BASIC MECHANISMS OF CORROSION AND CORROSION CONTROL FOR WATER AND WASTEWATER SYSTEMS

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Walking Through the Minefield of Corrosion
Market Driver for Corrosion Control is 
Entropy

Our “Business” is Guaranteed by a Fundamental Law of Nature:

$$\Delta S_{\text{universe}} \geq 0$$
Corrosion is the deterioration of a substance or its properties as a result of an undesirable reaction with the environment.

"Energy spontaneously tends to flow only from being concentrated in one place to becoming diffused or dispersed and spread out."

- NACE International

It is irreversible and degenerative and related to the Second Law Thermodynamics
Everything You Need to Know About Corrosion

4 Parts of a Corrosion Cell

- Anode (location where corrosion takes place)
  - Oxidation Half-Reaction
- Cathode (no corrosion)
  - Reduction Half-Reaction
- Electrolyte (Soil, Water, Moisture, etc.)
- Electrical Connection between anode and cathode (wire, metal wall, etc.)

Electrochemical corrosion can be stopped by eliminating any one of the 4 components
Electrochemical Corrosion Cell

Metallic Path

Electrolytic Path

A

+ ions

- ions

C
Anode
Cathode
Electrolyte
Metallic Path
Electron Flow
Can you find the anode?
The Corrosion Puzzle

Anode

Electrolyte

Cathode

Metallic Path

Corrosion
Remove any piece of the puzzle and corrosion stops!
U.S. Cost of Corrosion is about 3.1% of GDP (50% to 70% Related to Civil Engineering)

2010 US GDP = $14.72 Trillion
U.S. Cost of Corrosion = $460 Billion
Objectives of the Most Infrastructure Projects

• Provide a 50 + Year Useful Life

• Useful life means:
  – Functionality Assured
  – Structural Integrity Maintained
  – Operating Costs Controlled

• How do we do this?
  – Control the two time dependent degradation mechanisms
    • Corrosion
    • Fatigue
    • Creep (Generally Not Applicable)
Two distinct and different types of Situations:

- **New Pipe (Lot of Options)**
  - Chance to Do it Right
  - Right of Way Study through Construction

- **Existing Pipe (Limited Options)**
  - “Sins of the father”
  - Condition Assessment

For both, Corrosion Control is a Process, not a Project.
Material Selection/Design Details
- Choose materials compatible with environment.
- Do not create corrosion cell through design/construction details.

Corrosion Inhibitors
- Alter the environment adjacent to metal to passivate and protect metal.
- Concrete or mortar on steel are inhibitors.
Cathodic Protection
- Electrochemically alter the surface condition of the metal to move the anodic reactions elsewhere.

Coatings (exterior) and Linings (interior)
- Provide a barrier to the electrolyte and protect the metal. Usually dielectric material that prevents electron and ionic current flow.
Coatings and Cathodic Protection Work Together

- Cathodic protection can be applied without coatings.
- Coatings should not be used without cathodic protection.
- Cathodic protection effectively protects defects in the coating.
  - In many environments actually repairs the coating locally by depositing minerals that plug the holes in the coating.
Effect of Cathodic Protection

**Current**

**ANODE**
-0.65 volt

**CATHODE**
-0.50 volt

**I_{corr} = 1 mA**

**ANODE**
-0.65 volt

**CATHODE**
-0.60 volt

**I_{corr} = 0.3 mA**

**Before Cathodic Protection**

**After Cathodic Protection**

**Reduction in corrosion current**

**C.P. CURRENT**
Cathodic Protection Stops Leaks

Cumulative Breaks over Time

- Actual Breaks
- Projected Breaks without Protection

666 breaks projected without protection
103 breaks total - 3 after protection

Year
$$ are Directly Proportional to Current Capacity (Amps)

- Life Cycle Costs = Construction + Operating Costs
- Initial/Construction costs ~ Amps
- Operating/Maintenance Costs ~ Amps
- Anything and everything you do to reduce current requirement saves $$$. 
## CP Current Requirements for Water Industry Piping

<table>
<thead>
<tr>
<th>Pipe Material</th>
<th>Coating System</th>
<th>Current Requirement (ma/sf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel/Iron</td>
<td>None</td>
<td>1 to 3</td>
</tr>
<tr>
<td>Steel</td>
<td>AWWA C205</td>
<td>0.1 to 0.5</td>
</tr>
<tr>
<td>Steel/Iron</td>
<td>Dielectric Coating AWWA C214, 217, 222</td>
<td>0.0006 to 0.020</td>
</tr>
<tr>
<td>Ductile Iron with PE</td>
<td>AWWA C105</td>
<td>0.020 to 0.040</td>
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</tbody>
</table>
Water vs. Wastewater: External Corrosion

- Mechanisms are identical
- Corrosion Control for Exterior is Identical
- Materials, Design and Construction Practices
  - Similar.....
  - But Wastewater construction does not typically account for the eventual need for cathodic protection
    - Electrical Continuity of Pipelines and Structures
    - Electrical Isolation for Appurtenances
Water vs. Wastewater: Internal Corrosion

- Not the Same At All.
- Corrosion Rates for wastewater can be extremely high.
- More often internal corrosion leads to problems
- This is one reason why external corrosion is ignored.
• Dominated by Formation of Sulfuric Acid

\[
\begin{align*}
\text{H}_2\text{S} + 2\text{O}_2 &\rightarrow \text{H}_2\text{SO}_4 \\
\text{SO}_4^{2-} + \text{organic matter} &\rightarrow \text{S}^{2-} + \text{H}_2\text{O} + \text{CO}_2 \\
\text{S}^{2-} + 2\text{H}^+ &\rightarrow \text{H}_2\text{S}
\end{align*}
\]
“Indirect” Impact of Regulations on Corrosion

H₂S crown
2-10 ppm
pH 3-4

H₂S crown
~ 30 ppm
pH 1-2

Clean Water Act of 1980

Reduced metal concentrations in sewage
Elevated levels of bacterial growth

Elevated levels of bacterial growth
Water Line Corrosion

Internal Corrosion
DIP for Force Main Gas Pocket Corrosion
Corrosion Control for the Outside of CMC or Concrete Water Pipes

- AWWA C205, C300, C301, or C303
- Corrosivity of alignment must be determined
  - Saturated ASTM G57 Soil Resistivity > 1500 Ω-cm
    - Chlorides < 350 ppm in soil
    - Sulfates < 2,000 ppm in soil
    - No fluctuating groundwater in pipe zone.
  - pH > 5.0
References

- AWWA Manual M27 – External Corrosion
- AWWA Manual M28 – Rehabilitation of Water Mains
- AWWARF Report 90987 – External Corrosion and Corrosion Control of Buried Water Mains
- NACE International Standards SP0169; SP0207; Peabody Control of Pipeline Corrosion
Things we try to avoid...
Condition Assessment is Part of the Asset Preservation

- Financial Motivation
  - Shrinking Budgets
  - GASB 34

- Political Motivation
  - Career Limiting Events

- Regulatory Motivation
  - Jail – Oil and Gas Model
Selection of Condition Assessment Technology Depends on Several Factors

- Budget
- Accessibility/Availability of Asset
- Risk Tolerance
- Best Practice is to use multiple methods
You can do something without Technology!

- Historical Information
  - Design Information
  - Leak and Break Rates
- Geographical Information
  - Where should I look?
- Industry Metrics
- Use your brain....

![Map and Graph](image)
Steel Reservoir Condition Assessments

- **Raft Inspection**
  - Confined Space
  - Limited View

- **Dry Inspections**
  - Unpopular to WD’s
  - Limits Defects and access

- **Hatch Inspection**
  - Limited View
  - Confined Space

- **Dive Inspections**
  - Hours of Boredom, Punctuated by Moments of Terror
  - Clarity of View
Steel Reservoir Coating Condition Assessment
Based on Holistic Results 2001-2002

Coating Replacement Recommended Based on Coating Condition Above Waterline

Existing CP System may be Damaging Coating
PCCP is a Complex Pipe Material.

- Composite pipe product
  - Internal mortar or concrete lining
  - Steel Cylinder
  - Concrete Core(s)
  - High Strength Prestressed Wires
  - Exterior Mortar Coating
- 1942 “War Pipe” substitute high strength steel and concrete for steel
- 18 to 250-inch diameter
- Up to 350 psi Pressures
Due to its Materials of Construction, PCCP does not Leak Before it Breaks

Each stick of PCCP contains stored energy equal to between 20 and 200 lbs of dynamite.
The Integrity of PCCP is Directly Related to The Integrity of the Wires

- Wires Break – Surge or Transient
- Exterior Mortar Damaged
- Compression in Concrete Core Reduced
- Concrete Core in Tension - Cracking
- Pipe Leaks or Fails
- Steel Cylinder Corrodes
For PCCP, Based on its Era of Design Initial Estimate of Risk Can Be Made
Old School
Condition Assessment
Internal Inspections

• Pre-1992, the only way to inspect PCCP was to dewater the pipeline and perform internal inspections.

• Visual inspection identified unusual cracking or poorly detailed joints.

• Sounding techniques located hollows or delaminations resulting from a loss of prestress.

• Human ear, 20 to 20k Hz

• After age 40, 20 to 16k Hz
Electromagnetic Inspection: “New” Assessment Technology

In 1999 & 2001, supplemented the internal “sounding” procedures with Remote Field Eddy Current/Transformer Coupling measurements (RFEC/TC).

- “A simple analogy: think of RFEC/TC system as a radio receiver
- The prestressing wire behaves like the radio antenna
- With no breaks in the continuity of the prestressing wire, the radio receives a clear signal from the transmitting station
- If the continuity of the prestressing wire is broken, the clarity of the signal received is also reduced.”
Not all damage will be found by technology
False Positive and Negatives are Possible with All Techniques

<table>
<thead>
<tr>
<th>Pipe Number</th>
<th>PURE</th>
<th>PPIC</th>
<th>Actual</th>
</tr>
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<tbody>
<tr>
<td>MK 1430</td>
<td>47</td>
<td>55</td>
<td>152</td>
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<tr>
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<tr>
<td>MK 719</td>
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<td>45</td>
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</tr>
<tr>
<td>MK 714</td>
<td>23</td>
<td>30</td>
<td>52</td>
</tr>
</tbody>
</table>
Imagine trying to play an entire round of golf with a 7-iron.

- You can do it but you don’t score well.
- Generally, you need a driver and a putter...at least I do.

Technology provides data, not information.
There are four ways to control corrosion:

- Material Selection and Design
- Corrosion Inhibitors and Monitoring
- Coatings and Linings
- Cathodic Protection

Technology is a powerful and expensive tool that needs to be used wisely.

There is no substitute for laying eyes and hands on the structure.