Corrosion of Above Ground Pipe

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Abstract

The Water Corporation currently operates over 3,000 km of above-ground steel mains across Western Australia. As the Corporation does not have a defined coating maintenance strategy, a decision on whether such a policy is required to increase the durability of old in-service mild steel cement lined (MSCL) pipes must be made. This project aims to quantify the effects of applying protective coatings to existing above-ground MSCL pipes to extend their economic life.

The physical life of MSCL pipes due to external corrosion was estimated from Monte-Carlo simulations. Net present value calculations for the maintenance of coating systems specified in the Corporation's standard, (DS-95) under different atmospheric corrosivity environments were evaluated to determine the most economic approach to asset durability.

Simulation results indicate that old MSCL pipes without maintenance are unlikely to survive to the design life of 110 years. Cost calculations indicate that the Corporation's inorganic zinc silicate coating system is most economic due to its superior durability. Based on economic analysis, it is recommended that coating maintenance is conducted upon detection of 5 - 10% coating failure on MSCL pipes in high corrosivity environments to delay incurring pipe renewal costs; Coating maintenance incurs negligible benefits in low and medium corrosivity environments.

1. Introduction

The Corporation's standard, DS-95, has strict guidelines on the selection, preparation, and application of protective coatings on newly installed assets. However, the Corporation rarely conducts coating maintenance for its old in-service assets. There is interest in assessing the cost effectiveness of the choices of leaving the existing MSCL pipes as is, or implementing a coating maintenance program to enhance the durability of old in-service assets.

Severe consequences could be incurred if MSCL mains fail due to external corrosion:
- Disruption of communities, business, and services
- Water supply interruption and revenue loss
- Damage to public image and trust from clients
- Property and infrastructure damage

To increase the durability of in-service assets, it is best to conduct coating maintenance before the loss of coating integrity and corrosion of the substrate has taken place (Standards Australia, 2014). AS 2312 (Guide to the protection of structural steel against atmospheric corrosion by the use of protective coating) recommends conducting coating maintenance on assets when coating deterioration is observed in aggressive atmospheric environments. This is to avoid the costly surface preparations needed on heavily pitted steels before protective coatings can be applied. Maintenance of assets in low and mild atmospheric environments can be postponed to suit the asset's maintenance program (Standards Australia, 2014).

It is most cost-effective to repair coatings when 1% to 2% of coating deterioration has occurred for a uniformly scattered breakdown across the whole asset (Standards Australia, 2014). Touch-up operations are only practical when 5% to 10% of coating deterioration has appeared in a defined region (Helsel et al, 2022).

2. Process

2.1 MSCL Pipe Age Modelling

The physical life at which above-ground MSCL pipes reach a state of functional failure due to external corrosion under different atmospheric corrosivity environments and internal corrosion have been modelled by Monte-Carlo simulations. The maximum allowable operating pressure (MAOP) of metal pipes proposed by ASME B31G is used as the physical failure criterion and is evaluated as:

$$P_{max} = 0.72 \times \frac{2 \times S_F \times t}{OD}$$

$$If\ z \leq 20, S_F = 1.1 \times SMYS\ [(1 - 2/3(d/t))/(1 - 2/3(d/t)/\ (1 + 0.8z)\hat{}0.5)]$$

$$If\ z > 20, S_F = 1.1 \times SMYS\ (1 - d/t)$$

$$z\ =\ L^2/(OD \times t)$$

P_{max} is MAOP, S_F is failure stress due to defects, $SMYS$ is specified material yield strength, t is wall thickness, OD is outer diameter, L is the length of internal defect and d is the depth of internal defect.

The time taken for the MAOP to reduce to the current operating pressure due to wall thickness reduction represents the physical life of the pipe. The Monte-Carlo simulation involves normally distributed random number generator functions inbuilt in Python, which generate annual corrosion rates in different environments. Table 1 specifies the left and right bounds of 3 standard deviations from the mean for distributions used in the simulation. Protective coatings are considered to reach failure when the coating has reached its durability, as specified in AS 2312. The simulation, applying the logic depicted in figure 1, is conducted 5000 times to obtain a distribution of pipe age.

Atmospheric Corrosivity	Corrosion Rate of Steel ($\mu m/yr$)	Typical Environment
C1 – Very Low	< 1.3	Indoor
C2 – Low	1.3 – 25	Rural Area
C3 – Medium	25 – 50	Coastal Area
C4 – High	50 – 80	Seashore
C5 – Very High	80 – 200	Industrial Zone

Table 1 Atmospheric corrosivity category, adapted from Table 2.1 of AS 2312.

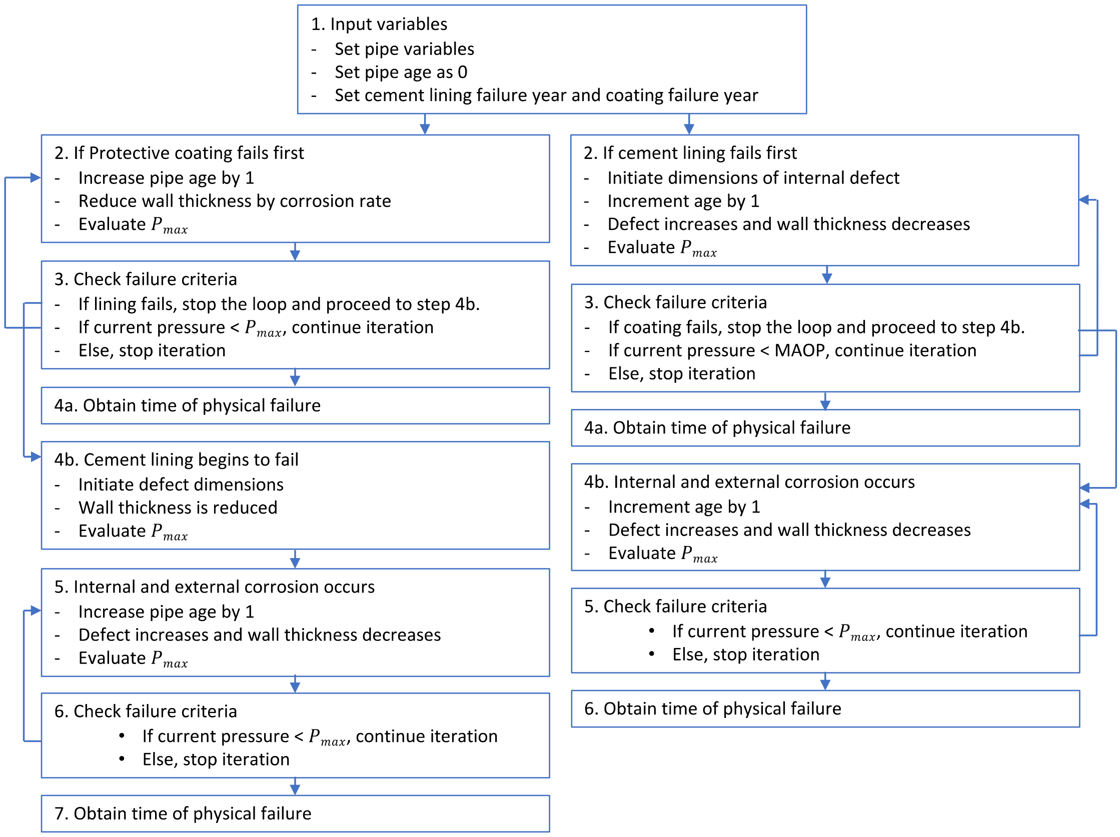

Figure 1 Time to failure model logic diagram

2.2 Coating Maintenance Cost Analysis

2.2.1 Life cycle cost of coating maintenance

It is assumed that a coating maintenance program includes initial coating, continuous cycles of touch-up, maintenance and full repaint operations until the structure reaches failure due to internal corrosion. The durability of protective coatings is specified in AS 2312 and is used as a time estimate for when first coating maintenance operations should occur. Table 2 lists the occurrence of coating maintenance operations in terms of durability and the cost in terms of the original cost of initial coating.

Operation	Occurrence (Yr.)	Cost if Original in Field
Initial Coating	0	Original
Touch-Up	D	Maintenance×40%
Maintenance (prime + full coat)	1.7D	Maintenance×70%
Full Repaint	1.7D+0.5D	Original×135%

Table 2 Cost and schedule of coating maintenance operations, adapted from Table 2 of Expected Service Life and Cost Considerations for Maintenance and New Construction Protective Coating Work.
'D' denotes durability, the year to first coating maintenance.
'Original' denotes the cost of the original coating.
'Maintenance' denotes the cost of applying maintenance coating to the full structure.

After establishing a schedule for all coating maintenance operations, the current cost of all maintenance operations must be compounded to future value terms with the current inflation rate. (For i is inflation rate and n is number of years)

$$FV = Current\ Cost \times (1 + i)^n$$

The future values must be discounted with the current interest rate to obtain the present value of coating operations occurring in the future. (For i is interest rate and n is number of years)

$$PV = FV \times 1/(1 + i)^n$$

The Average Equivalent Annual Cost (AEAC) is used to compare the life cycle cost of implementing different coating systems in a coating maintenance program. The AEAC distributes the NPV in equal annual costs over the lifetime of the structure.
(For i is interest rate and n is the structure life)

$$AEAC = NPV \times [\frac{i(1 + i)^n}{(1 + i)^n - 1}]$$

2.2.2 Cost analysis of base case vs coating maintenance

The AEAC of 2 scenarios is calculated to compare the life cycle costing of in-service above ground MSCL pipes:

- Base case: apply protective coating once and leave the asset until replacement is required.
- Conduct coating maintenance: follow the coating maintenance program, scheduled as per table 2, until replacement is required.

3. Results

3.1 MSCL Pipe Age - Model Results

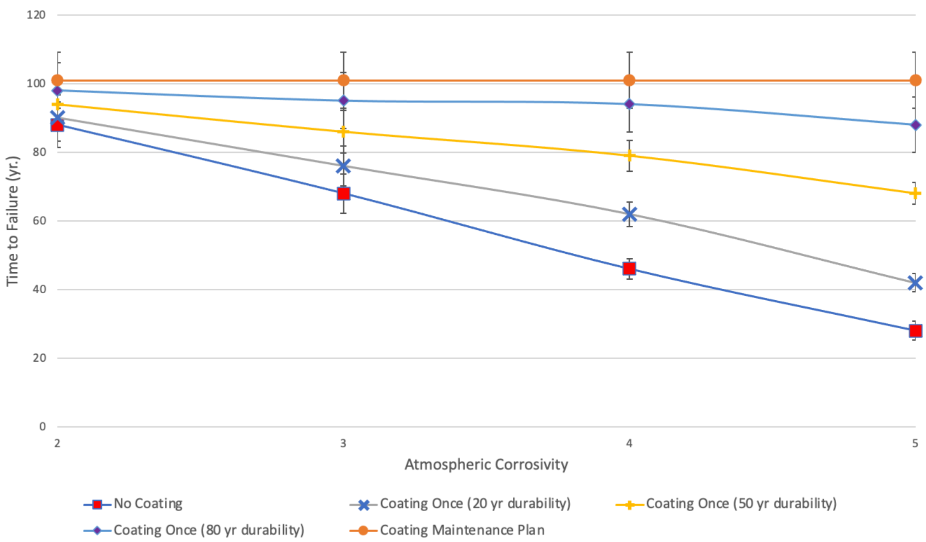

Figure 2 The effect of coating durability on the time to failure of a DN 900 MSCL pipe situated above ground.

From figure 2, it can be concluded that conducting coating maintenance has significant impact on the time to failure of MSCL pipes in medium to very aggressive environments. MSCL pipes with old specifications as listed in the Corporation's strategic product specification, SPS–100, are unlikely to survive to their design life of 110 years without conducting coating maintenance and patch repairs.

3.2 Cost Analysis

Coating System	Total Cost
B1 – Inorganic Zinc Silicate	$22
C1 – Zinc Rich Epoxy	$26
C2 – Zinc Rich Epoxy, Epoxy Mastic, Polyurethane	$49
C3 – Zinc Rich Epoxy, Epoxy Mastic	$40
C4 – Zinc Rich Epoxy, Polyurethane	$35
E1 – Epoxy Mastic (Maintenance)	$27
E3 – Epoxy Mastic, Polyurethane (Maintenance)	$37

Table 3 Cost of applying protective coating ($/m^2) with 25% contingency.

Atmospheric Corrosivity	Original Coating System		
	B1 – IZS	C2 – ZRE, EM, P	C4 – ZRE, P
Very Low	< $2.30	< $6.30	< $4.80
Low	$2.30	$6.30	$4.80
Medium	$3.70	$6.30	$6.20
High	$5.80	$10.50	-
Very high	$8.70	$14.20	-

Table 4 AEAC ($/m^2) of conducting coating maintenance on original coating systems under different atmospheric corrosivity environments to achieve asset durability of 110 years. (Assuming inflation rate of 5% and interest rate of 7.2%)

Atmospheric Corrosivity	Base Case Coating Systems			Maintenance and Repair Coating Systems		
	B1	C2	C4	B1	C2	C4
Low	$37	$45	$39	$35	$46	$38
Medium	$51	$56	$53	$38	$46	$41
High	$71	$77	Not Used	$44	$55	Not Used
Very high	$110	$116	Not Used	$52	$68	Not Used

Table 5 AEAC ($/m) comparison between base case and maintenance repair for a DN 900 MSCL pipe.

It is beneficial to conduct coating maintenance for pipes in aggressive atmospheric environments as pipe replacement costs would be deferred. Coating maintenance of pipes in low corrosivity environments are only marginally beneficial and can be delayed to be conducted with other maintenance activities.

4. Conclusions and Future Work

The time to failure model developed can be used to estimate the failure year of above ground MSCL pipes due to external and internal corrosion. From the simulation, in-service pipes with old specifications will require both patch repairs and coating maintenance to achieve the design life of 80 – 110 years.

It must be noted that the model has several limitations. The reduction in the corrosion rate of the substrate due to the formation of corrosion products is difficult to account for. In addition, the model does not consider localised corrosion at the bolsters and transition zones.

The AEAC of conducting coating maintenance and pipe renewals was evaluated to determine the most economic approach to maintaining in-service MSCL pipes. From an economic perspective, it is recommended that the Corporation should conduct coating maintenance upon detection of 5% - 10% coating failure on MSCL pipes in aggressive atmospheric environments to prevent incurring early pipe renewal cost; It is permissible to defer coating maintenance of pipes in low to medium corrosivity environments as cost benefits are marginal. As MSCL pipes mostly fail due to internal corrosion, it is recommended that internal conditions of MSCL pipes are investigated when pipe assets have been in-service for 60 – 70 years to allow patch welding operations to be conducted to increase asset service life.

Despite the economic analysis conducted, the decision process on whether to conduct coating maintenance or not is also dependent on the consequences of pipe failure and the acceptance criteria for coating condition. Future works includes the review and adaptation of coating maintenance practices and development of a coating maintenance management system which meets the needs of the Corporation.

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6. References

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