DYNAMIC\_VISCOSITY\_OF\_WATER[[1]](#footnote-1)

Comparative Analysis of Corrosion Mitigation Strategies  
 in Water Pipelines: Interior Epoxy Coating vs Bare Pipe  
[](https://zenodo.org/records/14911683)

I. Mella[[2]](#footnote-2)

*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).

# 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.

# 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](https://github.com/ignaciomella/Bare-vs-Coated-Water-Pipelines/), including an Excel workbook implementing the Newton-Raphson iterative technique for precise determination of Darcy-Weisbach friction factor.

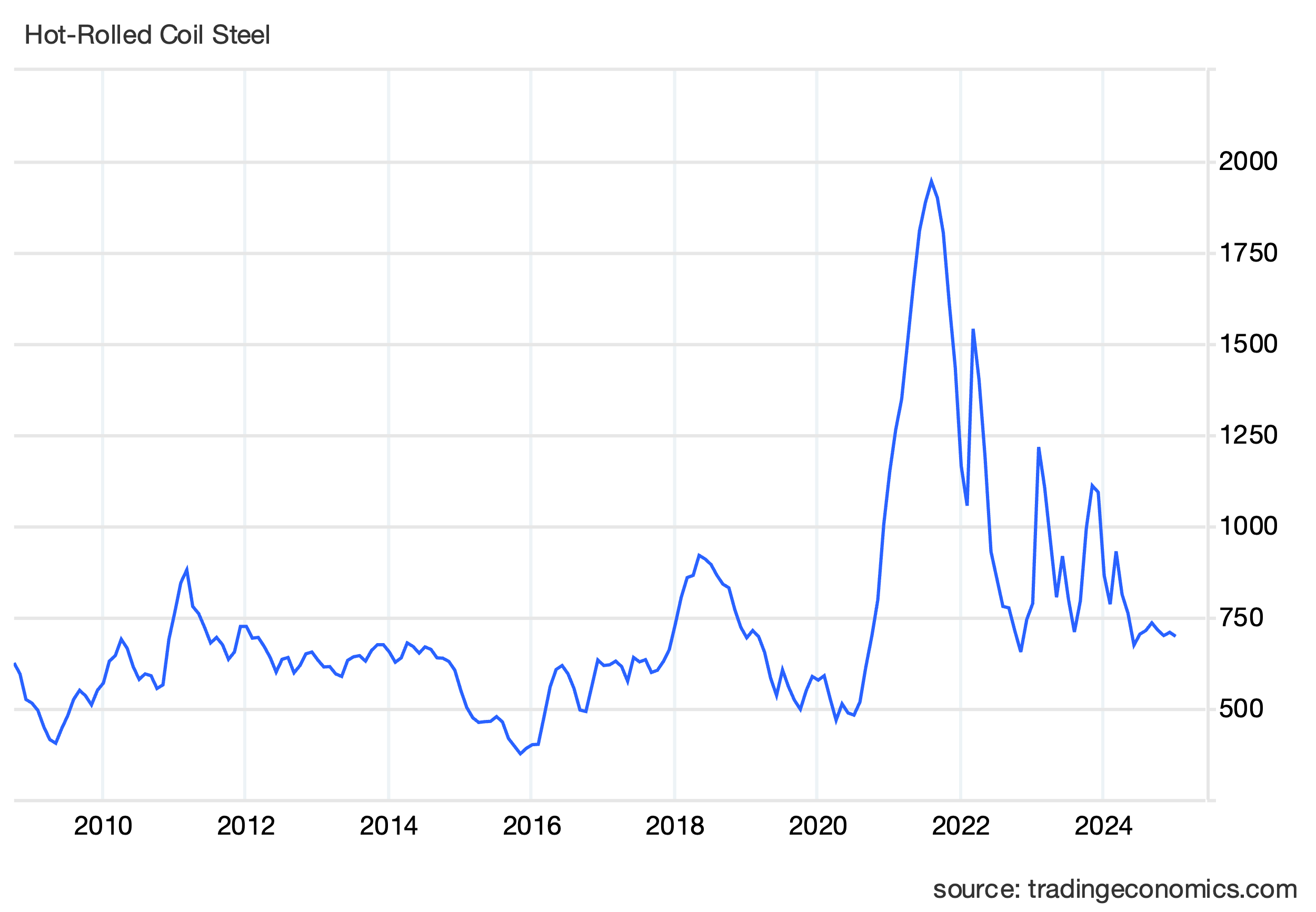
The author expects that this methodological transparency enables independent verification of results while providing an adaptable framework for evaluating corrosion management strategies under diverse operational conditions. This systematic approach aims to advance evidence-based decision-making in pipeline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

# Capital Expenditure Analysis

## 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 Chilean mining projects. This yields *CPW* = (550·2) + 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:

(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 |
|  | | |

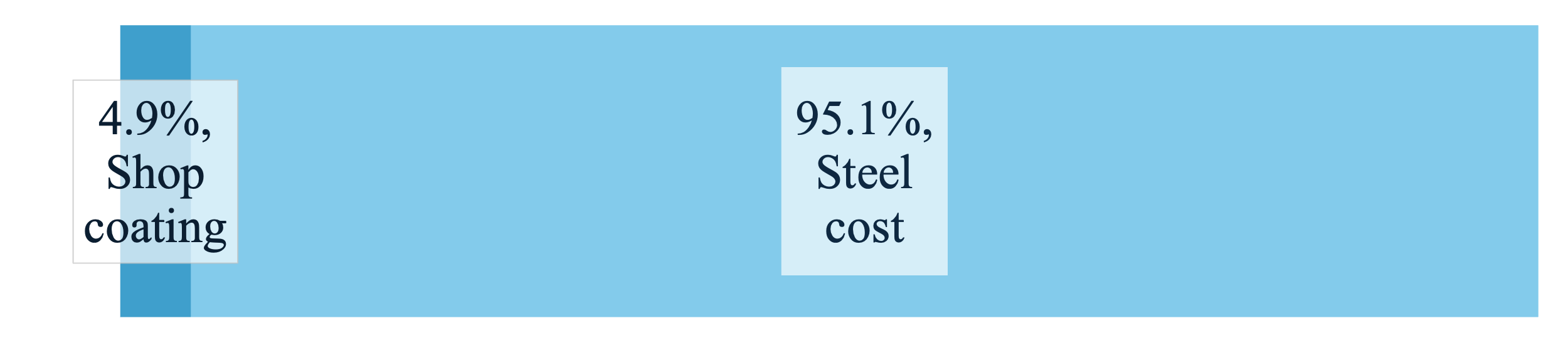
## Interior FBE Coating Economics

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:

(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 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].

## Internal Robotic Field Joint Coating

Post-weld interior coating necessitates advanced robotic crawler systems to mitigate heat-affected zone degradation of shop-applied fusion-bonded epoxy (FBE) layers. Modern units integrate abrasive blasting (SA 2.5 surface profile) and electrostatic application of epoxy via rotating nozzles, achieving 95% transfer efficiency for powder formulations [8] [9]. These systems now incorporate real-time quality assurance tools, including dry film thickness (DFT) gauges and 67.5 V/µm holiday detection, to address historical adhesion failures in field applications [10].

Field conditions—particularly temperature swings (±15°C), humidity variations (30–95% RH), and airborne contaminants—compromise coating integrity by altering cure kinetics. Studies demonstrate a 23% reduction in epoxy adhesion strength when applied at >85% RH versus controlled shop environments [11]. This environmental sensitivity explains why field-applied coatings exhibit 2.8× more pinhole defects than mill-applied systems, with improper surface preparation accounting for 61% of failures in third-party audits [12] [13].



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

Internal corrosion remains the dominant failure mechanism in pipelines conveying aggressive media, responsible for 49% of gas-gathering system incidents and 67 annual failures in hazardous liquid pipelines (2010–2013 data) [14]. In seawater applications, unpigmented FBE systems show 0.15–0.28 mm/yr corrosion rates when field-applied, versus 0.03–0.07 mm/yr for shop-coated equivalents [15]. This disparity stems from compromised interfacial bonds in field conditions, where residual chlorides >50 µg/cm² persist after blasting in 34% of cases [10] [16].

|  |  |
| --- | --- |
| 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.* |

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 [11].
* TYHOO Group: Focuses on cost-optimized modular robots designed specifically for pipelines with diameters under 28 inches [12].

Their cost per joint varies between $800 to $1,200 per joint depending mainly on the site location, the diameter and the length of the pipeline[13]. This analysis will consider a price per joint of $1,000 per joint. Annex B – shows the cost composition for robotic coating internal field joints.

For the 5,834-joint pipeline, this aggregates to $5,834,000 which is **7.7 times** the cost of the Interior FBE Coating.

Table 3. CAPEX Composition for Coated Pipe

|  |  |  |  |
| --- | --- | --- | --- |
| CAPEX Item | Cost | % | Surface |
| Total steel cost | $16,391,992 | 69.0% |  |
| Field joint coating | **$5,367,280** | 27.4% | 0.42% |
| Shop FBE coating | $761,048 | 3.6% | 99.58% |
| Total CAPEX | $22,520,319 | 100% | 100% |

Interior-coated FBE steel pipes are designed with a deliberate uncoated cutback at the pipe ends, typically 50 mm long, which represents 0.42% of the pipe's inner surface area. This cutback serves three critical purposes: it facilitates welding, prevents coating damage during the welding process, and allows for an easier application of field joint coatings.

However, the field-applied inner coating required for this small cutback area is approximately **1,817 times** more expensive per square meter than the shop-applied coating.

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.

|  |
| --- |
| **[A long pipe on a road  AI-generated content may be incorrect.](https://youtu.be/e14DHsekBIg?si=nDQ1uiHFtaoSzMGE)**  Photo 3. [SQM’s TEA project](https://youtu.be/e14DHsekBIg?si=nDQ1uiHFtaoSzMGE), a 32" seawater interior FBE coated pipeline was joined by Victaulic’s X07 couplings.  The need for robot field coating was eliminated. |
|  |

# Operational Expenditures

## Corrosion inhibitors injection

While corrosion allowance provides structural buffer through increased wall thickness, active inhibition via chemical treatments proves more cost-effective for long-distance pipelines. Experimental validation confirms a 26 ppm sodium polyphosphate dosage achieves target corrosion rates ≤0.15 mm/year through passivation film formation. Complementary biocide protocols apply weekly 4-hour shock treatments (20 ppm glutaraldehyde equivalent to 0.46 ppm continuous dose) for microbial control.

*Service-Based Infrastructure Model:* Third-party managed dosing systems replace owned infrastructure through subscription services ($1,000/month OPEX).

Providers maintain:

- Flow-responsive injection systems (0.7 m³/s baseline)

- Automated concentration control (±2% variance)

*OPEX Calculation Parameters:* Given:

- Annual operating hours: 8,400

- Flow rate: 0.7 m³/s → 21,168,000 m³/year

- Inhibitor cost: $1.8/kg (sodium polyphosphate)

- Biocide cost: $12.8/kg (glutaraldehyde)

Dosage requirements derived from:

- Continuous inhibitor:

26 ppm × 21,168,000 m³/year = 550,368 kg/year

- Biocide equivalent:

0.46 ppm × 21,168,000 m³/year = 9,660 kg/year

Table 4. Calculated Dosage to achieve  
at least 0.15 mm/yr corrosion rate.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| ***Item*** | ***Dosage*** *ppm* | ***Price*** *per  kg* [14] | ***Mass*** *kg per year* | ***Cost*** *($/year)* |
| Inhibitor | 26.00 | $1.7 | 550,368 | $920,215 |
| Biocide | 0.46 | $12.8 | 9,660 | $123,648 |
| Dosing Plant | | | | $12,000 |
|  |  |  | Total OPEX | $1,126,310 |

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):

(1)

Where *PV* is the Present Value, *FV* is the future value (annual OPEX of $1,126,310); *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 $10,223,565.

## 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 5. 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.

## 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:

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 6.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 |

(2)

Where is fluid density; *g* is the gravitational acceleration; *Q* is the volumetric flow rate; is the total head loss due to friction losses () plus elevation head ( = 1000 m); 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.

(3)

Where 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; 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.

(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:

(5)

Where is the fluid density (1030), is the fluid velocity on year 1 (1.915 m/s) derived from the flow ratio of 0.7 m³/s, is the pipe inside diameter (0.68464m) for wall thickness of 13.28 mm on year 1, is the dynamic viscosity (0.0013 Pa·s). Substituting values, . Again, substituting values on eq (4):

(6)

Solving for *f* using the Newton-Raphson iterative numerical technique which converges to *f* = 0.014030. Substituting values on eq (3):

(7)

Again, substituting values on eq (2):

(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.

*Coated Pipe Case Calculations*: 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.

Table 7. Electricity Consumption Present Value Comparison

|  |  |  |  |
| --- | --- | --- | --- |
| Energy Cost PV | Bare Pipe | Coated Pipe | Difference |
| Friction | $32,323,586 | $25,223,188 | $9,105,514 |
| Elevation | $115,054,517 | $115,054,517 | $0 |

# 

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | *Item* | *Bare Pipe* | *Coated Pipe* | *Difference* | |
| CAPEX | Corrosion Extra Steel | $5,659,618 |  | $5,659,618 |
| Field Joint Coating |  | $5,834,000 |  | ($5,834,000) |
| Shop FBE Coating |  | $761,048 |  | ($761,048) |
| OPEX | Friction Energy | $34,702,859 | $25,223,188 | $9,105,514 |  |
| Corrosion Inhibitors | $10,114,640 |  | $10,223,565 |  |
| Pipeline Inspections | $5,083,142 | $2,541,571 | $2,541,571 |  |
|  | Total | $55,242,241 | $34,307,021 | $20,935,220 |  |

# Analysis of Results

As previously presented in Table 8, the energy elevation costs ($115,054,517) remain identical for both scenarios. Since the energy required to transport the fluid uphill is unaffected by the choice of corrosion mitigation strategy, these costs will be excluded from this analysis.

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# 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 Shop Coating [ 0.8 ] Coated\nCAPEX to initial costs | Lower initial steel cost; additional $761,048for shop coating and $5,834,000 for field joint coating. |
| **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. |

# 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 9. 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 10. 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** |

Table 11. Cost components for robotic field coating

|  |  |
| --- | --- |
| ***Cost Component*** | ***Cost per Joint*** |
| 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 |

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|  |  |
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