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Climate Change Impacts (2014-2024) on Protective and Marine Coating Specifications for GCC Oil and Gas Infrastructure: From Fixed Soluble Salt Limits to Climate-Adapted Performance Qualification

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Highlights

- GCC coating exposure is increasingly controlled by combined heat, ultraviolet radiation, airborne chloride, humidity-driven wetness, industrial pollutants, abrasive dust and short-duration flooding.
- ISO 9223, ISO 12944 and NORSOK M-501 remain the technical base, but GCC specifications need explicit local modifiers for UV intensity, dust loading, chloride recontamination, time of wetness and ponding risk.
- Severe-duty oil and gas coating specifications commonly retain low water soluble salt targets, including values around 20 mg/m² (2 µg/cm²) equivalent after blasting. These targets remain technically important but require stronger field verification in marine-industrial climates.
- The proposed approach keeps low salt contamination as the preferred target, requires salt re-checks before primer and after exposure/delay between coats, and allows higher residual salt values only where the full coating system is performance-qualified at the defined contamination level.
- For severe marine and offshore service, the most defensible architecture is a zinc-rich primer, high-build MIO or glass-flake epoxy barrier and a UV-stable polyurethane, polysiloxane or fluoropolymer finish coat.

Abstract

Protective and marine coatings in the Gulf Cooperation Council (GCC) are no longer operating within a stable design envelope. Between 2014 and 2024, selected GCC oil and gas hubs experienced increasing thermal stress, with reported warming indicators generally in the range of approximately 0.3-0.5 °C per decade depending on location, dataset and method. Coating performance is also affected by high steel temperature, intense ultraviolet radiation, saline aerosol, humidity-driven wetting, industrial pollutants, abrasive dust and occasional short-duration flooding. This paper consolidates GCC exposure-screening data from selected oil and gas hubs with standards-based coating engineering to develop a climate-adapted specification framework. The screening suggests that Abu Dhabi and Kuwait City generally align with C3-C4 atmospheric severity when strong UV and dust modifiers are considered, Dammam and Muscat align with C4-C5 marine-industrial exposure, while Doha and Manama approach C5 conditions under combined humidity, chloride and pollutant loading. Offshore, splash-zone and shipyard locations may approach CX severity where chloride deposition, wetting and mechanical damage are sustained. A central finding is that surface cleanliness limits commonly used in project specifications, including low soluble salt targets around 20 mg/m² (2 µg/cm²) equivalent, remain technically desirable but are increasingly difficult to maintain in GCC field conditions because freshly prepared steel can be rapidly recontaminated by chloride aerosol, dust, humidity cycles and construction delays. The paper therefore proposes a balanced specification route: retain strict cleaning, repeated soluble salt testing and short coating windows as the default, but qualify surface-tolerant or chloride-tolerant coating systems at defined higher residual salt levels only where supported by manufacturer evidence, cyclic corrosion testing, adhesion performance, rust-creep limits and technical approval. The framework links each GCC climate stressor to likely coating failure mechanisms and specification controls, including zinc-rich primers, high-build lamellar epoxy barriers, UV-stable topcoats, stripe coating, edge retention, cyclic qualification and local exposure-rack feedback.

Keywords

Protective coatings; marine coatings; climate change; GCC; ISO 9223; ISO 12944; NORSOK M-501; soluble salts; chloride deposition; Bresle method; surface preparation; time of wetness; coating failure

Nomenclature and abbreviations

Term	Meaning	Term	Meaning
DFT	Dry film thickness	TOW	Time of wetness
GCC	Gulf Cooperation Council	MIO	Micaceous iron oxide
HALS	Hindered amine light stabilizer	UVA	Ultraviolet absorber
PU	Polyurethane	CX	Extreme corrosivity category for offshore-related exposure in ISO 12944
EIS	Electrochemical impedance spectroscopy	ITP	Inspection and test plan

Table 1. Abbreviations used in the manuscript.

1. Introduction

In the GCC, protective coatings are not cosmetic finishes. They are part of the asset integrity system for offshore platforms, refineries, tank farms, shipyard structures, desalination facilities, marine terminals and long-run pipework. A coating system normally fails because several stressors act together over time: heat, ultraviolet radiation, chloride deposition, condensation, dust contamination, mechanical damage, workmanship limitations and maintenance delay. Treating these factors as isolated variables can lead to specifications that are formally compliant but not fully matched to the local failure route.

The climate signal behind this problem is increasingly relevant to coating specification. Hereher [10] reported regional climate change trends across GCC countries during the early twenty-first century using satellite-derived land surface temperature, precipitation and sea surface temperature evidence. Nesterov et al. [12] analysed high-resolution sea surface temperature data in the Arabian Gulf, while Al Senafi et al. [11] showed that the Arabian/Persian Gulf is a shallow, climate-sensitive marine system where sea surface temperature is an important driver of coupled atmosphere-ocean variability. For coating systems, higher steel temperature can accelerate binder oxidation, increase thermal cycling stress, affect cure windows and change the probability of condensation at night.

Extreme rainfall is another practical issue. The April 2024 UAE and Oman event showed that even hyper-arid infrastructure can experience short-duration wetting, ponding and temporary immersion. World Weather Attribution [14] reported that the 14-15 April 2024 heavy precipitation event caused major disruption in the UAE and northern Oman, while WMO reporting on 2024 extremes placed the event within a wider pattern of high-impact weather. For coatings, this does not replace the normal marine/desert exposure, but it introduces an additional failure route at coating holidays, edges, bolted interfaces, damaged areas, poorly drained details and inadequately stripe-coated welds [13,14].

The existing standards framework remains essential. ISO 9223 classifies atmospheric corrosivity using first-year corrosion rates and key variables such as the temperature-humidity complex, sulfur dioxide pollution and airborne salinity [1]. ISO 12944 provides coating system selection, durability and laboratory performance guidance for steel structures [2-4]. ISO 12944-9 specifically addresses protective paint systems for offshore and related structures exposed to CX offshore and Im4 environments [4]. NORSOK M-501 remains a major reference for the selection of coating materials, surface preparation, application procedures and inspection for protective coatings applied to offshore and coastal facilities [5]. The limitation is not that these standards are weak. The limitation is that many client and project specifications apply them too generally, or carry forward historical cleanliness and coating acceptance values without fully considering GCC-specific modifiers such as extreme UV, dust abrasion, rapid chloride recontamination, high TOW and flooding/ponding risk.

A specific practical concern is soluble salt control. Many offshore-style and severe-duty coating specifications continue to use very low soluble salt limits, often around 20 mg/m² (2 μg/cm²) equivalent for critical service after abrasive blasting. Such limits are technically defensible because residual soluble salts can drive osmotic blistering, underfilm corrosion, rust creep and adhesion loss. However, in GCC marine and industrial climates, maintaining these low values consistently between final cleaning and primer application is becoming difficult under normal site conditions. Airborne chloride fallout, dust storms, high humidity, elevated steel temperature, masking delays, access changes and inspection hold points can recontaminate freshly prepared steel. This paper therefore argues for a climate-adapted specification model: low soluble salt remains the preferred quality target, but where the target cannot be reliably maintained, higher residual salt values should only be accepted if the selected primer or coating system is qualified for defined chloride tolerance under realistic cyclic exposure and formal technical approval.

GCC climate exposure translated into coating specification controls

Exposure driver	Probable coating response	Specification control
Heat + UV	Oxidation, chalking, gloss loss and embrittlement	UV-stable PU, polysiloxane or fluoropolymer finish
Humidity + wetness / high TOW	Blistering, adhesion loss and underfilm corrosion	Low-permeability high-build epoxy barrier; cure and dew-point control
Chloride aerosol	Creep from defects, pitting and rapid recontamination	Zinc-rich primer, barrier coat and repeated soluble salt testing
Dust + sand	Abrasion, micro-cracking and profile contamination	Abrasion-resistant finish, cleaning plan and dust tape control
SO_2 + chlorides	Acidic condensate and accelerated underfilm attack	Cyclic corrosion qualification rather than neutral salt spray alone
Flooding / ponding	Temporary immersion, edge failure and local delamination	Stripe coating, edge retention, drainage and holiday control

Fig. 1. Integrated climate-exposure, coating-failure and specification-control framework proposed for GCC service.

Interpretation note: ISO atmospheric corrosivity classification remains the base screen. GCC-specific modifiers such as UV intensity, dust loading, rapid chloride recontamination, high TOW and short-duration flooding should be added before final coating-system selection.

2. Materials and methods

2.1 Scope and selected locations

The study evaluates selected GCC oil and gas hubs: Dammam, Abu Dhabi, Doha, Kuwait City, Muscat and Manama. These locations represent a practical spread of marine-industrial, coastal-humid and desert-inland exposure. The values used in this paper are engineering screening inputs consolidated from the manuscript drafts and interpreted against published climate, marine and standards evidence. They are not a substitute for project-specific atmospheric testing, corrosion coupons, station-calibrated meteorology or local chloride-fallout mapping.

2.2 Data treatment and technical basis

The input variables were selected for direct coating relevance: temperature and UV as heat/photo-oxidation modifiers; relative humidity and TOW as wetness and condensation modifiers; chloride deposition as a marine aerosol and soluble salt recontamination driver; SO_2 as an industrial pollutant modifier; and dust/sand as an abrasive and cleanliness modifier. ISO 9223 was used as the base corrosivity screen because it remains the most appropriate starting point for atmospheric corrosion classification [1]. GCC-specific modifiers were then added because UV radiation, dust abrasion and temporary flooding are not fully captured by the ISO 9223 decisive parameters.

Input group	How it was used	Coating relevance	Limitation
Temperature and UV	Screened as heat and photochemical stress modifiers.	Binder oxidation, chalking, colour/gloss loss, embrittlement and thermal cycling stress.	Steel surface temperature can exceed air temperature; exact values require site monitoring.
Relative humidity and TOW	Used to screen wetness duration and condensation potential.	Osmotic blistering, adhesion loss, underfilm corrosion and cure-window restrictions.	TOW is strongly affected by geometry, ventilation, drainage, night cooling and offshore/onshore microclimate.
Chloride deposition	Used as marine aerosol loading and ISO 9223 salinity screen.	Pitting, corrosion creep, blistering and	Local chloride fallout varies with distance from

		recontamination of blasted steel.	sea, wind direction, dust and washing frequency.
Industrial pollutants	Coded as medium/high from refinery and urban exposure context.	Acid condensate and accelerated underfilm attack, especially when combined with chlorides.	Requires local SO_2/NO_x monitoring for final design.
Dust and sand	Treated as a GCC modifier outside formal ISO 9223 classification.	Abrasive erosion, surface contamination, profile contamination and topcoat roughness increase.	Event frequency is site and season dependent.
Flooding / ponding	Treated as short-duration immersion risk for low points, edges and damaged areas.	Blistering, edge failure, holiday corrosion and delamination.	Risk is strongly controlled by drainage and detailing.

Table 2. Data treatment and coating relevance of the exposure inputs.

2.3 Screening confirmation and uncertainty control

The city ranking in this manuscript should be read as a screening envelope, not as certified atmospheric corrosivity for a specific project site. Screening was developed by triangulating: (i) published GCC and Arabian Gulf climate literature for warming and sea-surface temperature trends [10-12]; (ii) ISO 9223 parameters for temperature-humidity complex, sulfur dioxide and airborne salinity [1]; (iii) ISO 12944 and NORSOK offshore/coastal coating requirements [2-5]; and (iv) engineering judgement on local exposure drivers such as coastal proximity, offshore construction, refinery/industrial influence, dust loading and drainage/ponding risk. The chloride values are therefore presented as planning bands mapped to ISO salinity logic and marine-industrial exposure, not as measured chloride deposition for each city. For project use, they shall be replaced or calibrated using local chloride deposition gauges, Bresle testing trend data, corrosion coupons, exposure racks and station-calibrated meteorology.

Screening variable	Evidence basis used in this paper	Project verification required
Warming and maximum temperature	Published GCC climate studies, regional SST literature and consolidated draft values.	Check against national meteorological station data and project site steel-temperature monitoring.
Relative humidity and TOW	Engineering estimate from humidity/wetness tendency and marine/offshore exposure context.	Calculate TOW from site hourly RH/temperature records and verify by condensation/dew-point observations.
Chloride deposition	ISO 9223 salinity framework and marine aerosol screening bands based on coastal/offshore exposure ranking.	Measure chloride fallout at site, repeat Bresle tests after delays and compare with corrosion coupon/exposure rack results.
SO_2/pollutants	Qualitative medium/high coding based on refinery, LNG, industrial and urban exposure context.	Replace with local SO_2/NO_x monitoring and plant emission data where available.
Dust and flooding	Regional desert dust and short-duration flooding/ponding risk treated as GCC modifiers.	Confirm by site housekeeping records, rainfall drainage review, dust tape tests and post-weather inspection history.

Table 3. Source traceability and verification route for the screening variables.

2.4 Classification and mechanism mapping

The ISO 9223 corrosivity category was used as the base screen. The paper then adds four practical GCC modifiers that are important in service but do not by themselves define an ISO 9223 category: ultraviolet exposure, dust/sand abrasion, chloride recontamination after preparation and temporary flooding or ponding. Each modifier is linked to a likely coating failure mechanism and then to a specification control. This approach avoids forcing all GCC assets into a single universal paint system and instead links the coating architecture to the dominant failure route.

Climate stressor	Likely coating effect	Specification response	Suggested verification
Heat and UV	Oxidation, chalking, gloss loss and embrittlement.	Weatherable finish coat with HALS/UVA package; suitable binder crosslink density and colour/gloss requirements.	ISO 16474-3 or ASTM G154 plus gloss and colour retention criteria.
High TOW and humidity	Blistering, adhesion loss and underfilm corrosion.	Low-permeability epoxy barrier; suitable cure and DFT control.	Condensation/immersion testing, EIS where required and pull-off adhesion.
Chlorides	Corrosion creep at defects, pitting at holidays and salt recontamination after blasting.	Zinc-rich primer, high-build barrier, soluble salt control and re-test after delay or between coats when exposed.	ISO 8502-6/9 testing and cyclic corrosion exposure.
Dust and sand	Abrasive thinning, microcracking and surface contamination.	Abrasion-resistant topcoat/filler package and cleaning plan.	ASTM D4060 or ASTM D968 where specified.
SO_2 with chlorides	Acid condensate and accelerated underfilm attack.	Multilayer epoxy/fluoropolymer or polysiloxane system.	Cyclic corrosion rather than neutral salt spray alone.
Flooding and ponding	Temporary immersion, edge failure and delamination.	Drainage, stripe coating, edge retention and immersion-resistant epoxy.	Immersion/hydrostatic resistance and holiday control.

Table 4. Mechanism mapping from GCC stressors to coating specification controls.

3. Results

3.1 Exposure screening by city

The consolidated screening values show that the selected locations do not share one uniform exposure pattern. Kuwait City has the highest heat screen but lower wetness than Doha or Manama. Abu Dhabi shows severe heat and UV but a lower humidity and chloride screen than the most humid coastal locations. Doha and Manama are the most severe combined humidity-chloride-pollutant screens in the selected set. Dammam and Muscat sit between these groups and are best treated as high to very high marine-industrial exposures. The lower warming indicator used for Muscat should not be interpreted as low coating severity; Muscat still combines marine humidity, chloride exposure and wetting duration, so its coating risk remains closer to a marine-industrial pathway than to a dry inland desert pathway.

City	Warming indicator (°C/dec.)	Max. temp. (°C)	RH (%)	TOW (days/yr)	UV	Cl^- envelope ($mg/m^2/day$)	SO_2 load	Screen
Dammam	0.46	52.3	65	135	11	250-350	High	C4-C5
Abu Dhabi	0.42	51.0	60	120	12	200-280	Medium	C3-C4
Doha	0.44	51.7	80	200	11	300-400	High	C5
Kuwait City	0.47	53.8	55	105	12	230-310	Medium	C3-C4
Muscat	0.18	49.5	75	180	11	280-360	Medium	C4-C5
Manama	0.40	50.8	85	220	10	320-420	High	C5

Table 5. Consolidated GCC exposure-screening values used in the manuscript. Values are regional engineering envelopes and must be calibrated with local monitoring before project use.
Data interpretation note: The values represent relative planning inputs for coating specification logic. They are not a claim that one city has a single uniform corrosivity category. For example, Abu Dhabi can include inland, coastal, island and offshore microclimates with different exposure severity.

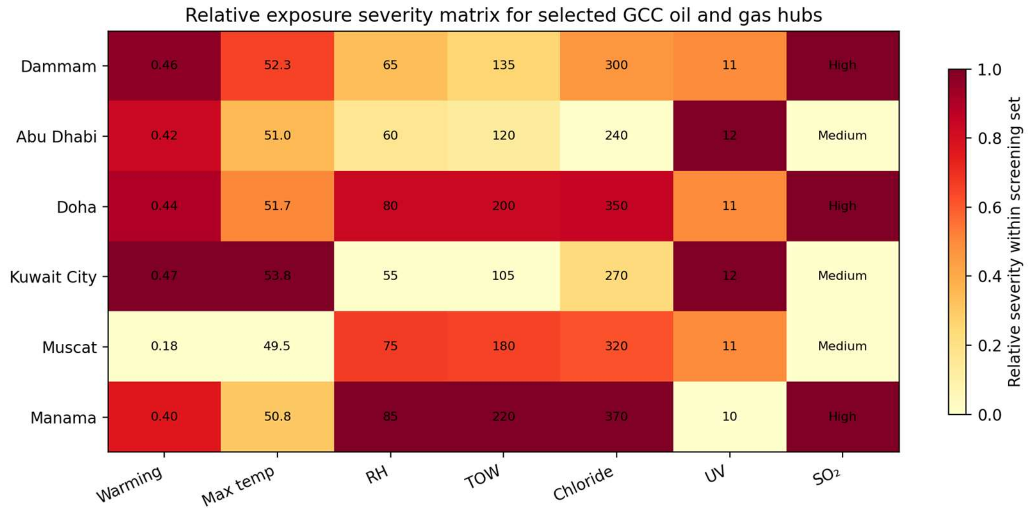

Fig. 2. Relative exposure severity matrix for selected GCC oil and gas hubs. Cell values are screening inputs only: °C/decade, °C, %, days/year, mg/m²/day, UV index and qualitative SO_2 coding. Values should be calibrated against local station data, chloride fallout measurements and project exposure evidence before specification use.

Technical note: This matrix is intended for coating selection logic, not as a replacement for ISO 9223 exposure testing, corrosion coupons, local chloride deposition monitoring or project specification requirements.

3.2 Humidity, wetness and chloride exposure

The most coating-relevant separation between the cities is the combined effect of wetness duration and chloride burden. A hot inland or semi-coastal site may drive chalking and thermal stress, while a humid coastal site drives blistering, underfilm corrosion and corrosion creep at defects. This distinction is important because the same coating system is often specified across different GCC environments even though the dominant failure route is different. It is also why TOW must be handled differently for dry onshore, coastal, offshore and splash-zone exposures.

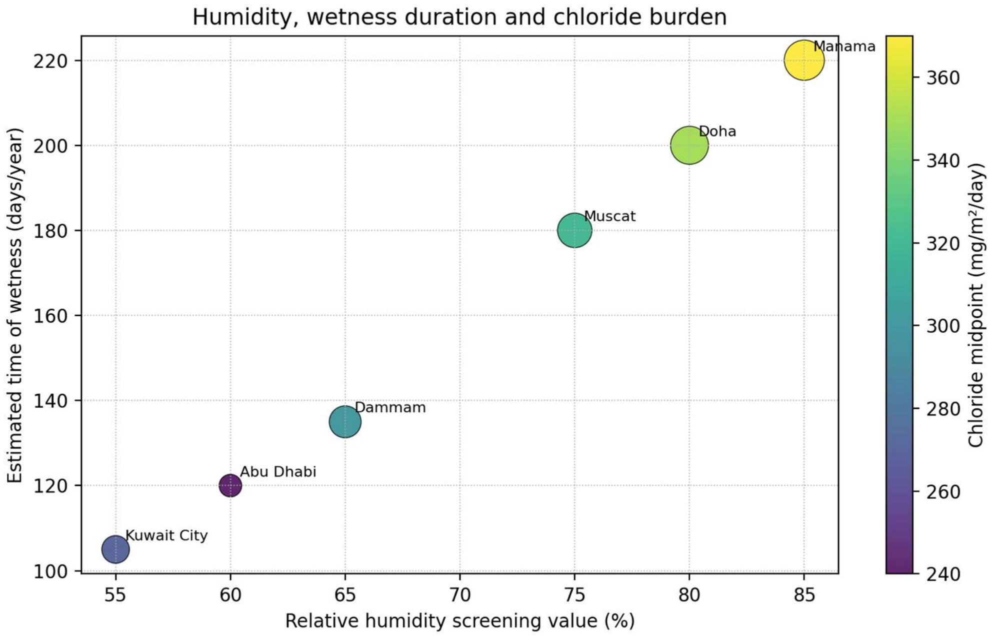

Fig. 3. Relationship between relative humidity, estimated time of wetness and chloride loading. Bubble size and colour represent the chloride midpoint value.

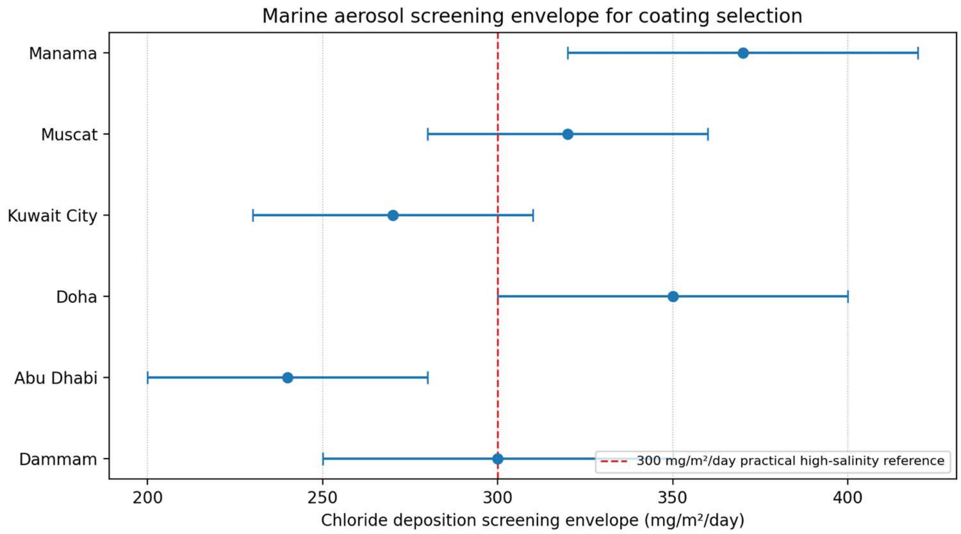

Fig. 4. Chloride deposition screening ranges for selected GCC locations, with the 300 mg/m²/day reference line shown as a practical high-salinity indicator. These ranges are screening bands derived from ISO 9223 salinity logic and GCC exposure judgement; they must be confirmed by site-specific chloride fallout monitoring before project use.

3.3 Coating architecture derived from exposure screen

The screening supports a layered specification approach rather than a single generic coating recommendation. Lower-wetness desert assets require UV and abrasion resistance first. Marine-industrial assets require stronger chloride resistance and barrier continuity. Offshore, splash-zone and shipyard structures require full system qualification for high salinity, cyclic wetting, mechanical damage, edges and access-related workmanship limitations.

Exposure screen	Typical GCC setting	Recommended architecture	Engineering rationale
C2-C3 with UV/dust modifier	Dry inland or desert assets.	Epoxy primer/barrier 120-160 µm plus aliphatic PU 60-80 µm.	Focus on chalking, thermal cycling and dust abrasion rather than wet corrosion alone.
C3-C4 industrial/coastal	Pipe racks, terminals and process units with moderate marine influence.	Zinc phosphate or epoxy primer, high-build epoxy intermediate and PU/polysiloxane finish.	Adds barrier thickness and chemical resistance for mixed pollutants and chlorides.
C4-C5 marine-industrial	Coastal terminals, jetties and humid refinery zones.	Zinc-rich primer 80-100 µm with specified zinc loading, epoxy MIO/glass-flake barrier 150-200 µm, polysiloxane or fluoropolymer finish 60-80 µm.	Combines sacrificial protection with lower permeability and stronger UV resistance.
C5-CX offshore/splash/shipyard	Offshore topsides, splash-zone structures and highly saline wet zones.	Inorganic or epoxy zinc-rich primer 90-110 µm with project-qualified zinc loading, reinforced epoxy 180-220 µm, UV-stable finish 70-90 µm.	Requires cyclic qualification, stripe coating, edge retention and tighter inspection hold points.

Table 6. Recommended coating architecture by GCC exposure screen.

Climate-adapted C5-CX coating architecture

For severe GCC marine/offshore atmospheric service, final coating selection requires project-specific qualification. Exposure severity drives layer selection, DFT control, surface cleanliness verification and cyclic performance qualification.

Key exposure driver	Coating relevance
UV + heat	photo-oxidation, chalking and thermal stress
Chloride aerosol	salt deposition and recontamination
Humidity + wetting	TOW, condensation and osmotic stress
Dust + sand	abrasion and surface contamination
SO_2 + chlorides	acid condensate and underfilm attack
Flooding / ponding	temporary immersion and edge failure

Layer	Component	Specification control
5	UV-stable finish coat	Aliphatic PU, polysiloxane or fluoropolymer-modified finish; HALS + UVA package; colour/gloss retention; optional anti-soiling finish. Key control: 70-90 μm DFT, or as qualified by project specification and manufacturer data.
4	High-build epoxy barrier	MIO or glass-flake reinforced epoxy barrier; low permeability; increased chloride path tortuosity; wetting and pollutant resistance. Key control: 180-220 μm DFT for severe marine/offshore atmospheric exposure, subject to qualification.
3	Zinc-rich primer	Inorganic zinc silicate or epoxy zinc-rich primer; sacrificial protection at defects, cut edges and mechanical damage. Key control: 75-100 μm DFT with project-qualified zinc loading and compatible overcoating window.
2	Prepared steel surface	Abrasive blast cleaning to Sa 2½-Sa 3 as specified; angular profile; dust, dew point and soluble salts verified before coating. Key control: ISO 8502-6/9 soluble salt testing; re-test after delay, high TOW exposure, dust event or suspected recontamination; stripe coat welds, bolts, edges and cut-outs.
1	Carbon steel substrate	Asset steelwork. Geometry, weld profile, drainage, edges, bolted details and access limitations control local coating risk. Key control: reduce water traps, sharp edges, coating holidays and inaccessible coating zones.

Fig. 5. Typical severe-service multilayer coating architecture for GCC C5-CX marine/offshore atmospheric exposure.

Architecture guidance only. Final DFT, resin chemistry, surface preparation, testing and acceptance criteria shall follow the project specification, NORSOK M-501 / ISO 12944-9 where applicable, coating manufacturer data sheet and project qualification report.

4. Discussion

4.1 Why atmosphere labels alone are not enough

A single C-category label is useful, but it can hide the true degradation pathway. Two sites may both be treated as C4 while having different coating risks: one may be dominated by UV and sand abrasion, while another may be dominated by chloride recontamination and condensation. In GCC practice, this distinction matters because surface preparation windows are short, airborne contamination can return quickly and topcoat weathering is severe.

The proposed framework therefore uses ISO categories as a base, then adds regional modifiers. This is more technically defensible than forcing every exposure into one universal coating system. It also helps inspectors and coating engineers explain why a system that performed acceptably in a temperate C4 environment may not deliver the same durability in a hot, dusty, chloride-rich GCC microclimate. The point is not that ISO 9223 is invalid; rather, dose-response classifications can underrepresent local extremes where high salinity, high temperature, complex wetting and pollutants act together. Similar limitations have been reported for subtropical high-salinity environments, which supports the need to treat GCC categories as a base screen that must be verified by local data and coating performance evidence [22].

4.2 Surface cleanliness and chloride recontamination risk in GCC coating works

Surface preparation remains the most important practical control. In marine and industrial GCC sites, blasted steel can be recontaminated by salt and dust during masking, access changes, ventilation interruptions, weather delays, scaffold modification, inspection waiting time or interruptions before primer application. Soluble salt testing by ISO 8502-6 and ISO 8502-9 should therefore be treated as a process control, not a one-time formality [6,7].

Many severe-duty project specifications use low soluble salt limits, commonly around 20mg/m²(2 µg/cm²) equivalent for critical marine, offshore or immersion-risk service. The low target is technically justified because residual chlorides and other ionic salts are hygroscopic. They attract moisture at the coating/steel interface, increase osmotic pressure, promote blistering, reduce adhesion and accelerate underfilm corrosion and rust creep from holidays, welds, edges and damaged areas. The concern is not the technical logic of low salts. The concern is whether a fixed historical limit can be consistently achieved and maintained under current GCC site conditions without additional climate-specific controls.

NORSOK M-501 remains an important benchmark for offshore coating quality, but many project specifications derived from NORSOK-type practice were written for a controlled offshore construction philosophy and are often applied globally. GCC climate conditions add a more aggressive recontamination pathway: high airborne chloride fallout, high dust loading, extreme steel temperature, humid night cycles and sudden rainfall or ponding. Under these conditions, the steel surface may pass a Bresle test immediately after cleaning and fail again after a short delay. For this reason, a single soluble salt result should not be considered permanent evidence of surface acceptability.

The practical recommendation is not to relax quality. The recommendation is to make the specification more technically honest. The default action for critical service should remain strict washing, abrasive cleaning, profile verification, soluble salt testing, dew point control, primer application within a controlled window and re-testing after significant delay or weather change. Where an applied primer or intermediate coat is exposed to chloride aerosol, dust, condensation, rain, blasting contamination, cleaning overspray or an exceeded overcoating interval, the surface shall be cleaned and re-tested before the next coat. In C5-CX and immersion-risk service, the ITP should make soluble salt re-checks mandatory before primer and conditional before each subsequent coat when exposure or delay creates a credible recontamination risk. If repeated attempts show that a 20 mg/m² target cannot be reliably maintained under documented site conditions, the project should not simply accept the higher value. It should move into a qualification route: select a primer or coating system that has been proven to perform at a defined residual salt level, document the allowed maximum, test it under realistic cyclic exposure, and obtain formal technical approval before use.

Surface cleanliness and chloride recontamination decision route

1. Prepare surface Wash / blast profile control	→	2. Test salts ISO 8502-6/9 record result	→	3. Check exposure Dust + chloride + TOW onshore/offshore delay risk	→	4. Decision Meets limit? prime or re-test
						↓
8. Feedback Defects, racks maintenance data	←	7. Hold points Salts, dew point DFT + cure re-test if exposed	←	6. Qualify system Cyclic tests at stated salt level manufacturer evidence + technical approval	←	5. If not met Re-clean or use qualified route

Fig. 6. Practical decision route for surface cleanliness, chloride recontamination, TOW exposure and coating-system qualification in GCC coating work.

Low soluble salt is preferred. Higher acceptance requires documented qualification evidence. Re-test after weather change, extended delay, dust exposure, masking delays, access interruptions, high-TOW overnight exposure, or contamination of primer/intermediate coats before overcoating.

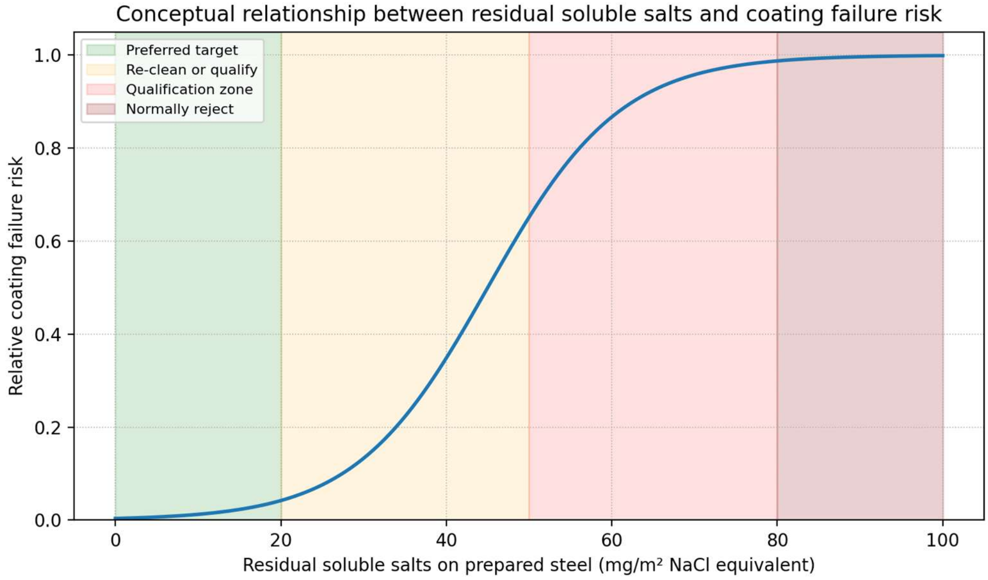

Fig. 7. Conceptual relationship between residual soluble salt level and coating failure risk. The curve is illustrative only; acceptance limits must be defined by the project specification, coating manufacturer data and qualification testing.

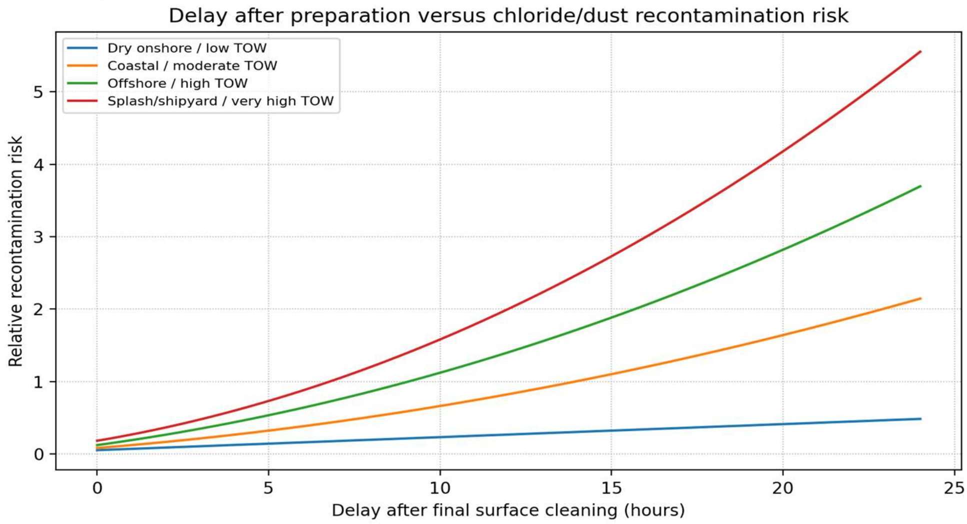

Fig. 8. Conceptual recontamination model showing why repeated soluble salt testing may be required when coating is delayed after preparation. Real values require site measurements and repeated Bresle testing. TOW and chloride fallout are expected to be higher offshore and in splash/shipyard conditions than in dry onshore service.

Measured soluble salts on prepared steel	Recommended action for critical GCC marine/offshore service	Technical justification
≤20 mg/m² NaCl equivalent, or lower project value	Accept only if visual cleanliness, profile, dew point, dust level and application window are also acceptable. Prime within the approved interval.	Represents the preferred low-risk target in many severe-duty specifications. Low salts reduce osmotic and underfilm corrosion risk.
>20 to 50 mg/m²	For critical offshore, splash or immersion-risk service, re-wash/re-blast and re-test. Consider conditional	This range may occur quickly in GCC field conditions. Acceptance without

	acceptance only if the project specification and manufacturer qualification allow it.	qualification transfers performance risk to the asset and the project risk register.
>50 to 80 mg/m²	Do not accept by default. Use only where a surface-tolerant or chloride-tolerant primer has been qualified at the stated contamination level and where formal technical approval is recorded.	This is a qualification zone, not a workmanship relaxation. Cyclic corrosion, adhesion, blistering and rust-creep performance must be demonstrated; published soluble-salt studies have shown why residual NaCl level can change epoxy coating performance and should be treated as a qualification variable rather than a universal field waiver [26].
>80 mg/m²	Reject for critical service unless a special engineered repair procedure is supported by coating manufacturer evidence and formally approved through the project technical route. Re-cleaning is normally required.	High ionic contamination creates strong risk of osmotic blistering, adhesion loss and rapid creep from defects.

Table 7. Proposed surface cleanliness acceptance logic for GCC coating specifications. Values are NaCl equivalent by ISO 8502-6/9 or as defined by the project specification.

4.3 Qualification testing should match the exposure

Neutral salt spray testing is easy to understand, but it is too narrow to represent the full GCC stress field. Severe GCC coating qualification should combine cyclic salt, UV/condensation, wet/dry exposure, abrasion and immersion resistance as applicable. ISO 12944-9 gives a more relevant direction for offshore and related structures because it addresses CX offshore and Im4 exposure with laboratory performance requirements [4]. ISO 20340 remains a familiar reference in many older project documents, although ISO 12944-9 is now the main route for offshore-related protective paint performance in the ISO 12944 series [8].

For offshore and coastal service, cyclic testing should be paired with rust-creep, blistering and adhesion acceptance criteria. For desert assets, weathering and abrasion resistance deserve more attention. For sites exposed to flooding or poor drainage, immersion resistance, holiday detection and edge protection become critical. The test schedule should follow the expected failure route at the asset, not a generic checklist. Where a product is proposed for a higher residual salt acceptance value, the product/system should be tested at that stated contamination level, not only at a generic clean-surface condition. Retesting is also required when the resin chemistry, primer, DFT range, surface preparation grade, curing condition or service environment differs from the original qualification evidence.

4.4 Formulation implications

The formulation logic is straightforward. Heat and UV require weatherable binders and stabilizer packages because polymer degradation reduces elongation, increases brittleness and accelerates chalking or gloss loss [23]. Chlorides require sacrificial protection at defects and low-permeability barrier coats. Humidity and wetness require resistance to osmotic blistering and adhesion loss. Dust requires a durable, cleanable and abrasion-resistant outer surface; solid-particle erosion literature shows that coating response depends strongly on coating thickness, ductility, filler reinforcement, impact angle and abrasive loading [24,25]. Flooding and ponding require edge protection, drainage, holiday control and temporary immersion resistance.

For this reason, the most robust severe-service architecture is usually a zinc-rich primer, a high-build epoxy barrier reinforced with MIO or glass flake, and a UV-stable finish coat such as aliphatic polyurethane, polysiloxane or fluoropolymer-modified polyurethane. The exact DFT, resin chemistry and test requirements should be selected with the coating manufacturer and project specification. Thickness alone does not prove durability. Performance must be demonstrated by relevant test evidence and controlled by the ITP during application.

4.5 Practical implementation framework

The implementation workflow in Fig. 9 is intended for specification writers, coating inspectors and asset integrity teams. It connects climate data, field surface condition, coating selection, qualification testing, application control and inspection feedback. This closes the gap between discussing climate risk in general terms and controlling coating work at site level.

1 CLASSIFY EXPOSURE ISO 9223 / ISO 12944 + GCC climate modifiers	→	2 SURVEY SURFACE Soluble salts, dust, profile, existing condition and TOW risk	→	3 SELECT SYSTEM Primer + barrier + finish coat matched to risk
				↓
4 QUALIFY SYSTEM Cyclic corrosion, UV, abrasion, immersion where required	←	5 CONTROL APPLICATION ITP hold points, dew point, DFT, cure and salt re-testing	←	6 INSPECT AND IMPROVE Defect trends, maintenance data, exposure rack feedback

Every selection decision should be tied to surface condition, qualification testing, application controls and inspection evidence.

Fig. 9. Practical workflow for climate-adapted coating specification, application and inspection in GCC service.

5. GCC-specific coating guidance

5.1 Marine and offshore environments

For offshore and coastal assets exposed to high salinity, cyclic wetting/drying and tidal or splash exposure, the preferred system is a zinc-rich primer, a reinforced high-build epoxy barrier and a UV-stable finish coat. The primer may be inorganic zinc silicate or epoxy zinc-rich, depending on project system and application conditions. Zinc loading, surface preparation and overcoating windows must follow the product data sheet and qualification report. The barrier coat should use MIO, glass flake or other lamellar reinforcement where low permeability and chloride path tortuosity are required. The finish coat should be a weatherable aliphatic polyurethane, polysiloxane or fluoropolymer-modified polyurethane where long-term gloss and colour retention are required.

In C5-CX exposure, stripe coating of welds, edges, cut-outs, bolts and difficult geometry should be mandatory. Edge retention, DFT distribution, cure, holiday detection and repair verification are as important as the selected resin. Where the coating is expected to experience temporary immersion or splash-zone wetting, qualification should include cyclic corrosion, immersion resistance and adhesion testing rather than relying only on dry atmospheric performance.

5.2 Desert and onshore facilities

Onshore desert assets in Kuwait, Abu Dhabi and inland GCC facilities experience extreme UV, thermal cycling and abrasive dust exposure. A high-build epoxy primer/barrier reinforced with lamellar pigments, overcoated with a UV-stabilized aliphatic polyurethane or polysiloxane topcoat, is generally appropriate for non-immersion service. Low-surface-energy or anti-soiling topcoats can reduce dust retention and cleaning demand, but they should be assessed for repairability and overcoating compatibility. Abrasion resistance should be demonstrated where sand impact is a credible damage mode.

5.3 Industrial hubs and refining complexes

Industrial hubs such as Dammam, Doha LNG areas and refinery zones face mixed marine chloride and SO_2/NO_x influence. This combination can create acidic condensates and accelerate underfilm attack. A multilayer system with a zinc-rich or inhibitive primer, high-build epoxy barrier and weatherable fluoropolymer, polysiloxane or polyurethane finish is more defensible than a simple decorative system. Qualification should include cyclic corrosion or wet/dry exposure that better represents chloride-pollutant synergy than static salt fog alone.

5.4 Surface-tolerant and chloride-tolerant primers

Advanced surface-tolerant primers, including epoxy phenalkamine, moisture-cured urethane and selected high-solids epoxy technologies, can help manage unavoidable field constraints, but they must not be used as a substitute for poor cleaning. Their use is justified only when the product has evidence of adhesion and corrosion resistance at the specified residual salt level and when the service environment is compatible with the primer chemistry. A claim that a primer is surface-tolerant is not enough. The qualification report should state the surface condition, residual salt level, exposure cycle, DFT, cure condition, acceptance criteria and failure mode.

6. Standards and testing recommendations

The effective specification of protective coating systems in the GCC should be anchored to recognized standards but extended by regional performance controls. ISO 9223 should remain the atmospheric corrosivity base screen. ISO 12944 should be used for protective paint system selection, durability and laboratory performance requirements. ISO 12944-9 is particularly relevant for offshore and related structures exposed to CX and Im4 environments [4]. NORSOK M-501 remains a key oil and gas reference for surface protection and protective coatings in offshore and coastal facilities [5]. ISO 8502-6 and ISO 8502-9 should be used to extract and quantify water-soluble salts on prepared steel surfaces [6,7].

Performance issue	Preferred test / control	Suggested acceptance logic
Soluble salts and recontamination	ISO 8502-6 and ISO 8502-9; repeat testing before primer, after delay/weather change and before subsequent coats when the previous coat has been exposed to contamination risk.	Meet project limit, commonly around 20 mg/m² for critical service, or use qualified higher limit only with technical approval supported by manufacturer evidence.
Offshore cyclic corrosion	ISO 12944-9; ISO 20340 where still specified; ASTM G85 A5 as supplementary cyclic exposure.	No unacceptable blistering; controlled rust creep; adhesion retained to project criteria.
UV/weathering	ISO 16474-3 or ASTM G154.	Gloss retention, colour change and chalking limits defined in specification.
Abrasion by dust/sand	ASTM D4060 Taber Abrasion; ASTM D968 Falling Sand.	Mass loss or film loss limit defined according to service severity.
Condensation and wetness	ISO 6270-2 or equivalent cyclic condensation testing.	No blistering or adhesion failure after specified exposure.
Immersion/ponding	ISO 2812-2 or project-specific hydrostatic/immersion testing.	No blistering, softening, delamination or unacceptable adhesion loss.
Film build and edge protection	ISO 19840 DFT measurement; stripe-coat hold points; edge retention checks.	DFT distribution and edge coverage to project acceptance criteria.

Table 8. Recommended testing and inspection controls for GCC climate-adapted coating specifications.

7. Limitations

- The exposure values are engineering screening inputs consolidated from draft manuscript data and available climate evidence. They are not a complete raw meteorological or chloride-fallout database.
- The corrosivity categories are engineering estimates. High-criticality projects should verify them with first-year corrosion coupons, local exposure racks, station-calibrated climate data and site chloride deposition monitoring.
- The proposed coating systems are architecture-level guidance. Final selection must consider substrate condition, operating temperature, immersion exposure, fireproofing/CUI interface, safety class, product data sheets, manufacturer qualification, project specifications and the ITP.

- Proposed residual salt ranges are not universal acceptance criteria. They are a specification logic for qualification. A higher residual salt level should only be accepted when the coating system is proven at that value and the risk basis is formally accepted.
- The paper focuses on atmospheric and marine/offshore external coating exposure. Internal corrosion, CUI, chemical immersion, tank lining, passive fire protection and thermal insulation systems require separate service-specific analysis.

8. Conclusions

Protective & marine coating performance in the GCC should be treated as a combined climate-corrosion and construction-control challenge. In these environments, coating failure is not driven by one factor alone. High temperature, ultraviolet radiation, airborne chlorides, humidity, dust deposition, pollutants, condensation and temporary flooding can act together and increase the risk of premature coating breakdown. These conditions become more critical when there are delays between abrasive blasting and primer application, because the freshly prepared steel surface can be rapidly recontaminated by soluble salts, dust and moisture before coating application.

The main field concern is the presence and re-deposition of water-soluble salts on the prepared substrate. Low soluble salt limits, including values around 20 mg/m² NaCl equivalent used in many severe-duty and offshore specifications, remain technically desirable because soluble salts can promote osmotic blistering, underfilm corrosion, adhesion loss and rust creep. However, in GCC marine-industrial climates, maintaining these low values consistently is difficult when there are application delays, inspection hold points, access limitations, high humidity, chloride fallout, dust storms or night-time condensation. As a result, surface cleanliness control must be considered a critical part of the coating design, not only a pre-application inspection item.

ISO 9223, ISO 12944 and NORSOK M-501 remain the correct technical foundation for coating selection, surface preparation, application and inspection. However, GCC project specifications should not simply apply these standards in a generic manner. They should include additional regional controls for high UV exposure, dust abrasion, chloride recontamination, time of wetness, condensation risk and temporary flooding or ponding. Without these controls, a coating system may comply with the written standard but still remain vulnerable to the actual service and application conditions experienced in the region.

For C4 to CX marine, offshore and coastal industrial exposure, the preferred coating system should be based on a robust multi-coat architecture. This normally includes a zinc-rich primer, a high-build epoxy barrier coat, and a UV-stable polyurethane, polysiloxane or fluoropolymer finish coat. Where required, the epoxy barrier layer should be reinforced with micaceous iron oxide or glass flake to improve barrier resistance, reduce permeability and limit underfilm corrosion. However, the coating system should not be selected only by generic exposure category. It should also be assessed against the expected level of surface contamination risk, coating delay risk, temperature exposure and wet-dry cycling.

Future GCC specifications should not resolve this issue by simply relaxing soluble salt acceptance limits. The correct approach is to adopt a climate-adapted coating specification. Strict surface cleaning and low salt targets should remain the first requirement. If delays occur after blasting, soluble salt testing should be repeated before primer application. If chloride, dust or condensation exposure occurs between coats, additional surface checks and cleaning should be required. Higher residual salt acceptance should only be permitted when the selected primer or coating system has been specifically qualified for that defined contamination level through cyclic corrosion testing, adhesion testing, blistering assessment and rust-creep evaluation.

In conclusion, coating systems for GCC assets should be selected and specified according to both the international standards and the actual regional exposure conditions. The paint system must be capable of tolerating the practical risks created by high temperature, chloride recontamination, dust, humidity and application delays, while the project specification must still enforce strict cleaning, testing and coating window controls. This standards-plus-environment approach provides a more reliable basis for long-term corrosion protection, reduces premature coating failure and supports better asset integrity management for offshore, marine and industrial structures in the GCC.

Declaration of competing interest

The author declares no competing interest related to the preparation of this manuscript.

Data availability

The figures and tables are based on exposure-screening values consolidated from the manuscript draft data and interpreted against public climate, marine and standards references. Project use requires verification against local station data, site surveys, exposure racks, corrosion coupons, coating manufacturer qualification and project specifications. The screening values are not direct measured corrosivity results for each city and should not be used as final project acceptance criteria without site calibration.

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