Corrosion Management and Material Selection for Crude Oil Export Equipment in Marine Environments: A Review

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Abstract
Crude oil export equipment, including subsea export pipelines, single point mooring systems, floating and submarine hoses, loading arms, storage tanks, and associated topside facilities, operates in one of the most aggressive corrosion environments encountered in the petroleum industry. The simultaneous action of chloride-rich seawater on external surfaces and multiphase produced fluids containing carbon dioxide, hydrogen sulphide, water, and microbial populations on internal surfaces creates a complex degradation regime that accounts for a substantial share of asset integrity failures, unplanned downtime, and environmental incidents in offshore terminals. This review consolidates the state of knowledge, as of 2020, on the corrosion mechanisms that govern the deterioration of crude oil export equipment in marine service, the materials engineering options available to designers, and the corrosion management strategies employed across the asset life cycle. Uniform, pitting, crevice, galvanic, erosion, microbiologically influenced, and environmentally assisted cracking mechanisms are examined in relation to the specific exposure zones of export infrastructure. Material selection is discussed for carbon and low alloy steels, martensitic, austenitic, duplex, and super duplex stainless steels, nickel-based alloys, clad and lined pipe, and non-metallic and composite materials, with reference to governing standards such as ISO 21457, NORSOK M-001, NACE MR0175/ISO 15156, and DNVGL recommended practices. Mitigation and control measures, including protective coatings, cathodic protection, chemical inhibition, corrosion allowance, and inspection and monitoring technologies, are reviewed alongside risk-based corrosion management frameworks. The review concludes by identifying persistent challenges, including microbiologically influenced corrosion prediction, preferential weld corrosion, ageing asset life extension, and the emerging role of digital monitoring and machine learning in corrosion management, and proposes directions for future research.

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1. Introduction

The export of crude oil from producing fields to tankers and onshore terminals depends on a chain of specialised equipment that is almost entirely immersed in, splashed by, or in intimate contact with seawater. Subsea export pipelines carry stabilised crude from processing facilities to loading points; single point mooring (SPM) systems, most commonly catenary anchor leg mooring (CALM) buoys, transfer the product through submarine and floating hoses to moored tankers; and floating production, storage and offloading (FPSO) vessels combine processing, storage, and export functions in a single hull. Each of these systems represents a large capital investment and a critical link in the revenue stream of an operator, and each is vulnerable to corrosion on both its seawater-exposed external surfaces and its product-wetted internal surfaces.

The economic significance of corrosion in this sector is considerable. The NACE International IMPACT study estimated the global cost of corrosion at approximately 2.5 trillion United States dollars per year, equivalent to about 3.4 percent of global gross domestic product, with the oil and gas production sector among the most heavily affected (Koch *et al*., 2016). Within offshore operations, corrosion has been repeatedly identified as a leading cause of loss of containment events, and failures of export infrastructure carry particularly severe consequences because they combine high-volume hydrocarbon inventories with direct discharge pathways to the marine environment (HSE, annual series; Roberge, 2012). Beyond the direct costs of repair and replacement, corrosion-related failures of export systems interrupt sales deliveries, trigger regulatory scrutiny, and expose operators to environmental liabilities.

Corrosion control for crude oil export equipment is complicated by the diversity of the exposure conditions involved. A single export system may span the marine atmospheric zone, the splash zone, the tidal and fully immersed zones, and the buried or mud zone, while internally it may be exposed to dry stabilised crude in some sections and to water-wet, solids-laden, microbially active fluids in others (Fontana, 1986). No single material or protective measure performs adequately across this entire envelope, and effective corrosion management therefore rests on a combination of informed material selection, protective systems, chemical treatment, and lifecycle inspection and monitoring, coordinated within a structured corrosion management framework (Energy Institute, 2019).

This review synthesises the literature available up to 2020 on corrosion and its management for crude oil export equipment in marine environments. Section 2 describes the marine exposure zones and the corrosion mechanisms of practical concern. Section 3 relates these mechanisms to the specific classes of export equipment. Section 4 reviews material selection options and methodologies. Section 5 examines mitigation, monitoring, and management strategies. Section 6 summarises the governing standards landscape, Section 7 addresses economic considerations, and Section 8 identifies open challenges and future research directions before conclusions are drawn in Section 9.

1.1. Scope of The Review

This review is bounded in three ways. First, it addresses equipment used for the export of stabilised or partially stabilised crude oil from an offshore or coastal production facility to a receiving tanker or onshore terminal. Upstream completion equipment, downstream refining assets, and gas export systems are considered only where their corrosion behaviour illuminates the export case. Second, it addresses the marine environment specifically, meaning the combined action of seawater, marine atmosphere, marine biota, and the thermal and mechanical loadings characteristic of offshore service. Third, it treats corrosion management as a lifecycle activity encompassing design, material selection, fabrication, commissioning, operation, inspection, life extension, and decommissioning, rather than as a purely metallurgical topic.

The equipment classes within scope are summarised in Table 1. They share three features that distinguish them from most other petroleum infrastructure: they are difficult or expensive to access for inspection and repair; they are exposed simultaneously to seawater externally and to hydrocarbon and water mixtures internally; and their failure discharges hydrocarbon directly into open water. Together these features raise the value of preventive corrosion control relative to reactive repair, and they explain why export systems attract material specifications and inspection regimes more conservative than an equivalent onshore installation would receive.

Table 1: Equipment classes within the scope of this review.

Equipment class	Principal components	Dominant access constraint
Subsea export pipeline	Line pipe, girth welds, field joints, tie-in spools, valves	Seabed burial; intervention by vessel and ROV
Single point mooring	Buoy hull, turntable, main bearing, product swivel, PLEM	Splash zone and immersed; offshore access
Transfer hoses	Floating hoses, submarine hoses, end fittings, flanges	Dynamic service; periodic recovery for testing
Mooring and anchoring	Chains, connectors, anchor legs, hawsers	Continuous immersion under dynamic load
Storage and cargo tanks	Bottom plates, shell, deckhead, internal structure	Confined entry; requires cleaning and gas freeing
Topside export equipment	Pumps, meters, loading arms, manifolds, pig traps	Accessible but production critical

1.2. Review Method and Sources

The literature considered here comprises peer-reviewed journal papers, conference proceedings of the principal corrosion and offshore engineering societies, international and national standards, classification society recommended practices, industry guidance documents, and publicly available regulatory investigation reports. Standards and recommended practices are treated as primary sources in their own right rather than as secondary commentary, because in this field they codify accumulated operating experience that is rarely published elsewhere and because they carry contractual force in project execution.

Three limitations of the available evidence base should be stated at the outset. First, corrosion failure data held by operators is commercially sensitive and only a fraction reaches open publication, so the published record over-represents unusual or litigated failures and under-represents routine degradation. Second, laboratory corrosion testing frequently fails to reproduce field conditions, particularly for microbiologically influenced corrosion and under-deposit attack where the controlling variables are hydrodynamic and biological rather than purely electrochemical. Third, predictive models calibrated on one field's fluid chemistry often transfer poorly to another. These limitations argue for conservatism in design and for monitoring regimes that assume the model may be wrong.

1.3. Structure of The Paper

Section 2 describes the marine exposure zones and the corrosion mechanisms of practical concern, treating each mechanism in terms of its initiation conditions, propagation behaviour, and the design or operational levers that control it. Section 3 maps these mechanisms onto the specific equipment classes of Table 1. Section 4 reviews the material options and the selection methodology, including fabrication and qualification considerations that determine whether a specified material performs as intended. Section 5 examines the mitigation, monitoring, and management measures applied across the lifecycle. Section 6 summarises the standards landscape, Section 7 addresses economic and environmental considerations, and Section 8 draws on adjacent regulated sectors for models of oversight. Section 9 identifies open challenges and research directions, and Section 10 concludes.

2. Marine Environments and Corrosion Mechanisms

2.1. Marine Exposure Zones

Seawater is an aerated, near-neutral electrolyte containing on average about 3.5 percent dissolved salts, dominated by sodium chloride, with dissolved oxygen concentrations typically between 5 and 8 milligrams per litre in surface waters (LaQue, 1975). The corrosivity experienced by a structure varies strongly with its position relative to the waterline. Five zones are conventionally distinguished: the marine atmospheric zone, subject to salt-laden aerosols and condensation; the splash zone, wetted intermittently by spray and waves and continuously replenished with oxygen; the tidal zone, alternately immersed and exposed; the fully immersed zone; and the buried or mud zone beneath the seabed (Fontana, 1986; LaQue, 1975). Field data compiled over many decades show that the splash zone is the most aggressive location for unprotected carbon steel, with corrosion rates frequently in the range of 0.3 to 0.5 millimetres per year and locally higher, because the surface remains wet, oxygenated, and beyond the reach of cathodic protection (LaQue, 1975; Melchers, 2009). Fully immersed steel typically corrodes at 0.1 to 0.2 millimetres per year in temperate waters, while buried zones exhibit lower oxygen-driven rates but may support anaerobic microbial activity (Melchers, 2009).

Long-term immersion corrosion of steels does not proceed at a constant rate. Melchers has shown through phenomenological modelling that corrosion loss follows a multi-phase progression in which an initial oxygen-controlled phase gives way, after the establishment of thick rust layers, to a phase in which anaerobic conditions beneath the corrosion products enable sulphate-reducing bacteria to sustain longer term attack (Melchers, 2014). This behaviour has direct implications for the life prediction of uncoated or coating-damaged regions of export infrastructure.

2.2. Uniform and Galvanic Corrosion

Uniform or general corrosion of carbon steel in aerated seawater is driven by the cathodic reduction of dissolved oxygen and is comparatively predictable, which is why it is normally addressed by a design corrosion allowance combined with coatings and cathodic protection (Fontana, 1986). Galvanic corrosion arises wherever dissimilar metals are electrically coupled in the seawater electrolyte, a situation that is difficult to avoid entirely in export systems that combine steel structures, copper alloy seawater components, stainless steel piping, and nickel alloy fasteners. The high conductivity of seawater extends the effective interaction distance of galvanic couples, and unfavourable area ratios, in which a small anodic component is coupled to a large cathodic surface, can produce rapid perforation (Francis, 2017). Design controls include isolation joints, compatible material pairing, and the deliberate use of sacrificial components.

2.3. Pitting and Crevice Corrosion

Chloride-induced localised corrosion is the dominant threat to passive alloys in seawater. Pitting initiates at weak points in the passive film, frequently at manganese sulphide inclusions in stainless steels, and propagates autocatalytically as the local environment within the pit acidifies and concentrates in chloride (Frankel, 1998). Crevice corrosion occurs under gaskets, fasteners, deposits, and marine fouling, where restricted mass transport allows differential aeration cells and aggressive local chemistry to develop; it initiates at lower temperatures and potentials than open-surface pitting and is therefore usually the limiting localised corrosion mode for stainless steels in seawater service (Frankel, 1998; Sedriks, 1996). Resistance to these mechanisms is commonly ranked by the pitting resistance equivalent number (PREN), calculated from the chromium, molybdenum, and nitrogen contents of the alloy, with a PREN of at least 40 conventionally required for reliable performance in ambient temperature seawater (Sedriks, 1996). The critical pitting temperature and critical crevice temperature, measured for example under ASTM G48 conditions, provide complementary selection criteria (Frankel, 1998).

2.4. Erosion-Corrosion and Flow-Assisted Degradation

Export streams that carry produced sand or that pass through chokes, bends, reducers, and pump internals at high velocity can suffer erosion-corrosion, in which mechanical removal of protective films accelerates electrochemical attack (Parsi *et al*., 2014). The phenomenon is of particular concern at pipe bends and hose end fittings in SPM systems, where flow direction changes concentrate impingement. Velocity limits for erosional service are commonly screened using the API RP 14E C-factor approach, although the limitations of that empirical method for corrosive, sand-laden service are well documented and mechanistic erosion models are increasingly preferred (Parsi *et al*., 2014).

2.5. Microbiologically Influenced Corrosion

Microbiologically influenced corrosion (MIC) is repeatedly cited as one of the least predictable and most damaging internal threats to crude oil export infrastructure. Sulphate-reducing bacteria and archaea, iron-oxidising and manganese-oxidising organisms, acid-producing bacteria, and methanogens colonise water-wetted internal surfaces, tank bottoms, and dead legs, forming biofilms beneath which locally aggressive chemistries develop (Skovhus *et al*., 2017). Mechanisms include cathodic depolarisation, the production of biogenic hydrogen sulphide and organic acids, and direct electron uptake from the metal in the case of certain electroactive organisms (Skovhus *et al*., 2017; Eckert and Skovhus, 2018). Failures attributed to MIC include high-profile pipeline leaks in which localised pitting rates far exceeded design corrosion allowances, and the mechanism is strongly associated with low-flow or stagnant conditions, water accumulation, and inadequate biocide coverage (Eckert and Skovhus, 2018). Diagnosis has advanced from culture-based enumeration towards molecular microbiological methods, including quantitative polymerase chain reaction and next-generation sequencing, which allow the abundance and activity of corrosion-relevant populations to be characterised (Skovhus *et al*., 2017).

2.6. Internal Sweet and Sour Corrosion

Although export crude is nominally stabilised and dehydrated, residual water, dissolved carbon dioxide, and hydrogen sulphide render the internal environment of export pipelines and tanks corrosive whenever a free water phase wets the steel. Carbon dioxide (sweet) corrosion of carbon steel proceeds through carbonic acid chemistry and is strongly influenced by temperature, carbon dioxide partial pressure, pH, flow, and the protectiveness of iron carbonate scales; the semi-empirical model of de Waard and colleagues and the mechanistic models reviewed by Nesic remain the basis of most industrial prediction tools (de Waard *et al*., 1991; Nesic, 2007). Kermani and Morshed noted that carbon dioxide corrosion remains the most common cause of internal corrosion failures in oil and gas production, in large part because carbon steel remains the default material of construction (Kermani and Morshed, 2003). Hydrogen sulphide introduces sour corrosion and, more importantly, environmentally assisted cracking phenomena, including sulphide stress cracking, hydrogen-induced cracking, and stress-oriented hydrogen-induced cracking, which impose compositional, hardness, and processing limits on steels selected for sour service under NACE MR0175/ISO 15156 (NACE MR0175/ISO 15156, 2015).

2.7. Environmentally Assisted Cracking in Seawater

External environmentally assisted cracking threats include chloride stress corrosion cracking of austenitic stainless steels, particularly at elevated temperatures under thermal insulation, and hydrogen embrittlement of high-strength steels and precipitation-hardened alloys under cathodic protection (DNVGL-RP-F112, 2018). Duplex stainless steels, though resistant to chloride stress corrosion cracking at moderate temperatures, can suffer hydrogen-induced stress cracking when excessive cathodic polarisation acts on material containing unfavourable microstructures, a mechanism implicated in documented subsea component failures (DNVGL-RP-F112, 2018). Corrosion fatigue is a further life-limiting mechanism for dynamically loaded export components such as mooring chains, hawsers attachments, and steel catenary risers, with seawater reducing fatigue endurance relative to air even under cathodic protection (Dover and Madhava Rao, 1996).

2.8. Under-Deposit Corrosion and Solids Accumulation

Export lines operating below the critical velocity for solids transport accumulate sand, wax, scale, and corrosion products at low points and along the pipe invert. Beneath these deposits the local environment diverges sharply from the bulk fluid: oxygen and inhibitor access are restricted, hydrolysis of dissolved species acidifies the occluded volume, and chloride concentrates by migration to balance the charge of dissolving iron (Roberge, 2012; Fontana, 1986). The result is a self-sustaining occluded cell that behaves much as a crevice does on a passive alloy, except that it forms on carbon steel where no passive film is present to begin with. Deposits also shelter microbial consortia from biocide contact, so under-deposit corrosion and microbiologically influenced corrosion frequently occur together and are difficult to distinguish in post-failure examination (Skovhus *et al*., 2017; Eckert and Skovhus, 2018).

The practical significance is that under-deposit attack defeats the two barriers most operators rely upon. Corrosion inhibitor cannot reach the metal beneath a consolidated deposit at any injection concentration, and corrosion allowance is consumed locally at rates far exceeding the general rate on which the allowance was based. Control is therefore mechanical rather than chemical: maintenance pigging to remove the deposit, flow assurance to maintain transport velocity, and design measures that avoid unnecessary low points and dead legs (Eckert and Skovhus, 2018; Papavinasam, 2014). Where pigging is impracticable, the credible assumption for integrity assessment is that under-deposit attack is occurring and is not being measured by any general corrosion monitoring device.

2.9. Top-Of-Line Corrosion and Vapour Space Attack

In pipelines and tanks carrying a wet hydrocarbon stream through a cooler ambient environment, water condenses on the upper internal surface. Because inhibitor is carried in the liquid phase along the pipe invert, the condensing film at the top of the line is uninhibited, and its very low volume means that the small quantity of dissolved carbon dioxide it contains produces a low pH before iron carbonate saturation is reached (de Waard *et al*., 1991; Nesic, 2007). Corrosion rates at the twelve o'clock position can therefore exceed those at the bottom of the same pipe despite the far smaller water volume. The equivalent phenomenon in storage and cargo tanks is deckhead corrosion, where condensation combines with oxygen and hydrogen sulphide in the vapour space to produce pitting of the underside of the tank top and of upper structural members (API RP 652, 2014).

Control options are limited. Thermal insulation reduces the condensation rate by narrowing the temperature difference; volatile inhibitors that partition into the vapour phase can provide partial protection; and in tanks, internal coating of the deckhead and upper shell is the standard remedy and is mandated by international performance standards for certain vessel types (API RP 652, 2014; ISO 12944, 2017). Inspection strategy must reflect the mechanism: an ultrasonic monitoring programme that measures only the pipe invert will not detect top-of-line attack, and corrosion coupons mounted in the liquid phase are blind to it entirely.

2.10. Oxygen ingress and mixed oxidant environments

Production and export systems are designed to exclude oxygen, and the corrosion models used for internal assessment generally assume its absence. In practice oxygen enters through tank breathing, imperfect blanket gas systems, seal leakage on pumps operating below atmospheric pressure, open drain returns, and the introduction of aerated seawater during ballasting, hydrotesting, or preservation (Roberge, 2012; API RP 652, 2014). The consequence is disproportionate. Oxygen is a far more efficient cathodic reactant than carbonic acid, and concentrations in the tens of parts per billion are sufficient to elevate corrosion rates materially and to destabilise the protective iron carbonate and iron sulphide films on which the inhibited system depends. Mixed oxidant conditions, in which oxygen coexists with hydrogen sulphide, additionally generate elemental sulphur and polysulphides that are aggressively corrosive to carbon steel and can compromise otherwise adequate corrosion resistant alloys.

Hydrotest and preservation practice deserves specific attention in export projects. Seawater used for pipeline hydrotesting introduces oxygen, chloride, nutrients, and a full marine microbial inoculum into a system that will subsequently sit static for months between construction and first oil. Inadequate treatment of hydrotest water with oxygen scavenger and biocide, or excessive lay-up duration, has been repeatedly implicated in early-life microbiologically influenced corrosion of new export lines (Skovhus *et al*., 2017; Eckert and Skovhus, 2018). The corrosion introduced during this window is a construction outcome rather than an operational one, but it is inherited by the operating asset.

2.11. Corrosion Fatigue and Dynamically Loaded Components

Mooring chains, connectors, hoses, risers, and buoy structural details experience continuous cyclic loading from waves, current, vessel motion, and product transfer operations. Seawater reduces fatigue endurance relative to air by eliminating the fatigue limit and by accelerating crack initiation at corrosion pits, which act as pre-existing stress concentrators (Dover and Madhava Rao, 1996). The interaction is synergistic rather than additive: cyclic loading ruptures protective films and exposes fresh metal, while corrosion roughens the surface and creates initiation sites, so the combined damage exceeds the sum of the separate mechanisms. Cathodic protection restores part of the fatigue endurance by suppressing the electrochemical contribution, but overprotection generates hydrogen and can reduce endurance in high strength materials, producing an optimum potential window rather than a monotonic benefit (DNVGL-RP-F112, 2018; DNVGL-RP-B401, 2017).

For mooring components the design consequence is that corrosion allowance and fatigue life must be assessed together rather than sequentially. A chain link that has lost diameter to corrosion carries higher stress, accumulates fatigue damage faster, and reaches its endurance limit sooner than the as-built fatigue calculation assumed. Inspection strategy follows: dimensional measurement of chain diameter is not merely a corrosion measurement but an input to a revised fatigue assessment, and the two must be recombined at each integrity review (Dover and Madhava Rao, 1996; OCIMF SMOG, 2015).

2.12. Hydrogen Damage Mechanisms

Hydrogen enters steel from two sources in export service: from the corrosion reaction itself where hydrogen sulphide is present and acts as a recombination poison, and from cathodic protection where the applied potential drives hydrogen evolution. Once absorbed, atomic hydrogen produces several distinct damage forms. Sulphide stress cracking affects hard microstructures under tensile stress and is controlled by hardness limits, chemistry restrictions, and post-weld heat treatment under NACE MR0175/ISO 15156 (NACE MR0175/ISO 15156, 2015). Hydrogen induced cracking forms internal blisters and step-wise cracks at elongated manganese sulphide inclusions and is controlled by clean steelmaking practice and low sulphur content rather than by hardness. Stress oriented hydrogen induced cracking combines the two and is associated with high residual stress in weld heat affected zones (NACE MR0175/ISO 15156, 2015).

Hydrogen induced stress cracking of duplex and super duplex stainless steels under cathodic protection is a distinct and, in the offshore context, particularly consequential mechanism, because it affects materials selected precisely for their corrosion resistance and it manifests without any preceding wall loss. Susceptibility depends on microstructure, particularly ferrite content and the distribution of austenite, on the level of applied and residual stress including local stress concentration at welds and threads, and on the achieved protection potential (DNVGL-RP-F112, 2018). Design against it is codified in DNVGL-RP-F112 and rests on limiting stress in polarised duplex components, controlling microstructure through welding procedure qualification, and, where practicable, isolating such components from the cathodic protection system (DNVGL-RP-F112, 2018; DNVGL-RP-B401, 2017).

2.13. Summary of Mechanisms

Table 2 consolidates the mechanisms discussed in this section against their initiation conditions, the equipment most affected, and the primary control measures. The table is intended as an orientation aid rather than a substitute for site-specific threat assessment, since the relative importance of each mechanism depends strongly on fluid chemistry, operating temperature, flow regime, and the maintenance regime actually achieved.

Table 2: Corrosion mechanisms affecting marine crude oil export equipment.

Mechanism	Principal initiating conditions	Most affected equipment	Primary controls
General corrosion	Aerated seawater; water-wet steel	External steelwork, buoy hull	Coatings, CP, corrosion allowance
Splash zone attack	Intermittent wetting; full oxygen access	Buoy hull, riser, caisson	TSA, sheathing, cladding, extra allowance
Galvanic corrosion	Dissimilar metals coupled in seawater	Flanges, fasteners, valve internals	Material pairing, isolation, area ratio control
Pitting	Chlorides exceeding passive film stability	Stainless piping, tubing, fittings	PREN selection, CPT margin
Crevice corrosion	Occluded geometry, gaskets, deposits	Flanged joints, hose fittings, supports	Alloy selection, joint design, sealing
Erosion-corrosion	High velocity, sand, flow direction change	Bends, chokes, pump internals, hose ends	Velocity limits, sand control, hard facings
MIC	Water accumulation, stagnation, nutrients	Pipeline low points, tank bottoms, dead legs	Pigging, biocide, water removal
CO2 corrosion	Free water, CO2 partial pressure, low pH	Internal pipeline, wet crude systems	Inhibition, allowance, dehydration
Sour cracking	H2S with tensile stress and hard structure	Welds, forgings, high strength components	MR0175/ISO 15156 compliance, hardness limits
Under-deposit	Solids settling under low flow	Pipeline invert, tank bottoms	Pigging, flow management, design
Top-of-line	Condensation in uninhibited vapour region	Pipeline crown, tank deckhead	Insulation, volatile inhibitor, coating
Corrosion fatigue	Cyclic load with corrosive environment	Mooring chain, riser, hose, connectors	CP potential window, design stress, inspection
HISC	Cathodic hydrogen in duplex microstructure	Subsea duplex components, bolting	RP-F112 design, stress limits, isolation

3. Crude Oil Export Equipment and Corrosion Exposure

3.1. Subsea Export Pipelines

Export pipelines are predominantly constructed from API 5L carbon steel line pipe, externally protected by fusion-bonded epoxy, three-layer polyolefin, or coal tar enamel coatings supplemented by sacrificial anode cathodic protection, and often weighted with concrete (DNVGL-ST-F101, 2017). External corrosion is generally well controlled where coating and cathodic protection systems are properly designed and maintained; the dominant integrity threats are internal, arising from water drop-out at low points and low-flow sections, carbon dioxide corrosion, MIC, and under-deposit attack beneath sludge and sand accumulations (Eckert and Skovhus, 2018; Kermani and Morshed, 2003). Preferential weld corrosion, in which the weld metal or heat-affected zone corrodes anodically relative to the parent pipe, is a recurring problem in seawater-handling and wet crude systems and is sensitive to weld consumable chemistry (Alawadhi and Robinson, 2011). Because girth welds combine metallurgical discontinuity with residual stress, non-destructive examination of welds forms a critical element of integrity verification for export lines, and the integration of such examination into corrosion risk assessment and integrity management programmes has been reviewed for hydrocarbon processing facilities (Atta *et al*., 2020).

3.2. Single point mooring systems and hoses

CALM buoys and other SPM terminals expose a concentrated inventory of corrosion-susceptible components: the buoy hull spans the splash and immersed zones; the turntable and swivel assemblies combine dissimilar metals with dynamic seals; anchor chains suffer combined corrosion, abrasion, and fatigue in the tidal and immersed zones; and the pipeline end manifold sits on the seabed under coating and cathodic protection (OCIMF SMOG, 2015). Bonded rubber submarine and floating hoses, manufactured and tested to the OCIMF Guide to Manufacturing and Purchasing Hoses for Offshore Moorings, degrade through seawater ageing of elastomers, corrosion of steel end fittings and embedded reinforcement helices, and fatigue of the bonded structure, and are therefore subject to strict periodic testing, retirement criteria, and often double-carcass leak detection designs (OCIMF SMOG, 2015; OCIMF GMPHOM, 2009). Corrosion of hose flange faces and bolting, aggravated by galvanic coupling and crevice conditions under gaskets, is a common maintenance finding at SPM terminals (OCIMF SMOG, 2015).

3.3. Storage Tanks and Fpso Cargo Systems

Crude oil storage tanks at export terminals and FPSO cargo tanks corrode internally at two characteristic locations: the bottom plates, where a settled water phase containing salts, solids, and active microbial consortia accumulates, and the vapour space and deck head, where condensation, oxygen, and hydrogen sulphide sustain sour condensate attack (API RP 652, 2014). Pitting of tank bottoms is the life-limiting mechanism and has motivated mandatory internal coating requirements for ballast tanks and, under IMO performance standards, for crude cargo tanks of new tankers (API RP 652, 2014). External corrosion of atmospheric terminal tanks is concentrated at the soil-to-air interface and under insulation. FPSO hulls additionally face classic marine hull corrosion management demands, complicated by the inability to dry-dock on normal survey cycles, which places a premium on coating quality, impressed current or sacrificial protection, and in-service inspection (ABS, 2019).

3.4. Loading Arms, Manifolds, Pumps, And Valves

Marine loading arms, metering skids, export pumps, and valves combine product wetting with marine atmospheric exposure. Swivel joints and seal counterfaces require materials that resist both crevice corrosion and wear; pump internals face erosion-corrosion in solids-laden service; and small-bore instrument tubing in the marine atmosphere is a well-documented weak point for chloride pitting of standard 316 stainless steel, prompting a widespread move to super austenitic, super duplex, or 6 percent molybdenum tubing in exposed locations (Sedriks, 1996; ISO 21457, 2010).

3.5. Risers, riser bases, and flexible pipe

Risers connect seabed pipework to floating or fixed facilities and traverse every marine exposure zone in a single component. Steel catenary and top-tensioned risers combine the internal corrosion regime of the export line with external splash zone exposure and dynamic loading, which is why their design typically incorporates enhanced corrosion allowance in the splash zone, thermally sprayed aluminium or thick elastomeric sheathing over the splash region, and fatigue-driven weld quality requirements more onerous than the pipeline itself (Dover and Madhava Rao, 1996; DNVGL-ST-F101, 2017). The riser touchdown zone and riser base present additional complications: trenching and soil interaction disturb coatings, cathodic protection current distribution is uneven, and inspection access is poor.

Flexible pipe presents a different degradation picture. Its steel armour wires sit in an annulus that, in service, becomes flooded with water permeating through the internal polymer sheath and saturated with carbon dioxide and hydrogen sulphide diffusing from the bore. The annulus environment is stagnant, of low volume, and effectively unaddressable by inhibition, so armour wire corrosion and, where sour species are present, cracking of high strength armour become the life-limiting mechanisms. Monitoring focuses on annulus vent gas testing and volume measurement to detect sheath breach, and integrity management depends heavily on manufacturer-specific service life models.

3.6. Mooring Systems, Chains, And Connectors

The mooring system of an export buoy or floating facility is a corrosion problem disguised as a structural one. Anchor chain corrodes by general seawater attack in the immersed zone, at accelerated rates in the splash and thrash zones where coatings cannot be maintained and cathodic protection is intermittent, and preferentially at the interlink contact surfaces where relative motion continuously abrades any protective film. Corrosion allowance in chain is expressed as diameter loss and is combined with an assumed wear allowance, but the two mechanisms interact, and field measurements commonly show loss rates exceeding design assumptions in the most exposed links (Dover and Madhava Rao, 1996; OCIMF SMOG, 2015).

Connectors, shackles, and swivel components introduce localised risks: crevices at pin and bush interfaces, galvanic couples between chain steel and higher alloy connector materials, and hydrogen embrittlement risk where high strength steels are used under cathodic protection (DNVGL-

RP-F112, 2018). Because mooring failure is a total loss scenario for an export buoy, inspection intervals are governed by classification rules and typically combine periodic ROV survey, dimensional measurement of representative links, and retirement criteria based on combined corrosion and wear loss (OCIMF SMOG, 2015).

3.7. Pig Traps, Metering Skids, And Valves

Pig launchers and receivers are among the most corrosion-prone items on an export system despite being topside and accessible. They are intermittently operated, retain liquid after each operation, are frequently opened to atmosphere, and accumulate the solids and sludge that the pig has just swept from the line. The combination of retained water, introduced oxygen, and concentrated debris produces aggressive localised attack in the barrel invert, at the closure seal face, and in small-bore drain and vent connections (Roberge, 2012; Papavinasam, 2014). Metering skids suffer analogous problems in dead-legged sample and pressure tapping lines.

Valves present a compound problem because they combine several materials, contain crevices by design, and must maintain sealing performance rather than merely containment. Seat and stem materials are selected for wear and galling resistance as well as corrosion resistance, and this frequently drives the use of nickel alloy or hard-faced components inside a carbon or low alloy steel body. Small-bore instrument tubing and fittings in the marine atmosphere remain a recognised weak point, since standard 316 stainless steel pits under chloride-bearing surface deposits, and the resulting leaks are disproportionately frequent relative to the value of the components involved (Frankel, 1998; Sedriks, 1996).

3.8. Ballast, Void, And Secondary Spaces

Buoy compartments, FPSO ballast tanks, void spaces, and cofferdams are not product-carrying but are integral to buoyancy, stability, and structural integrity. They are subject to classic marine corrosion of coated steel in intermittently flooded or humid service, with breakdown concentrated at edges, welds, and structural intersections where coating thickness is hardest to achieve. International performance standards for protective coatings in seawater ballast spaces exist precisely because coating failure in these compartments historically produced structural degradation that was discovered late (API RP 652, 2014; ISO 12944, 2017). For export buoys the compartment inspection problem is aggravated by confined entry requirements offshore, which lengthens intervals and increases reliance on coating quality achieved at build.

3.9. Equipment-to-threat Mapping

Table 3 maps the mechanisms of Section 2 onto the equipment classes discussed above, indicating for each combination whether the threat is normally a primary design driver, a secondary consideration, or not typically credible. Such a matrix forms the starting point of the threat assessment required by corrosion management guidance, and its value lies in exposing combinations that a purely equipment-focused or purely mechanism-focused review would overlook (Energy Institute, 2019).

Table 3: Indicative mapping of corrosion threats to export equipment classes.

Threat	Export pipeline	SPM buoy	Hoses	Tanks	Mooring
Splash zone attack	Secondary	Primary	Secondary	Secondary	Primary
Pitting / crevice	Secondary	Primary	Primary	Primary	Secondary
Galvanic	Secondary	Primary	Primary	Secondary	Primary
CO2 corrosion	Primary	Secondary	Secondary	Secondary	Not credible
MIC	Primary	Secondary	Secondary	Primary	Secondary
Under-deposit	Primary	Not credible	Secondary	Primary	Not credible
Top-of-line	Primary	Not credible	Secondary	Primary	Not credible
Erosion-corrosion	Secondary	Secondary	Primary	Not credible	Not credible
Corrosion fatigue	Secondary	Primary	Primary	Secondary	Primary
Sour cracking	Primary	Secondary	Secondary	Secondary	Secondary
HISC	Secondary	Primary	Secondary	Not credible	Primary

4. Material Selection for Marine Crude Oil Export Service

4.1. Selection Methodology and Governing Standards

Material selection for export equipment is normally conducted as a structured evaluation of the internal and external service environments against candidate materials, documented in a material selection report. ISO 21457 and NORSOK M-001 provide the principal frameworks, requiring the assessment of carbon dioxide and hydrogen sulphide partial pressures, temperature, chlorides, water chemistry, flow regime, sand production, and design life, and the qualification of materials against localised corrosion and cracking limits (ISO 21457, 2010; NORSOK M-001, 2014). Where hydrogen sulphide is present, NACE MR0175/ISO 15156 governs the qualification of metallic materials against sulphide stress cracking and related mechanisms (NACE MR0175/ISO 15156, 2015). Life cycle cost analysis, rather than lowest initial cost, is the recommended economic basis, since the cost of a subsea intervention or terminal shutdown frequently dwarfs the initial premium of a corrosion-resistant alloy (Kermani and Morshed, 2003; ISO 21457, 2010).

4.2. Carbon and low alloy steels

Carbon steel remains the default material for export pipelines, buoy structures, tanks, and structural components, on account of its cost, weldability, strength range, and established fabrication base. Kermani and Morshed observed that carbon and low alloy steels account for the overwhelming majority of tubular goods and facilities in the industry, with corrosion managed rather than eliminated (Kermani and Morshed, 2003). In marine export service, carbon steel is used with external coatings and cathodic protection, an internal corrosion allowance typically of 3 to 6 millimetres for pipelines, chemical inhibition where water wetting is expected, and hardness and chemistry controls for sour service (Kermani and Morshed, 2003; NACE MR0175/ISO

15156, 2015; DNVGL-ST-F101, 2017). Its principal limitations are susceptibility to carbon dioxide corrosion, MIC, and preferential weld corrosion internally, and its complete dependence on protective systems externally.

4.3. Stainless steels

Martensitic 13 percent chromium steels serve in mildly sour, carbon dioxide-containing production service but are not seawater-resistant. Standard austenitic grades 304 and 316 suffer pitting and crevice corrosion in quiescent seawater and chloride stress corrosion cracking above approximately 60 degrees Celsius, restricting them to sheltered atmospheric or fresh water duties (Frankel, 1998; Sedriks, 1996). Duplex stainless steel 2205 (UNS S32205, PREN approximately 35) and super duplex grades such as UNS S32750 and S32760 (PREN above 40) combine high strength with strong resistance to chloride pitting and stress corrosion cracking, and are widely used for seawater piping, hose fittings, manifolds, and instrument tubing; their caveats are the need for careful welding to avoid deleterious sigma phase and nitride precipitation, temperature limits for crevice corrosion in chlorinated seawater, and susceptibility to hydrogen-induced stress cracking under excessive cathodic protection (Sedriks, 1996; DNVGL-RP-F112, 2018). Super austenitic 6 percent molybdenum alloys (for example UNS S31254) offer comparable seawater resistance where duplex fabrication constraints are unattractive (Sedriks, 1996).

4.4. Nickel-Based Alloys, Copper Alloys, And Titanium

Nickel-chromium-molybdenum alloys 625 and C-276 and nickel-copper alloy 400 provide near-immunity to seawater localised corrosion and serve as weld overlay and solid components in critical wetted parts, swivels, and sour wellhead-to-export interfaces, at a substantial cost premium (Sedriks, 1996; ISO 21457, 2010). Copper-nickel alloys 90-10 and 70-30 resist biofouling and perform well in flowing seawater piping, although they are vulnerable to sulphide-polluted waters and to erosion above design velocities (Francis, 2017). Titanium is effectively immune to ambient seawater corrosion and finds use in seawater heat exchangers and specialised components, limited mainly by cost and by hydriding risk under cathodic protection (Sedriks, 1996).

4.5 Clad pipe, linings, and non-metallic materials

Where internal conditions exceed the capability of inhibited carbon steel but a solid corrosion-resistant alloy is uneconomic, metallurgically clad or mechanically lined pipe with a 3 millimetre alloy 625 or 316L layer over a carbon steel backing offers a widely adopted compromise for flowlines and export headers (ISO 21457, 2010). Non-metallic options have expanded steadily: high-density polyethylene liners rehabilitate corroded water and multiphase lines; glass-reinforced epoxy piping serves ballast, firewater, and some hydrocarbon duties; and thermoplastic composite pipe and flexible reinforced polymer pipelines were, by 2020, qualified under DNVGL standards for offshore service, offering inherent immunity to electrochemical corrosion (DNVGL-ST-F119, 2018). Bonded elastomeric hoses remain the standard product transfer element at SPM terminals, with nitrile and chloroprene compounds selected for crude compatibility and seawater ageing resistance respectively (OCIMF GMPHOM, 2009). Elastomer selection for seals and hoses must also account for explosive decompression and aromatic content of the crude (OCIMF GMPHOM, 2009).

Table 4 summarises the principal material classes, their marine performance, and typical export applications.

Table 4: Summary of candidate materials for crude oil export equipment in marine service.

Material class	Marine corrosion performance	Key limitations	Typical export applications
Carbon / low alloy steel (API 5L, structural grades)	Poor unprotected; managed with coatings, CP, inhibition, corrosion allowance	CO2 corrosion, MIC, preferential weld corrosion, splash zone attack	Export pipelines, buoy hulls, tanks, structures
316L austenitic SS	Moderate atmosphere; pits and crevices in seawater; CSCC above about 60 C	Not suitable for immersed seawater; chloride SCC	Sheltered piping, internals, low-chloride duties
Duplex 2205 / super duplex S32750, S32760	Good to excellent (PREN 35 to >40); high strength	Weld precipitates; crevice limits in warm chlorinated seawater; HISC under CP	Seawater piping, hose fittings, manifolds, tubing
6 Mo super austenitic (S31254)	Excellent seawater pitting and crevice resistance	Cost; segregation in welds needs overmatching filler	Seawater systems, instrument tubing
Ni alloys 625, C-276; alloy 400	Outstanding; near-immune to localised attack	High cost; used as overlay where possible	Weld overlay, swivels, valves, critical wetted parts
Cu-Ni 90-10, 70-30	Good in clean flowing seawater; antifouling	Sulphide pollution; velocity limits	Seawater cooling and service piping
Titanium grades 2, 5	Effectively immune in ambient seawater	Cost; hydriding under CP; galling	Heat exchangers, specialised components
GRE, HDPE liners, thermoplastic composite pipe	Immune to electrochemical corrosion	Temperature and pressure limits; permeation; qualification	Liners, service piping, emerging flowline use
Bonded elastomeric hoses (OCIMF)	Designed for seawater and crude exposure	Ageing, fatigue, end fitting corrosion; finite certified life	SPM floating and submarine hoses

4.6. Localised corrosion resistance indices and their limits

Selection of passive alloys for seawater service is normally screened using the pitting resistance equivalent number, calculated as the chromium content plus 3.3 times molybdenum plus 16 times nitrogen, with tungsten-bearing grades using a modified expression. The convention that a PREN of at least 40 is required for ambient temperature seawater has served the industry well as a first filter (Sedriks, 1996). It is nonetheless a screening index and not a performance guarantee, and three qualifications matter in export service.

- PREN is calculated from nominal composition, whereas performance depends on the composition and microstructure actually achieved, particularly in welds and heavy sections where segregation and secondary phase precipitation reduce local resistance below the parent metal value.
- PREN correlates with open-surface pitting resistance, but crevice corrosion initiates at lower temperatures and is usually the limiting mode in real assemblies containing gaskets, supports, and deposits, so critical crevice temperature is the more relevant criterion for seawater-wetted joints.
- The index says nothing about resistance to stress corrosion cracking, hydrogen induced stress cracking under cathodic protection, sour service suitability, erosion resistance, or galling, all of which may govern selection independently.

Table 5 summarises indicative composition, PREN, and localised corrosion temperature limits for the alloy families commonly considered. The temperature values are indicative of laboratory test rankings rather than design limits, and project specifications should establish limits from qualification testing under representative chemistry, including any chlorination regime applied to seawater systems (Frankel, 1998; Sedriks, 1996; ISO 21457, 2010).

Table 5: Indicative localised corrosion resistance of candidate alloys for seawater service.

Alloy family	Indicative composition	PREN	Relative CPT	Typical seawater role
316L austenitic	17Cr-11Ni-2Mo	~24	Low	Sheltered or non-immersed duties only
Duplex 2205	22Cr-5Ni-3Mo-0.16N	~35	Moderate	Process piping, structural, moderate chloride
Super duplex 25Cr	25Cr-7Ni-4Mo-0.27N	>40	High	Seawater piping, fittings, manifolds
6Mo super austenitic	20Cr-18Ni-6Mo-0.2N	>42	High	Seawater systems, instrument tubing
Alloy 625	58Ni-22Cr-9Mo-Nb	>45	Very high	Overlay, critical wetted components
Alloy C-276	57Ni-16Cr-16Mo-4W	>65	Very high	Severe service, mixed oxidant conditions
Titanium Gr 2	Commercially pure Ti	Not applicable	Very high	Heat exchangers, specialised components

4.7. Welding, Fabrication, and The Gap Between Specification and Delivery

A material selection report specifies a base material, but the asset is built from welded assemblies, and the weld is where most corrosion problems originate. Three fabrication issues recur across export projects.

- **Preferential Weld Corrosion in Carbon Steel**

Where weld metal is electrochemically active relative to the parent pipe in the service environment, corrosion concentrates in a narrow band along the weld, producing perforation long before the general corrosion allowance is consumed. Susceptibility is governed principally by the alloying of the weld consumable relative to the pipe, and mitigation rests on selecting consumables that produce weld metal marginally noble to, or matched with, the parent material under the anticipated chemistry, verified by testing rather than assumed (Alawadhi and Robinson, 2011). The mechanism is particularly relevant to export systems because their girth welds are numerous, buried, and inaccessible to routine visual verification.

- **Secondary Phase Precipitation in Duplex Stainless Steels**

Duplex and super duplex grades derive their properties from a balanced ferrite-austenite microstructure. Excessive heat input, prolonged time in the sigma phase precipitation range, or inadequate shielding produces intermetallic phases and chromium nitrides that reduce corrosion resistance and toughness locally by a substantial margin. Qualification of welding procedures with ferrite counting, corrosion testing of weld coupons, and control of heat input and interpass temperature during production welding are therefore not documentation formalities but the mechanism by which the specified corrosion resistance is actually realised (Sedriks, 1996; DNVGL-RP-F112, 2018).

- **Coating Application and Field Joints**

The factory-applied coating on line pipe is generally of high and verifiable quality. The field joint, applied on a laybarge or at a tie-in spread under weather and schedule pressure, is the recognised weak point of the external corrosion barrier, and coating breakdown factors used in cathodic protection design implicitly acknowledge this by assuming progressive loss of coating efficiency over the design life (DNVGL-ST-F101, 2017; ISO 12944, 2017; DNVGL-RP-B401, 2017). Surface preparation, applied thickness, and cure verification at field joints therefore have a direct and quantifiable effect on anode consumption and on the achievable design life of the protection system.

These three examples share a structural feature worth naming: in each case the corrosion outcome is determined by execution quality at a stage of the project when commercial pressure is highest and corrosion expertise is least present. This is one of the clearest points at which the technical and organisational strands of corrosion management meet, and it explains why fabrication quality assurance, contractor management, and inspection coverage during construction appear repeatedly in analyses of subsequent operating problems (Arumosoye and Obriki, 2020; Obogo *et al*., 2020b; Obogo *et al*., 2019b).

4.8. A structured material selection workflow

Consolidating the guidance of ISO 21457 and NORSOK M-001 with the mechanism discussion of Section 2, a defensible material selection sequence for export equipment proceeds through the following steps (ISO 21457, 2010; NORSOK M-001, 2014).

- Define the internal and external service envelopes over the full design life, including start-up, shutdown, upset, preservation, and life extension conditions rather than steady-state design conditions alone.
- Establish sour service classification against NACE MR0175/ISO 15156 using the maximum credible hydrogen sulphide partial pressure and in-situ pH, not the expected value.
- Screen candidate materials against localised corrosion criteria for the external seawater environment, using crevice rather than pitting criteria where occluded geometry exists.
- Assess environmentally assisted cracking, including chloride stress corrosion cracking, sour cracking, and hydrogen induced stress cracking where cathodic protection will be applied to duplex or high strength materials.
- Where carbon steel is retained, quantify the corrosion allowance from a defensible internal corrosion model, state the inhibitor availability assumed, and confirm that the assumed availability is achievable by the planned chemical injection and monitoring arrangement.
- Verify fabricability, including welding procedure feasibility, availability of qualified consumables, and inspection access for the resulting joints.
- Compare shortlisted options on life cycle cost including chemical, pigging, inspection, intervention, and deferred production consequences rather than on installed cost.
- Document assumptions explicitly, since the material selection report becomes the reference against which life extension and change of service are later assessed.

The final step deserves emphasis in the export context. Many marine export systems now operate well beyond their original design life under fluid conditions that differ from those assumed at selection, frequently with higher water cut and changed souring status as fields mature. Where the original selection assumptions were not documented, the reassessment required for life extension has no baseline and must be reconstructed from inspection evidence alone, at substantially greater cost and lower confidence (Energy Institute, 2019; DNVGL-ST-F101, 2017).

5. Corrosion Management Strategies

5.1. Protective Coatings and Linings

Coatings are the first line of external defence for all classes of export equipment. Subsea pipelines employ fusion-bonded epoxy or three-layer polyethylene and polypropylene systems, with field joints coated by heat-shrink sleeves or liquid epoxies whose quality is a recognised weak point (DNVGL-ST-F101, 2017; ISO 12944, 2017). Buoy hulls, loading arms, and topside structures are protected by multi-coat epoxy and polyurethane or polysiloxane systems selected and tested to ISO 12944 and NORSOK M-501 for the C5-M marine and immersed categories, with thermally sprayed aluminium increasingly specified for splash zone and long-maintenance-interval service (ISO 12944, 2017). Internally, tank bottoms and cargo tanks receive high-build epoxy or glass flake linings, and IMO performance standards mandate protective coatings for seawater ballast spaces (API RP 652, 2014). Coating breakdown, quantified through breakdown factors in cathodic protection design codes, governs anode demand across the design life, so coating and cathodic protection design are inseparable (DNVGL-RP-B401, 2017).

5.2. Cathodic Protection

Cathodic protection supplements coatings on all immersed and buried surfaces. Sacrificial aluminium-zinc-indium anodes dominate subsea pipeline and structure protection because of their reliability and independence from power supplies, with design conducted to DNVGL-RP-B401 for structures and DNVGL-RP-F103 for pipelines to achieve protection potentials of minus 0.80 volts versus silver/silver chloride or more negative (DNVGL-RP-B401, 2017). Impressed current systems serve large hulls and terminals where current demands are high. Two constraints deserve emphasis for export systems: first, cathodic protection is ineffective in the splash zone, which must rely on coatings, sheathing, or corrosion-resistant cladding; and second, overprotection more negative than about minus 1.1 volts generates hydrogen and creates hydrogen-induced stress cracking risk for super duplex components and high-strength steels, so potential control and design against HISC per DNVGL-RP-F112 are required where such materials are polarised (DNVGL-RP-F112, 2018; DNVGL-RP-B401, 2017). Retrofitting anode sleds and monitoring depletion by remotely operated vehicle survey are standard life extension activities for ageing export pipelines (DNVGL-ST-F101, 2017).

5.3. Chemical Treatment and Internal Corrosion Control

Internal corrosion of carbon steel export lines is managed chemically where water wetting cannot be excluded. Film-forming corrosion inhibitors, typically nitrogen-based surfactant chemistries injected continuously at tens of parts per million, can reduce carbon dioxide corrosion rates by more than 90 percent when coverage is maintained, and inhibitor availability is used as a key performance indicator in corrosion management systems (Kermani and Morshed, 2003; Papavinasam, 2014). Interest in environmentally benign inhibitor chemistries has grown alongside tightening discharge regulations, and plant-extract based green inhibitors for steel protection have been the subject of systematic review as candidate replacements for conventional formulations (Atta *et al*., 2018). Batch treatment between pig runs serves lines without continuous injection. Biocides, most commonly glutaraldehyde, tetrakis hydroxymethyl phosphonium sulphate, and quaternary amines, are applied in batch regimes against biofilm-forming consortia, ideally in combination with mechanical cleaning because established biofilms shield organisms from chemical attack (Skovhus *et al*., 2017; Eckert and Skovhus, 2018). Oxygen scavengers and drag reducers complete the chemical portfolio. Operational measures are equally important: maintenance pigging removes the water, solids, and sludge that sustain under-deposit corrosion and MIC, dead legs are minimised or flushed, and tank water bottoms are drawn off routinely (Eckert and Skovhus, 2018; API RP 652, 2014).

5.4. Inspection and Monitoring

Verification of corrosion control closes the management loop. Intrusive techniques, including weight-loss coupons and electrical resistance probes at representative locations, provide time-averaged and near-real-time internal corrosion rates, while linear polarisation resistance probes respond within minutes in water-continuous systems (Papavinasam, 2014). Non-destructive testing techniques, including manual and automated ultrasonics, radiography, and electromagnetic methods, underpin corrosion risk assessment for process and export equipment, and their integration into structured integrity management programmes has been critically reviewed for refinery and hydrocarbon processing facilities (Atta *et al*., 2020). Non-intrusive wall thickness monitoring by ultrasonic sensors, including permanently installed and wireless arrays, matured rapidly in the years before this review and supports corrosion trending at critical locations without process penetration (Papavinasam, 2014). Complementary machinery condition monitoring, for example sensor-based fault detection and thermodynamic performance assessment on export pumps and rotating equipment, detects the mechanical consequences of erosion-corrosion and seal degradation that wall thickness measurement alone would miss (Sunday *et al*., 2020; Yeboah and Ike, 2020).

In-line inspection of piggable export pipelines by magnetic flux leakage and ultrasonic intelligent pigs remains the definitive internal condition assessment, feeding defect assessment per DNVGL-RP-F101 and repair planning; unpiggable lines depend on external ultrasonic campaigns, guided wave screening, and cathodic protection surveys (DNVGL-ST-F101, 2017). For the onshore approaches, landfall sections, and terminal corridors of export systems, remote sensing has become an important complement to walked surveys. A review of unmanned aerial vehicle applications in pipeline and corridor monitoring describes the use of optical, thermal, and light detection and ranging payloads for leak indication, coating and support condition assessment, and encroachment detection (Dagodzo and Patrick, 2020). Earlier work on unmanned aerial vehicle integration into infrastructure inspection programmes and on transmission line inspection methods established the operational and regulatory groundwork on which these pipeline applications build, while geographic information system enabled asset frameworks provide the spatial register against which corrosion findings and repair histories are managed (Dagodzo, 2018a; Dagodzo, 2018b; Patrick *et al*., 2020).

Subsea external integrity is monitored through remotely operated vehicle visual and potential surveys, while SPM hoses undergo periodic hydrostatic, electrical continuity, and vacuum testing with retirement governed by OCIMF criteria (OCIMF SMOG, 2015; OCIMF GMPHOM, 2009). Risk-based inspection frameworks, notably API RP 580 and 581 and DNVGL-RP-G101, allocate inspection resources according to the probability and consequence of failure, and are the dominant planning basis at export terminals (Energy Institute, 2019; API RP 580/581, 2016; Atta *et al*., 2020). The wider maintenance philosophy within which inspection sits has shifted in the same direction, from reactive and calendar-based intervention towards condition-based and predictive regimes supported by sensor data (Sunday *et al*., 2020; Sunday *et al*., 2019).

5.5. Corrosion Management Systems

Individual barriers are only effective when coordinated. Guidance issued by the UK Energy Institute and the corrosion management framework promoted through the NACE IMPACT study describe a management system in which corrosion threats are assessed, barriers and their performance standards are defined, key performance indicators such as inhibitor availability, pig run frequency, and anode potential compliance are tracked, and deviations trigger corrective action within a documented governance structure (Koch *et al*., 2016; Energy Institute, 2019). Failures of export infrastructure investigated by regulators have repeatedly been traced not to unknown mechanisms but to lapses in the execution of known management activities, underlining that organisational discipline is as decisive as materials technology (HSE, annual series; Energy Institute, 2019).

5.6. Digitalisation and Data-Driven Integrity Management

Corrosion management is increasingly absorbed into a broader movement towards data-driven asset performance management. The shift in maintenance philosophy from reactive and calendar-based intervention towards condition-based and predictive regimes supported by sensor data is documented across mechanical and building services asset classes, and the underlying logic applies directly to export equipment: measurements are collected continuously, trended against a degradation model, and used to time intervention rather than to confirm damage after the fact (Sunday *et al*., 2020; Sunday *et al*., 2019). Predictive analytics models developed for demand and resource forecasting illustrate the data quality, validation, and threshold-setting problems that any corrosion rate prediction system must also solve (Aifuwa *et al*., 2020).

A corrosion management system is, in data terms, a long-lived record of measurements, assumptions, and interventions that must remain trustworthy across decades and multiple operators. The information governance literature is therefore relevant even though it was not written with pipelines in mind. Frameworks for legal and ethical risk modelling in enterprise data protection governance, for comparative data protection and secure cloud implementation, and for agile supply chain digital transformation with embedded information technology risk and standards compliance controls describe the controls that keep such records complete, attributable, and auditable (Mbonu *et al*., 2018; Mbonu *et al*., 2019a; Mbonu *et al*., 2020b). Identity and access management across hybrid environments, infrastructure-as-code governance for reproducible configuration, and enterprise log analytics with automated incident response determine who may alter an inspection record or a cathodic protection setpoint and whether that change leaves a trace, which is an integrity question as much as an information technology one (Mbonu *et al*., 2020a; Mbonu *et al*., 2020c; Mbonu *et al*., 2019b).

5.7. Operational Technology Security and The Availability of Corrosion Controls

Digitalisation introduces a dependency that traditional corrosion management did not carry. Cathodic protection monitoring units, chemical injection controls, and inspection data historians increasingly sit on operational technology networks exposed to cyber threat. A systematic review of operational technology network security in electric utilities, covering compliance regimes and architectural threat mitigation, establishes that the availability and integrity of such instrumentation cannot be assumed (Adegbite *et al*., 2020). The defensive practices developed in enterprise security have direct analogues in integrity assurance: security audit and enterprise risk assessment frameworks, intrusion detection and prevention models, and privacy-centric security engineering for digital and cloud systems embody the same logic that corrosion engineers apply through barrier verification, monitoring, and risk-based resource allocation (Dosunmu and Ogundele, 2019; Dosunmu and Ogundele, 2020; Okoruwa *et al*., 2020). Assessment of security-critical directory and access management systems, and their implementation for enterprise network management, addresses the practical control of privileged access to the systems that hold integrity data (Ladapo *et al*., 2018; Ladapo *et al*., 2019). The corrosion relevance is straightforward: a compromised or unavailable monitoring system silently removes a barrier from the integrity case without producing any physical indication.

5.8. Safety Management, Human Performance, And Organisational Discipline

Corrosion barriers are installed, inspected, and restored by people working under maintenance and safety management systems, and the quality of those systems determines whether design intent survives into operation. A critical review of occupational safety management systems in oil and gas maintenance projects, together with work on internal quality, health, safety, and environment audit systems, identifies competence, procedural adherence, permit discipline, and audit closure as the mechanisms through which planned barrier maintenance is actually delivered (Arumosoye and Obriki, 2020; Obogo *et al*., 2020a). The same literature emphasises leading indicators over lagging ones: near-miss and hazard observation data utilisation, systematic hazard identification and risk control practices, data-driven occupational safety risk control in large energy infrastructure projects, and management walkthrough coverage provide the early signals that also tend to precede integrity failures (Arumosoye and Obriki, 2019; Obogo *et al*., 2019a; Obogo *et al*., 2019c; Obriki and Arumosoye, 2018). Human error causation frameworks address why correctly specified procedures are nonetheless departed from at the work face (Obriki and Arumosoye, 2020).

Several features of export terminal work make these findings particularly applicable. Heat stress in tropical marine settings degrades the quality of inspection and maintenance performed in confined, elevated, and enclosed locations, a recognised pathway to both injury and defective workmanship (Arumosoye and Obriki, 2018). Much of the work is executed by contractors, and governance-oriented models for contractor safety performance in multi-contract industrial projects, together with construction safety risk governance models for multi-contractor environments, describe the interface controls needed to ensure that coating application, welding, and anode installation meet specification when performed by third parties (Obogo *et al*., 2020b; Obogo *et al*., 2019b). Risk management models for heavy lifting and crane operations bear on the execution of anode retrofit, hose change-out, and equipment replacement campaigns at export terminals, where the corrosion-driven maintenance task is itself a major lifting hazard (Obogo *et al*., 2020c). Leadership-driven safety culture transformation in large workforces addresses the softer determinants of whether specified corrosion control practices are actually followed (Obriki and Arumosoye, 2019).

5.9. Procurement, Materials Readiness, And Assurance

Execution depends on materials and spares being available when a corrosion finding requires action. Work on inventory availability and plant uptime improvement in energy facilities describes the mechanism by which procurement performance becomes an integrity variable: a deferred anode retrofit, hose replacement, or coating campaign is frequently a supply chain outcome rather than an engineering judgement (Okonkwo *et al*., 2018b). Strategic procurement optimisation in oil and gas operations, supply chain risk management for engineering, procurement, and construction projects, cost reduction through contract negotiation and vendor governance, and logistics efficiency models that address port and customs delay together define the commercial conditions under which corrosion-critical materials and specialist services are secured, particularly where long lead corrosion-resistant alloy items must cross borders (Agbabiaka *et al*., 2019; Okonkwo *et al*., 2020; Okonkwo *et al*., 2018a; Okonkwo *et al*., 2019). Geographic information system enabled procurement frameworks and multi-stakeholder governance alignment in joint venture operations address the coordination problem that arises when several partners share responsibility for an export facility (Akin-Oluyomi *et al*., 2020; Eyetsemitan *et al*., 2020). Data-driven profitability and predictive demand analysis inform how spares holdings for such items are sized (Aifuwa *et al*., 2020; Okojie and Abioye, 2020). Decision frameworks reconciling chemical safety with circular economy targets bear on the selection and disposal of corrosion control chemicals and replaced components (Akomolafe and Agu, 2018).

Assurance closes this loop. The internal audit literature on technology-enabled risk assessment, risk-based internal control models for regulated sectors, data-driven risk evaluation for institutions in emerging markets, and integrated governance and compliance strategies provides the methodological basis for auditing a corrosion management system against its own performance standards, which is what regulators and classification societies require operators to demonstrate (Akomolafe and Agu, 2019a; Akomolafe and Agu, 2019b; Akomolafe and Agu, 2019c; Adeyelu, 2018).

5.10. Comparative assessment of monitoring and inspection techniques

No single technique provides a complete picture of corrosion state, and the practical question in designing a monitoring regime is which combination of methods covers the credible threats identified in the assessment of Section 3. Table 6 compares the principal techniques against what they actually measure, their response time, and their characteristic blind spots. The blind spot column is the operationally important one, because most surprises in corrosion management arise from threats that the installed monitoring was structurally incapable of detecting rather than from measurements that were taken and ignored (Papavinasam, 2014; Atta *et al*., 2020).

Table 6: Comparison of corrosion monitoring and inspection techniques for export systems.

Technique	What it measures	Response time	Characteristic blind spots
Weight loss coupon	Average metal loss at coupon location	Weeks to months	Localised attack away from coupon; not representative of invert or top of line
Electrical resistance probe	Cumulative metal loss, near real time	Hours to days	Localised pitting; probe location bias
Linear polarisation resistance	Instantaneous corrosion rate	Minutes	Requires continuous water phase; not valid in hydrocarbon-wetted conditions
Ultrasonic thickness, manual	Wall thickness at discrete points	Per campaign	Coverage limited by access and scaffolding; misses between points
Permanent ultrasonic sensors	Wall thickness trend at fixed points	Continuous	Fixed location; requires power and data path
In-line inspection	Metal loss over full pipeline length	Per run	Requires piggability; tool detection thresholds; feature sizing tolerance
ROV survey and CP potential	External condition and protection level	Per campaign	Buried sections; internal condition entirely
Chemical and microbial sampling	Fluid corrosivity and microbial activity	Per sample	Bulk fluid may not represent occluded local environments
Hose testing to OCIMF	Pressure integrity and continuity	Per interval	Progressive internal degradation between test intervals

Two design principles follow from the table. First, techniques should be selected in complementary pairs so that the blind spot of one is covered by another, for example combining in-line inspection for spatial coverage with permanently installed sensors for temporal resolution at known critical locations. Second, the monitoring regime should be revisited whenever the threat assessment changes, since a regime designed around carbon dioxide corrosion will not detect the onset of microbiologically influenced corrosion following a change in water cut or a period of low flow (Skovhus *et al*., 2017; Eckert and Skovhus, 2018).

5.11. Corrosion Management Performance Indicators

Corrosion management systems are audited against performance indicators that express whether barriers are functioning rather than whether corrosion has yet occurred, on the reasoning that the latter is a lagging measure of a process that operates over years (Energy Institute, 2019; Obogo *et al*., 2020a). Indicators in common use across export operations include inhibitor availability expressed as the percentage of time injection met target rate, pigging campaign compliance against plan, biocide batch treatment completion, cathodic protection potential readings within the acceptable window, inspection plan completion against schedule, closure of corrosion-related actions within due date, and the proportion of monitoring locations returning valid data.

The parallel with leading indicator practice in safety management is direct and has been developed extensively in that literature, where near-miss reporting, hazard observation rates, and audit closure serve the same anticipatory function (Arumosoye and Obriki, 2019; Obogo *et al*., 2020a; Obogo *et al*., 2019a; Obriki and Arumosoye, 2018). The transferable insight is that indicators are only useful where the organisation responds to deterioration in them, and that indicator systems degrade into reporting exercises when the response pathway is unclear. Auditing methodology drawn from risk-based internal control practice offers a structured means of testing whether the indicator actually drives action or merely records it (Akomolafe and Agu, 2019a; Akomolafe and Agu, 2019b).

5.12. Protective Coating System Selection

Coating selection for export equipment balances the severity of the exposure zone against the maintenance access available over the design life. Table 7 summarises the systems in common use. The governing consideration in each case is not the laboratory performance of the coating but whether the surface preparation and application conditions assumed by the specification can be achieved at the location where the coating is applied, which is why field-applied systems consistently underperform factory-applied equivalents (DNVGL-ST-F101, 2017; ISO 12944, 2017).

Table 7: Protective coating systems commonly specified for marine export equipment.

System	Typical application	Service life expectation	Principal limitations
Fusion bonded epoxy	Subsea pipeline external	Design life with CP support	Field joint quality; handling damage
Three layer polyolefin	Subsea pipeline external, higher duty	Design life with CP support	Shielding of CP current if disbonded
Multi-coat epoxy / polyurethane	Topsides, buoy hull above water	10 to 15 years to first major maintenance	Requires access for maintenance painting
Thermally sprayed aluminium	Splash zone, long maintenance interval	20 years or more	Application cost; surface preparation demand
Glass flake epoxy	Splash zone, immersed steelwork	10 to 20 years	Application thickness control
High build epoxy lining	Tank internals, ballast spaces	Design life if correctly applied	Edge and weld coverage; curing conditions
Heat shrink sleeve	Pipeline field joints	Variable in practice	Recognised weak point of the barrier

5.13. Chemical Treatment Programme Design

The chemical treatment programme for an export system is normally specified as a package rather than as individual products, since the components interact and the injection infrastructure is shared. Table 8 summarises the principal chemical classes, their function, and the failure modes associated with each. The recurring theme across all classes is that availability, meaning the proportion of operating time during which the chemical actually reached the metal at the intended concentration, matters more than the nominal dose rate specified in the design (Papavinasam, 2014). A programme designed for ninety-five percent availability and delivered at seventy percent will not achieve the corrosion rate assumed in the corrosion allowance calculation, and the shortfall accumulates silently.

Table 8: Chemical treatment classes applied in crude oil export systems.

Chemical class	Function	Characteristic failure modes of the treatment
Film forming inhibitor	Reduce CO2 and general internal corrosion of carbon steel	Injection outage; poor distribution in stratified flow; no access beneath deposits; incompatibility with other chemicals
Biocide	Control biofilm and microbial populations	Batch frequency too low; established biofilm resists contact; resistance development; ineffective in dead legs
Oxygen scavenger	Remove dissolved oxygen from injected or hydrotest water	Insufficient residence time; ingress downstream of injection point
Scale inhibitor	Prevent mineral deposition that shields the surface	Threshold dose sensitivity; incompatibility with corrosion inhibitor
Demulsifier and dehydration aid	Reduce free water carried into the export stream	Upset conditions carrying water into a system assumed dry
Volatile or vapour phase inhibitor	Partial protection of top-of-line condensing regions	Partitioning behaviour uncertain; limited field validation

Programme design should therefore specify not only the products and dose rates but the measurement by which availability will be demonstrated, the action to be taken when availability falls below target, and the corrosion allowance consequence of sustained under-delivery. Where these are not stated, the corrosion allowance is effectively an unmonitored assumption (Energy Institute, 2019; Papavinasam, 2014).

6. Recurring Failure Patterns and Their Lessons

Analysis of published failure investigations, regulatory findings, and operator experience reveals a limited number of recurring patterns rather than a wide diversity of novel mechanisms. Recognising the pattern is often more useful than refining the mechanism, because the corrective action attaches to the pattern.

6.1. The low-flow, water-accumulating line

An export line designed for a production rate that the field no longer achieves operates below the velocity needed to sweep water and solids. Water accumulates at low points, solids consolidate, inhibitor is excluded from the metal beneath, microbial consortia establish, and localised attack proceeds at multiples of the design rate while general corrosion monitoring reports acceptable values. The failure appears sudden but has been developing since the production decline began (Skovhus *et al*., 2017; Eckert and Skovhus, 2018). The lesson is that corrosion threat assessment must be revisited when operating conditions change, and that declining production is itself a corrosion event.

6.2. The construction legacy

A line hydrotested with inadequately treated seawater and left static through an extended commissioning delay begins operation with an established microbial population and an oxygen-damaged internal surface. Early-life leaks follow within a few years and are frequently attributed to operational shortcomings when their origin lies in the construction phase (Skovhus *et al*., 2017; Eckert and Skovhus, 2018). The lesson concerns the handover between project and operations: preservation records, hydrotest water treatment certificates, and lay-up duration are integrity documents and should be transferred and retained as such.

6.3. The unmonitored interface

Corrosion concentrates at interfaces: the splash zone, the soil-to-air transition, the underside of pipe supports, the crevice under a gasket, the field joint, the weld. These locations are systematically under-monitored because they are precisely where access is hardest, and monitoring plans tend to be populated with locations that are convenient to reach. The result is a monitoring record that is accurate but unrepresentative (Papavinasam, 2014; Atta *et al*., 2020). The lesson is that monitoring location selection should be driven by the threat assessment and should explicitly document why inaccessible high-risk locations are not covered and what compensating measure applies.

6.4. The deferred intervention

An inspection identifies a defect requiring repair, the repair requires a spare or a specialist vessel, procurement or scheduling delays the intervention across successive planning cycles, and the defect grows. The engineering diagnosis was correct and timely, but the barrier was never restored. This pattern is well represented in the maintenance management literature and connects corrosion outcomes directly to procurement performance, materials readiness, and the discipline with which corrective actions are tracked to closure (Arumosoye and Obriki, 2020; Obogo *et al*., 2020b; Okonkwo *et al*., 2018b). The lesson is that the integrity management system must track open corrosion actions with the same rigour applied to the inspection that generated them.

6.5. The competent-material, incompetent-installation failure

A correctly specified super duplex component fails by hydrogen induced stress cracking because it was polarised by a cathodic protection system designed without reference to it, or a duplex weld fails because production welding departed from the qualified procedure, or a coated joint fails because surface preparation was inadequate under schedule pressure (DNVGL-RP-F112, 2018; Alawadhi and Robinson, 2011; ISO 12944, 2017). In each case the material selection report was sound and the failure occurred in execution. The lesson is that material selection and fabrication quality assurance are a single control, not two, and that verification of the second is the only evidence that the first has been delivered.

7. Standards and Regulatory Framework

The corrosion management of crude oil export equipment is codified in an extensive body of international standards. The most frequently invoked documents include: ISO 21457 and NORSOK M-001 for material selection; NACE MR0175/ISO 15156 for sour service qualification; API 5L and DNVGL-ST-F101 for line pipe and submarine pipeline systems; DNVGL-RP-B401, F103, and F112 for cathodic protection and HISC avoidance; ISO 12944 and NORSOK M-501 for protective coatings; ISO 15589 for pipeline cathodic protection; API 650 and API 653 for terminal tank construction and inspection; the OCIMF hose guidelines for SPM transfer systems; and API RP 580/581 and DNVGL-RP-G101 for risk-based inspection (NACE MR0175/ISO 15156, 2015; DNVGL-ST-F101, 2017; OCIMF SMOG, 2015; OCIMF GMPHOM, 2009; ISO 21457, 2010; NORSOK M-001, 2014; ISO 12944, 2017; DNVGL-RP-B401, 2017; API RP 580/581, 2016). Classification society rules govern FPSO hull and cargo system integrity, and national regulators impose corrosion management expectations through safety case and pipeline integrity management regimes (HSE, annual series; ABS, 2019).

8. Economic and Environmental Considerations

8.1. Life Cycle Cost and Investment Logic

Material and corrosion management decisions for export systems are ultimately economic. The IMPACT study estimated that implementing established corrosion management best practice could save 15 to 35 percent of the global cost of corrosion (Koch *et al.*, 2016). For export equipment specifically, the comparison is between the capital premium of corrosion-resistant alloys or clad pipe and the operating cost and residual risk of inhibited carbon steel, evaluated over the field life; published selection guidance emphasises net present value analysis incorporating chemical costs, pigging, inspection, deferred production during repairs, and the consequence costs of loss of containment (Kermani and Morshed, 2003; ISO 21457, 2010). Deepwater and long-tieback developments shift the balance towards corrosion-resistant materials because intervention costs are extreme, whereas shallow-water terminals with good access often favour carbon steel plus management. Life extension of ageing export pipelines and SPM systems beyond original design life, a widespread situation by 2020, imposes additional reassessment, monitoring, and retrofit costs that should be anticipated in whole-life economics (DNVGL-ST-F101, 2017; OCIMF SMOG, 2015).

8.2. Environmental and Sustainability Dimensions

Corrosion management at marine export facilities intersects with environmental performance in three ways. First, the consequence of failure is discharge to a sensitive receiving environment, which is why consequence modelling dominates risk-based inspection scoring for export systems (API RP 580/581, 2016). Second, the chemicals used to control corrosion, including inhibitors, biocides, and oxygen scavengers, are themselves regulated discharges; this is the practical driver behind interest in green inhibitor chemistries derived from agricultural and plant extracts, which have been systematically reviewed as candidate replacements for conventional steel protection formulations (Atta *et al.*, 2018). Decision frameworks that reconcile chemical safety obligations with circular economy targets illustrate the trade-offs involved when a lower-toxicity option carries a performance or lifecycle penalty (Akomolafe and Agu, 2018). Third, the energy supply to export terminals and to impressed current protection systems is itself changing, and work on renewable integration programmes, co-optimisation of technical performance with affordability in constrained settings, and load distribution for hybrid installations is relevant to the electrification of terminal auxiliary and protection loads (Sunday and Omoegun, 2018; Sunday and Omoegun, 2019; Komi and Adeniji, 2020).

9. Lessons from Adjacent Regulated Safety-Critical Sectors

Because the corrosion literature is dominated by technical mechanisms rather than regulatory practice, useful models for oversight can be drawn from adjacent sectors facing comparable problems of periodic certification, ageing infrastructure, and resource-constrained enforcement. Civil aviation is the closest analogue. Predictive compliance monitoring frameworks that detect systemic safety risk from routine reporting data address the question of how an authority extracts early warning from records generated for another purpose, which is the regulatory counterpart of trending corrosion inspection findings across an asset population (Adeyelu, 2018). Adaptive safety management system implementation models for operators in developing economy contexts speak directly to terminals in regions where regulatory capacity and access to specialist expertise are constrained (Adeyelu, 2019). Risk quantification models that convert hazard exposure into airworthiness impact assessment offer a transferable structure for expressing corrosion findings in terms of fitness for continued service rather than wall loss alone (Adeyelu, 2020).

10. Challenges and Future Directions

Several challenges remained open at the time of this review. First, MIC prediction is immature: despite advances in molecular monitoring, no validated model reliably converts microbial community data into corrosion rate forecasts, and threat assessment remains largely qualitative (Skovhus *et al.*, 2017; Eckert and Skovhus, 2018). Second, preferential weld corrosion and the corrosion of aged girth welds in wet crude service continue to produce failures that escape general corrosion monitoring (Alawadhi and Robinson, 2011). Third, the interaction of cathodic protection with high-strength and duplex materials, and the management of HISC in ageing subsea assets, require continued attention as protection systems are retrofitted (DNVGL-RP-F112, 2018; DNVGL-RP-B401, 2017). Fourth, inspection of unpiggable export lines and of the splash zone remains technically difficult and costly (DNVGL-ST-F101, 2017). Fifth, the industry-wide shift of assets beyond design life concentrates risk in equipment whose corrosion allowances and coatings are largely consumed (Energy Institute, 2019; DNVGL-ST-F101, 2017). Sixth, and less often framed as a corrosion problem, the reliability of the organisational systems that deliver inspection, maintenance, and materials supply remains a limiting factor, since a correctly diagnosed threat that is not closed out by a resourced intervention has not been managed (Arumosoye and Obriki, 2020; Okonkwo *et al.*, 2018b; Eyetsemitan *et al.*, 2020). Seventh, the growing dependence of integrity assurance on instrumentation, networks, and long-lived digital records introduces availability and data governance failure modes that are not yet routinely represented in corrosion risk assessments (Adegbite *et al.*, 2020; Mbonu *et al.*, 2018; Mbonu *et al.*, 2019b).

Promising directions identified in the literature to 2020 include: permanently installed wireless ultrasonic and electrochemical sensor networks feeding centralised corrosion analytics, building on the sensor-based fault detection approaches already demonstrated in other asset classes (Sunday *et al.*, 2020; Sunday *et al.*, 2019); the application of machine learning to in-line inspection data fusion and corrosion rate prediction, drawing on the predictive analytics methods maturing in adjacent operational domains (Aifuwa *et al*., 2020); wider qualification of thermoplastic composite pipe and polymer liners that remove the corrosion mechanism altogether (DNVGL-ST-F119, 2018); environmentally benign green inhibitors and optimised biocide stewardship (Atta *et al*., 2018; Akomolafe and Agu, 2018); and unmanned aerial and underwater inspection platforms that reduce the cost of external condition surveillance, extending the corridor monitoring practice already established onshore to landfalls and terminal approaches (Dagodzo and Patrick, 2020; Dagodzo, 2018b). Realising these gains will require corresponding attention to the security and availability of the operational technology on which they depend (Adegbite *et al*., 2020; Dosunmu and Ogundele, 2019), to the governance of the long-lived data records that underpin life extension decisions (Mbonu *et al*., 2018; Mbonu *et al*., 2020a; Mbonu *et al*., 2019b), and to the maintenance and procurement systems that convert a prediction into a completed repair (Arumosoye and Obriki, 2020; Agbabiaka *et al*., 2019; Okonkwo *et al*., 2018b). The convergence of these technologies with structured corrosion management systems offers the prospect of moving from periodic, conservative integrity assessment towards continuous, condition-based management of export infrastructure (Yang, 2008; Sunday *et al*., 2019).

11. Recommendations for Practice

The following recommendations follow from the review and are directed at operators, designers, and integrity engineers responsible for marine crude oil export systems.

- Treat the material selection report as a living integrity document. Record the assumed fluid chemistry, water cut, souring status, inhibitor availability, and design life explicitly, and re-open it whenever operating conditions depart materially from those assumptions.
- Design the monitoring regime from the threat assessment rather than from access convenience, and document which credible threats are not covered by any installed technique together with the compensating measure applied.
- Assume that under-deposit and top-of-line mechanisms are active wherever flow conditions permit water or solids accumulation, and verify by direct means rather than inferring their absence from general corrosion monitoring.
- Manage the construction and commissioning window as an integrity phase. Specify hydrotest water treatment, limit lay-up duration, and transfer preservation records to operations as integrity documentation.
- Verify that specified corrosion resistance is actually delivered, through welding procedure qualification with corrosion testing, ferrite control for duplex grades, consumable selection testing against preferential weld corrosion, and field joint coating verification.
- Where duplex or high strength materials are polarised by cathodic protection, apply hydrogen induced stress cracking design rules explicitly and control the protection potential window rather than maximising protection.
- Express chemical treatment performance as availability rather than dose rate, define the response when availability falls short, and state the corrosion allowance consequence of sustained under-delivery.
- Track corrosion-related corrective actions to closure with the same rigour applied to the inspection that generated them, recognising that procurement lead time and intervention scheduling are integrity variables.
- Combine corrosion and fatigue assessment for dynamically loaded components rather than performing them sequentially, since section loss alters the fatigue assessment on which the remaining life depends.
- Plan for life extension from the outset by retaining design assumptions, inspection history, and repair records in a form that will remain interpretable across changes of operator and information system.

12. Conclusions

Corrosion of crude oil export equipment in marine environments is governed by a well-characterised but demanding combination of external seawater mechanisms, dominated by splash zone attack, localised corrosion of passive alloys, and galvanic effects, and internal mechanisms, dominated by carbon dioxide corrosion, MIC, under-deposit attack, and sour cracking where hydrogen sulphide is present. No single material satisfies the full exposure envelope. Carbon steel, protected by coatings, cathodic protection, inhibition, and corrosion allowance, remains the economic default for pipelines, structures, and tanks, while duplex and super duplex stainless steels, 6 percent molybdenum austenitics, nickel alloys, clad products, and engineered elastomers and composites address duties beyond its capability. The literature to 2020 demonstrates that the mechanisms and countermeasures are largely known; the differentiator between reliable and failure-prone export systems is the quality of the corrosion management system that selects, implements, monitors, and maintains the barriers over the asset life. Future gains are expected less from new alloys than from better prediction of localised threats such as MIC, from inherently corrosion-free non-metallic systems, and from the digitalisation of monitoring and integrity management.

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