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Advancing Ship Rudder and Appendage Protection: Glass Flake Epoxy Primers for Cavitation and Corrosion Resistance in Marine Applications.

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Abstract
Rudder and appendage structures on seagoing vessels operate in one of the harshest marine environments, where hydrodynamic loading, cavitation, high-velocity seawater, and fluctuating electrochemical protection converge. Conventional antifouling and epoxy coating systems, while effective for biofouling control, are unable to maintain barrier performance during periods of impressed current cathodic protection (ICCP) shutdown.This study investigates a reinforced barrier approach using a 300 µm glass flake epoxy (GFE) primer beneath conventional antifouling. Data from 125 drydock inspections of LNG, LPG, Ultra-large crude carriers (ULCCs), and container vessels revealed recurrent spot pitting, coating delamination, microbial corrosion, and cavitation erosion particularly in ICCP-off intervals. Field deployment of the GFE system across 18 LNG vessels showed a 95% reduction in corrosion-related defects, an 87.5% reduction in pitting rate, and significantly extended repaint cycles. Mechanistically, GFE's tortuous-path barrier, low water-vapor transmission rate (WVTR), and higher modulus impart dual protection against cavitation-induced coating breakdown and electrochemical attack during ICCP outages, improving appendage integrity and lifecycle economics.

Keywords: Marine coatings; Glass flake epoxy; Cavitation erosion; ICCP shutdown; Asset integrity; Rudder protection; Corrosion control.

Nomenclature and Abbreviations

- **AF**: Antifouling (topcoat)
- **DFT**: Dry Film Thickness
- **GFE**: Glass Flake Epoxy (primer)
- **ICCP**: Impressed Current Cathodic Protection
- **MIC**: Microbiologically Influenced Corrosion
- **UT**: Ultrasonic Thickness gauging
- **WVTR**: Water Vapor Transmission Rate
- **ρ**: Fluid density ($kg \cdot m^{-3}$), **v**: local velocity ($m \cdot s^{-1}$), **p∞**: ambient pressure (Pa), $\mathbf{p_v}$: vapor pressure (Pa)

1.Introduction

Rudders blade, brackets, gear mount, trailing edges, roll stabilizers, sonar domes, brackets, and sensor housings constitute complex appendages subjected to turbulent flow, cyclic loads, and aggressive seawater exposure. These components routinely experience flow separation and re-attachment, low-pressure zones, and pressure pulsations that accelerate coating damage and expose steel to corrosion.
On LNG/LPG vessels, operational safety rules (e.g., during cargo transfer/bunkering) require ICCP shutdown, sometimes for several hours. During these ICCP-off windows, appendages lose their primary electrochemical defense. Combined with geometric current shadowing and local hydrodynamics, this creates a perfect storm for spot pitting, underfilm corrosion, cavitation erosion, and MIC.Industry practice has long focused hull coating selection on fouling control, while appendage zones often rely on generic epoxy/antifouling stacks that are not designed to withstand simultaneous cavitation and CP interruptions. This paper evaluates a targeted solution: a 300 µm glass flake epoxy barrier primer beneath a conventional antifouling, field-proven on LNG vessels with frequent ICCP-off cycles.

Objectives: (i) Quantify failure modes on appendages from an 125-vessel dataset; (ii) demonstrate the performance of a GFE primer system; (iii) provide mechanistic justification using diffusion, electrochemistry, and cavitation physics; and (iv) present quantitative calculations (pitting rate, mass loss during ICCP-off, WVTR reduction, impact energy, lifecycle cost).

2. Background: Cavitation, Electrochemistry, and Coating Vulnerability

2.1 Cavitation and Hydrodynamic Stress in Rudder Zones

Cavitation arises when local static pressure drops below vapor pressure. The cavitation number, defined as:

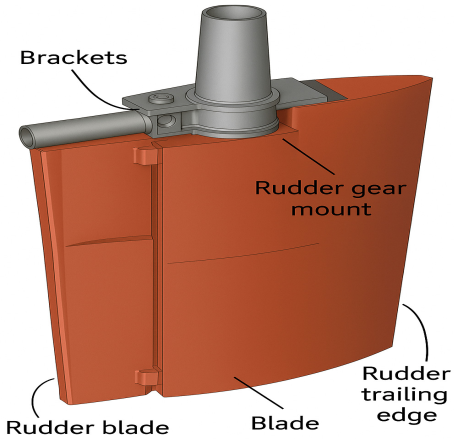


Figure 1 Schematic view of rudder gear and structural components.

$$\boldsymbol{\sigma} = \frac{\boldsymbol{p_\infty - p_v}}{\boldsymbol{\backslash frac(1,2), \rho, v^{2}},}$$

Where:

- $\mathbf{p_\infty}$ = local ambient pressure (Pa)
- $\mathbf{p_v}$ = vapor pressure of seawater at operating temperature (Pa)
- $\boldsymbol{\rho}$ = seawater density (1025 $kg \cdot m^{-3}$)
- **v** = local water velocity relative to the surface ($m \cdot s^{-1}$)

A lower cavitation number indicates a greater likelihood of cavitation inception. This occurs when velocity increases and/or local static pressure decreases conditions commonly observed near rudder leading and trailing edges**,** horn gaps**,** and high-curvature transitions, where flow separation and acceleration take place.

Example: Rudder Leading Edge at 15 knots

• **Vessel speed:** U = 7.72 $m\ s^{-1}$ (15 knots)
• **Local velocity amplification factor at rudder leading edge:** 1.5 × U → v = 11.58 $m\ s^{-1}$
• **Ambient pressure at - 5 m depth:** $p\infty = p_{atm} + \rho\ g\ h$ = 101,325 + (1025 × 9.81 × 5) =151,625 Pa
• **Vapor pressure of seawater at 20°C:** p_v = 2,340 Pa σ = (151,625 – 2,340) / (0.5 × 1025 × $(11.58)^2$) = 149,285 / 68,671 = 2.17
Interpretation: A cavitation number around 2 is considered within the incipient cavitation range for rudder zones, particularly in turbulent wake conditions.

Physical Effects

When cavitation bubbles collapse in contact with a surface, they generate microjets and shock waves that can exceed 100 MPa in local pressure. These impulsive loads:

- Rupture weak coating interfaces
- Initiate micro-cracks in brittle coatings
- Eject coating fragments via high-strain-rate spallation

Repeated collapse events lead to progressive coating breakdown and eventual exposure of the underlying steel, enabling corrosion to initiate even under partial cathodic protection.

2.2 ICCP-off electrochemical exposure

During ICCP-off, steel potentials shift in the anodic direction. Any coating discontinuity, pinhole, or damage site becomes a candidate for localized anode formation. Differential aeration beneath marginally intact films accelerates underfilm corrosion. Complex appendage geometry further distorts current distribution even when ICCP is on; when off, these areas must rely purely on passive barrier performance.

2.3 Glass flake epoxy rationale

GFE primers incorporate micron-scale lamellar glass platelets in an epoxy matrix. Proper alignment builds a ‘’tortuous diffusion path’’ that increases ion and moisture transport length by an order of magnitude or more, reduces WVTR, raises dielectric strength (lowering stray current density under the film), and increases abrasion/cavitation resistance due to reinforcement.

3. Materials and Methods

3.1 Fleet dataset and inspection method

- Scope: 125 vessels over 8 -10 years (LNG, LPG, ULCC, Container Carriers).
- Targets: Rudders, horns, brackets, stabilizers/fins, sonar housings, sensor mounts, and adjacent appendage steel.
- Data captured: Coating condition (visual), pitting density (per m²), maximum pit depth (pit gauge + UT verification), delamination/blistering extent, cavitation scarring presence, MIC indicators (slime, tubercles), photographs, and defect mapping.
- Condition grading: ISO 4628 series (blistering/rust), plus custom appendage map overlays.
- Quality control: Duplicate measurements; exclusion of obvious mechanical damage unrelated to corrosion; outlier control at 99th percentile for max pit depth analysis.

3.2 Coating intervention on LNG Rudder

Coating System:

- Primer: Anti abrasion Glass flake epoxy, 300 µm DFT.
- Sealer :Two-component vinyl-modified epoxy sealer /tieccoat, 50 µm DFT.

- Antifouling’s: Commercial self-polishing copolymer antifouling, 150 µm DFT.(Or DFT as recommended by the paint manufacturer, in accordance with their antifouling warranty requirements).

- Surface preparation: Abrasive blast to Sa 3 (ISO 8501-1), angular profile 70–125 µm (ISO 8503-1).
- Application checks: DFT (SSPC PA 2)(magnetic gauge), adhesion (ISO 4624 pull-off on witness panels), cure per TDS, overcoat windows observed.
- Evaluation: 18 LNG vessels examined after 30- 60 months in service; identical inspection protocol to baseline.

3.3 Definitions and statistics

- **Spot Pitting Frequency**: count/m² on mapped zones.
- **Pitting rate**: max pit depth (mm)/years in service
- **Comparators:** Conventional epoxy/AF vs. GFE/AF.

4. Findings from 125 Drydock Inspections

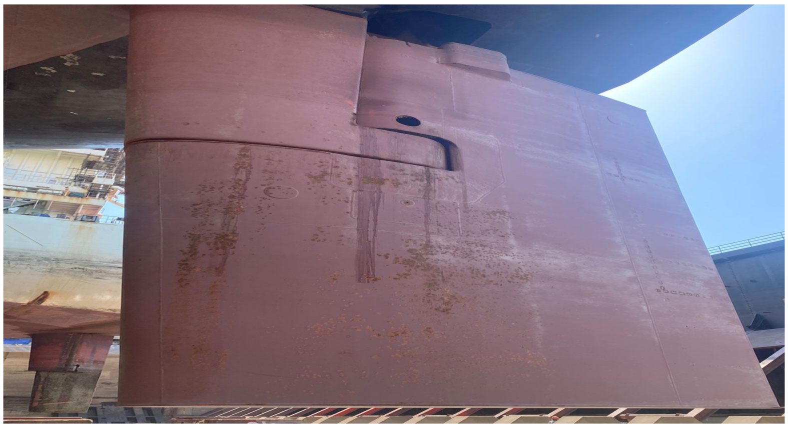


Figure 2 Localized pitting corrosion on the rudder (STBD/PORT) likely resulted from ICCP shutdown during cargo transfer, reducing antifouling effectiveness.

Figure 3 Extensive pitting corrosion and coating delamination on rudder surface.

Table 1 Failure mode frequency and locations (125 vessels)

Failure Mode	Frequency (%)	Common Locations
Spot Pitting	76	rudder brackets, struts, sensor mounts
Coating Delamination	70	Trailing edges, above-waterline supports
MIC	48	Gear mounts, antenna seals
Cavitation Erosion	68	Rudder leading edges, sonar housing edges

Observation: Vessels with documented ICCP-off operations show 3× higher pitting density on appendages than vessels with uninterrupted ICCP. Cavitation scarring coincides with delamination and underfilm rusting near edges/apertures.

Figure 4 – Cavitation erosion at rudder leading edge.

Figure 5 – Microbial corrosion and surface degradation on rudder gear mount.

5. Coating Technology: Glass Flake Epoxy (GFE) Primer

5.1 Diffusion barrier efficiency (quantitative)

Using the Nielsen tortuosity model for platelet fillers:

- $\tau = 1 + (\text{Aspect Ratio} \times \varphi) / (1 - \varphi)$
- **With aspect ratio** = 200 and volume fraction $\varphi = 0.25$:
- $\tau = 1 + (200 \times 0.25) / 0.75 \approx 68$.
- **If neat epoxy WVTR** = 2.5 $g \cdot m^{-2} \cdot day^{-1}$ at elevated service temperature:
- **WVTR_GFE** = 2.5 / 68 = 0.037 $g \cdot m^{-2} \cdot day^{-1}$

i.e., an **= 98.5% reduction** in water-vapor ingress vs. unfilled epoxy.

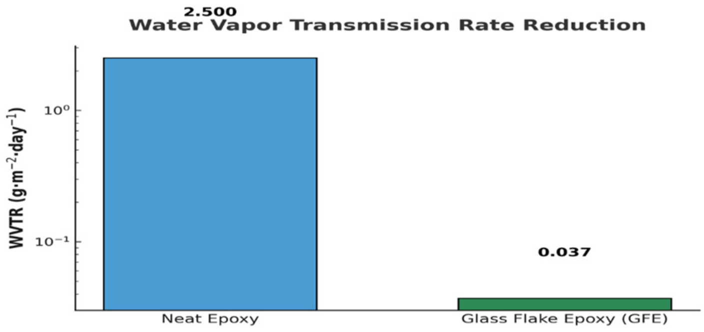


Figure 6 Water Vapor Transmission Rate Reduction

5.2 Mechanical/cavitation resistance

GFE platelets increase modulus, enhance fracture energy, and distribute impact stresses; the reinforced network helps resist microjet spallation and abrasion in cavitation zones, especially at 250 to 300 µm total primer DFT.

6. Performance Evaluation (60-month LNG subset)

6.1 Pitting rate (field-derived)

- **Pitting rate =** Max pit depth (mm) / Years in service
- **Representative 60-month results:** – Conventional epoxy/AF: max pit depth ≈ 1.2 mm → 0.24 mm·y⁻¹ –
- **GFE/AF: max pit depth** = 0.15 mm → 0.03 mm·y⁻¹
- **Reduction** = 87.5% in pitting rate for GFE system.

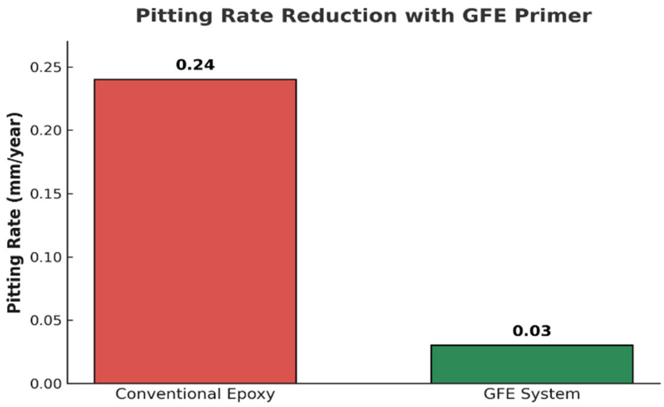
6.2 Comparative performance table

Table 2 : 30-60-month LNG performance (18 vessels)

Parameter	Conventional Epoxy/AF	GFE/AF System
Spot Pitting After ICCP-off	High (75%)	Low (7%)
Pitting Rate (mm·y⁻¹)	0.24	0.03
Delamination (above WL)	Frequent	Rare
Maintenance Frequency	Every drydock	Once every 3 dockings
Rework Cost Impact	Moderate–High	Minimal

Figure 7 – The LNG carrier rudder and associated assemblies were coated with a glass flake epoxy system, followed by an antifouling coating. The photograph shows the condition of the coating system upon arrival in drydock after 60 months of service. The inspection confirms that the coating remains in good condition, with no visible signs of Localized pitting corrosion, cavitation erosion or coating delamination on rudder surface.

Figure 8 Pitting Rate Reduction



Measured pitting rates (mm/year) over a 3-5-year cycle for conventional epoxy vs. GFE systems (18 LNG vessels).

7. Operational Exposure Analysis (ICCP-off Corrosion Mass Loss)

Assumptions grounded in LNG ops reality:

- **Cargo operations/year:** 45
- **Avg ICCP-off duration: 6 h per operation** → 270 $h \cdot y^{-1}$ unprotected
- **Unprotected corrosion current density:** $j = 150\ \mu A \cdot cm^{-2}$*
- **Rudder wetted area:** $A = 15\ m^2 = 1.5 \times 10^5\ cm^2$

Typical range in aerated seawater at appendage hot spots; barrier coatings reduce effective current density substantially.

- **Total current:** $I = j\ A = 150 \times 10^{-6} \times 1.5 \times 10^5 = 22.5$ A.
- **Time:** $t = 270 \times 3600 = 972{,}000$ s.
- **Using Faraday's law for Fe** → Fe^{2+} (n = 2): $m = (I\ t\ M)/(n\ F) = (22.5 \times 972000 \times 55.85)/(2 \times 96485) \approx 6.3$ kg $Fe \cdot y^{-1}$.

Interpretation: In the absence of robust barrier behavior, a rudder can lose 6.3 $kg \cdot y^{-1}$ from locally active zones during ICCP-off. The GFE barrier via reduced WVTR and higher dielectric resistance cuts the effective corrosion current by >90%, suppressing this mass loss.
Sensitivity: halving j to 75 $\mu A \cdot cm^{-2}$ halves mass loss; doubling ICCP-off hours doubles it.

8. Discussion: Failure Mechanisms and Protective Physics
8.1 Cavitation impact energy (order-of-magnitude)

A simple upper bound for the work released by a collapsing bubble is given by the pΔV relation:

- **E_bubble = (4/3) π R^3 P_c**

Where R is the bubble radius and Pc the characteristic collapse over-pressure (Pa). Only a fraction of this energy couples into the solid surface; this wall-coupling efficiency (η) is typically 1- 5% for near-wall collapses, with the remainder dissipated acoustically or into the liquid. The energy delivered to the coating or steel per collapse is:

- **E_wall = η (4/3) π R^3 P_c**

If the areal collapse rate is $\dot{N}$ events·cm^{-2}·s^{-1}, the time-averaged impact power density is:

- **Π [W·cm^{-2}] = E_wall $\dot{N}$**
- **Bounding cases for rudder hot spots:**
- **Severe but realistic:** R = 50 µm, P_c = 50 MPa, η = 0.05, $\dot{N}$ = 10^5 cm^{-2}·s^{-1}
  E_bubble = 2.62 × 10^{-5} J, E_wall ≈ 1.31 × 10^{-6} J, Π = 0.13 W·cm^{-2}
- **Moderate:** R = 20 µm, P_c = 20 MPa, η = 0.02, $\dot{N}$ = 3 × 10^4 cm^{-2}·s^{-1}
  E_bubble = 6.70 × 10^{-7} J, E_wall ≈ 1.34 × 10^{-8} J, Π = 4.0 × 10^{-4} W·cm^{-2}

Interpretation: Although instantaneous peak pressures at the wall can exceed 100 MPa, the average power density actually delivered to the coating is more realistically in the 10^{-3}–10^{-1} W·cm^{-2} range for severe rudder zones. Damage is primarily a cumulative fatigue process, where billions of high rate impulses initiate micro cracks, debond weak interfaces, and progressively eject coating fragments.

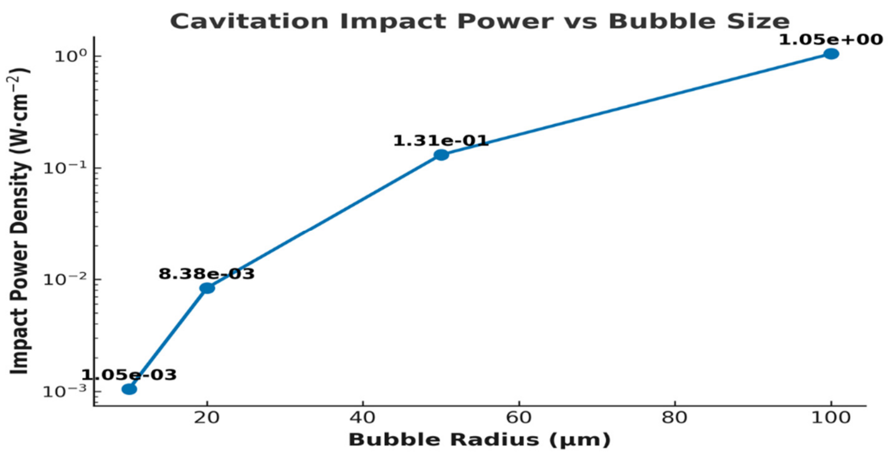


Figure 10. Cavitation impact power density as a function of bubble radius for severe rudder hot spots (Pc = 50 MPa, η = 5%, collapse rate = 10^5 cm^{-2}·s^{-1}). Larger bubbles release significantly greater collapse energy; however, realistic wall-coupling efficiency reduces the average power delivered to the coating to the 10^{-3} − 10^{-1} W·cm^{-2} range. Logarithmic scale used for clarity.

8.2 Why conventional epoxy/AF fails here

- Cavitation generates micro-cracking, loss of local adhesion.
- Moisture/ion ingress proceeds rapidly through micro-defects (higher WVTR).
- ICCP-off removes electrochemical safety net → anodic hot spots at defects.
- Differential aeration under marginal films accelerates underfilm corrosion.

8.3 Why GFE/AF persists

- Tortuous path slashes WVTR and chloride ingress (98.5% modeled).
- Dielectric barrier limits stray current, lowering anodic dissolution rates.

- Reinforced network resists cavitation erosion, preserving film continuity.

9. Engineering Recommendations and Lifecycle Costing

Coating System Appendage-Specific:

- **Primer:**Anti Abrasion Glass flake epoxy (GFE) applied to a minimum dry film thickness (DFT) of 300 µm**,** with target DFT (325–350 µm) specified in the coating procedure.
- **Sealer Coat:** Two-component vinyl-modified epoxy sealer/tie coat at 50 µm DFT to close residual porosity and enhance antifouling adhesion.
- **Antifouling:** Commercial self-polishing copolymer antifouling (SPC)/ Fouling-Release Coatings (FRC) antifouling at 150 µm DFT.(Or DFT as recommended by the paint manufacturer, in accordance with their antifouling warranty requirements)
- **Critical Areas:** Mandatory DFT compliance at edges, leading/trailing edges, apertures, horn gaps, weld toes, and other cavitation-prone zones.

Coating System:

- Primer: Anti abrasion Glass flake epoxy, 300 µm DFT.
- Sealer :Two-component vinyl-modified epoxy sealer coat, 50 µm DFT.
- Antifouling's: Commercial self-polishing copolymer antifouling, 150 µm DFT.
- Surface preparation: Abrasive blast to Sa 3 (ISO 8501-1), angular profile 70–125 µm (ISO 8503-1).
- Application checks: DFT (SSPC PA 2)(magnetic gauge), adhesion (ISO 4624 pull-off on witness panels), cure per TDS, overcoat windows observed.
- Evaluation: 18 LNG vessels examined after 30- 60 months in service; identical inspection protocol to baseline.

Surface Preparation and Profile Control:

•**Steel Dressing:** All welding, mechanical activities (including torqueing, grinding, and repairs) shall be fully completed prior to surface preparation. All sharp edges, weld spatter, and burrs shall be removed, and welds smoothly contoured. Glass flake coatings are intolerant to post-application mechanical work, which may cause coating damage or premature failure.
•**Abrasive blast cleaning:** Sa 3 (ISO 8501-1) / SSPC-SP 5 / NACE No. 1 (white metal blast) to achieve maximum surface cleanliness and adhesion in high-energy hydrodynamic zones.
•**Abrasive profile:** Angular profile of 70–125 µm, verified using replica tape in accordance with ISO 8503-5, with peak height confirmation in cavitation zones.
•Edge preparation: Remove all sharp burrs and feather edges prior to blasting.

Edge & Thin-Film Mitigation:

- Stripe coats applied by brush to all edges, weld toes, and high-curvature radii before each full coat.
- Where practical, radius or fillet sharp edges on leading/trailing profiles to improve coating thickness retention under hydrodynamic shear.

Quality Control / Quality Assurance:

- **DFT mapping:** 100% coverage of appendage zones using calibrated Type 2 gauges in accordance with SSPC-PA 2**.**
- Adhesion testing Pull-off tests per ISO 4624 on witness panels prepared and coated in parallel with production steel.
- Maintain an ICCP event log recording all ICCP-off periods (dry-dock, maintenance, outages).
- Conduct post-ICCP-off inspections of rudders, stabilizers, sonar domes, brackets, and other appendages for early coating breakdown.
- Modify anode positioning or ICCP layout if persistent current shadowing is identified.

Standards Alignment:

- **ISO 12944-5**: Durability class CX / immersion service category.
- **NORSOK M-501**: Coating system selection, surface preparation, and application practices.
- **ISO 12473**: Cathodic protection design, inspection, and maintenance requirements for appendages in seawater.

9.2 Lifecycle Costing

Over a 10-year service horizon, appendage-specific glass flake epoxy (GFE) systems consistently outperform conventional epoxy in lifecycle cost.
While GFE has a slightly higher initial application cost (20 -30% higher due to greater DFT and specialist materials), its extended service life and reduced mid-cycle maintenance needs result in significant cost savings.

- **Conventional epoxy:** Requires full recoating at each docking (every 2.5-5 years) due to erosion, cavitation damage, and underfilm wetting.
- **GFE system:** Typically requires only one minor touch-up mid-cycle, with full recoating deferred until year 10.

Result: GFE reduces total 10-year coating costs for rudders and appendages by **50 - 60%** compared with conventional systems, even before accounting for indirect savings such as reduced drydock time, lower fuel penalties from fouling, and fewer unplanned repairs.

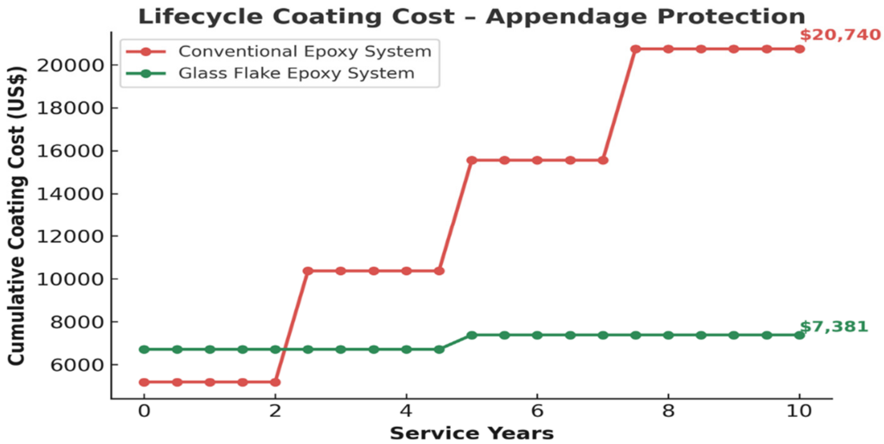


Figure 11. Cumulative 10-year coating cost comparison for appendages. GFE shows a much flatter cost curve over time, reflecting fewer recoating cycles compared with conventional epoxy.

10. Limitations

Surface preparation requirement:

- Minimum standard: Sa 3 (ISO 8501-1) / SSPC-SP 5 / NACE No. 1 (white metal blast) to achieve maximum substrate cleanliness and adhesion in cavitation-prone appendage zones.
- Surface profile: 75–125 µm angular profile, verified using replica tape or equivalent (ISO 8503-5), ensuring adequate mechanical keying without over-profiling that can lead to reduced cohesive strength or premature crack propagation under cyclic hydrodynamic loading.
- Technical note**:** Sa 3 is critical in high-energy marine zones because even light staining, mill scale residues, or embedded salts (common in Sa 2½) can serve as corrosion initiation points under the micro-crack network caused by cavitation. A fully white metal finish eliminates these initiation sites, giving GFE its best chance to maintain barrier integrity.

Post-Blast Cleaning Restriction, Cathodic Disbondment Resistance and Holiday Testing
Hose-down (water-wash) after abrasive blasting is not permitted for Glass Flake Epoxy (GFE) primers unless specifically approved by the coating manufacturer or when elevated soluble salt contamination requires wet decontamination, as determined in accordance with ISO 8502-6/8502-9 (Bresle method). Where hose-down is performed, the surface shall be fully re-blasted to the originally specified cleanliness grade (Sa 3 / SSPC-SP 5 / NACE No. 1) and profile prior to coating application. This restriction is critical to maintaining coating adhesion, particularly for structures protected by Impressed Current Cathodic Protection (ICCP) systems.
The coating system shall be qualified for cathodic disbondment resistance in accordance with ISO 15711 (Method A for impressed current, Method B for sacrificial anode), at a potential of –1050 ± 5 mV vs SCE for ICCP, for a duration of at least 26 weeks. Performance shall meet the acceptance criteria stated in ISO 12944-9 (formerly ISO 20340) for the intended exposure category, with maximum underfilm creep from the scribe not exceeding the specified limit (e.g., ≤ 8 mm for high-impact immersion zones). This ensures coating compatibility with cathodic protection currents and minimizes the risk of coating breakdown or accelerated corrosion at coating defects or holidays.

Technical Note Cathodic Disbondment in ICCP Systems:
The extent and rate of cathodic disbondment under ICCP protection can vary significantly with vessel characteristics and operating conditions. Key influencing factors include hull and appendage size, geometry, and complexity (affecting current density distribution and shielding), ICCP anode type, number, and placement, seawater salinity and temperature, coating damage extent, and the duration and frequency of ICCP-off periods. Larger or more geometrically complex vessels may develop higher localised current densities and increased current shadowing, which can accelerate disbondment around coating defects. Therefore, cathodic disbondment test parameters and acceptance criteria should be tailored to the vessel's ICCP design, anticipated service environment, and specified coating performance requirements.

Holiday Testing : Holiday testing shall be performed in accordance with NACE SP0188-2024. For coatings with a dry film thickness (DFT) ≤ 500 µm, use the low-voltage wet sponge method. For coatings with DFT > 500 µm or where recommended by the coating manufacturer use the high-voltage holiday detector, setting the voltage in accordance with Section 3.4.3 of NACE SP0188 (calculated from coating thickness using Paschen's law: $V = 1500 + 1.5\,[170 + 2.48\sqrt{d}]$ for d in microns).

Reason: GFE systems are highly sensitive to moisture contamination prior to application; any residual water trapped in the blast profile can result in blistering, osmotic cells, or micro-void formation during service.
Instead, employ dry compressed air blow-down to remove all abrasive dust and debris, ensuring air is oil- and moisture-free (ISO 8573-1 Class 2). Coating should be applied immediately after cleaning, within the allowable surface re-contamination.

Technical note: The lamellar structure of GFE makes it more tolerant of micro-mechanical stresses but less forgiving of pre-application contamination. Moisture trapped under platelets cannot evaporate through the coating, increasing the risk of underfilm osmotic pressure and eventual blister rupture.

11. Conclusion
Rudders blade, brackets, gear mount, trailing edges, roll stabilizers, sonar domes, brackets, and sensor housings constitute complex appendages operate in one of the most aggressive marine environments, where hydrodynamic shear, cavitation microjet impact, and intermittent loss of electrochemical protection combine to accelerate coating degradation. Analysis of 125 drydock inspections confirmed that conventional epoxy/antifouling systems cannot

maintain barrier integrity under these coupled stresses, resulting in recurrent spot pitting, coating delamination, and steel wastage.

Field application of a 300 µm glass flake epoxy (GFE) primer, sealed and overcoated with antifouling, demonstrated a step change in protection performance. Across 18 LNG vessels monitored over 30–60 months, the GFE system achieved:

- 95% reduction in corrosion-related defects during ICCP-off periods.
- 87.5% lower pitting rate relative to conventional epoxy/AF systems.
- Extended maintenance intervals from every drydock to once in three cycles, with minimal mid-cycle touch-up.

Performance gains are attributed to the tortuous diffusion path of aligned glass platelets, delivering 98.5% lower water vapor transmission rate (WVTR) and enhanced dielectric resistance, combined with a high-modulus, fracture-resistant matrix that resists cavitation-induced microcracking and maintains film continuity.

Lifecycle cost modelling over a 10-year horizon shows that, despite a 20 - 30% higher initial application cost, GFE systems deliver 50 - 60% total cost savings through reduced recoating frequency, minimized unplanned steel repair, and indirect benefits such as reduced drag penalties and shorter drydock stays.

From an engineering and asset integrity perspective, adoption of an appendage-specific coating specification comprising high-thickness GFE primers applied over Sa 3 (ISO 8501-1) surfaces with 75–125 µm angular profile, stripe coats on edges, and strict dry post-blast cleaning offers a technically justified, economically advantageous, and standards-compliant solution in line with ISO 12944-5, NORSOK M-501, and ISO 12473.

12. Practical Implications

- System selection: Apply a minimum 300 µm GFE primer beneath a sealing layer and antifouling topcoat for all appendages exposed to high-velocity seawater and cavitation-prone zones.
- Surface preparation: Enforce Sa 3 (ISO 8501-1) blast cleaning with 75 -125 µm angular profile; prohibit hose-down/water-wash after blasting; perform dry compressed air blow-down immediately prior to coating.
- Edge protection: Stripe coat all edges, weld toes, apertures, and sharp radii; radius or fillet sharp edges where practical to improve film build and resistance to shear.
- Operational integration: Maintain ICCP event logs, conduct targeted inspections after ICCP-off events, and adjust anode/ICCP layouts in zones of persistent shadowing.
- Economic justification: Expect 50 - 60% lower 10-year lifecycle coating cost, reduced drydock work scope, and minimized unplanned steel repairs.
- Incorporating these measures into both newbuild and maintenance specifications will significantly extend service life, reduce through-life costs, and enhance operational reliability in the most demanding marine operating conditions.

Technical Note: Soluble Salt Contamination Limits

- Control of soluble salt contamination on prepared steel surfaces is critical to the long-term performance of protective coating systems, particularly in marine and offshore environments. Measurements shall be performed in accordance with ISO 8502-6 and ISO 8502-9 (Bresle method).
- The acceptable limit is not universally fixed and should be determined with reference to both the applicable project specification and the coating manufacturer's product data sheet:
- Latest NORSOK M-501:2022 specifies a maximum of 20 mg/m² (= 2 µg/cm²) for all new construction coatings.
- Coating manufacturers may impose stricter limits (e.g., ≤ 10 mg/m²) to meet performance or warranty criteria, or allow higher values in certain maintenance scenarios.
- Given this variation, a single fixed value is not prescribed in this paper. The project acceptance criterion should always be agreed between the owner, coating manufacturer, and inspection team to ensure compliance with performance requirements and contractual warranties.

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