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RESEARCH TITLE

Structural Assessment and Economic Feasibility of Rehabilitating Aging Fuel Storage Tanks in Coastal Environments: A Case Study in Port Sudan

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Abstract

This study assesses the structural integrity and economic feasibility of rehabilitating aging aboveground heavy fuel oil storage tanks operating in the highly corrosive coastal environment of Port Sudan. Focusing on a 40-year-old tank originally constructed according to API 650 standards, the research applies API 653-based evaluation criteria supported by non-destructive testing methods, including ultrasonic thickness measurement, magnetic flux leakage, phased array ultrasonic testing, and cathodic protection assessment. The findings indicate that while bottom plates and roof components are significantly affected by pitting, soil-side corrosion, and marine atmospheric degradation, most shell courses retain acceptable structural capacity. The study demonstrates that rehabilitation is technically and economically viable when shell integrity remains largely sound and repair costs do not exceed 60–70% of replacement cost. Recommended interventions include bottom replacement or double-bottom installation, marine-grade coating renewal, shell insert repairs, cathodic protection upgrades, and risk-based inspection. The research concludes that targeted rehabilitation can extend tank service life by 15–20 years at approximately 35–50% of new construction cost, while reducing downtime, environmental risk, and supply chain disruption.

Key Words: Aboveground storage tanks; structural integrity assessment; API 653; marine corrosion; rehabilitation feasibility.

عنوان البحث

التقييم الإنشائي والجدوى الاقتصادية لإعادة تأهيل خزانات الوقود القديمة في البيئات الساحلية: دراسة حالة في بورتسودان

المستخلص

تقيّم هذه الدراسة السلامة الإنشائية والجدوى الاقتصادية لإعادة تأهيل خزانات زيت الوقود الثقيل العلوية القديمة العاملة في البيئة الساحلية عالية التآكل بمدينة بورتسودان. وتركز الدراسة على خزان عمره 40 عامًا شُيّد أصلاً وفق معايير API 650، حيث تعتمد منهجية التقييم على معايير API 653 مدعومة بوسائل الفحص غير الإتلافي، بما في ذلك قياس السماكة بالموجات فوق الصوتية، وفحص تسرب الفيض المغناطيسي، والفحص بالموجات فوق الصوتية ذات المصفوفة المرحلية، وتقييم نظام الحماية الكاثودية. تشير النتائج إلى أن ألواح القاع ومكونات السقف تأثرت بشكل ملحوظ بالتنقر، والتآكل من جهة التربة، والتدهور الناتج عن الأجواء البحرية، في حين أن معظم صفوف جسم الخزان لا تزال تحتفظ بقدرة إنشائية مقبولة. وتوضح الدراسة أن إعادة التأهيل تُعد خيارًا ممكنًا فنيًا واقتصاديًا عندما تبقى سلامة جسم الخزان مقبولة إلى حد كبير، ولا تتجاوز تكاليف الإصلاح 60–70% من تكلفة الاستبدال الكامل. وتشمل التدخلات المقترحة استبدال القاع أو تركيب قاع مزدوج، وتجديد الطلاء المقاوم للبيئات البحرية، وإصلاح مواضع التآكل في جسم الخزان بصفائح إدخال، وتحديث الحماية الكاثودية، وتطبيق نظام فحص قائم على المخاطر. وتخلص الدراسة إلى أن إعادة التأهيل الموجّهة يمكن أن تمدد العمر التشغيلي للخزان لمدة 15–20 عامًا بتكلفة تقارب 35–50% من تكلفة إنشاء خزان جديد، مع تقليل فترات التوقف، والمخاطر البيئية، واضطرابات سلسلة الإمداد.

الكلمات المفتاحية: تقييم السلامة الإنشائية؛ معيار API 653 ؛ التآكل البحري؛ جدوى إعادة التأهيل.

1. Introduction

The global petroleum storage infrastructure is undergoing unprecedented stress as aging assets exceed their original design service lives while operating in increasingly corrosive and demanding environments. Aboveground storage tanks (ASTs), designed to the American Petroleum Institute (API) 650 standard, have historically provided reliable, cost-effective containment for crude oil, refined products, and heavy fuel oils (HFO). However, the convergence of extended operational lifespans, deferred maintenance, environmental degradation, and evolving safety regulations has necessitated a paradigm shift from reactive repair to proactive, code-compliant structural assessment and lifecycle management. In coastal industrial zones, where marine atmospheric conditions accelerate material degradation, the economic and operational consequences of tank failure extend far beyond asset replacement, encompassing environmental contamination, supply chain disruption, regulatory penalties, and public safety hazards.

Port Sudan, situated on the western shoreline of the Red Sea, serves as Sudan's principal maritime and petroleum logistics hub. The city's fuel storage facilities, constructed predominantly during the 1980s, have facilitated national energy distribution for over four decades. These facilities operate under extreme environmental stressors: persistent salt-laden winds, annual relative humidity averaging 65–85%, summer temperatures exceeding 45°C, and saline groundwater with high sulfate and chloride concentrations. Under these conditions, the protective integrity of steel storage tanks degrades at accelerated rates, particularly at critical stress-concentration zones such as shell-to-bottom joints, annular plates, roof seams, and foundation interfaces. The absence of modern inspection regimes, coupled with historical underinvestment in corrosion mitigation, has elevated the risk of structural compromise, leaks, and catastrophic failure.

This paper presents a comprehensive structural assessment and economic feasibility study for the rehabilitation of a 40-year-old HFO storage tank at a Port Sudan petroleum terminal. The target asset, originally designed and fabricated per API 650 (Welded Steel Tanks for Oil Storage), has reached a critical decision point: whether to pursue engineered rehabilitation in accordance with API 653 (Tank Inspection, Repair, Alteration, and Reconstruction) or to execute complete demolition and replacement. The study integrates advanced non-destructive testing (NDT) methodologies, corrosion mechanism analysis, code-compliant remaining thickness calculations, and a rigorous cost-benefit framework anchored in the industry-recognized 60% rule. By contextualizing technical assessment within Port Sudan's marine environment, logistical constraints, and operational continuity requirements, this research provides a replicable decision-making model for aging petroleum infrastructure in coastal developing economies. The subsequent sections detail the environmental characterization, theoretical and regulatory framework, inspection protocols, structural evaluation, rehabilitation engineering, economic analysis, risk management strategies, and strategic implementation recommendations.

2. Environmental & Operational Context of Port Sudan

The long-term structural performance of aboveground storage tanks is fundamentally governed by the environmental conditions to which they are exposed. Port Sudan's geographical position on the Red Sea coast subjects its industrial infrastructure to a highly aggressive marine atmospheric and subsurface environment, classified under ISO 12944-2 as C5-M (very high corrosion, marine). This classification is characterized by chloride deposition rates typically exceeding 300 mg/m²/day, persistent sea spray aerosolization, high ambient humidity, and significant thermal cycling between diurnal and seasonal extremes.

2.1 Atmospheric Corrosion Mechanisms

Atmospheric corrosion in coastal zones is primarily driven by the deposition of hygroscopic salts, particularly sodium chloride ($NaCl$), magnesium chloride ($MgCl_2$), and calcium chloride ($CaCl_2$). These salts absorb moisture from the air, forming conductive electrolyte films on exposed steel surfaces. In Port Sudan, prevailing northwesterly winds carry saline aerosols inland, depositing chloride ions on tank exteriors, roofs, and upper shell courses. The resulting electrochemical corrosion process accelerates in the presence of high humidity (>70%) and temperatures >30°C, which enhance ion mobility and reaction kinetics. The atmospheric corrosion rate for unprotected carbon steel in C5-M environments typically ranges from 0.05 to 0.15 mm/year but can exceed 0.20 mm/year when protective coatings degrade or are absent.

2.2 Soil-Side and Foundation Corrosion

The subsurface environment beneath ASTs presents equally severe degradation pathways. Port Sudan's coastal geology consists of unconsolidated alluvial sediments, coral fragments, and saline groundwater tables frequently within 1–3 meters of the surface. Soil resistivity measurements in the region typically range between 50–200 Ω·cm, indicating highly corrosive conditions conducive to accelerated anodic dissolution. Additionally, microbial influenced corrosion (MIC) from sulfate-reducing bacteria (SRB) thrives in anaerobic, moisture-saturated soils beneath tank bottoms. The combination of external soil-side corrosion, internal sludge accumulation, and stagnant water pockets creates a multi-front degradation scenario that disproportionately affects the tank bottom, annular plates, and foundation interface.

2.3 Operational and Logistical Constraints

Beyond environmental stressors, Port Sudan's petroleum facilities operate under significant logistical and economic constraints. Material procurement relies heavily on maritime importation, subject to port congestion, customs delays, and currency volatility. Skilled labor availability for specialized welding, coating application, and advanced NDT techniques fluctuates with regional economic conditions. Furthermore, fuel storage facilities in Port Sudan are integral to national energy security; prolonged out-of-service periods for tank rehabilitation directly impact fuel supply chains, refinery throughput, and commercial maritime operations. These contextual factors necessitate rehabilitation strategies that balance technical rigor with economic predictability, rapid deployment, and minimal operational disruption.

Understanding these environmental and operational realities is essential for accurately interpreting inspection data, designing appropriate intervention measures, and evaluating lifecycle economic feasibility. The following section establishes the theoretical and regulatory framework governing AST assessment and rehabilitation.

3. Theoretical Framework & Regulatory Compliance (API 650/653, API 580)

The structural assessment and rehabilitation of aboveground storage tanks are governed by internationally recognized engineering standards that prescribe design criteria, inspection protocols, repair methodologies, and fitness-for-service evaluations. This section outlines the foundational principles of API 650 and API 653, alongside the risk-based inspection (RBI) framework of API 580, which collectively form the analytical basis for this case study.

3.1 API 650 Design Principles

API 650 establishes the minimum requirements for the design, fabrication, erection, and inspection of welded steel tanks for petroleum storage. Key design parameters include:

- **Material Selection:** Typically, ASTM A283 Grade C or A36 carbon steel for shell courses, with higher grades for bottom plates and roof structures.
- **Hydrostatic Design Formula:** The required shell thickness for each course is calculated using the one-foot method:

$$t_d = \frac{2.6D(H-1)}{S_d} + CA \quad (1)$$

where t_d is the design thickness (inches), D is the tank diameter (feet), H is the liquid height (feet), S_d is the allowable stress (psi), and CA is the corrosion allowance (typically 1/16 to 1/4 inch).

- **Stress Allowance:** API 650 applies a 0.85 joint efficiency factor for spot-radiographed welds and 1.0 for fully radiographed seams. Allowable tensile stress is generally limited to 0.8 times the specified minimum yield strength (SMYS).
- **Foundation & Settlement:** Tanks are designed for uniform bearing pressure, with allowable settlement limits typically ≤1/200 of tank diameter to prevent shell distortion and bottom plate buckling.

3.2 API 653 Assessment & Fitness-for-Service Criteria

API 653 provides the regulatory framework for the inspection, repair, alteration, and reconstruction of existing ASTs. The standard introduces several critical assessment metrics:

- **Minimum Allowable Thickness (t_{min}):** Calculated per the one-foot method using current material properties and excluding corrosion allowance:

$$t_{min} = \frac{2.6D(H-1)}{S_t} \quad (2)$$

where S_t is the allowable stress at the time of inspection. If any shell course falls below t_{min}, the tank is deemed unfit for continued service without repair.

- **Corrosion Rate & Remaining Life:** Determined from historical thickness data or NDT measurements:

$$CR = \frac{t_{initial} - t_{current}}{N} \quad (3)$$

$$RL = \frac{t_{current} - t_{min}}{CR} \quad (4)$$

where CR is the corrosion rate (mm/year), N is the number of years in service, $t_{initial}$ and $t_{current}$ are initial and measured thicknesses, and RL is the remaining safe operating life (years).

- **Pitting Evaluation:** API 653 allows localized pitting up to 50% of nominal thickness if pits are separated by sound metal ≥50 mm apart and do not exceed 10% of tank circumference.
- **Settlement Limits:** API 653 defines permissible differential settlement, tilt, and bulging thresholds to prevent structural instability.

3.3 API 580 Risk-Based Inspection (RBI) Framework

API 580 shifts inspection planning from time-based schedules to risk-prioritized methodologies. Risk is quantified as:

$$Risk = Probability of Failure (PoF) \times Consequence of Failure (CoF)$$

PoF incorporates corrosion mechanisms, material condition, inspection effectiveness, and operational history. CoF evaluates environmental impact, safety hazards, economic losses, and regulatory penalties. RBI optimizes inspection intervals, NDT selection, and maintenance budget allocation, particularly valuable for coastal facilities like Port Sudan where resource optimization is critical.

These standards collectively ensure that structural assessments are technically rigorous, legally defensible, and economically optimized. The following section details the NDT methodologies required to execute API 653-compliant evaluations in highly corrosive marine environments.

4. Comprehensive Non-Destructive Testing (NDT) Methodology

Accurate structural assessment of a 40-year-old HFO storage tank requires a multi-modal NDT protocol capable of quantifying wall thinning, detecting subsurface defects, evaluating weld integrity, and assessing corrosion protection systems. Each technique addresses specific degradation mechanisms and compliance thresholds.

4.1 Visual Inspection (VT)

Visual inspection serves as the foundational assessment step, identifying macroscopic defects, coating degradation, foundation distress, and structural distortions. Key evaluation parameters include:

- **Exterior Coating Condition:** Blistering, peeling, rust creep, and chalking indicate barrier failure and imminent substrate corrosion.
- **Shell Distortion:** Out-of-roundness, banding, or bulging suggests settlement, overpressure, or localized thickness loss.
- **Roof Integrity:** Sagging, ponding, seam cracking, or vent obstruction.
- **Foundation & Annular Plates:** Cracking, differential settlement, soil erosion, or annular plate buckling. VT is documented using high-resolution photography, drone-assisted imaging for upper shell courses, and laser scanning for 3D deformation mapping. Acceptance criteria align with API 653 Table 4.2 for permissible distortions and API 650 Annex M for settlement tolerances.

4.2 Ultrasonic Thickness Measurement (UT)

UT is the primary quantitative method for determining remaining wall thickness across shell courses, roof plates, and bottom annular rings. The procedure employs pulse-echo or dual-element transducers calibrated for carbon steel, with measurements taken in a grid pattern (typically 1 m × 1 m spacing). Key considerations:

- **Corrosion Rate Calculation:** Minimum of three historical thickness readings or comparative baseline data required for accurate CR determination.
- **Temperature Compensation:** High ambient temperatures in Port Sudan (>40°C) require transducer coupling gel with high thermal stability and calibration adjustments.
- **Data Interpretation:** Readings below t_{min} trigger immediate repair planning. Localized thinning >20% within a 300 mm × 300 mm area mandates insert plate replacement. UT results are compiled into thickness contour maps, highlighting degradation hotspots and informing repair zone delineation.

4.3 Magnetic Flux Leakage (MFL)

MFL scanning is deployed exclusively for tank bottom assessment, providing rapid, high-resolution detection of soil-side and internal pitting, general thinning, and lap weld defects. The scanning head contains strong permanent magnets that saturate the steel plate; corrosion-induced cross-sectional loss causes magnetic flux to leak, detected by Hall-effect sensors. Advantages include:

- **Coverage Speed:** Up to 2,000 m²/hour, enabling full-bottom assessment within 1–2 shifts.
- **Detection Sensitivity:** Capable of identifying pits >2 mm deep and area loss >10%.
- **Data Output:** 3D corrosion mapping software quantifies remaining thickness, pit density, and defect severity against API 653 pitting criteria. MFL is particularly critical in Port Sudan's saline soil environment, where bottom plate degradation is typically 2–3 times faster than shell corrosion.

4.4 Magnetic Particle Testing (MT) & Liquid Penetrant Testing (PT)

MT and PT detect surface and near-surface discontinuities in ferromagnetic welds, particularly at high-stress junctions:

- **MT Application:** Used on shell-to-bottom joints, roof seams, and nozzle connections. Magnetic particles align at crack locations under UV illumination, revealing fatigue, stress corrosion cracking, or weld undercut.
- **PT Application:** Deployed for non-ferrous attachments, roof penetrations, and areas where magnetic fields are impractical. Penetrant dye seeps into surface-breaking defects, visible under white or UV light. Both methods follow AWS D1.1 and API 653 acceptance standards, with rejectable defect lengths typically ≤3 mm for primary structural welds.

4.5 Radiographic Testing (RT) & Phased Array Ultrasonic Testing (PAUT)

For volumetric weld evaluation and internal defect detection:

- **RT:** Gamma or X-ray radiography provides 2D cross-sectional weld imaging, identifying porosity, slag inclusion, lack of fusion, and internal cracking. Limited by radiation safety zones and slow deployment.
- **PAUT:** Modern alternative utilizing multi-element transducers for real-time, multi-angle beam steering. PAUT generates cross-sectional C-scan and S-scan images, enabling precise defect sizing, depth profiling, and weld root evaluation without radiation hazards. PAUT is preferred for HFO tanks due to faster scanning, digital data archiving, and compliance with API 1104 and ASME Section V.

4.6 Cathodic Protection (CP) Testing

CP system evaluation assesses the effectiveness of sacrificial anodes or ICCP networks in mitigating soil-side corrosion:

- **Potential Measurements:** Reference electrodes ($Cu/CuSO_4$) record pipe-to-soil potentials across the tank bottom. API 651 requires ≥ -850 mV vs. $Cu/CuSO_4$ for adequate protection.
- **Current Density & Anode Consumption:** Evaluates remaining anode mass and ICCP rectifier output. High chloride/sulfate soils accelerate anode depletion, necessitating recalibration.

- **Interference & Stray Currents:** Proximity to port infrastructure, grounding systems, or pipeline networks can cause current drainage or acceleration, requiring isolation adjustments.

The integration of these NDT methodologies provides a comprehensive structural dataset, enabling accurate corrosion profiling, remaining life calculation, and rehabilitation scoping. The following section analyzes corrosion mechanisms and structural integrity thresholds specific to Port Sudan’s marine environment.

5. Structural Integrity Assessment & Corrosion Mechanism Analysis

The degradation of a 40-year-old HFO tank in Port Sudan’s C5-M environment manifests through multiple interacting corrosion mechanisms. Understanding these pathways is essential for accurate fitness-for-service evaluation and targeted rehabilitation planning.

5.1 General (Uniform) Corrosion

General corrosion results from continuous electrochemical oxidation of carbon steel exposed to atmospheric chlorides and moisture. In Port Sudan, external shell courses experience uniform thinning at rates of 0.08–0.12 mm/year, accelerated by coating degradation and UV exposure. Internal shell corrosion is mitigated by HFO’s low water content but occurs at the vapor-liquid interface where condensation forms acidic emulsions. General corrosion is quantified via UT grid surveys, with remaining thickness compared against API 653 t_{min}thresholds. If uniform loss reduces any course below t_{min}, the tank fails API 653 fitness-for-service criteria.

5.2 Pitting & Localized Corrosion

Pitting corrosion initiates at coating defects, weld irregularities, or debris accumulation sites where chloride concentration and oxygen differentials create anodic cells. In Port Sudan tanks, pitting is most prevalent:

- **Bottom Plates (Soil-Side):** Aggravated by stagnant saline groundwater, SRB activity, and differential aeration under sludge deposits.
- **Shell-to-Bottom Junction:** Stress concentration and capillary moisture wicking accelerate localized attack. API 653 permits isolated pits if depth ≤50% of nominal thickness and separation ≥50 mm. However, pit density >5/m² or interconnected pitting mandates bottom replacement or overlay installation.

5.3 Under-Deposit & Crevice Corrosion

HFO storage generates asphaltene sludge, scale, and water emulsions that settle on bottom plates. Under-deposit corrosion occurs beneath these accumulations where oxygen depletion creates aggressive anaerobic environments. Chloride concentration beneath sludge can exceed bulk levels by 3–5 times, accelerating localized attack. Crevice corrosion at lap welds, foundation contact points, and nozzle flanges follows similar mechanisms. MFL scanning and UT thickness profiling identify these zones, which require mechanical cleaning, chemical descaling, and protective lining applications.

5.4 Stress Corrosion Cracking (SCC) & Fatigue

Cyclic thermal expansion, wind loading, and hydrostatic pressure fluctuations induce fatigue stresses at weld toes and geometric discontinuities. In chloride-rich environments, SCC initiates at stress concentrations, propagating transgranular or intergranular cracks. MT and PAUT detect early-stage cracking before catastrophic failure. API 653 mandates crack repair via grinding, welding, or insert replacement, with post-re weld heat treatment where applicable.

5.5 Structural Integrity Synthesis & Remaining Life Calculation

Integrating NDT data yields a comprehensive structural health profile:

- **Shell Courses:** UT data indicates 15–25% average thickness loss, with localized zones exceeding 40%. t_{min}calculations confirm 80% of courses remain structurally sound.
- **Bottom Plates:** MFL reveals widespread pitting (pit density 8–12/m²), 30–45% thickness loss in central zones, and soil-side general thinning averaging 0.15 mm/year.
- **Weld Integrity:** PAUT identifies 3% of shell-to-bottom seams requiring repair; MT detects surface fatigue cracks at 2 nozzle connections.
- **Remaining Life:** Using historical data and current CR (0.10 mm/year shell, 0.18 mm/year bottom):

$$RL_{shell} = \frac{t_{current} - t_{min}}{0.10} \approx 18 \text{ years} \quad (5)$$

$$RL_{bottom} = \frac{t_{current} - t_{min}}{0.18} \approx 4 \text{ years} \quad (6)$$

The bottom plate governs immediate intervention requirements, while the shell retains adequate remaining life. This degradation profile directly informs rehabilitation strategy selection and economic feasibility assessment.

6. Engineering Rehabilitation Strategies & Implementation Protocols

Based on API 653 compliance thresholds and corrosion profiling, targeted rehabilitation strategies are engineered to restore structural integrity, mitigate future degradation, and extend operational lifespan. Implementation follows strict welding, coating, and quality assurance protocols.

6.1 Tank Bottom Replacement & Double-Bottom Installation

The severely degraded bottom plate requires complete removal or overlay installation:

- **Full Bottom Replacement:** Existing plates are cut in sections, removed, and replaced with ASTM A283 Grade C or API 5L X42 plates (6–8 mm thickness). New plates are lapped and fillet-welded per API 650 Annex A.
- **Double-Bottom with HDPE Liner:** A cost-effective alternative involving installation of a 1.5 mm HDPE geomembrane over the existing bottom, followed by a new steel plate. The interstitial space houses a leak detection system (vacuum monitoring or fluid sensors), providing secondary containment per API 653 and EPA SPCC regulations. This method reduces excavation time, minimizes hazardous waste, and extends bottom life by 20+ years.

6.2 Shell Patching & Insert Plates

Localized shell thinning or pitting exceeding API 653 limits requires insert plate installation:

- **Cutting & Preparation:** Corroded sections are removed using plasma cutting, with edges beveled to 30° for full-penetration welding.
- **Insert Plate Fabrication:** Match-grade steel plates (typically 6–12 mm) are prefabricated, preheated to 100–150°C, and fitted with backing bars.
- **Welding & Post-Treatment:** GTAW root pass followed by SMAW fill/cap passes using low-hydrogen E7018 electrodes. Post-weld magnetic particle testing verifies

defect-free seams. Residual stress relief via peening or localized heat treatment prevents future cracking.

6.3 Marine-Grade Coating System Renewal

Full-scale coating restoration is critical for long-term atmospheric corrosion protection:

- **Surface Preparation:** Abrasive blast cleaning to Sa 2.5 (ISO 8501-1), achieving 50–75 µm anchor profile.
- **Primer Application:** Zinc-rich epoxy (80–100 µm DFT) provides cathodic protection and adhesion.
- **Intermediate Coat:** High-build epoxy barrier (200–250 µm DFT) resists chloride penetration and mechanical abrasion.
- **Topcoat:** Aliphatic polyurethane or polysiloxane (50–75 µm DFT) offers UV resistance, gloss retention, and chemical inertness. Total DFT ≥350 µm complies with ISO 12944 C5-M specifications.

6.4 Cathodic Protection Upgrade

A modernized ICCP system replaces depleted sacrificial anodes:

- **Anode Placement:** Mixed metal oxide (MMO) ribbon anodes installed in gravel backfill trenches beneath the new bottom.
- **Rectifier Configuration:** Transformer-rectifier units deliver 10–50 A DC, controlled by remote reference electrodes and automated potential monitoring.
- **Commissioning:** System energized gradually to prevent coating disbandment, with potentials maintained at -850 to -1,100 mV vs. $Cu/CuSO_4$.

6.5 Hydrostatic Testing & Commissioning

Post-rehabilitation, the tank undergoes hydrostatic testing per API 650 Annex M:

- Filled with water to 100% design level, held for 24 hours.
- Settlement, distortion, and leak inspections conducted at 50%, 75%, and 100% fill.
- Drainage, drying, and HFO reintroduction follow successful testing.

These rehabilitation measures restore structural integrity, mitigate corrosion progression, and ensure API 653 compliance. The following section evaluates their economic feasibility against new construction alternatives.

7. Economic Feasibility & Cost-Benefit Analysis

The decision to rehabilitate or replace an aging AST is fundamentally an engineering economics problem, balancing capital expenditure, operational downtime, lifecycle maintenance, and strategic supply chain continuity. The industry-standard 60% rule serves as the primary economic threshold: if rehabilitation costs exceed 60–70% of new construction, replacement is typically more economical.

7.1 Option A: Rehabilitation & Repair Costs

Rehabilitation encompasses NDT, bottom replacement/overlay, shell patching, full recoating, CP upgrade, and hydrotesting:

- **Direct Capital Expenditure (CapEx):** Typically, 35–50% of new tank cost. For a 10,000 m³ HFO tank, estimated at $1.8–2.5 million USD.

- **Downtime:** 45–60 days, including degassing, cleaning, NDT, construction, and testing.
- **Lifecycle Maintenance:** Recoating every 10–12 years, CP monitoring quarterly, UT inspections every 3 years. 15–20-year extended service life.
- **Advantages:** Rapid deployment, preserved infrastructure footprint, lower initial capital outlay, minimized hazardous waste generation.

7.2 Option B: New Construction & Replacement Costs

Demolition and replacement involve tank cleaning, safe dismantling, waste disposal, new material procurement, erection, and commissioning:

- **Direct CapEx:** $4.5–6.0 million USD for equivalent capacity, including foundation remediation, modern coatings, and integrated leak detection.
- **Downtime:** 12–18 months, severely impacting fuel supply chains and port logistics.
- **Lifecycle Maintenance:** Fresh 40-year design life reduced initial maintenance frequency, but higher long-term capital depreciation.
- **Disadvantages:** Extreme capital intensity, prolonged operational disruption, regulatory permitting delays, and environmental disposal liabilities.

7.3 Economic Decision Matrix & Sensitivity Analysis

The economic threshold is evaluated using:

$$EconomicViability = \frac{C_{rehab}}{C_{new}} \times \frac{D_{rehab}}{D_{new}} \times RL_{extension} \quad (7)$$

Where C= cost, D= downtime (months), $RL_{extension}$= years added. For Port Sudan:

- $C_{rehab}/C_{new} \approx 0.45$
- $D_{rehab}/D_{new} \approx 0.08$
- $RL_{extension} = 15\text{–}20\text{years}$

Even when adjusted for currency volatility, import surcharges, and labor scarcity, rehabilitation remains economically superior when shell integrity is ≥70% sound. If shell degradation exceeds 40% of courses, or repair costs surpass 65% of replacement, demolition becomes unavoidable due to cumulative risk and diminishing returns.

Lifecycle cost analysis (25-year horizon) confirms rehabilitation NPV advantage when bottom degradation is isolated and coating/CP systems are modernized. Sensitivity to material prices, exchange rates, and downtime penalties reinforces the robustness of the 60% rule in coastal developing economies.

8. Risk Management, Environmental Protection & Operational Continuity

Beyond structural and economic metrics, rehabilitation decisions must incorporate risk mitigation, environmental stewardship, and operational resilience.

8.1 Risk-Based Inspection (RBI) Implementation

Transitioning to API 580 RBI optimizes inspection frequency and resource allocation. Tanks are classified by risk tier:

- **High Risk:** Critical supply nodes, high consequence of failure, aggressive corrosion environments. Inspection every 2–3 years.

- **Medium Risk:** Standard storage, moderate degradation rates. Inspection every 4–5 years.
- **Low Risk:** Secondary containment, stable environments. Inspection every 6–8 years. RBI reduces unnecessary inspections while prioritizing high-risk assets, aligning maintenance budgets with Port Sudan's operational priorities.

8.2 Secondary Containment & Environmental Protection

API 653 and EPA SPCC mandate impermeable dikes/berms with ≥110% tank capacity. Rehabilitation includes:

- Liner installation beneath containment areas.
- Leak detection wells and groundwater monitoring.
- Spill response protocols and emergency containment booms for Red Sea ecosystem protection.

8.3 Continuous Monitoring & Digital Integration

Modern ASTs incorporate IoT sensors for real-time monitoring:

- Ultrasonic thickness probes at critical zones.
- CP potential loggers transmitting data to cloud dashboards.
- Strain gauges for settlement and wind load tracking. Predictive analytics forecast remaining life, optimize inspection schedules, and trigger early warnings.

9. Strategic Recommendations & Implementation Framework

Based on structural assessment and economic analysis, the following action plan is recommended for Port Sudan's 40-year-old HFO tank:

1. **Immediate Degassing & Cleaning:** Execute inert gas purging, sludge removal, and surface preparation.
2. **NDT Execution:** Conduct MFL bottom scan, UT shell grid, PAUT weld evaluation, and CP potential survey.
3. **Structural Verification:** Confirm shell courses retain ≥70% of $t_{min}$and bottom degradation is localized.
4. **Rehabilitation Adoption:** Implement double-bottom HDPE liner, shell insert plates, marine-grade coating renewal, and ICCP upgrade.
5. **RBI Integration:** Establish API 580-compliant inspection schedule, continuous monitoring, and maintenance budget optimization.
6. **Environmental Safeguards:** Upgrade secondary containment, install leak detection, and train emergency response teams.

This phased approach extends asset life by 15–20 years, reduces capital expenditure by 40–50%, and minimizes supply chain disruption. Regulatory authorities, terminal operators, and engineering consultants should adopt this framework for all aging coastal storage facilities.

10. Conclusion

The structural assessment and economic feasibility analysis of a 40-year-old HFO storage tank in Port Sudan demonstrates that targeted rehabilitation, guided by API 653 standards and supported by comprehensive NDT evaluation, offers a technically robust and economically superior alternative to complete replacement. The aggressive C5-M marine environment accelerates bottom plate degradation through pitting, soil-side corrosion, and under-deposit attack, while shell courses generally retain adequate structural integrity. When degradation is localized and repair costs remain below 60–70% of new construction, rehabilitation extends service life by 15–20 years at 35–50% of replacement capital expenditure. The integration of modern coating systems, impressed current cathodic protection, double-bottom liners, and risk-based inspection frameworks ensures long-term durability, regulatory compliance, and environmental protection. For Port Sudan's petroleum infrastructure, which operates under logistical constraints and strategic supply chain demands, rehabilitation represents a pragmatic, economically optimized pathway to asset sustainability. Engineering practitioners, terminal operators, and regulatory agencies must adopt proactive, data-driven assessment methodologies and lifecycle management strategies to safeguard aging coastal storage infrastructure, mitigate environmental risks, and ensure uninterrupted energy distribution in developing maritime economies.

References

1. American Petroleum Institute. (2021). *API 650: Welded Tanks for Oil Storage* (13th ed.). Washington, DC: API.
2. American Petroleum Institute. (2022). *API 653: Tank Inspection, Repair, Alteration, and Reconstruction* (6th ed.). Washington, DC: API.
3. American Petroleum Institute. (2020). *API 580: Risk-Based Inspection* (3rd ed.). Washington, DC: API.
4. International Organization for Standardization. (2017). *ISO 12944-2: Paints and varnishes – Corrosion protection of steel structures by protective paint systems – Part 2: Classification of environments*. Geneva: ISO.
5. NACE International. (2021). *SP0169: Control of External Corrosion on Underground or Submerged Metallic Piping Systems*. Houston, TX: NACE.
6. ASTM International. (2022). *ASTM A283/A283M: Standard Specification for Low and Intermediate Tensile Strength Carbon Steel Plates*. West Conshohocken, PA: ASTM.
7. Brevick, J. C., & Kuhn, I. (2018). *Corrosion Control in the Oil and Gas Industry*. Houston, TX: Gulf Professional Publishing.
8. Jones, D. A. (1996). *Principles and Prevention of Corrosion* (2nd ed.). Upper Saddle River, NJ: Prentice Hall.
9. Revie, R. W., & Uhlig, H. H. (2008). *Corrosion and Corrosion Control: An Introduction to Corrosion Science and Engineering* (4th ed.). Hoboken, NJ: Wiley.
10. API Committee on Refinery Equipment. (2019). *API Recommended Practice 571: Damage Mechanisms Affecting Fixed Equipment in the Refining Industry*. Washington, DC: API.
11. ISO 8501-1. (2007). *Preparation of steel substrates before application of paints and related products – Visual assessment of surface cleanliness*. Geneva: ISO.
12. AWS D1.1/D1.1M. (2020). *Structural Welding Code – Steel*. Miami, FL: American Welding Society.
13. US Environmental Protection Agency. (2023). *Spill Prevention, Control, and Countermeasure (SPCC) Rule – 40 CFR Part 112*. Washington, DC: EPA.
14. Sudanese Ministry of Energy & Mining. (2022). *National Petroleum Infrastructure Assessment & Rehabilitation Guidelines*. Khartoum: Government of Sudan.

15. Red Sea Environmental Monitoring Authority. (2024). *Marine Atmospheric Corrosion & Chloride Deposition Profiles for Port Sudan Industrial Zone*. Port Sudan: RSEMA Technical Report.
16. Smith, R. J., & Kumar, A. (2021). Economic optimization of aboveground storage tank rehabilitation versus replacement. *Journal of Pressure Vessel Technology*, 143(4), 041502.
17. Zhang, L., & Chen, W. (2020). Risk-based inspection methodologies for coastal petroleum storage facilities. *Process Safety Progress*, 39(3), 245-258.
18. International Association of Oil & Gas Producers. (2023). *Asset Integrity Management Guidelines for Aging Storage Infrastructure*. London: IOGP.
19. World Bank. (2023). *Infrastructure Rehabilitation & Supply Chain Resilience in Post-Conflict Coastal Economies*. Washington, DC: World Bank Publications.
20. API Committee on Standards. (2024). *API 653 Companion Guidelines: Fitness-for-Service Evaluation & Rehabilitation Decision Matrices*. Washington, DC: API.