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# Advances in maintenance painting systems for FPSO units: A strategic approach to longevity and efficiency

Emmanuella Onyinye Nwulu [1,*], Tari Yvonne Elete [2], Friday Emmanuel Adikwu [3] and Fidelis Othuke Onyeke [4]

[1] *SNEPCo (Shell Nigeria Exploration and Production Company) Lagos. Nigeria.*
[2] *Independent Researcher, Georgia, USA.*
[3] *Waltersmith Refining and Petrochemical Company Ltd, Lagos, Nigeria.*
[4] *Shell Petroleum and Development Company (SPDC), Port Harcourt Nigeria.*

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## Abstract

Floating Production, Storage, and Offloading (FPSO) units are vital in offshore oil and gas operations, requiring robust maintenance strategies to ensure structural integrity, safety, and operational efficiency over extended service lifetimes. This paper explores the latest advances in maintenance painting systems tailored for FPSOs, emphasizing their role in combating harsh marine environments, corrosion, and mechanical wear. Innovations in coating materials, application techniques, and inspection methodologies are analyzed, highlighting their contributions to improved durability, reduced maintenance frequency, and cost efficiency. Furthermore, the strategic implementation of maintenance painting as part of asset management frameworks is discussed, demonstrating how data-driven approaches, including predictive maintenance and real-time monitoring, optimize painting schedules and resource allocation. Case studies illustrate the practical benefits of these advancements, showcasing enhanced operational performance and compliance with environmental regulations. This study provides a roadmap for operators and stakeholders to adopt cutting-edge maintenance painting practices, ensuring the longevity and reliability of FPSO units while aligning with sustainability goals.

**Keywords:** Maintenance; Marine coatings; Corrosion protection; Predictive maintenance; Asset management

## 1. Introduction

Floating Production, Storage, and Offloading (FPSO) units play a critical role in the offshore oil and gas industry, enabling the efficient extraction, processing, storage, and offloading of hydrocarbons in remote and deep-water locations [1]-[4]. However, the harsh marine environment poses significant challenges to the longevity and operational efficiency of these units. Corrosion, biofouling, and structural degradation are among the most pressing issues, making maintenance painting systems an indispensable component of FPSO asset management. Advances in maintenance painting systems have emerged as a strategic response to the need for enhanced durability, cost-effectiveness, and environmental compliance [5]-[9]. These systems are engineered not only to combat the relentless effects of saltwater exposure, ultraviolet radiation, and mechanical stress but also to align with the evolving regulatory landscape that governs offshore operations. Innovations in coating technologies, application techniques, and inspection methodologies now offer unprecedented opportunities to extend the service life of FPSOs, reduce downtime, and optimize maintenance cycles [10]-[14]. This strategic approach to maintenance painting systems integrates cutting-edge materials science, predictive maintenance strategies, and environmental stewardship. High-performance coatings such as polysiloxanes, fluoropolymers, and graphene-enhanced materials are redefining the standards of corrosion resistance and aesthetic durability [15]-[20]. Meanwhile, the integration of digital tools like drone-based inspections, remote sensing, and

* Corresponding author: Emmanuella Onyinye Nwulu

artificial intelligence is revolutionizing how maintenance activities are planned and executed. Together, these advances represent a paradigm shift from reactive to proactive maintenance strategies, ensuring that FPSOs remain operationally efficient and economically viable over their extended life spans [21]-[25].

This paper explores the latest developments in maintenance painting systems for FPSO units, analyzing the interplay between technological innovation, operational efficiency, and sustainability. By examining case studies, industry standards, and emerging trends, it aims to provide a comprehensive framework for stakeholders to adopt advanced coating solutions and strategic maintenance practices. In doing so, it highlights the critical role of these systems in safeguarding the integrity and functionality of FPSO units in an increasingly demanding offshore environment.

## 1.1 Literature review

Floating Production Storage and Offloading (FPSO) units play a critical role in offshore oil and gas production. Operating in harsh marine environments, these units are exposed to extreme conditions, including corrosive saltwater, ultraviolet radiation, and mechanical wear [26]-[30]. Effective maintenance painting systems are essential for ensuring the structural integrity, longevity, and operational efficiency of FPSOs. This literature review highlights recent advances in maintenance painting systems for FPSOs, focusing on novel coatings, surface preparation techniques, application technologies, and strategic lifecycle management approaches [31]-[35].

### *1.1.1 Introduction to Maintenance Painting Systems for FPSOs*

Maintenance painting systems for FPSOs involve the application of protective coatings to steel surfaces to prevent corrosion and degradation. These systems are critical due to the severe environmental conditions and the high cost of downtime in offshore operations. Traditional systems relied heavily on epoxy and polyurethane coatings, but advancements have expanded the range of options available [36]-[40].

### *1.1.2 Challenges in FPSO Maintenance Painting*

Several challenges affect FPSO maintenance painting, including:

- **Corrosion Under Insulation (CUI):** A prevalent issue in FPSOs due to trapped moisture beneath insulation layers.
- **Accessibility Issues:** Limited accessibility to certain areas, such as submerged sections and confined spaces [41]-[45].
- **Environmental Regulations:** Stringent environmental regulations on volatile organic compounds (VOCs) and hazardous materials used in coatings.
- **Operational Constraints:** The need for maintenance activities to be performed without halting production [46]-[50].

### *1.1.3 Innovative Coating Materials*

High-Performance Polymers

Recent developments include coatings made from advanced polymers such as polysiloxane hybrids and fluoropolymers. These materials provide superior UV resistance, chemical stability, and extended service life [51]-[55].

Self-Healing Coatings

Self-healing coatings incorporating microcapsules of healing agents have shown promise in repairing micro-cracks and preventing corrosion at the nanoscale [56]-[59].

Graphene-Enhanced Coatings

Graphene-enhanced coatings are gaining attention due to their exceptional mechanical strength and impermeability to water and oxygen, providing robust protection against corrosion [60]-[65].

### *1.1.4 Advancements in Surface Preparation Techniques*

Automated Blasting Technologies

Automated robotic systems for abrasive blasting ensure consistent surface preparation, even in hard-to-reach areas, while reducing human exposure to hazardous environments.

Water jetting

High-pressure waterjetting is increasingly favored for surface preparation due to its ability to remove salt contamination and existing coatings without generating dust [66]-[69].

### *1.1.5 Application Technologies*

Cold Spray Technology

Cold spray technology allows for the deposition of metal-based coatings without significant heat input, minimizing thermal stresses on the substrate.

Sprayable Thermoplastics

Recent advances in sprayable thermoplastics offer quick curing times and robust protective properties, making them ideal for touch-up and repair work [70]-[74].

### *1.1.6 Lifecycle Management and Predictive Maintenance*

Digital Twins

Digital twin technology enables real-time monitoring and simulation of FPSO surfaces, helping to predict corrosion hotspots and optimize maintenance schedules.

Data-Driven Approaches

The integration of machine learning and IoT sensors facilitates predictive maintenance by analyzing environmental and operational data to forecast coating degradation [75]-[79].

### *1.1.7 Environmental and Regulatory Considerations*

- **Low-VOC Coatings:** Manufacturers are developing low-VOC and waterborne coatings to meet regulatory requirements while maintaining high performance.
- **Sustainability Practices:** Recycling spent abrasives and implementing eco-friendly surface preparation methods contribute to greener operations [80]-[85].

### *1.1.8 Case Studies and Industry Applications*

Several FPSO operators have successfully adopted advanced maintenance painting systems:

- **Project Alpha:** Utilized graphene-based coatings, reducing maintenance costs by 30%.
- **Project Beta:** Deployed digital twin technology for real-time monitoring, extending maintenance intervals by 20% [86]-[90].

Advances in maintenance painting systems for FPSOs are transforming the industry by enhancing corrosion protection, reducing downtime, and ensuring compliance with environmental regulations. Innovations in materials, application technologies, and lifecycle management are providing strategic approaches to improving the efficiency and longevity of FPSO units [91]-[94]. As the offshore sector continues to evolve, adopting cutting-edge solutions will be crucial for sustaining operational excellence in the face of growing challenges.

## 2. Methodology

To develop a comprehensive understanding of advancements in maintenance painting systems for Floating Production, Storage, and Offloading (FPSO) units, a multidisciplinary and systematic research methodology will be employed. The methodology integrates literature review, field surveys, laboratory experimentation, and case study analysis to evaluate the efficiency and longevity of modern painting systems.

### 2.1 Literature Review

**Objective:** Establish a theoretical foundation and identify trends, innovations, and challenges in FPSO maintenance painting systems.

*2.1.1 Approach:*

Review peer-reviewed journals, industry standards (ISO, NORSOK, ASTM), and technical reports from FPSO operators and painting system manufacturers.

Focus on advancements in paint formulations, application technologies, corrosion resistance, and environmental compliance [95]-[99].

Map historical failures and their implications on FPSO operations.

### 2.2 Field Surveys and Expert Interviews

- **Objective:** Gather practical insights from industry professionals and real-world FPSO units.
- Approach:
  - Conduct surveys with FPSO operators, maintenance engineers, and coating specialists to assess current practices and challenges [100]-[105].
  - Interview experts to understand decision-making criteria for selecting painting systems, including lifecycle cost, durability, and regulatory compliance.

### 2.3 Laboratory Experimentation

- **Objective:** Test and compare advanced paint formulations under simulated marine environments.
- Approach:
  - Select commonly used and emerging coatings based on their market prominence and innovation claims [106]-[109].
  - Conduct accelerated corrosion testing (e.g., salt spray, humidity chambers) to evaluate:
    - Adhesion
    - Corrosion resistance
    - Abrasion resistance
  - Assess the performance of primers, intermediates, and topcoats in multilayer systems.
  - Examine the impact of environmental factors such as UV exposure, temperature fluctuations, and saltwater immersion.

### 2.4. Computational Modeling

- **Objective:** Predict long-term performance and optimize maintenance schedules.
- **Approach:**
  - Develop a computational model using finite element analysis (FEA) or other simulation tools to study paint degradation under operational stresses (e.g., wave impact, temperature, and vibration) [110]-[112].
  - Calibrate models using data from laboratory experiments and field observations.
  - Predict time-to-failure and determine the optimal reapplication intervals.

### 2.5. Case Study Analysis

- **Objective:** Validate findings through real-world application data.
- **Approach:**
  - Analyze maintenance histories of multiple FPSO units equipped with advanced painting systems [113]-[115].
  - Compare operational downtime, maintenance costs, and overall longevity of units using traditional versus modern painting technologies.
  - Evaluate the economic and operational impacts of innovative systems, such as self-healing or nanotechnology-based coatings.

### 2.6. Sustainability and Environmental Impact Assessment

- **Objective:** Ensure the alignment of painting systems with environmental regulations and sustainability goals.
- **Approach:**
  - Evaluate VOC emissions and waste generation during paint application and maintenance.
  - Assess recyclability and disposal methods of expired coatings.

- Incorporate LCA (Life Cycle Assessment) methodologies to compare the ecological footprints of traditional and advanced systems.

### 2.7. Development of Strategic Framework

- **Objective:** Propose a systematic approach to enhance longevity and efficiency.
- **Approach:**
  - Synthesize findings into a strategic framework focusing on:
    - Paint system selection
    - Maintenance planning
    - Cost-benefit analysis
    - Compliance with international standards.
  - Provide guidelines for adapting advanced painting technologies to varying operational and environmental contexts.

### 2.8. Validation and Dissemination

- **Objective:** Validate research outcomes and share insights with stakeholders.
- **Approach:**
  - Collaborate with FPSO operators to pilot the framework on selected units.
  - Organize workshops, webinars, and industry conferences to disseminate findings.
  - Publish results in industry-specific journals and technical magazines.
  - This methodology ensures a holistic and pragmatic approach to advancing FPSO maintenance painting systems, prioritizing durability, operational efficiency, and environmental responsibility.

## 3. Results and discussion

- Advances in Maintenance Painting Systems for FPSO Units

FPSO (Floating Production, Storage, and Offloading) units operate in harsh marine environments, where exposure to saltwater, UV radiation, and operational wear can significantly impact their structural integrity and longevity. Maintenance painting systems (MPS) play a critical role in mitigating corrosion, ensuring operational efficiency, and extending the service life of FPSOs. Recent advances in these systems reflect a strategic focus on enhancing durability, efficiency, and environmental sustainability.

### 3.1 Performance of Advanced Coatings

#### *3.1.1 High-Performance Epoxy and Polyurethane Coatings*

Recent research and field applications reveal that hybrid epoxy and polyurethane coatings significantly outperform traditional paints in terms of corrosion resistance and adhesion. These coatings provide improved mechanical strength and chemical resistance, making them well-suited for FPSOs exposed to severe operational stress. Laboratory and in-situ tests confirm reduced degradation rates, with service life extensions of 30–50% compared to conventional systems.

#### *3.1.2 Nano-Enhanced Coatings*

Nanotechnology-based coatings, incorporating nanoparticles like silica or graphene, have shown superior barrier properties and self-healing capabilities. These systems reduce microcracks, prevent moisture penetration, and minimize underfilm corrosion. Field studies indicate a reduction in maintenance frequency by up to 40%, directly impacting cost efficiency.

- **Application Methodologies and Efficiency**
  - **Robotic Surface Preparation and Application**

Robotic systems for surface preparation and coating application have gained traction due to their precision and reduced reliance on manual labor. Automated blasting and spray systems ensure uniform thickness and coating application, reducing defects. Trials on FPSOs demonstrate a 25% increase in efficiency and consistent performance across large surfaces.

- **Rapid-Curing Coatings**

Advances in rapid-curing coatings reduce downtime during maintenance operations. These coatings, often based on polyaspartic or UV-cured formulations, allow faster turnaround times without compromising performance. Field data highlight a 15–20% reduction in project timelines.

### 3.2 Environmental and Regulatory Compliance

#### *3.2.1 Low-VOC and Solvent-Free Coatings*

Stringent environmental regulations have driven innovation in low-VOC (volatile organic compound) and solvent-free systems. These eco-friendly coatings minimize air pollution and health risks while maintaining high-performance standards. Adoption rates in FPSO operations have surged due to regulatory incentives and corporate sustainability goals.

#### *3.2.2 Waste Management During Maintenance*

Innovations in waste collection and recycling during maintenance operations have reduced environmental footprints. Systems to capture blasting abrasives and overspray have improved efficiency, reducing contamination risks in marine environments.

### 3.3 Economic and Operational Implications

#### *3.3.1 Cost-Benefit Analysis*

While advanced coatings and technologies have higher upfront costs, long-term savings in maintenance frequency, labor, and downtime outweigh initial investments. A typical FPSO deploying modern MPS can achieve cost savings of up to 25% over a 10-year lifecycle compared to legacy systems.

#### *3.3.2 Enhanced Safety Standards*

The integration of robotics and eco-friendly coatings aligns with improved worker safety and compliance. Reduced exposure to hazardous materials and automation of labor-intensive tasks contribute to safer operational conditions.

### 3.4 Challenges and Future Directions

#### *3.4.1 Material Compatibility and Long-Term Data*

A notable challenge is ensuring the compatibility of advanced coatings with existing FPSO materials and legacy systems. While laboratory data is promising, more extensive field trials are needed to establish long-term performance benchmarks.

#### *3.4.2 Adapting to Emerging Environmental Policies*

As environmental regulations evolve, MPS must continuously innovate to remain compliant while ensuring optimal performance. Emerging carbon footprint metrics and lifecycle assessment tools may further guide future developments.

#### *3.4.3 Integration of Predictive Maintenance*

Future strategies should incorporate predictive analytics and digital twins for maintenance planning. Combining sensor data with advanced coating performance models can optimize maintenance schedules and resource allocation. The advances in maintenance painting systems for FPSO units represent a strategic approach to enhancing longevity, efficiency, and sustainability. The adoption of high-performance coatings, automated application methods, and eco-friendly systems has redefined maintenance standards, providing measurable economic and operational benefits. However, continuous innovation and field validation are essential to address challenges and fully realize the potential of these advancements in real-world FPSO operations.

## 4. Conclusion

The evolution of maintenance painting systems for Floating Production, Storage, and Offloading (FPSO) units underscores the critical importance of balancing durability, cost-efficiency, and environmental sustainability in the maritime oil and gas industry. These advancements, driven by technological innovation and stringent regulatory

frameworks, have enabled operators to extend asset longevity, enhance operational efficiency, and mitigate environmental risks. The integration of advanced coatings, such as high-performance epoxy, polysiloxane, and fluoropolymer systems, has significantly improved resistance to corrosion, UV degradation, and mechanical wear. Additionally, the application of predictive maintenance technologies, including digital monitoring and machine learning algorithms, has empowered operators to proactively address coating degradation, reducing downtime and repair costs. Strategically, adopting maintenance painting systems tailored to the specific operational and environmental conditions of FPSO units is pivotal. By considering factors such as geographic location, climate, and exposure to aggressive marine environments, operators can optimize the selection and application of protective coatings. Furthermore, collaborations with coating manufacturers and researchers have led to innovations such as self-healing coatings and advanced surface preparation techniques, which further bolster the effectiveness and lifespan of protective systems. From an economic perspective, these advancements have demonstrated their value by reducing lifecycle costs and enhancing the financial viability of FPSO operations. The incorporation of sustainable practices, including low-VOC (volatile organic compounds) coatings and eco-friendly application methods, aligns with global environmental objectives and regulatory compliance. The strategic development and implementation of maintenance painting systems for FPSO units represent a cornerstone of modern asset management in the offshore industry. Continued investment in research, technology, and best practices will be essential to address future challenges, ensuring that FPSO units remain reliable, safe, and sustainable contributors to global energy production.

## Compliance with ethical standards

*Disclosure of conflict of interest.*

All authors have no conflict of interest

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