Best Practices in Preventing & Mitigating the Corrosion Risk of Roadway Deicers to Winter Maintenance Equipment

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Outline

- Introduction
- Role of Chloride-Based Deicers
- Corrosion Mitigation Strategies
  - Preventive Methods
- Conclusion
- Proposed Research Needs
- Acknowledgments
Emerging challenges


INTRODUCTION

- Deicers are increasingly applied onto roads: ~20 million t/yr (U.S.)
- Mainly chloride-based salts: NaCl, MgCl₂, CaCl₂, …$2.8 B to vehicles
- A major risk to DOT vehicles
  - Carbon steel, cast iron, Al alloys, Mg alloys, Cu and Cu alloys
  - 25-30% of these costs are preventable
Localized Corrosion

- Differ from general corrosion due to poor materials selection
- Localized corrosion can take diverse forms, e.g.: pitting corrosion, crevice corrosion, filiform corrosion, intergranular corrosion, galvanic corrosion, stress corrosion cracking (SCC), fatigue corrosion (e.g., rust jacking), fretting corrosion, Microbially Influenced Corrosion, etc.
- It can cause unexpected failures: difficult to prevent
Brake shoes

Rust jacking
Double Frame

Rust jacking

Double Frame

Rust jacking
Spring

Rust jacking
Corrosion-Prone Parts

Most Severe
- electrical wiring
- frames
- brackets and supports
- brake air cans
- spreader chute

High Repair Costs
- chassis
- axles
- brakes
- frame
- suspension
- tires & wheels
- electrical components
Current Costs of Corrosion Management

- The average estimated annual costs per northern transportation agency:
  - Training programs ($190,938)
  - Materials selection ($320,667)
  - Design improvements ($45,000)
  - Corrosion monitoring & testing ($10,000)
  - Proactive maintenance ($171,424)
  - Reactive maintenance ($325,000)

It is possible to conduct risk analysis to identify the critical 20% of corrosion-related failures and focus more on training and risk-based maintenance.

Assuming the 20/80 rule (and in light of the data from the survey responses), the benefit/cost ratio of further improving corrosion from deicers to northern DOT fleet equipment can be estimated as follows: \( \frac{80\% \times 25\% \times \$14,050,368}{20\% \times \$1,063,029} = 13.2 \)

**ROLE OF CHLORIDE-BASED DEICERS**

- Absorbs water even at low humidity
- Increases the conductivity of water
- Chloride ions act as **catalyst** for metallic corrosion and attack the passive layer in a localized fashion
Unusual Role of Magnesium Chloride (20 wt.%)

Unusual Role of Magnesium Chloride (20 wt.%)

Strength loss: differ from trends in mass loss or % rusty area
Unusual Role of Magnesium Chloride

The Mg$^{2+}$ and Cl$^{-}$ ions only compromised the surface layer of SS 304, but penetrated deep into the matrix of Al 1100 to form oxides. For C 1010: pitting corrosion more than the surface layer, but little Mg or Cl signal deep inside.
**CORROSION MITIGATION STRATEGIES**

- **Good training and facility management**

- **Reactive methods** deal with existing corrosion
  - Replacement of damaged component
  - Rust convertors (e.g., tannic and phosphoric acid)
  - Other corrective maintenance activities

- **Preventive methods** minimize the premature failure
  1. **Materials selection**
  2. **Design improvements**
  3. **Anti-corrosion coatings**
  4. **Washing**
  5. **Salt removers**
  6. **Corrosion inhibitors**
  7. **Agro-based materials for snow/ice control**

**New Equipment Specification:** *Build to Last*
Flow of tasks for managing corrosion of defense equipment assets

- Review databases of approved materials, processes, fasteners, and standard parts
- Conduct tests
- Form Corrosion Control Teams, finalize Corrosion Control Plan
- Prepare requirements for vendors, test plans, minutes of board team actions, design guidelines
- Prepare Corrosion Control Specifications (finish specifications)
- Specify corrosion control engineering drawings or procurement package
- Prepare/review manufacturing work instructions
- Include corrosion control requirements on purchase orders
- Implement corrosion control for in-house assembly and production
- Monitor components in service usage
- Consider corrosion in design changes and MRB action
- Prepare Technical Orders for corrosion-related maintenance
- Audit vendors for ability to produce parts and materials to finish specification requirements
- Implement corrosion controls in vendor production of parts, equipment, and materials

1. Materials Selection

- Magnesium alloys and mill product forms of aluminum alloys 2020, 7079, and 7178 should not be used for structural applications.

- The use of 7xxx-T6 Al alloys should be limited to a thickness of no more than 0.080 inches. Where SCC is the main problem, 7075-T6 can be replaced by 7050-T7451.

- Higher carbon content and hardness in steel would make it susceptible to SCC or embrittlement. In SCC of austenitic stainless steel (300 series SS) by chlorides, substitution of duplex stainless steels will often eliminate the problem.

- Using steels containing molybdenum such as 316 SS can reduce pitting corrosion. Intergranular corrosion can be reduced by using the stabilized (321 or 347) or low-carbon (304L or 3I6L) stainless steels.
In-field success of some proactive maintenance methods: (a) aluminum fuel tank, (b) stainless steel hydraulic pipes, (c) poly tandem fender guards, (d) E-coated frame rail.
2. Design Improvements

- Where water may accumulate, include holes for drainage. Minimum diameter for all drains should be 0.375”. The drainage holes should be shielded or oriented to avoid direct road splash.

- Avoid sharp corners that make it difficult for protective coatings to function.

- Remove notches and other stress-concentrating features. Rounded filets and angles also reduce stress concentrations.

- Crevice corrosion can be minimized by proper design of welded joints and gaskets that minimize crevices, sealing the crevices and periodic cleaning.

- Contact between dissimilar metals should be avoided. Where it is not possible, both metals should be coated.

- Use a coating with low water vapor transmission characteristics and excellent adhesion. Zinc-rich coatings can be considered for carbon steel because of their cathodic protection ability.

Considerations for welded joints

- Eliminate the weld splatter using blasting or chipping
- Rough welding should be ground smooth
- If feasible, welds should be double coated
- Where corrosion is possible, use **continuous welds** instead of discontinuous welds (tack or skip welds)
- Remove brackets and extra metal followed by ground smoothing areas of previous contact
- Remove weld flux after finishing welding
Using a sealed S.S. enclosure to protect operations-critical components
3. Anti-Corrosion Coatings

Surface preparation is very important

Coating Effectiveness Evaluated by Multielectrode Array Sensors

Coating Effectiveness Evaluated by Multielectrode Array Sensors

MAS Probes: Rust Bullet™ protected well; but the cyclic exposure to MgCl₂ led to greater coating deterioration than NaCl.
Coatings for Corrosion Protection

- Coatings must be long-lasting, easy to apply, eco-friendly, cost-effective, and provide high performance. Preferably self-healing.

- An ordinary coating that is applied to a well prepared surface may perform better than a high-quality coating which is installed over a substrate with inappropriate or poor surface preparation.
  
  - Use of a suitable salt remover effectively increases coating performance.
  
  - In situations where grit blasting is prohibited or unusable for safety and environmental reasons; rust removers should be used for surface preparation prior to coating.
  
  - When time is critical, time can be saved by using a rust converter.

  - Rust converters could be applied to the metal surface as a primer coat supplemented with oil based or epoxy paint.

  - Rust converters are not suitable for damaged coatings.
4. Washing (Daily!)

- Hot water and then fast drying.
- Low pressure wash and high flow rate (300 psi/300 gpm).
- Salt removers to remove the residual salt in crevices. But the effectiveness of salt removers is alloy-specific.
Washing

- Washing should **focus on trouble spots** like frame rails, brake components, underneath of the chassis and other areas that tend to collect materials.
- Preferably do not use a **pressure washer**, because water can be forced into areas and cannot escape which leads to corrosion.
- Use physical action together with washing to remove the road salt.
- More cleaning liquid is not necessarily better, a high concentration of washing compound may attack some of the plastic components.
- Once active corrosion of metals has started, washing should be coupled with other means, e.g., applying **spray-on corrosion inhibitor**.
Sugarbeet leaves extract could form an organic protective layer on the surface of both coated and bare carbon steel (C1010) samples, with much more anti-corrosion benefit for bare coupons. But this organic layer can be removed by power wash.

5. Salt Removers

- Washing by Water
- Soapy Water
- HoldTight™

(a) SS304L
(b) Al 1100
(c) C 1010

(d) SS304L
(e) Al 1100
(f) C 1010

(g) SS304L
(h) Al 1100
(i) C 1010
The salt remover HoldTight™ can significantly enhance the corrosion resistance of carbon steel and stainless steel in 30 wt.% MgCl$_2$, but not that of the aluminum alloy.

6. Corrosion Inhibitors
A variety of inhibitors show promising results in corrosion protection of iron, steel, aluminum, and aluminum alloys.

Numerous compounds have been identified as alternatives to toxic chromate inhibitors.

Organic inhibitors offer low cost, low environmental impact, and effective corrosion protection of steel and aluminum, whereas inorganic inhibitors could provide the advantages of enhanced strength and anti-high temperatures.

The inhibitor concentration and service condition both play a vital role in their performance and cost-effectiveness.

Inhibitor Effectiveness Evaluated by Multielectrode Array Sensors

After 8 cycles to 2.3% NaCl

to 3.0% MgCl₂

MAS Probes: Krown T40™ protected well (reduced the corrosion rate of all three metals in both diluted deicers by at least 99%).

7. Agro-based Materials for Snow/Ice Control

10% MgCl₂ containing 5% sugarbeet leaves extract (A) and 10% MgCl₂ (B)

A Novel Approach

• Some agro-based inhibitors offer additional benefits as ‘cryoprotectants’: reducing the freezing point!

• Inhibitors from renewable resources are highly desirable: less toxic, readily available, bio-degradable, more cost-effective.

• Green inhibitors feature organic compounds containing heteroatoms such as P, S, N and O which can adsorb onto the metallic surface and form a protective layer.

• A novel chemical/biological process for deriving “green” inhibitors was developed.

Preparation of extract

Urea + Ca(OH)$_2$ + NaOH + ground plant waste + deionized water

- Adjusting pH above 11.5
- Fast stirring then freezing at -13 °C
- Partially frozen solution stirred again and simultaneously 500 mL DI water was added into it.
- pH adjusted to 8.5 by adding HNO$_3$ and NaOH. Then, a mixture of KH$_2$PO$_4$, NaH$_2$PO$_4$·H$_2$O and MgSO$_4$·7H$_2$O was added to the solution to create a medium suitable for the growth of bacteria.

- Bacillus Megaterium bacteria (NRRL B-14308) was added to the solution, which was subsequently placed in a shaker for 14 days.
- Concentrating by heating (95 °C, total volume halved)
Green Inhibitor Derived from Waste Peony Leaves

- The inhibitor was stable over time and its main active ingredients ($C_{19}H_{27}N_4O_{10}P$ and $C_{17}H_{16}N_3O_9P$) adsorb onto the steel surface, block cathodic active sites, make the surface hydrophobic, decrease the surface free energy and facilitate the formation of a passive layer.
Green Inhibitor Derived from Apple Pomace

Apple Pomace (AP, fruit waste)

Chemical/Biological Degradation

C_{26}H_{50}NO_{7}P

Green Corrosion Inhibitor

-Imag. (Ω cm^2)

Real (Ω cm^2)

Blank
1 v/v % AP extract
2 v/v % AP extract
3 v/v % AP extract
Molecular structure of main compounds

Fatty acid hydrophobic tail

$\text{C}_{26}\text{H}_{50}\text{NO}_{7}\text{P}$

Positively charged head

$\text{C}_{31}\text{H}_{43}\text{N}_{5}\text{O}$
Potentiodynamic polarization (PDP)

C1010 steel after 16-d immersion in NaCl solution containing 0 to 3 vol.% WAPE
Corrosion Inhibition Efficiency

\[ IE_0\% = \left[ 1 - \frac{R_{ct(uninhibited)}}{R_{ct(inhibited)}} \right] \times 100 \]

<table>
<thead>
<tr>
<th>Definition</th>
<th>Different concentrations of WAPE</th>
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<tbody>
<tr>
<td>Sample</td>
<td>WAPE0</td>
</tr>
<tr>
<td>IE%</td>
<td>----</td>
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</table>
Digital Photos

- The steel coupon exposed to uninhibited salt brine (a) was partially covered by orange rust.

- The surface layer in the 3.5 wt.% NaCl with higher inhibitor concentrations (WAPE at 3 vol.%) was more uniform and complete.

The surface morphology of steel coupons after 7-d continuous exposure to various inhibitor/NaCl solutions.
The corrosion inhibition by apple pomace extract was mainly due to the adsorption of \( \text{C}_{26}\text{H}_{50}\text{NO}_7\text{P} \) molecules, which forms a barrier phosphate layer on the surface of steel coupons.
From lower binding Energy to higher one (right to left)

<table>
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<tr>
<td>Component</td>
<td>Fe</td>
<td>$\alpha$-Fe$_2$O$_3$</td>
<td>$\alpha$-FeO(OH)</td>
<td>amorphous Fe$^{3+}$</td>
</tr>
</tbody>
</table>

all of the amorphous Fe$^{3+}$ phase and some of the Fe and $\gamma$-FeO(OH) phases were converted to $\alpha$-Fe$_2$O$_3$

XPS results for (a) WAPE0 and (b) WAPE3 steel coupons
Key Findings: Apple Pomace Sourced Inhibitor

- The whole apple pomace extract is an anodic inhibitor that blocks the anodic active sites on the surface of carbon steel, while acting as a catalyst in converting all of the amorphous Fe$^{3+}$ phase and some of the Fe and γ-FeOOH phases to α-Fe$_2$O$_3$.

- The corrosion inhibition by whole apple pomace extract was mainly due to the adsorption of C$_{26}$H$_{50}$NO$_7$P molecules, as active ingredient, which induces the formation of α-Fe$_2$O$_3$ as a passive layer on the steel. It also increases the hydrophobicity of the surface through the adsorption of the fatty acid chain of C$_{26}$H$_{50}$NO$_7$P compound.
**CONCLUSION**

- Agencies should implement an extensive preventive maintenance program that may involve materials selection, design improvements, anti-corrosion coatings, use of salt removers together with routine washing; spray-on corrosion inhibitors and many other operational changes which can be supplemented by corrective maintenance practices to minimize the negative impact of deicer corrosion to equipment asset.
PROPOSED RESEARCH NEEDS

- Evaluating the Use of **Sacrificial Coatings** to Protect DOT Fleet from Deicer-Exacerbated Corrosion
- Cost-Effective **Cleaning Strategies** for Protecting DOT Equipment Assets from Corrosion
ACKNOWLEDGMENTS

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- WSDOT
- Clear Roads
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- CAMMSE/CESTiCC
- Simpson Strong-Tie, ...

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WSU Geo-Analytical Laboratory

WSU Laboratory for Cellular Metabolism and Engineering

Students at the WSU Laboratory of Corrosion Science & Electrochemical Engineering

Photos by various State DOTs
QUESTIONS?

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Electrical issues

- Eliminate the junction boxes wherever possible, and relocate them to inside the cab off the floor.
- Install modified protective cover for battery.
- Use high-quality weather-proof terminations (e.g., buss-style connectors) and compression fittings in addition to shrink wrapping susceptible electrical wiring components.
- Do not probe the wires to test for continuity and avoid any damage of wiring insulation.
- Apply a non-conductive; non-sodium based di-electric grease on all electrical connections (plugs, sockets, battery terminals, etc.).
- Make clean the electrical connectors on a regular basis (at least every six month) with water (not soap) and a wire brush, and re-grease with dielectric grease.
- Minimize connectors to the extent possible by using continuous wiring.
- Use anti-corrosive spray for protecting the battery posts and terminals.
- Do not apply paint to the rubber seals around lights.
**Brake components/chassis**

- Inspect all brake components even by removing brake drums to checking the entire lining surface, the brake shoe web, rollers, cam, etc.
- Be careful about automatic slack adjusters (ASA). Make sure ASAs are thoroughly lubed and there is no evidence of internal rusting.
- Require throttle, brake, and clutch pedals to be suspended in specifications.
- Install corrosion sealed air brake chambers and spray on protective coatings on all brake valves.
- Pull brake drums on a regular basis.
- Use rubberized undercoating for aluminum brake valves.
- In the rebuilding process specify rust-proof painted and epoxy-coated brake shoes.
- Specify **self-healing undercoats**, full fenders and fender liners for chassis.
- Install a large full width, full height under chassis sand guard on all front discharge sanding bodies.
Frame/body/beds and other parts

- Carbon steel fuel, hydraulic and air tanks can be replaced with aluminum tanks.
- Replace standard E-coat steel painted wheels with powder coated versions. Use powder coating for fuel tank and frame rails.
- Use stainless steel truck boxes, pre-wetting tanks, and sanders.
- Use zinc anodes in solution tanks and zinc nickel alloy engine oil pan.
- Use stainless steel couplers, under tailgate spreaders and cooler lines.
- Use poly faced snow plows to reduce corrosion and also lessen weight. Use stainless steel.
- Use greaseable tailgate linkages and attach them to on board automatic lube system.
- Replace radiators every two years (based on Washington State DOT recommendations).
- Install grit guards on wheels.
- Wrap hydraulic fittings with anticorrosive wrap.
- Use glad hand seals with dust flaps for air system.
LC-MS

- Contains O, N, P, and C: organic compounds that contain heteroatoms

<table>
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<th>Formula</th>
<th>Retention time (min)</th>
<th>m/z</th>
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