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Managing Water in the West

Corrosion Protection in Penstocks

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U.S. Department of the Interior
Bureau of Reclamation

Corrosion Protection in Penstocks

Webinar Objectives:

- Penstocks
- Review of Corrosion
- Condition assessments
- Common lining Materials
- Maintenance planning
- Specification development and project management
- Construction support



Penstocks

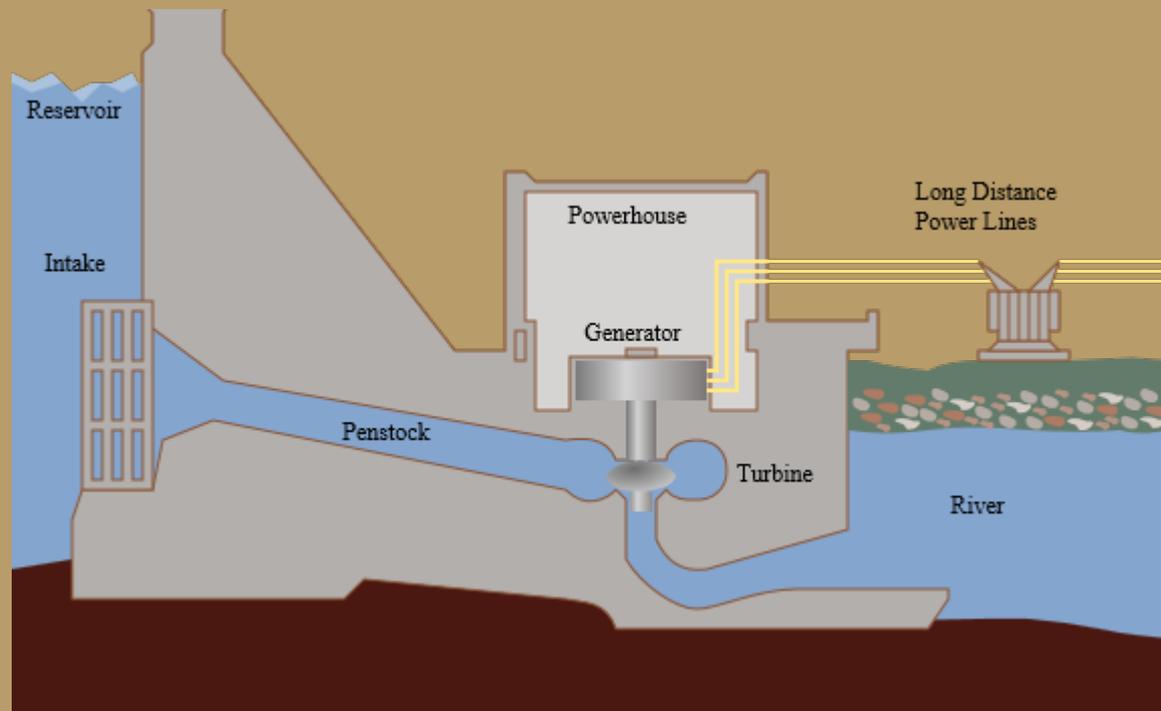
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Penstocks

Pressure vessels (typically steel lined) to convey water from the reservoir to the scroll case and turbine. Length and diameter vary widely and depend on the facility.

Designed for high pressure depending on the head of the reservoir

FIST (Facilities Instructions, Standards, and Techniques) Volume 2-8: Inspection of Steel Penstocks and Pressure Conduits states that they should be thoroughly inspected every 5 years



Review of Corrosion

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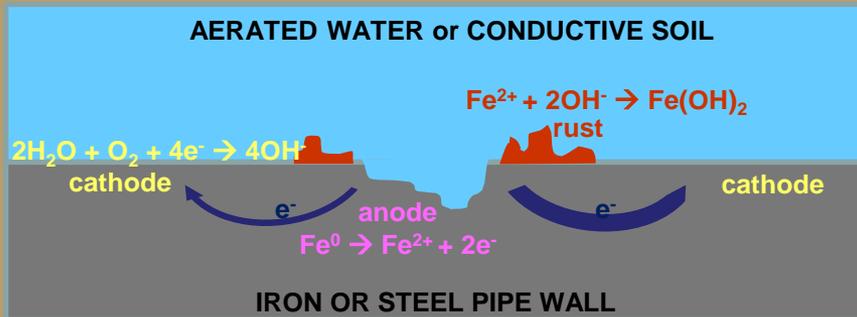
The Corrosion Reaction

ex. oxidation, "rusting," electroplating, anodizing

Electrochemical Reaction Between a Metal and an Electrolyte

ex. steel, copper, aluminum

ex. soil, water



Four Required Components for Corrosion:

1. Anode (Corrodes)
2. Cathode (Protected)
3. Metallic Return Path (ex. Tank)
4. Electrolyte (Usually Soil or Water)

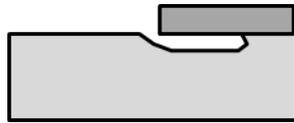
ACME

Forms of Corrosion Typical for Penstocks

Uniform or
General Attack



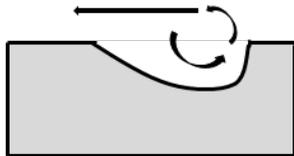
Crevice
Corrosion



Pitting



Erosion
Corrosion



Forms
of
Corrosion
Typical for
Penstocks

Dealing with Corrosion:

- Create barrier between metal and electrolyte- **Coating**
- Avoid use of dissimilar metals
- Cathodic Protection is less effective in penstocks due to the depolarizing effects of high water flow.

General or Uniform Corrosion

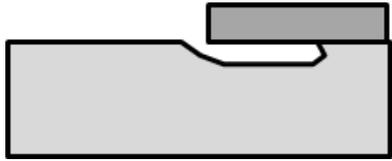


- Reactions occur uniformly over the surface, often at a steady and predictable rate
- Most important form based on weight of metal corroded
- Some Solutions:
 - Select a more corrosion resistant material
 - Apply protective coatings
 - Cathodically protect the structure
 - Specify corrosion allowance



El Vado Dam
Spillway, 1995

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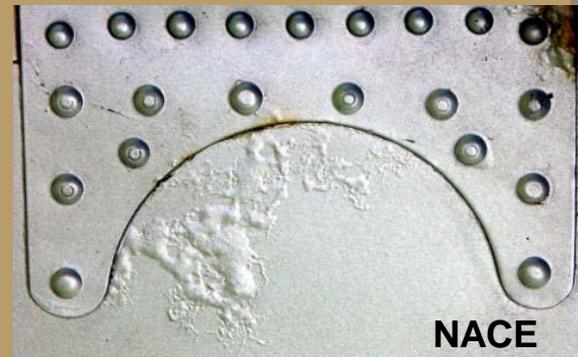


Crevice Corrosion

- Intensive localized corrosion within crevices and under coatings
- Examples:
 - expansion joints
 - piping supports
- Solutions:
 - Design components to eliminate crevices.
 - Coating repairs and caulking



Palo Verde Diversion Dam
Radial Gates, 2013





Pitting Corrosion

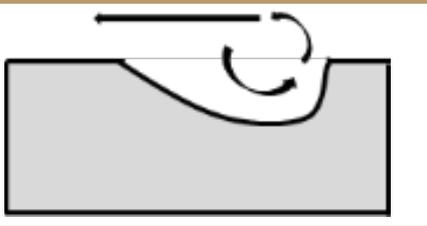
- Localized attack in an otherwise resistant surface
- Often occurs when protective coating breaks down
- Some Solutions:
 - Select suitably resistant material (316 vs. 304 SS)
 - Apply Protective Coating
 - Cathodic Protection
 - Avoid designs where stagnation, or alternate wetting and drying, can occur in pits



Dam
Outlet Works, 2003



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Erosion Corrosion

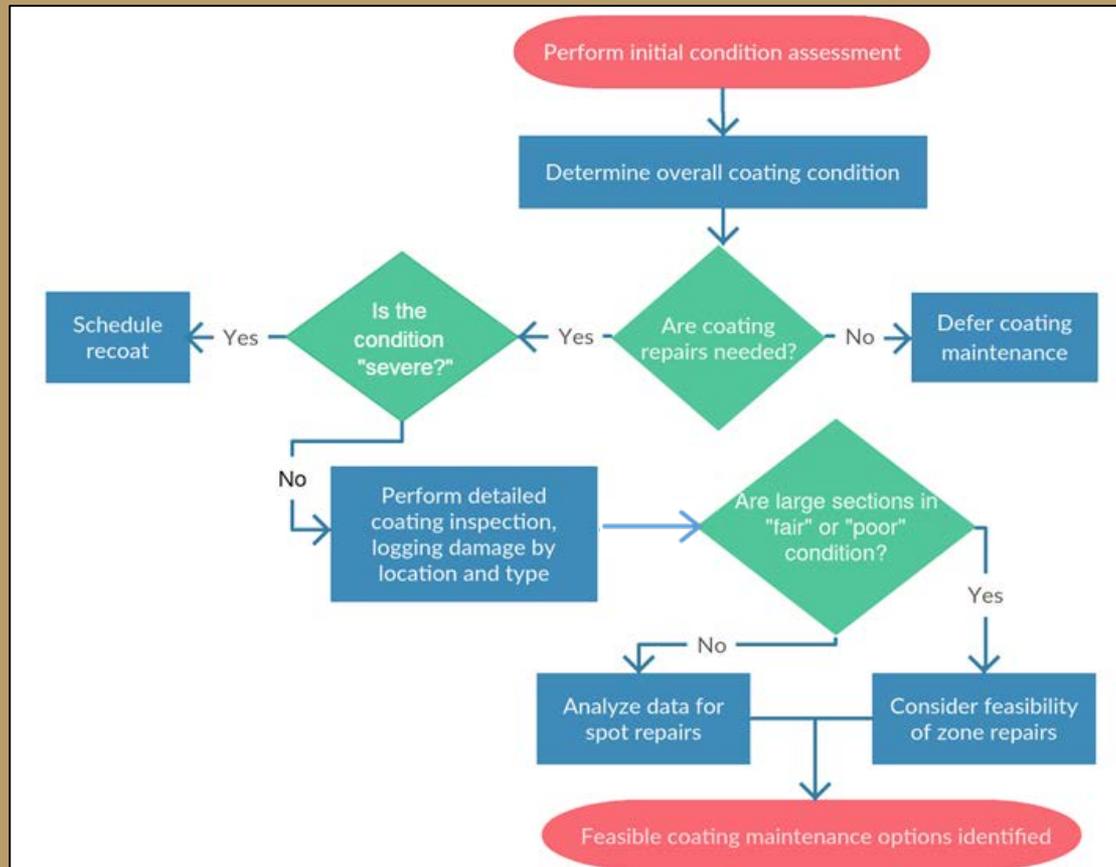
- Accelerated corrosion due to flow of a corrosive fluid or slurry across a metal surface
- Electrochemical and Mechanical Process
- Very High Corrosion Rates
- Some Common Forms:
 - Cavitation
 - High Velocity
 - Abrasion
- Some Solutions:
 - Design to prevent turbulence/impingement
 - Select suitably resistant material
 - Protective coatings
 - Cathodic Protection to help with the electrochemical part
 - High flow rates may require large currents for protection



Five Year Penstock Inspections per FIST

1. Initial assessment (thorough visual examination of): penstock shell condition (interior and exterior), welds, bolts and rivets, expansion joints and sleeve-type couplings, air valves and vents, control valves, manholes and other penetrations, anchor blocks and supports, appurtenances, linings and coatings, and instrumentation.
2. Record penstock shell thickness measurements using non-destructive examination (NDE) methods (usually ultrasonic) at selected locations along the penstock.
3. Detailed assessment using NDE techniques for specific items of concern that were observed during the visual examination.
4. Simulate the emergency control system operation to ensure the emergency gates or valves will close and that documentation (physical test or calculations) exists to indicate they will completely close.
5. Perform load rejection tests for comparison against hydraulic transient analysis results and design criteria to ensure safe operating conditions.
6. Readjust the governor to establish a safe wicket gate timing to prevent over-pressurization of the penstock and to ensure maximum response capability.
7. Have design personnel evaluate the data obtained during the penstock inspection. Perform data and stress analysis to determine if the penstock is in accordance with defined acceptance criteria.

Penstock Coating Inspections



Planning a Safe Inspection

- **Certifications**
 - Fall protection (likely rope access)
 - Confined space, permit required
 - Lock out tag out (LOTO) (*now hazardous energy control program (HECP)*)
- **Job hazard analysis (JHA) other considerations**
 - Safety shoes or felt soles, waders, helmet, hearing protection, other personal protective equipment (PPE)
 - Effective lighting and backup lighting
 - Radio communications, backup communication
 - Rescue plan
 - Coating sampling for hazardous materials



Potential Inspection Conditions

- Partially-filled pipes (sand or water),
- Spray/leakage past the headgate
- Low visibility
- Difficult communications due to noise
- Linings include coal tar enamel, coal tar epoxy, vinyl, epoxy, polyurethane
- Lining may be covered in a layer of silt or biofilm
- Substrate may be damaged, corroded or deformed.



Detailed Inspection Checklist

- Pipe shell assessment:
 - Ultrasonic Testing: document metal thickness readings: typically 5-10 gauge readings per segment
 - Inspect for any bulging or deformations
- **Lining material** and approximate **dry film thickness**
- Systematic visual inspection of lining by segment:
 - Lining deterioration - spalls, cracking, spot rusting:
 - Condition (excellent, good, fair, or poor)
 - Rust rating (ASTM D 610)
 - Percent spot rusting
 - Approximate area of any damage
- Systematic visual inspection of exterior coatings (if applicable)
- Visual inspection of: pipe penetrations, drains, expansion / contraction joints, stiffeners, supports and appurtenances



Inspection Log

Ranking	Description	Approximate Damage* (per 1,000 ft ² and as percentage)
Excellent	Coating is in nearly perfect “as-applied” condition. Coating has limited visible damage.	< 1 ft ² (< 0.1%)
Great	Coating has small damaged areas in a few locations. Coating could have some early stages of degradation with surface microcracking, but no visible corrosion.	1-5 ft ² (0.1-0.5%)
Good	Coating has small damaged areas occurring in several localized areas. Coating could have some early stages of degradation with microcracking, but no visible corrosion.	6-10 ft ² (0.6-1.0%)
Fair	Coating has small to medium sized damaged areas appearing in several locations or larger damaged areas in a few locations.	11-50 ft ² (1.1-5.0%)
Poor	Coating has many small to medium sized damaged areas appearing in many locations, larger damaged areas in a several locations, or a single very large damaged area.	51-100 ft ² (5.1-10.0%)
Severe	Coating has extensive small to medium sized damaged areas that appear widespread throughout the inspection area, or many large damaged areas	> 100 ft ² (> 10.0%)

* The approximate damage provides a measure of the average density observed throughout the structure.
Note: ft² = square feet.

Detailed Inspection Log

Example of Detailed Inspection Log of Corrosion and Defects by Pipe Segment										
Pipe Segment (20 feet/ segment)	Damage by clock position				Coating Cracking by clock position				Surface Area/ Segment (ft ²)	Notes
	Crown Area (10-2)	Invert Area (4-8)	Left Spring-line (8-10)	Right Spring-line (2-4)	Crown Area (10-2)	Invert Area (4-8)	Left Spring-line (8-10)	Right Spring-line (2-4)		
1	—	—	3: 0.5" spots	3: 3" spots	1:12"	3: 6"	—	—	10	Segment contains the siphon breaker and temporary dike. There are anchors at 4, 6, and 8 o'clock.
2	1: 2" spot	—	—	—	See notes	—	3: 5"	2: 4" 1: 7"	37	Rust in cracks on the pipe crown across a 6-foot-wide swath in last 5-foot length of the pipe segment; 30 ft ² zone repair plus seven spot repairs.
3	—	—	—	—	See notes	—	2: 12"	—	122	Rust in cracks on the pipe crown across a 6-foot-wide swath over the length of the pipe segment.
4	—	1:3" spot	—	—	—	—	—	—	1	Coating is in excellent condition.
Total Surface Area:									170	

Linings for Penstocks

Coal Tar Enamel

- Lining system used by Reclamation and others since 1930s
- Applied in the molten state: may be hand daubed, spin coated, or mopped on
- DFT up to 120 mils (or more)
- Contains Polyaromatic Hydrocarbons (PAH) toxic
- Long lasting, thermoplastic material
- Long lasting in moist, cool conditions
- Can dry and become brittle during aging
- Typical failure mode is alligator cracking, spalling, or sometimes pinhole rusting



Hand Daubed Coal Tar on pipe crown



Hand Daubed Coal Tar with drips, note piezometer tap

Aged Coal Tar Enamel



Alligator cracking

Brittle failure at rivet



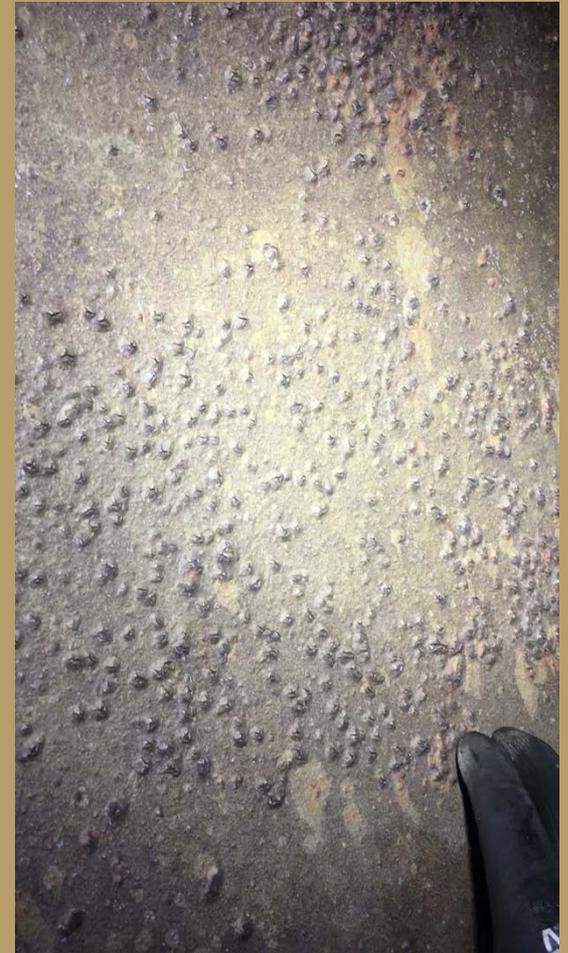
Complete degradation

Corrosion at joint



Linings for Penstocks - Vinyl

- Lining system used by Reclamation and others until the early 1990's (VOCs)
- Less common than Coal Tar Enamel
- DFT ~ 12 mils
- Used penstocks with very cold temperatures
- Aging vinyl may show blister formation but does not crack like coal tar



Blister formation on aged vinyl

Coating Maintenance Options

Maintenance Painting Options

Progressively increase in complexity, work, & expense:

1. No painting
 - Deferral of maintenance
 - Decommission planned
2. Spot repairs
3. Zone repairs
4. Total removal and recoat
5. Structural liner to rehabilitate severely degraded substrate



Valve with coating spot repairs

Deferral of Maintenance

- Coating is in good condition
- Structure's service life is limited
- Full recoat almost required (> 10% damage)
- Full recoat required but allocate funds to maintaining other coatings
- A contributing deficiency must be resolved first (example: control leaks, seepage, or drips)

Fix leaks!



Fix seepage!

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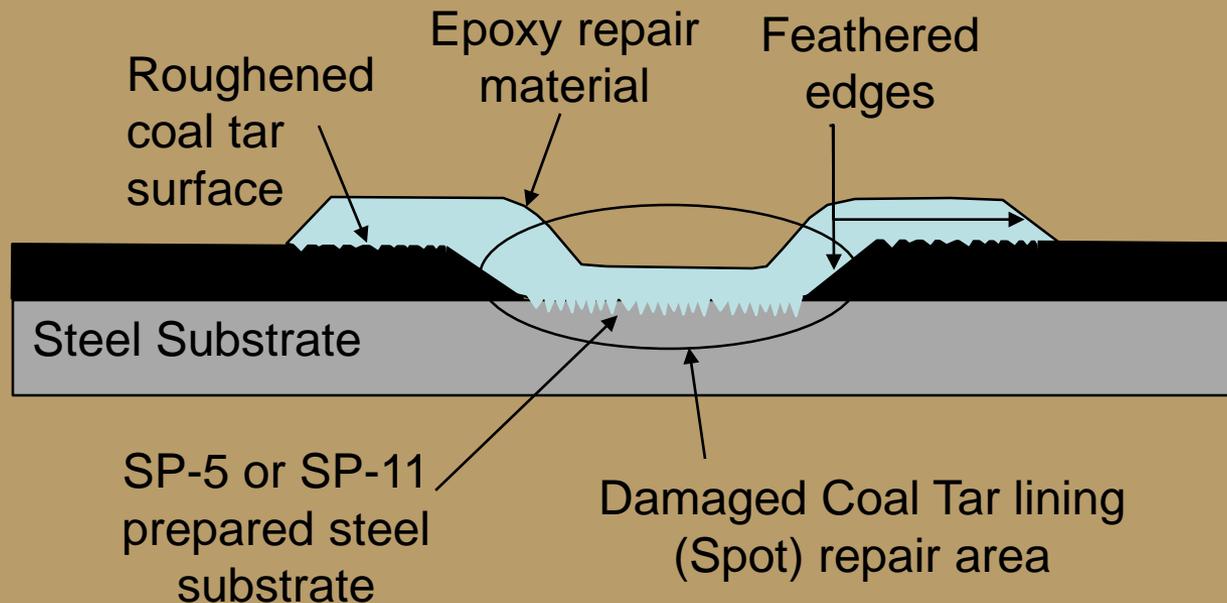
Spot Repairs

- Document or approximate the number of repairs needed
 - May be cost prohibitive at $> 15\%$ of area
 - Add a few inches around perimeter to feather
- Where do you draw the line?



Spot Repairing Coal Tar

- Skaja's research: Use 100% solids epoxy to repair Coal Tar Enamel
- Solvent content can soften and weaken coal tar
- Preserve as much good coal tar as feasible
- For more information; Coal Tar Repair Manual or contact the Materials and Corrosion Lab (MCL)



Total Removal and Recoat

- Economical for $> 15\%$ repairs (rule of thumb)
- Restarts maintenance cycle
- Coal Tar enamel requires high pressure water-jetting to remove due to thickness.



Coal tar enamel lining (70+ years)



Coal tar enamel lining

Ideal Maintenance Cycle

1. Total removal and replacement starts the new cycle
2. Several rounds of spot repairs
3. Spot repair with full overcoat (except immersion)
4. Coating degrades to the point where additional repairs are no longer practical

Example:

Year	Action
0	Initial painting
8	Spot repair
12	Spot repair
16	Spot repair + overcoat
22	Full recoat



Progression of Maintenance Project

- **Scope definition**
 - What items will receive painting maintenance? Do other items such as scroll cases, draft tubes, filling and drain lines also require attention?
 - What items must be protected or treated separately?
 - Piezometer taps
- **Coatings specification**
 - Guide specification available online
 - Contract TSC for services
- **Construction Support :**
Quality Assurance
(NACE CIP or similar)



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Project & Specification Considerations

- Available outages and timeframe for accomplishing work
- Identify the presence of rivets which may require stripe coating
- Identify couplings, contraction / expansion joints. Do expansion joints need work?
- Identify staging areas and points of access for the contractor
- Manhole spacing
- Isolation & dewatering requirements
- Temporary utilities: availability of air, water, power
- Surface prep: High pressure water jetting followed by abrasive blasting
- Soluble salt testing: Extra washing may be necessary to remove contaminants
- Substrate condition, is welding needed?
- Is cathodic protection feasible?

Items to include in the specification:

- Hazardous Materials test results
- Relevant photographs of project and existing conditions
- Drawings showing access

Robotic Application



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Replacement Lining Materials

- 100% solids epoxies – 50+ mils
- **Materials and Corrosion Laboratory** evaluates products for inclusion into Guidespecs based on:
 - Immersion testing: Rust creep / EIS testing
 - Prohesion testing: Rust creep
 - BOR testing (prohesion with immersion)
 - Rapid Impact
 - Abrasion Resistance
 - Erosion Resistance
 - Cathodic disbondment
 - Adhesion / Wet Adhesion



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Construction Support

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Inspectors on a Job Site

- **Contractor's Inspector**
 - Preferably third party inspector
 - Will perform all of the testing and reporting required by specification
 - Should be NACE or SSPC certified and have experience with the infrastructure/equipment being coated and the coating type
- **Government Inspector**
 - Typically Reclamation employee (can be TSC staff)
 - Will observe all tests performed by Contractor's Inspector
 - May also conduct their own testing
 - Should be familiar with each test required by the spec, be able to recognize “good” vs. “bad” data readings, be competent with each testing device and know how to properly calibrate it

Coating Inspector Roles

1. Observe
2. Test to verify Contractor's results
3. Verify specification conformance

Why use a Coating Inspector?

- Assure that you are getting a quality coating job

Risks that Inspector can help mitigate:

Poor surface prep or coating application by contractor →

Reduced coating service life or premature coating failure →

Poor protection of the structure

Reclamation Coatings/Corrosion Team



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Questions? Comments?

De Sitter's "Law of Fives"

\$1 spent in getting the structure designed and built correctly
is as effective as spending
\$5 when the structure has been constructed but corrosion has yet to start,
\$25 when corrosion has started at some points, and
\$125 when corrosion has become widespread.

Thank you to everyone who provided photos and information for this webinar!

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