondary corrosion risks elsewhere in the system.

### 6.5.4 Selection Criteria

Selection of internal protection systems for fresh water distribution pipelines subject to intermittent saline exposure must be based on a comprehensive evaluation of environmental severity, hydraulic conditions, material compatibility, and regulatory constraints. Chloride concentration range during potential seawater intrusion events represents a primary design parameter, as elevated chloride levels directly influence corrosion kinetics, passive film stability, and long-term lining performance. The frequency, duration, and cumulative exposure to saline conditions should be considered when determining required barrier properties and chemical resistance.

Dissolved oxygen concentration is also a critical factor, particularly in systems where oxygen reduction controls the cathodic reaction. Elevated oxygen availability may increase corrosion current density and influence coating underfilm corrosion risk in the event of localized defects. Operating temperature must be evaluated because permeability, chemical resistance, and mechanical properties of organic linings are temperature dependent. Thermal cycling may also affect adhesion integrity and crack propagation risk in both organic and cementitious systems.

The hydraulic regime significantly influences corrosion behavior and protection strategy. Flowing systems exhibit different mass transport characteristics compared to stagnation-prone segments. Regions of low flow or dead legs are more susceptible to differential aeration and deposit stabilization, potentially requiring enhanced inspection or more robust lining systems. Maintenance accessibility should be incorporated into material selection decisions, as inspection feasibility, repair logistics, and long-term monitoring requirements vary depending on system configuration.

Where the pipeline supplies potable or domestic water, compliance with applicable regulatory standards, such as NSF/ANSI 61 or equivalent certification schemes, is mandatory for all internal coating systems. Certification ensures compatibility with drinking water service and prevents secondary contamination risks.

Internal protection strategies must be implemented as part of an integrated corrosion management approach. Organic linings or cementitious systems alone cannot compensate for uncontrolled seawater intrusion, inadequate flushing, or persistent sediment accumulation. Effective mitigation requires coordination between material selection, operational segregation procedures, post-exposure flushing protocols, chemical stabilization, and periodic inspection. Only through combined control of environmental severity and barrier integrity can long-term corrosion risk be effectively managed.

### 6.6 Monitoring and Inspection Strategy

Given the localized nature of degradation observed in this investigation, a uniform corrosion monitoring approach is insufficient. Instead, a risk-based inspection strategy targeting stagnation-prone and chloride-exposed regions is required.

#### 6.6.1 Thickness Monitoring

Ultrasonic thickness (UT) measurement should be incorporated into the integrity management program at predefined high-risk locations identified through mechanistic assessment and operational history. Particular attention should be directed toward flange bores and gasket seating regions, low points along horizontal runs, dead legs, bypass segments, and sections previously subjected to documented seawater intrusion. These regions are inherently susceptible to stagnation, differential aeration, and deposit-stabilized corrosion processes and therefore warrant prioritized monitoring.

Baseline wall thickness measurements should be established immediately following spool replacement, system rehabilitation, or initial commissioning to define reference conditions. Subsequent UT surveys should be conducted at defined inspection intervals and results trended over time to quantify localized penetration rates and identify accelerating degradation. Data trending should incorporate minimum measured thickness values rather than average readings, as localized thinning governs structural integrity under internal pressure.

At flange interfaces and other geometrically complex regions, grid-based inspection is recommended to capture asymmetric thinning patterns. Circumferential and longitudinal mapping improves detection of localized attack associated with crevice formation and under-deposit corrosion. Where pitting is present, general thickness measurements should be supplemented with pit-depth evaluation using calibrated pit gauges, high-resolution UT techniques, or phased-array methods where accessible. Because structural integrity is controlled by minimum remaining ligament thickness, identification of deepest penetration rather than nominal wall reduction is critical for reliable remaining life assessment.

Thickness monitoring data should be evaluated in conjunction with operational records, particularly documented seawater exposure events, to correlate environmental disturbances with observed corrosion progression. Integration of inspection results into a structured corrosion rate assessment framework enables risk-based decision making regarding repair, replacement, or protective intervention.

#### 6.6.2 Water Chemistry Surveillance

Chemical monitoring must accompany physical inspection as part of an integrated corrosion management strategy, particularly following any confirmed or suspected seawater intrusion event. Variations in water chemistry directly influence electrochemical stability, corrosion kinetics, and the persistence of localized attack mechanisms identified in the present investigation.

Chloride concentration represents the primary indicator of saline contamination and should be monitored to verify complete flushing of seawater from the system. Because chloride ions contribute directly to film destabilization and localized corrosion, post-exposure measurements should confirm return to baseline fresh water concentrations prior to reinstating normal operation. A defined acceptance threshold for chloride content should be established based on historical fresh water chemistry data and system-specific tolerances. Operation under elevated chloride levels should be avoided, as incomplete flushing may sustain electrochemical instability beneath deposits and in stagnation-prone regions.

Dissolved oxygen concentration should also be monitored, as oxygen reduction controls the cathodic reaction in neutral aqueous environments. Elevated dissolved oxygen may increase corrosion current density, particularly where protective films have been destabilized. Conversely, localized oxygen depletion beneath deposits may indicate development of differential aeration cells. Monitoring of oxygen levels therefore provides indirect insight into corrosion driving forces.

Measurement of pH is necessary to confirm maintenance of alkaline conditions favorable to passive film stability. Significant pH fluctuations following saline exposure or stagnation may indicate hydrolysis reactions, microbial activity, or incomplete system stabilization. Electrical conductivity should be trended as a general indicator of ionic strength and overall electrolyte aggressiveness, particularly during flushing operations.

Where microbiologically influenced corrosion is considered a potential contributing factor, surveillance may include microbiological indicators such as total bacterial count or adenosine triphosphate (ATP) analysis where available. While such measurements do not directly quantify corrosion rate, they assist in identifying conditions favorable to biofilm development and deposit-stabilized microenvironments.

Water chemistry surveillance data should be integrated with thickness monitoring results and operational records to establish correlations between environmental disturbances and observed metal loss progression. Re-entry into stable service following saline contamination should only occur once chloride concentration, conductivity, pH, and dissolved oxygen values have returned to established baseline ranges consistent with controlled fresh water operation.

### 6.6.3 Event-Triggered Inspection Protocol

Any confirmed or suspected seawater intrusion event should initiate a structured response protocol designed to minimize electrochemical instability and prevent sustained localized corrosion. Immediate system flushing is required to remove chloride-bearing electrolyte and reduce ionic strength within the affected segments. Flushing effectiveness should be verified through post-flush chloride measurement to confirm that concentrations have returned to established baseline fresh water values prior to restoration of normal operation.

Following chemical stabilization, targeted inspection of the affected piping sections should be scheduled at the earliest practical maintenance opportunity. Inspection scope should prioritize stagnation-prone regions, flange interfaces, low points, and any segments directly exposed during the intrusion event. Where feasible, localized thickness measurements and visual assessment of deposit formation should be conducted to detect early-stage under-deposit corrosion before significant penetration develops.

Accurate documentation of exposure duration, estimated chloride concentration, hydraulic conditions during the event, and specific piping sections involved is essential. Such records enable correlation between environmental disturbance and subsequent inspection findings, facilitating quantitative corrosion rate evaluation and refinement of risk-based monitoring intervals.

Implementation of an event-triggered inspection protocol ensures that corrosion risk is addressed proactively following chemical upset conditions, rather than relying solely on fixed inspection intervals. By integrating operational response, chemical verification, and targeted inspection, the likelihood of progressive localized degradation following saline contamination can be significantly reduced.

### 6.6.4 Hydraulic Performance Monitoring

Progressive tuberculation and internal deposit accumulation result in measurable hydraulic restriction that can be detected through system performance data. Because reduction in effective flow area increases local velocity and frictional losses, monitoring of differential pressure, pump load, and flow rate provides an indirect but practical indicator of internal obstruction. Under constant operating conditions, unexpected increases in pressure drop across a defined piping segment or a decline in flow efficiency may indicate progressive internal deposition or localized constriction.

Hydraulic behavior in pressurized piping systems can be interpreted in the context of the Darcy–Weisbach relationship, in which pressure loss varies with velocity squared and is influenced by effective hydraulic diameter. As tuberculation reduces internal diameter, both frictional resistance and localized turbulence increase. Sustained deviation from baseline hydraulic performance parameters should therefore prompt evaluation for internal obstruction and potential corrosion-related narrowing.

Integration of hydraulic monitoring data with thickness inspection results and operational history enhances early detection of progressive degradation. Correlation between increasing pressure differential trends and localized metal loss identified during inspection can improve predictive assessment of obstruction growth and remaining service life. While hydraulic monitoring alone cannot quantify corrosion penetration, it provides a valuable non-intrusive screening tool that supports proactive integrity management.

### 6.6.5 Inspection Interval Determination

Inspection frequency should be determined using a risk-based approach that integrates measured corrosion progression, operational exposure history, and system criticality. Localized corrosion rate derived from trending ultrasonic thickness data represents a primary quantitative parameter for interval selection. Where measurable penetration has been observed, inspection intervals should be calculated to ensure that minimum remaining wall thickness does not approach structural design limits prior to the next scheduled assessment.

Operational history is equally significant, particularly in systems with documented seawater intrusion events. The frequency, duration, and cumulative exposure to saline conditions directly influence electrochemical instability and potential acceleration of localized attack. Systems with repeated chloride cycling warrant more conservative inspection intervals compared to those operating under stable fresh water chemistry.

Presence of stagnation-prone segments, dead legs, or geometrically complex regions such as flange interfaces further increases susceptibility to under-deposit corrosion and differential aeration. These regions may require localized inspection intervals shorter than those applied to straight, continuously flowing pipe sections.

Consequence of failure must also be incorporated into inspection planning. Fresh water systems supplying domestic or critical onboard services may require enhanced monitoring due to potential operational disruption, contamination risk, or safety implications associated with leakage.

In systems with documented saline cycling, shortened inspection intervals are justified because under-deposit corrosion may progress non-linearly. Once localized electrochemical cells are established beneath deposits, penetration rates may accelerate relative to uniform corrosion assumptions. Accordingly, inspection scheduling should account for potential variability and uncertainty in localized attack progression rather than relying solely on average corrosion rate estimates.

### 4.5 Synergistic Degradation Mechanism

The degradation observed in the investigated pipeline is best described as a synergistic interaction among chloride-assisted oxygen corrosion, differential aeration processes, and microbiologically influenced corrosion (MIC). Rather than representing a single dominant mechanism, the severity of metal loss reflects the combined and mutually reinforcing effects of electrochemical destabilization, deposit accumulation, and biological activity under intermittent saline exposure conditions.

Chloride ingress associated with seawater intrusion increases electrolyte conductivity and destabilizes corrosion product films formed during fresh water service. This promotes localized anodic activation and enhances oxygen reduction–controlled corrosion kinetics. Concurrently, accumulation of corrosion products and sediments establishes differential aeration cells in which oxygen-depleted regions beneath deposits function as anodic sites while adjacent oxygen-rich surfaces act as cathodes. These electrochemical gradients sustain localized dissolution beneath tubercles.

Where marine microorganisms are introduced during saline exposure events, biofilm development may further modify the local chemical environment. Microbial colonization within deposit-stabilized regions can promote oxygen depletion, generate metabolic by-products, and intensify electrochemical heterogeneity. Although the extent of microbiological contribution cannot be quantified without laboratory confirmation, the observed morphology is consistent with corrosion processes potentially enhanced by biofilm-mediated microenvironments.

The combined action of chloride-assisted film breakdown, differential aeration beneath deposits, and potential microbial activity produces corrosion severity exceeding that typically expected under stable fresh water conditions. This synergistic mechanism explains the pronounced tuberculation, deep under-deposit penetration, and localized concentration of damage identified in the present investigation.

## 7. Conclusions

Severe localized internal corrosion was identified in a carbon steel pipeline nominally designated for fresh water service. Macroscopic and cross-sectional evaluation confirmed extensive tuberculation, substantial hydraulic restriction, and deep under-deposit penetration concentrated at flange interfaces and stagnation-prone regions.

Operational history indicates intermittent seawater exposure during fresh water generation outages. Elevated chloride concentration and increased electrolyte conductivity associated with these events likely destabilized corrosion product films formed under fresh water service. Cyclic transition between saline and non-saline conditions prevented stabilization of oxide layers and sustained localized anodic activity.

Differential aeration beneath consolidated deposits, combined with chloride accumulation and restricted mass transport, explains the morphology of under-deposit pitting observed. Hydraulic constriction resulting from progressive tuberculation may have further intensified localized corrosion through increased oxygen transport and shear-induced deposit disturbance.

The findings demonstrate that intermittent saline intrusion can significantly increase corrosion severity in systems nominally classified as fresh water service. Effective mitigation requires strict operational segregation, defined post-exposure flushing and chemical stabilization procedures, targeted inspection of stagnation-prone regions, and evaluation of internal protection strategies where operational segregation cannot be guaranteed.

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