Comparative Analysis of Corrosion Mitigation Strategies in Water Pipeline Systems

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Abstract— **This white paper presents a lifecycle cost analysis of two corrosion mitigation strategies for water pipeline systems: corrosion allowance through increased wall thickness and the application of interior epoxy coatings. The study evaluates the economic and operational performance of both approaches over a 25-year service life, considering capital expenditures (CAPEX), operational expenditures (OPEX).**

I. Introduction

The strategic selection of corrosion mitigation approaches significantly impacts both operational longevity and lifecycle costs in water transmission infrastructure. This investigation evaluates two prevalent methodologies: corrosion allowance designs utilizing increased wall thickness versus epoxy-coated pipeline systems employing protective barriers.

Corrosion allowance designs employ structural overengineering to accommodate predictable material degradation rates, while epoxy coatings provide electrochemical isolation that prevents corrosive interactions. Though seemingly straightforward, these approaches carry divergent implications for hydraulic efficiency and operational expenditures.

Pipeline systems relying solely on wall thickness augmentation inherently reduce internal diameters, directly increasing pumping energy requirements. This hydraulic inefficiency becomes compounded by the elevated surface roughness characteristics of uncoated steel compared to epoxy-lined alternatives. Furthermore, bare steel systems necessitate continuous chemical inhibitor treatments to mitigate corrosion progression - introducing recurring material costs and operational complexities absent in coated systems.

This study conducts a comprehensive techno-economic analysis encompassing both capital expenditures (CAPEX) and operational costs (OPEX) across a 30-year service horizon. The evaluation framework incorporates hydraulic modeling, material degradation rates, and chemical treatment protocols to quantify total ownership costs for both mitigation strategies.

II. Case Study Parameters and Computational Methodology

The analysis employs a representative industrial water transport scenario with parameters standardized for comparative evaluation.

Table 1. Arbitrary Project Parameters

Parameter	Value	Unit
Pipeline length	70	km
Static head (elevation change)	1000	m
Pipeline outside diameter	28	inches
Density of water	1030	kg/m³
Dynamic viscosity of water	0.0013	Pa·s
Design flow rate	700	L/s
Service life	25	years
Annual hours of operation	8,400	h/yr
Pump efficiency	82	%
Annual discount Rate	10	%

All computational models and datasets are publicly accessible via GitHub, including an Excel workbook implementing the Newton-Raphson iterative technique for precise determination of Darcy-Weisbach friction factor.

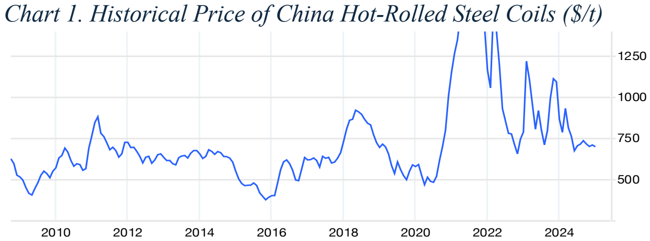
The author expects that this methodological transparency enables independent verification of results while providing an adaptable framework for evaluating corrosion management strategies under diverse operational conditions. This systematic approach aims to advance evidence-based decision-making in pipeline engineering practices.

III. Capital Expenditure Analysis

A. Steel Pipe Economics

This cost model integrates current hot-rolled coil (HRC) market indices, manufacturing premiums, and logistical expenses to establish baseline steel pipe pricing. Recent Chinese market data indicates API 5L X70 pipe costs typically range at 1.8–2.2x HRC spot prices, reflecting value-added processes from coil to finished pipe [1].

Chart 1. Historical Price of China Hot-Rolled Steel Coils ($/t)



The delivered cost per ton (CPW) derives from three primary components: a $550/t HRC baseline, 2x manufacturing multiplier, and $170/t transportation cost for

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Chilean mining projects. This yields $CPW = (550{\cdot}2) + 170 =$ \$ 1,270 /t through first-principles cost aggregation [2, 3].

The corrosion rate for the bare pipe strategy it is assumed at 0.15 mm/yr which should holds validity for industrial water systems with adequate inhibitors injection [4]. However, seawater models would require adjustment to 0.25–0.35 mm/year baseline rates with additional 0.12–0.18 mm/year biofouling roughness increments [5].

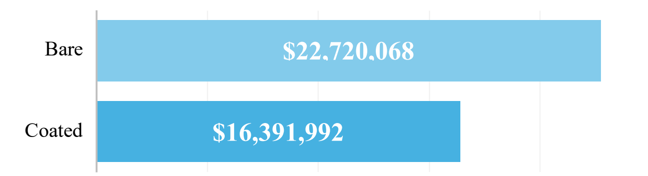
At a corrosion rate of 0.15 mm/yr, the initial bare pipe wall thickness required is 9.53 mm + 0.15 mm/yr · 25 yr = 13.28 mm which will help us calculate the total pipeline steel costs via hollow cylinder volumetrics:

$$Steel_{COST} = \frac{\pi}{4} \cdot (D^2 - (D-t)^2) \cdot L \cdot \rho \cdot \mathrm{CPW} \qquad (1)$$

Where D = 0.7112 m (external diameter), t = 13.28 mm (bare pipe) or 9.53 mm (coated system), L = 70 km (pipeline length), and ρ = 7850 kg/m³ (X70 steel density). This parametric approach enables direct comparison of wall thickness strategies while accounting for current metallurgical market conditions. Replacing these values in eq (1):

TABLE 2. STEEL COST FOR EACH STRATEGY

Item	*Bare*	*Coated*
Wall thickness	13.28 mm	9.53 mm
Steel Weight	16,000 t	11,544 t
Cost of steel	\$20,320,061	\$14,660,443



B. Bare Pipeline Systems: Chemical Dosing Infrastructure

Bare pipelines require integrated chemical dosing plants to maintain corrosion inhibition and biological control. These facilities combine storage tanks, injection pumps, precision metering systems, and automated controls to proportionally administer treatments relative to flow rates (0.7 m³/s baseline). Continuous operation ensures maintained inhibitor concentrations targeting a 0.15 mm/yr corrosion rate.

Capital expenditures for such systems range \$208,000–\$370,000, with a mid-range valuation of \$272,160.applied in this analysis. This cost envelope reflects industrial-grade components, regional supply chain factors, and automation requirements for flow-responsive chemical management.

A critical limitation of corrosion allowance strategies lies in their presumption of uniform material degradation. Practical failure modes predominantly stem from localized pitting corrosion, where concentrated material loss penetrates wall thicknesses before nominal corrosion allowances are consumed. This discrepancy underscores the importance of complementary protective measures beyond structural overengineering.

C. FBE Interior Coating Economics

Shop-applied interior fusion-bonded epoxy (FBE) coatings, typically applied at thicknesses up to 500 µm, offer cost efficiencies [6]. These efficiencies stem from industrialized application processes that deliver superior resistance to chloride-induced corrosion and abrasion caused by suspended solids. Additionally, these coatings ensure consistent quality, minimize material waste, and reduce labor costs.

Current pricing of \$3.50–\$5.00/m² for surface treatment processes reflects the integration of material inputs, thermal energy requirements, and automated systems in modern pipe mills, with specific costs varying by region and coating type. This analysis adopts a conservative \$5.00 per square meter cost per interior surface area (CPS) to calculate coating expenditures:

$$FBE_{CAPEX} = \pi \cdot \mathrm{D} \cdot L \cdot CPS \qquad (2)$$

Where D = 0.69214 m (coated interior diameter) and L = 70 km (pipeline length). Implementation costs total \$761,048, representing 4.9% of baseline steel material expenditures.

Chart 2. Shop FBE coating compared to steel cost.

Industry benchmarks from the Saline Water Conversion Corporation's R&D Center corroborate this 5% average ratio of coating-to-steel costs in large-diameter pipelines [7].

D. Internal Robotic Field Joint Coating

Post-weld interior coating requires specialized robotic systems to address heat-affected zone degradation of factory-applied FBE layers. These crawler-mounted units perform abrasive blasting followed by epoxy application via rotating nozzles using either powder or liquid formulations [8].

1998 Project, Minera Escondida Monturaqui, Atacama, Chile 18” – 42” Water Pipeline. 7,500 Field Joint Internally Coated with FBE

Field conditions, including temperature fluctuations (±15°C), humidity (30–95% RH), and airborne particulates, significantly undermine coating adhesion and curing consistency. Studies highlight that field-applied coatings are more prone to defects compared to shop-applied systems, with internal corrosion being a leading cause of pipeline failures [8]. Poor surface preparation further exacerbates these vulnerabilities, creating weak points prone to premature degradation.

The next two images illustrate a comparative analysis of coating performance and adhesion quality between factory-FBE and field-applied liquid epoxy coatings. These photos highlight the challenges associated with field-applied coatings, particularly in areas near weld seams, where surface preparation and environmental conditions significantly impact coating adhesion.

Photo 1. Displays a clean adhesion test result for a factory-applied FBE coating. The uniform removal of the coating indicates strong adhesion to the substrate, achieved through controlled application processes in a factory setting with optimal surface preparation and curing conditions.

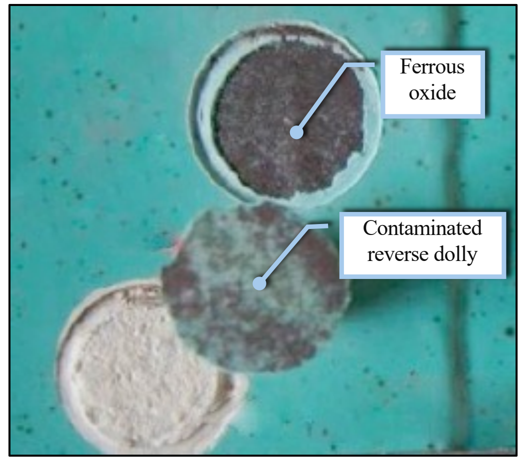


Photo 2. Shows the results of an adhesion test on a field-applied liquid epoxy coating near a weld seam. The presence of ferrous oxide (rust) and contamination on the reverse dolly highlights suboptimal surface preparation and environmental challenges during field application. These defects compromise coating adhesion and increase the risk of corrosion in service.

Studies on pipeline damage indicate that internal corrosion is a leading cause of failures, accounting for up to 60% in pipelines exposed to highly corrosive environments such as seawater or untreated fluids [10].

Currently, two leading providers dominate the internal field joint coating robot service market:

- Aegion/CRTS. Offers advanced robotic systems with higher upfront costs (+20–30%) but lower rework expenses due to superior precision and quality control [1].
- TYHOO Group: Focuses on cost-optimized modular robots designed specifically for pipelines with diameters under 28 inches [2].

TABLE 3. COST COMPONENTS FOR ROBOTIC FIELD COATING

Cost Component	*Cost per Joint* [13]
Mobilization of Crew & Equipment	$22.08
Demobilization of Crew & Equipment	$13.80
Personnel & Robotic Equipment	$505.08
Pre-blasting Personnel & Equipment	$149.04
Internal Coating Application	$181.24
Pipe-End Pre-blasting	$48.76
Total Cost per Joint	$920.00

For the 5,834-joint pipeline, this aggregates to $5,367,280 eightfold higher than factory coating expenditures.

TABLE 4. CAPEX COMPOSITION

CAPEX Item	Cost	%
Total steel cost	$16,391,992	70.5%
Field joint coating	$5,367,280	25.8%
Shop FBE coating	$761,048	3.7%
Dosing plant		1.3%
Total CAPEX	**$22,520,319**	**1.3%100%**

Field-applied interior coatings are at least 10 times more expensive per surface area than shop-applied FBE coatings due to the added complexity of field conditions. Despite the higher costs, their quality is significantly inferior, as evidenced by issues like poor adhesion and contamination near weld seams (see Photo 2). These challenges have driven the market to innovate alternative solutions, such as:

- **FlexSleeve**®. A stiff polymer sleeve with bore seals that is inserted into pipe ends before welding.
- **SIDGMAN**®. A two-piece system—one male and one female—welded in the shop to the ends of each pipe, so that they end up as field welded pipe flanges.
- **Style X07**. A very high-pressure Victaulic coupling listed under ASME B31.4. It has been installed in two projects in Chile: 24" MLP INCO and 32" SQM TEA.

Photo 1. SQM's TEA project, a 32" seawater interior FBE coated pipeline was joined by Victaulic's X07 couplings. The need for robot field coating was eliminated. Project achieved a rate of 15 minutes per joint per crew of six unskilled workers.

IV. Operational Expenditures

A. Corrosion inhibitors injection

While corrosion allowance provides additional wall thickness to counteract material loss, corrosion inhibitors actively reduce the corrosion rate, offering a more economical long-term solution for pipeline protection. For long-distance pipelines, relying solely on corrosion allowance can result in prohibitively high costs. The use of corrosion inhibitors usually offers a more economical solution to manage corrosion over time.

Based on experimental data, a 26 ppm dosage of sodium polyphosphate inhibitor is recommended to maintain a corrosion rate at or below 0.15 mm/year. Sodium polyphosphate acts as a passivating agent, forming a thin protective film on the metal surface that serves as a barrier against corrosive agents. Additionally, a biocide is applied weekly as a 4-hour shock treatment at 20 ppm (equivalent to a continuous dose of 0.46 ppm) to prevent microbial growth, including bacteria, fungi, and algae.

Given the pipeline's flow rate of 0.7 m³/s, and the annual operating hours is 8,400, the total annual volume transported is 21,168,000 m³. Using these parameters and the dosages above, the operational expenditures (OPEX) for corrosion and biocide inhibitors are calculated as follows:

TABLE 5. CALCULATED DOSAGE TO ACHIEVE AT LEAST 0.15 MM/YR CORROSION RATE.

Chemical item	***Dosage*** *ppm*	***Price*** *per kg* [4]	***Mass*** *kg per year*	***Cost*** *($/year)*
Inhibitor	26.00	$1.7	550,368	$920,215
Biocide	0.46	$12.8	9,660	$123,648
			Total OPEX	$1,043,863

To compare future OPEX cash flows with CAPEX on an equal footing, future cash flows must be discounted to their present value (PV). The present value is calculated using the following equation (1):

$$PV = \sum_{n=1}^{25} \frac{FV_n}{(1+r)^n} \tag{1}$$

Where PV is the Present Value, FV is the future value (annual OPEX of $1,043,863); r is the discount rate, 10%; n is the number of years into the future. Assuming cash flows occur at the end of each period over a 25-year service life, the inhibitors' OPEX present value is calculated as $9,475,189.

B. Inspections

Bare uncoated steel pipes with corrosion allowance and internally epoxy-coated pipes require distinct inspection strategies due to their differing approaches to corrosion management.

For bare steel pipes, inspections focus on monitoring wall thickness loss over time using techniques such as magnetic flux leakage (MFL) or ultrasonic testing (UT). These methods detect material degradation, with repairs involving weld patches, sleeves, or section replacements. Inspection intervals are typically every 3–5 years, with annual costs ranging from $8,000 to $15,000 per kilometer.

In contrast, internally epoxy-coated pipes require inspections to assess coating integrity using techniques like electrochemical impedance spectroscopy (EIS) or linear polarization resistance (LPR).

Repairs involve reapplying liquid epoxy to damaged areas. Coated pipes benefit from longer inspection intervals of 5–10 years and lower annual costs of $4,000 to $8,000 per kilometer.

Table 5 summarizes the key differences in inspection methodologies, frequencies, and costs:

TABLE 6. INSPECTIONS FEATURE COMPARISON.

Concept	***Bare Pipe***	***Coated pipe***
Main Inspection Methodology	Magnetic flux leakage (MFL) and/or ultrasonic testing (UT).	Electrochemical impedance spectroscopy (EIS) and/or linear polarization resistance (LPR).
Repair	Weld patches, sleeves or replace entire section.	Reapply liquid epoxy to the interior surface.
Periodicity	3–5 years.	5–10 years.
Cost/Year	$8,000–$15,000/km	$4,000–$8,000/km

For analytical purposes, this study assumes annual inspection costs of $8,000/km for internally FBE-coated pipes and $4,000/km for bare steel pipes. Given a pipeline length of 70 km:

- The annual OPEX for bare pipes is $560,000.
- The annual OPEX for coated pipes is $280,000.

Using a 10%, discount rate over a 25-year service life:

- The present value (PV) of inspection costs for bare pipes is $5,083,142.
- The PV of inspection costs for coated pipes is $2,541,571.

C. Energy consumption

Chile's industrial electricity pricing incorporates generation costs, transmission fees, and distribution charges. The generation component reflects marginal system costs influenced by fossil fuel prices and renewable penetration. Transmission and distribution costs remain regulated, with recent tariff adjustments adding complexity to pricing calculations.

For large industrial consumers, July 2024 data showed an average rate of $128/MWh. This baseline industrial rate of $128/MWh requires adjustment through three critical factors: fuel price volatility (45.77% fossil dependency amid declining coal production), renewable integration costs ($5-8/MWh for grid stability with 27% solar/wind penetration), and transmission constraints ($3-12/MWh regional differentials). Chile's 2024 Tariff Stabilization Law further modifies pricing via:

- Generation component adjustments. (+15% from 2022 baseline, CPI-indexed).
- Debt servicing surcharge ($0.02/kWh until 2035).
- Transmission upgrades. ($1.2/MWh fee).

This comprehensive adjustment framework elevates the 2024 effective rate to:

$$P_{2024} = (128 \cdot 1.15) + (0.02 \cdot 1000) + 1.2 = 168.4 \frac{\$}{\text{MWh}}$$

It is important to note that the energy costs for the Chilean mining sector costs rose from $85/MWh (2015) to $112/MWh (2024), 40% above Peruvian competitors.

This analysis adopts a projected rate of *P* = $175/MWh for years 2025 onwards. This rate *P* is used in equation (2) which calculates de cost of energy consumed by the pipeline project pump(s).

TABLE 7.HISTORICAL PRICE CONTEXT

Year	*Avg. Industrial Rate*	*Key Influencers*
2022	$145/MWh	Coal phase-out begins
2023	$158/MWh	Gas price spike
2024	$168/MWh (adjusted)	Debt repayment initiated
2025	$175/MWh (projected)	Full tariff normalization

$$C = \frac{\rho \cdot g \cdot Q \cdot \left(H_f + H_z\right) \cdot t \cdot P}{\eta} \tag{2}$$

Where ρ is fluid density; *g* is the gravitational acceleration; *Q* is the volumetric flow rate; $H_t = h_f + h_z$ is the total head loss due to friction losses (h_f) plus elevation head (h_z = 1000 m); η is the pump efficiency (82%) and *t* is the annual operating time (8,400 hours).

To estimate energy required to overcome friction losses in the pipeline the Darcy-Weisbach equation (3) is used. For this analysis.

$$h_f = \mathrm{f} \cdot \frac{L}{D} \cdot \frac{v^2}{2g} \tag{3}$$

Where h_f is the head loss due to friction losses in the pipeline; *f* is the Darcy-Weisbach friction factor, a dimensionless parameter representing energy loss due to friction in a pipe; *L* is the length of the pipeline; v is the velocity of the fluid; *g* is the acceleration due to gravity; and *D* is the inside diameter of the pipeline, where larger diameters reduce friction losses by lowering fluid velocity for a given flow rate.

To calculate the Darcy-Weisbach friction factor *f*, the Colebrook-White equation is utilized.

$$\frac{1}{\sqrt{f}} = -2 \log_{10}\left(\frac{k}{3.7 \cdot D} + \frac{2.51}{Re \cdot \sqrt{f}}\right) \tag{4}$$

Where *f* is the Darcy-Weisbach friction factor; *k* is the pipe's roughness height and *D* is the pipe inside diameter; *Re* is the Reynolds number; and the logarithmic term accounts for both surface roughness and viscous effects in turbulent flow. The equation is implicit in *f* and requires iterative or numerical methods to solve.

Bare Pipe Case Calculations

For the bare pipe case, on year 1, the Reynolds number is calculated as using equation:

$$Re = \frac{\rho \cdot v \cdot D}{\mu} \tag{5}$$

Where ρ is the fluid density (1030 kg/m^3), v is the fluid velocity on year 1 (1.915 m/s) derived from the flow ratio of 0.7 m^3/s, *D* is the pipe inside diameter (0.68464m) for wall thickness of 13.28 mm on year 1, μ is the dynamic viscosity (0.0013 Pa·s). Substituting values, $Re = 1{,}035{,}210$. Again, substituting values on eq (4):

$$\frac{1}{\sqrt{f}} = -2 \log_{10}\left(\frac{0.00010}{3.7 \cdot 0.68464} + \frac{2.51}{\cdot\sqrt{f}}\right) \tag{6}$$

Solving for *f* using the Newton-Raphson iterative numerical technique which converges to *f* = 0.014030.

Substituting values on eq (3):

$$h_f = 0.014030 \cdot \frac{70000}{0.68464} \cdot \frac{1.915^2}{2 \cdot 9.81} = 269.32 \text{ m} \tag{7}$$

Again, substituting values on eq (2):

$$C_{bare\ yr\ 1} = \frac{1030 \cdot 9.81 \cdot 0.7 \cdot (269.32 + 1000) \cdot 8400 \cdot 0.000175}{0.0013} = \$16{,}089{,}032 \tag{8}$$

For the bare pipe case, previous calculation procedure is repeated for the next 25 years, decreasing the wall thickness by the design corrosion rate of 0.15 mm/yr; from 13.28 mm on year 1 to 9.53 mm on year 25; and increasing the pipe roughness from 0.1 mm on first year to 0.3 mm by the end of year 25.

Same procedure is done for the **coated pipe case**, only this time, wall thickness is maintained at 9.53 mm, and pipe roughness increases from 0.01 mm on first year to 0.05 mm by year 25 end. Results for both the bare and coated pipe are listed on Annex A – Energy Consumption Calculations.

The consequent Present Value for the cost of electricity during these 25 years at a discount rate of 10% is:

TABLE 8. ELECTRICITY CONSUMPTION PRESENT VALUE COMPARISON

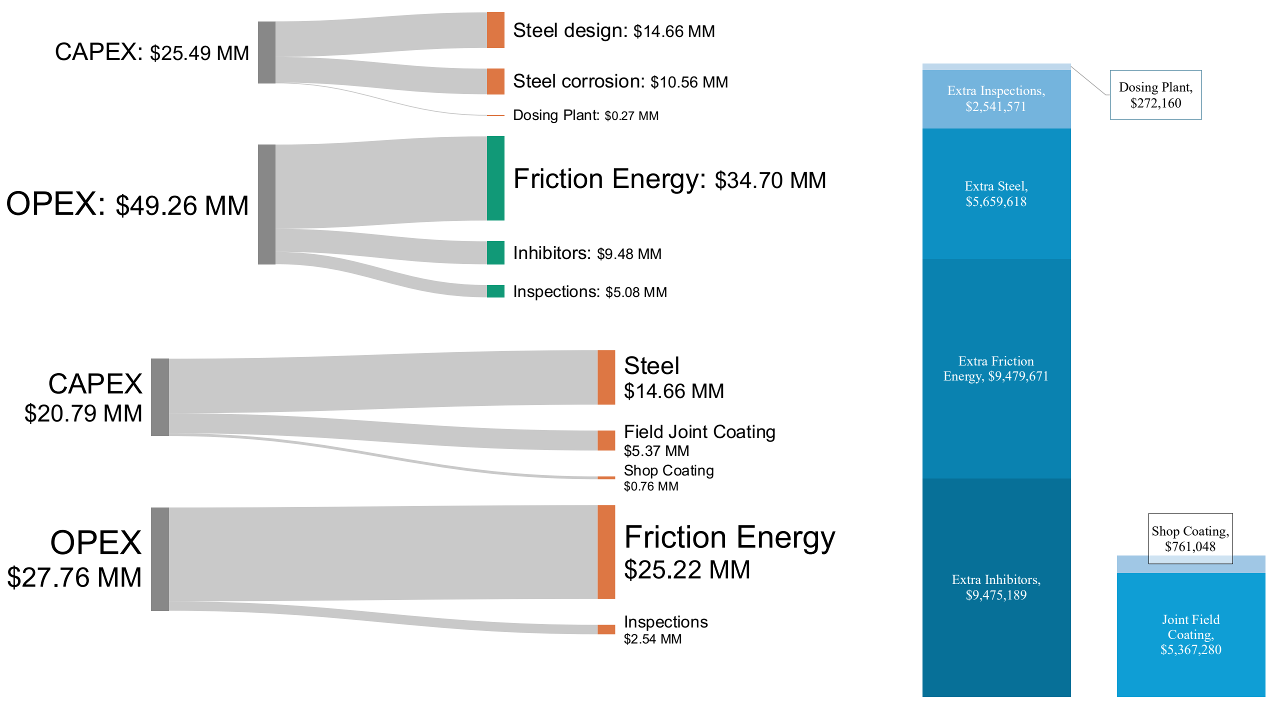
Energy Cost PV	Bare Pipe	Coated Pipe	Difference
Friction	$32,323,586	$25,223,188	$7,100,398[a]
Elevation	$115,054,517	$115,054,517	$0

[a] Friction-related energy consumption for coated pipes is significantly lower than for bare pipes due to reduced roughness and hydraulic inefficiencies over time.

I. Analysis of Results

As shown in Table 9, a comparison of CAPEX and the Present Value (PV) of OPEX over the 25-year service period reveals a 11.5%% cost advantage for the coated pipeline strategy, with a total lifecycle cost of $163,608,047 versus $184,907,928 for the bare pipe approach. This translates to a savings of $21,299,881 over the evaluation period.

However, since



Item	Bare Pipe	Coated Pipe	Difference	
Inhibitors	$9,475,189		$9,479,671	
Steel	$22,720,068	$14,660,443		$5,659,618
Field Joint Coating		$5,367,280	$5,367,280	
Friction Energy	$32,323,586	$25,223,188	$9,475,189	
Elevation Energy	$115,054,517	$115,054,517		
Inspections	$5,083,142	$2,541,571	$2,541,571	
Shop FBE		$761,048		$761,048
Dosing Plant	$272,160		$272,160	
Total	**$184,928,662**	**$165,339,595**		**$19,589,067**

Table 9. CAPEX and Present Value of OPEX for each corrosion mitigation strategy.

Below a graphical representation. Of

However, this comparison includes elevation energy costs ($115,054,517) which are equal for both strategies and therefore irrelevant to this analysis. Excluding these elevation costs provides a clearer picture of the differential impact between approaches.

The primary cost drivers of the corrosion allowance strategy are the additional expenses associated with corrosion inhibitors, increased electricity consumption due to higher friction losses, and the extra steel required to compensate for material loss over time. Remarkably, each of these cost components individually exceeds the combined cost of shop and field coatings for an internally coated pipeline.

This stark contrast underscores the inherent cost inefficiency of the bare pipe strategy. Further exploration into niche applications or unique project constraints could provide valuable insights into this question.

- **Material Savings**: The bare pipe requires 29.6% more steel by mass (13.28 mm vs 9.53mm wall thickness), accounting for $6,328,077 in additional capital expenditure.

- **Operational Efficiencies**: The coated system demonstrates $7,100,398 savings in net present value energy savings from reduced pipe roughness (0.01-0.05mm vs 0.1-0.3mm) and increased pipe inside diameter, and does not require inhibitors, saving $9,475,189 in present value from the OPEX of inhibitors injection.

- **Maintenance Optimization**: Combined inspection and chemical treatment costs for the bare pipe total $2,541,571 higher than the coated pipe strategy.

II. Conclusion

This study provides a comprehensive evaluation of two corrosion mitigation strategies—corrosion allowance via increased wall thickness and interior Fusion Bonded Epoxy (FBE) coating—for water transport pipelines. The analysis, grounded in a 25-year lifecycle cost assessment, highlights **significant economic and operational advantages** of the epoxy-coated pipeline approach over the corrosion allowance strategy. Key findings include:

1. **Cost-Effectiveness**: The epoxy-coated pipeline demonstrates a 10.6% total lifecycle cost advantage when elevation energy costs are included. When excluding these unavoidable costs, the coated pipeline's differential advantage becomes even more pronounced, driven by reduced material requirements, lower energy consumption, and minimized maintenance costs.
2. **Material Efficiency**: The corrosion allowance strategy requires 29.6% more steel due to increased wall thickness (13.28 mm vs. 9.53 mm), resulting in an additional capital expenditure of $6.33 million. This highlights the inefficiency of using thicker walls to account for long-term corrosion.
3. **Operational Savings**: The epoxy-coated pipeline achieves $7.1 million in energy savings due to its smoother internal surface and larger effective diameter, which reduce friction losses during pumping operations. Additionally, it eliminates the need for costly corrosion inhibitors, saving $9.48 million in present value over the service life.
4. **Maintenance Optimization**: Inspection and repair costs for the epoxy-coated pipeline are substantially lower than those for the bare pipe with corrosion allowance, yielding $2.54 million in savings over 25 years due to less frequent and less invasive maintenance requirements.
5. **Technical Viability**: While robotic field joint coating for FBE pipelines incurs higher costs and unreliability risks compared to factory-applied coatings, alternative solutions such as Victaulic's X07 couplings and other innovative technologies can eliminate this expense altogether, further enhancing the feasibility of epoxy-coated pipelines.

Aspect	Corrosion Allowance	Internally Coated Pipe (FBE)
Capital Expenditure (CAPEX)	Requires 29.6% more steel due to increased wall thickness, adding $6.33 million to initial costs	Lower initial steel cost; additional $761,048 for shop coating and $5.37 million for field joint coating1.
Operational Costs (OPEX)	- High energy costs due to increased friction from rougher pipe surface and smaller internal diameter. - Requires corrosion inhibitors, adding $11.84 million in present value over 25 years.	- Smoother surface reduces friction, saving $7.1 million in energy costs. - No need for inhibitors, reducing complexity and cost.
Maintenance	- Frequent inspections and repairs due to progressive wall thinning. - Higher inspection costs ($5.08 million over 25 years).	- Less frequent inspections (every 5-10 years) and lower costs ($2.54 million over 25 years).
Durability	Relies on material thickness; prone to localized pitting corrosion that may lead to failures.	Effective barrier against corrosion; weak points at field joints if improperly coated.
Technical Challenges	Simple design but less adaptable to varying corrosion rates or localized damage.	Requires specialized application techniques; challenges with field joint coating quality.
Energy Efficiency	Higher friction losses increase pumping energy consumption by $7.1 million in present value.	Improved hydraulic efficiency reduces energy consumption.

III. Summary

Corrosion Allowance: While simpler to implement, this strategy incurs higher material, energy, and maintenance costs over the pipeline's lifecycle. It is less adaptable to localized corrosion risks and relies heavily on chemical inhibitors, which pose environmental concerns.

Internally Coated Pipe (FBE): Offers better long-term cost savings due to reduced energy consumption and maintenance needs. However, it requires careful application and quality control during installation, particularly at field joints.

Overall, the internally coated pipe strategy demonstrates superior lifecycle performance but involves higher initial technical complexity.

APPENDIX A

Table 10. Bare pipe Electricity cost calculations.

#NAME?

Yr	Pipe roughness [mm]	Interior Diameter [mm]	Wall thickness [mm]	Fluid Velocity [m/s]	Friction factor f [ ]	Head Loss [m]	Pump Friction [kW]	Pump Elevation [kW]	Electricity Friction [M$]	Electricity Elevation [M$]
1	0.100	682.140	14.53000	1.915	0.014030	269.32	2322	8623	$3,413,697	$12,675,334
2	0.108	682.557	14.32167	1.913	0.014180	271.37	2340	8623	$3,439,685	$12,675,334
3	0.117	682.973	14.11333	1.911	0.014325	273.31	2357	8623	$3,464,266	$12,675,334
4	0.125	683.390	13.90500	1.908	0.014466	275.14	2372	8623	$3,487,545	$12,675,334
5	0.133	683.807	13.69667	1.906	0.014602	276.89	2387	8623	$3,509,618	$12,675,334
6	0.142	684.223	13.48833	1.904	0.014734	278.54	2402	8623	$3,530,569	$12,675,334
7	0.150	684.640	13.28000	1.901	0.014862	280.11	2415	8623	$3,550,473	$12,675,334
8	0.158	685.057	13.07167	1.899	0.014987	281.60	2428	8623	$3,569,398	$12,675,334
9	0.167	685.473	12.86333	1.897	0.015108	283.02	2440	8623	$3,587,405	$12,675,334
10	0.175	685.890	12.65500	1.895	0.015227	284.38	2452	8623	$3,604,550	$12,675,334
11	0.183	686.307	12.44667	1.892	0.015342	285.66	2463	8623	$3,620,882	$12,675,334
12	0.192	686.723	12.23833	1.890	0.015455	286.89	2474	8623	$3,636,447	$12,675,334
13	0.200	687.140	12.03000	1.888	0.015565	288.06	2484	8623	$3,651,288	$12,675,334
14	0.208	687.557	11.82167	1.885	0.015673	289.18	2493	8623	$3,665,442	$12,675,334
15	0.217	687.973	11.61333	1.883	0.015778	290.24	2503	8623	$3,678,945	$12,675,334
16	0.225	688.390	11.40500	1.881	0.015881	291.26	2511	8623	$3,691,830	$12,675,334
17	0.233	688.807	11.19667	1.879	0.015983	292.23	2520	8623	$3,704,127	$12,675,334
18	0.242	689.223	10.98833	1.876	0.016082	293.16	2528	8623	$3,715,863	$12,675,334
19	0.250	689.640	10.78000	1.874	0.016179	294.04	2535	8623	$3,727,065	$12,675,334
20	0.258	690.057	10.57167	1.872	0.016275	294.88	2543	8623	$3,737,757	$12,675,334
21	0.267	690.473	10.36333	1.869	0.016368	295.69	2550	8623	$3,747,962	$12,675,334
22	0.275	690.890	10.15500	1.867	0.016461	296.46	2556	8623	$3,757,699	$12,675,334
23	0.283	691.307	9.94667	1.865	0.016551	297.19	2563	8623	$3,766,990	$12,675,334
24	0.292	691.723	9.73833	1.863	0.016640	297.89	2569	8623	$3,775,852	$12,675,334
25	0.300	692.140	9.53000	1.860	0.016728	298.56	2574	8623	$3,784,304	$12,675,334
								Bare Pipe Case. Present Value (annual OPEX discounted at 10% rate)	$32,323,586	$115,054,517

Table 11. Coated pipe Electricity cost calculations

Analyzed case: FBE coated. Initial wall thickness = 9.53 mm; year 25 wall thickness = 9.53 mm. Initial pipe roughness = 0.01 mm; year 25 pipe roughness = 0.05 mm. Fixed parameters: Elevation head = 1000 m; pump efficiency = 0.82%; energy cost = 0.174 $/kWh; outside diameter = 28"; flow rate = 700 L/s; density of water = 1030 kg/m3; viscosity of water = 0.0013 Pa·s

Yr	Pipe roughness [mm]	Interior Diameter [mm]	Wall thickness [mm]	Fluid Velocity [m/s]	Friction factor f	Head Loss [m]	Pump Friction [kW]	Pump Elevation [kW]	Electricity Friction [M$]	Electricity Elevation [M$]
1	0.0100	692.140	9.53000	1.860	0.011929	212.91	1836	8623	$2,698,730	$12,675,334
2	0.0117	692.140	9.53000	1.860	0.011980	213.83	1844	8623	$2,710,311	$12,675,334
3	0.0133	692.140	9.53000	1.860	0.012031	214.73	1852	8623	$2,721,728	$12,675,334
4	0.0150	692.140	9.53000	1.860	0.012080	215.61	1859	8623	$2,732,985	$12,675,334
5	0.0167	692.140	9.53000	1.860	0.012130	216.49	1867	8623	$2,744,089	$12,675,334
6	0.0183	692.140	9.53000	1.860	0.012178	217.35	1874	8623	$2,755,043	$12,675,334
7	0.0200	692.140	9.53000	1.860	0.012226	218.21	1882	8623	$2,765,852	$12,675,334
8	0.0217	692.140	9.53000	1.860	0.012273	219.05	1889	8623	$2,776,522	$12,675,334
9	0.0233	692.140	9.53000	1.860	0.012319	219.88	1896	8623	$2,787,055	$12,675,334
10	0.0250	692.140	9.53000	1.860	0.012365	220.70	1903	8623	$2,797,457	$12,675,334
11	0.0267	692.140	9.53000	1.860	0.012411	221.51	1910	8623	$2,807,731	$12,675,334
12	0.0283	692.140	9.53000	1.860	0.012456	222.31	1917	8623	$2,817,880	$12,675,334
13	0.0300	692.140	9.53000	1.860	0.012500	223.10	1924	8623	$2,827,908	$12,675,334
14	0.0317	692.140	9.53000	1.860	0.012544	223.89	1930	8623	$2,837,819	$12,675,334
15	0.0333	692.140	9.53000	1.860	0.012587	224.66	1937	8623	$2,847,616	$12,675,334
16	0.0350	692.140	9.53000	1.860	0.012630	225.42	1944	8623	$2,857,302	$12,675,334
17	0.0367	692.140	9.53000	1.860	0.012672	226.18	1950	8623	$2,866,879	$12,675,334
18	0.0383	692.140	9.53000	1.860	0.012714	226.93	1957	8623	$2,876,351	$12,675,334
19	0.0400	692.140	9.53000	1.860	0.012756	227.66	1963	8623	$2,885,721	$12,675,334
20	0.0417	692.140	9.53000	1.860	0.012797	228.40	1969	8623	$2,894,990	$12,675,334
21	0.0433	692.140	9.53000	1.860	0.012837	229.12	1976	8623	$2,904,163	$12,675,334
22	0.0450	692.140	9.53000	1.860	0.012877	229.84	1982	8623	$2,913,240	$12,675,334
23	0.0467	692.140	9.53000	1.860	0.012917	230.54	1988	8623	$2,922,224	$12,675,334
24	0.0483	692.140	9.53000	1.860	0.012956	231.25	1994	8623	$2,931,118	$12,675,334
25	0.0500	692.140	9.53000	1.860	0.012995	231.94	2000	8623	$2,939,924	$12,675,334
								Bare Pipe Case. Present Value (annual OPEX discounted at 10% rate)	**$25,223,188**	**$115,054,517**

References

[1] CRTS, Inc, "INTERNALLY COATED FIELD JOINTS ON WELDED STEEL PIPELINES.," [Online]. Available: https://www.iecengenharia.com.br/wp-content/uploads/2017/11/bt_img/crts---completo.pdf.

[2] TYHOO Group, "Internal Field Joint Coating Robot," 2023. [Online]. Available: https://www.tyhoogroup.com/index.php/default/category/25.html.

[3] Confidential, Interviewee, *Internal Girth Weld Coating · Firm Proposal.* [Interview]. Sept 2024.

[4] C. Supplier, Interviewee, *Tratamiento Aguas Acueducto.* [Interview]. May 2022.