Protecting Maintenance Equipment against Chloride Roadway Deicers: Corrosion Mechanisms, Test Methods, and Proactive Approaches

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Prepared for Presentation at the TRB 2014 Annual Meeting and for Publication in the Transportation Research Record

TRB committee: Maintenance Equipment (AHD60)

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ABSTRACT

Roadway maintenance equipment in cold climates is exposed to high amounts of chloride-based deicers that are inherently corrosive. As such, various structural, hydraulic, and electrical components on maintenance equipment are vulnerable to the deleterious effects of chloride roadway deicers and their premature deterioration can negatively affect the performance, reliability and service life of the equipment fleet. This work aims to shed more light on this important asset management issue, by providing an overview of the relevant corrosion mechanisms, corrosion-prone parts, and test methods. More importantly, this work presents an overview of current approaches available to manage the risk of deicer corrosion to equipment assets, including design considerations, materials selection, and maintenance strategies. The information aims to enable equipment engineers and managers to gain a better understanding of this technical issue and to make more informed decisions in corrosion risk management.
INTRODUCTION

In the last two decades, the northern regions of North America have experienced a gradual increase in the use of roadway deicers. As a result, concerns over the potentially negative effects of roadway deicers on the transportation infrastructure \[1-6\] and the natural environment have significantly increased \[7-9\]. Meanwhile, the corrosive effects of roadway deicers on motor vehicles, particularly on roadway maintenance equipment, have been a less documented yet equally important issue \[10, 11\]. Roadway maintenance equipment in cold climates are exposed to high amounts of chloride-based deicers that are inherently corrosive \[12-15\]. As such, various structural, hydraulic, and electrical components on the maintenance equipment are vulnerable to the deleterious effects of chloride roadway deicers (as shown in Figure 1) and their premature deterioration can negatively affect the value, performance, reliability and service life of the equipment fleet and increase its life-cycle cost and safety risk \[11,16\].

Figure 1. Side discharge salt spreader showing extensive corrosion.

The implementation of best engineering practices and anti-corrosion technologies could reduce the cost of metallic corrosion from 25% to 30% \[16\]. Yet, the knowledge underlying the corrosion and corrosion mitigation for metals at the risk of chloride-based deicers remains scattered. In this context, this work provides an overview of the relevant corrosion mechanisms, corrosion-prone parts, and test methods. More importantly, this work presents an overview of current approaches available to manage the risk of deicer corrosion to equipment assets, including design considerations, materials selection, and maintenance strategies. The information aims to enable equipment engineers and managers to gain a better understanding of this technical issue and to make more informed decisions in corrosion risk management.
CORROSION MECHANISMS

Types of corrosion

Corrosion is an electrochemical process initiated by an electrolyte present on the surface of a metal, and there are many possible types of corrosion depending on the specific combination of metal and its service environment. General or uniform corrosion occurs over a substantial amount of the metallic surface and is the most predictable type. Yet, in reality, most corrosion occurs in a localized manner (i.e., attacking a specific area of the metal) and is more difficult to predict. Among them, crevice corrosion occurs at the interface of a metal and another surface, often where a confined or stationary area is formed to trap electrolyte. Commonly, this is observed beneath surface deposits, seals, gaskets, washers, clamps, sleeves, and similar junctions. Pitting corrosion is frequently observed on the surface of metals (e.g., stainless steel) and is often difficult to detect considering the relatively small amount of metal loss during the process.

Intergranular corrosion initiates at grain boundaries of metals (e.g., aluminum alloys) and commonly spreads along adjacent grain boundaries. Galvanic corrosion occurs when two dissimilar metals are in contact with one another in the presence of an electrolyte. As a result, electrical current flows from the metal acting as the anode to the metal acting as the cathode. The presence of residual stresses from the metal’s manufacturing processes and cyclic loadings during service are common causes of stress corrosion cracking (SCC) and corrosion fatigue, respectively, which are forms of corrosion exacerbated by the mechanical stress.

In 2005, the authors conducted an investigation of the corrosion of trucks exposed to deicers applied on Montana highways and detected significant crevice corrosion between the conjunction of the winch frame and the truck frame and in conjunctions on the truck frame. In addition, filiform corrosion was observed under the coating near frame corners and on brake chambers. Other forms of less significant corrosion were also observed on the trucks, such as pitting corrosion on the outer surfaces of stainless steel parts and aluminum fuel tanks, galvanic corrosion and SCC in the welding zones or conjunction of dissimilar metals. According to a recent NCHRP report, “crevice corrosion and poultice corrosion typically occur where dirt and moisture are trapped – between adjacent pieces of metal, under gaskets and at fasteners, or on the surface of motor vehicle components. This is compounded by ingress of snow and ice control chemicals that increase the conductivity of the trapped moisture”.

Pitting corrosion poses a great risk to the integrity of metal as it is a self-accelerating process featuring a combination of small anode (pitted area) and large cathode (non-pitted area) on the metal. Recent research has discovered that on carbon steel surfaces, an anodic area forms at the location of sodium chloride (NaCl) and a cathodic region forms around it. The size of the cathodic region is proportional to the amount of NaCl coverage [18]. The main corrosion product on carbon steel is lepidocrocite (γ-FeOOH), and the time of wetness has a greater impact on corrosion when the temperature was less than 25°C [19]. Pit growth occurs where the H+ ions formed during hydrolysis starts to diffuse. Pitting proceeds at the greatest rate near the perimeter of the droplet where corrosion product concentration is lowest, causing corrosion in the lateral direction [17, 20]. This lateral corrosion occurs because at the perimeter the metal ions are not saturated and the perimeter is closer to the cathode, causing
the metal dissolution to occur at a greater rate [20]. Research has shown that the early
corrosion of high-strength steels is characterized by the formation of a layer of corrosion
product followed by preferential attack of the ferritic phase. Analysis of corrosion rate
revealed that as pit depth increased the rate of corrosion decreased [21]. The study examined
the corrosion of stainless steel (304 SS) under a thin layer of chloride solution and found the
active site of the pit grows to a maximum depth of 10 μm [22]. Stainless steel (430 SS and
304 SS) were subjected to cyclic corrosion testing consisting of 1-hr immersion in chloride-
containing solution and a few hours of drying. Pit formation and growth were found to occur
before the surface of the metal dries completely [22]. During the drying stage, the surface
dryness can lead to passivation of the pit. Pit formation and growth can be induced by thin
electrolyte layers that exist during atmospheric corrosion, which cause a buildup of corrosion
products over the anodic areas of the metal. This buildup is due to a lack of lateral diffusion,
which also causes pits to form in clusters [22].

During a two-year field study of deicer corrosion to specimens mounted on winter
maintenance equipment [23], intergranular corrosion attack was observed on all 5182-O
aluminum (Al) specimens (as shown in Figure 2) and a few A356 cast Al specimens and
general corrosion on all 1008 steel and most A356 cast Al specimens. Initial corrosion of Al
alloys consists of an attack on the S-phase and Al-Cu-Fe-Mn-(Si) intermetallics [25], causing
them to de-alloy and create trenching around the intermetallic particles [26]. The cooperative
corrosion stage is observed as domes of corrosion within a ring of corrosion product occur
around clusters of intermetallic particles. After the penetrating attack of the grain boundary
network, the corrosion begins to spread laterally. The minor grain attack then develops into
more extensive intergranular attack and grain etch-out, forming pits [26]. For pure aluminum,
the cathode is the portion of the metal exposed to NaCl and the anodic attack occurs at the
border with the adjacent passive metal [18].

Figure 2. Scanning electron microscope (SEM) evidence of selective attack of grain
boundary (left) and Mg2Al3 precipitates (right) on Al specimens exposed to field chloride-
based deicers [23].

Zinc is commonly used as an anti-corrosion coating for iron and steel and is often applied
through hot dipping or electrochemical processes. Zinc is more reactive than the other metals
and is thus commonly used as a sacrificial coating. The corrosion mechanism of zinc in a
NaCl-containing environment consists of the deposition of the electrolyte on the surface of
the zinc followed by the dispersion of an alkaline electrolyte film that extends from the boundary, doubling or tripling the initial radius of the drop. The corrosion product in the center of the initial droplet was found to be zinc hydroxychloride, while sodium carbonate (Na$_2$CO$_3$) is present at the perimeters. The rate of corrosion dispersion is related to the electrical potential gradient between the anodic region at the center of the initial droplet and the cathodic region located at the perimeter [27].

**Corrosion-Prone Parts**

According to a survey of transportation professionals in 2012 [11], chloride deicer exposure “poses the most significant risk of metallic corrosion to dump trucks, liquid deicer applicators, hoppers, front end loaders, and supervisor trucks or crew pickups”. At the component level, the most severe deicer corrosion risk was found in electrical wiring, frames, brackets and supports, brake air cans, fittings, and spreader chute. Figure 3 shows the distribution of corrosion-related repair costs among the equipment owned by the Washington State Department of Transportation (WSDOT). This indicates that metallic corrosion mostly led to repair costs in four groups: chassis, axles, brakes, frame, steering, suspension, tires & wheels; equipment dependent attachments; engine; and electrical components.

![Figure 3. Allocation of corrosion-related repair costs among WSDOT equipment.](image-url)
The extent of metallic corrosion is directly related to exposure time to chloride deicers. As such, components most significantly impacted by corrosion are often located on the underbody of equipment or in close proximity to the road surface and application devices. Common components most likely to be impacted by roadway deicers are brake shoes, trailer underbodies, trailer landing gear, junction boxes, door headers, sills, bulk heads, mud flap brackets, threshold plates, logistics posts, and roof bows [28]. The structural components of the underbody are normally composed of low-carbon steel and high-strength steel. These underbody components commonly experience pitting, crevice, galvanic, and cosmetic corrosion. Cosmetic corrosion often originates where the coating or paint is damaged or penetrated [28]. Sites likely to exhibit corrosion also include areas where dirt and other materials can deposit and remain wet such as metal folds and joints, breaks in painted surfaces, threaded-screws, and beneath coatings that do not adhere well to the surface beneath [30].

CORROSION TEST METHODS

To evaluate the risk of corrosion and the effectiveness of mitigation strategies, a variety of test methods to assess chloride-induced corrosion to metals have been developed. Among them are laboratory test methods and on-site test methods. In order to predict and manage corrosion damage, the original condition with respect to corrosion must be defined, such as environmental corrosivity and exposure time. Accurate corrosion projections are difficult to obtain due to the stochastic nature of corrosion and the time associated with the corrosion process. Accelerated laboratory testing is at the risk of not realistically simulating the field conditions, whereas outdoor exposure testing can be very time consuming [31].

Recently, a survey performed by the Steel Structures Painting Council (SSPC) revealed that the salt spray test is the most widely used corrosion assessment method [32]. This test entails exposing mild steel plates of size (150mm × 100mm × 2mm) in a salt spray chamber followed by drying. The metallic samples are often subjected to electrochemical measurements, of which electrochemical impedance spectroscopy (EIS) is particularly useful for revealing the mechanistic information about interfaces [33-35].

The PNS/NACE gravimetric test method is a common procedure for measuring the corrosivity of deicers. It is a modification of the National Association of Corrosion Engineers (NACE) Standard TM0169-95 by the Pacific Northwest Snowfighters (PNS). This test method entails applying 30 ml of a 3% chemical deicer solution per square inch to the surface of a coupon for testing. Then a 72-hr cyclic immersion procedure is used, with a 10-min exposure time in the solution followed by a 50-min air exposure. Electrochemical techniques are suggested as a supplement to this gravimetric method so as to obtain data related to corrosion mechanisms and kinetics in a timely manner [34]. Furthermore, the SHRP H-205.7 test method was developed by the Strategic Highway Research Program (SHRP) to analyze the effectiveness of corrosion inhibitors in deicing chemicals. This test method uses continuous immersion to evaluate the corrosive effects of deicers on metal. As it does not include wet-dry cycling, it does not simulate the field exposure scenario very well and long exposure times are required before significant weight loss can be detected [36].
The U.S. Army has developed an accelerated corrosion and durability test to collect corrosion and material performance data that can be related to service life of military vehicles in highly corrosive environments. This test is based on tests developed by General Motors and has been found to accurately simulate 10 years of cosmetic corrosion and 3 years of crevice corrosion.

This method combines accelerated corrosion tests and durability tests to introduce typical situations encountered over the service life of the vehicle. The procedure is outlined in Figure 4. The application portion of the test includes a grit trough, salt mist, and humidity chamber. The grit trough allows small particles to accumulate on surfaces, which increases time of wetness and introduces abrasive particles to the coatings. The salt mist applies a high concentration salt solution to the vehicle typical of roadways with deicers applied and the use of the high temperature and high humidity chamber is to increase the rate of corrosion [38].

While most corrosion tests show their high efficiency of saving costs on corrosion effect, researchers have experienced that the downside of those experiments is the required long time periods. For example, salt spray accelerated test methods requires 2000 hours of exposure and electrochemical measurements can take up to 10 weeks for results. Accelerated test methods similar to this have been proven to be very difficult to develop when the goal is to decrease the time of failure while preserving the failure mechanisms. Some discoveries have shown that corrosion resistance performance can be obtained through thermal cycling and monitoring low frequency impedance changes of coating systems. Bierwagen discovered that the use of thermal cycling paired with electrochemical impedance spectroscopy provides a faster, quantitative method to evaluate coating corrosion resistance, which leads to corrosion resistance results obtained within a week of testing [39].

Recently, a new system called the wire beam electrode (WBE), which uses a multi electrode technique, has been applied to corrosion studies. An electrochemically non-uniform metal surface occurs when a metal surface is exposed to an electrolyte causing localized defects in protective coatings and a polarization voltage across the surface. Galvanic corrosion current
and corrosion potential are measured and analyzed to assess the distribution of corrosion rates with the wire beam electrode system [40].

Crevice corrosion has typically been studied using traditional methods involving weight loss measurements and inspection, which provide details on mechanisms and processes. However, the wire beam electrode system is able to assess instantaneous corrosion rates [41]. Electrochemical noise resistance coupled with wire beam electrode methods offers some advantages for determining corrosion rates and patterns. The noise resistance is defined as the ratio of the standard deviations of the potential noise and the current measured noise. The noise resistance has been found to be equivalent to the polarization resistance, therefore being used to determine rates of corrosion [42]. It was determined that the time-average noise resistances from stainless steel sensors provide a strong relationship with solution corrosivity. Furthermore, coupled multi-electrode array sensors also provide a strong correlation with solution corrosivity [43].

Evaluating anti-corrosion coatings often depends on electrochemical properties such as corrosion potential, DC resistance, AC impedance at room temperature, AC impedance as a function of temperature, current flowing through a coating at high potential, repetitive cathodic polarization, cathodic delamination, and current/time measurements. Properly collecting and analyzing these parameters can provide valuable coating performance information [44].

PROACTIVE APPROACHES TO DEICER CORROSION MANAGEMENT

Current approaches available to manage the risk of deicer corrosion to equipment assets, including design considerations, materials selection, and maintenance strategies can greatly improve performance, reliability and service life of winter maintenance equipment while reducing overall costs related to corrosion impacts and extensive corrosion to equipment. A discussion comprising the methods and knowledge of corrosion management strategies observed from recent and past experiences is presented. For instance, it is well known that specific metals are more susceptible to corrosion than others, which makes choosing materials for desired applications an essential component of corrosion protection. Subsequently, information gained from survey responses and a maintenance operation site visit focused on specific maintenance practices to improve and maintain designs that will assist in the reduction of corrosion to equipment is presented.

A survey to gain insight on the current practices related to best practices or products used by various industries and agencies to protect their equipment or vehicles from the corrosive effects of chloride deicers was performed. The survey consisted of 15 multipart questions and was published online at https://www.surveymonkey.com/s/ZL77RPB. The survey was distributed to various professional forums, including NACE Corrosion Network, Corrosion Prevention Association (CPA), equipment engineers, Northern State DOTs, and relevant Linkedin groups. A total of 105 responses were received (30 from government agencies and 75 from private entities), among which 40 responses were complete and used for further analysis.
The agency survey identified annual expenditures in the current practices of managing deicer-related metallic corrosion in the equipment fleet of responding agencies that report it as being a significant issue. While there are some responses from cities and counties, most responses came from state DOTs in the U.S. Table 1 reports the average estimated cost of corrosion management in six areas as follows: training programs ($190,938), materials selection ($320,667), design improvements ($45,000), corrosion monitoring and testing ($10,000), proactive maintenance ($171,424), and reactive maintenance ($325,000). As such, the total cost of current corrosion management related to deicer exposure is estimated to be $1,063,029 per year. The coefficient of variance among the six cost items averaged 143%, which is attributed to the inherent diversity in the responding agencies’ fleet size, level of deicer exposure and other environmental conditions, rules of practices in corrosion management, etc. Nonetheless, it is assumed that the average cost numbers reported here reflect the current practice by an “average agency” (e.g., a northern state DOT with an average fleet size asset) [29-33].

Table 1: Annual expenditures of current practices in managing equipment corrosion due to deicer exposure.

<table>
<thead>
<tr>
<th>No. of Responses</th>
<th>Training programs</th>
<th>Materials selection</th>
<th>Design improvements</th>
<th>Corrosion monitoring/testing</th>
<th>Proactive maintenance</th>
<th>Reactive maintenance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>$190,938</td>
<td>$320,667</td>
<td>$45,000</td>
<td>$10,000</td>
<td>$171,424</td>
<td>$325,000</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>$342,845</td>
<td>$568,651</td>
<td>$43,157</td>
<td>NA</td>
<td>$279,106</td>
<td>$319,598</td>
</tr>
<tr>
<td>Coefficient of Variance</td>
<td>180%</td>
<td>177%</td>
<td>96%</td>
<td>NA</td>
<td>163%</td>
<td>98%</td>
</tr>
</tbody>
</table>

The agency survey also identified the current risks of deicer corrosion to the equipment fleet of responding agencies that report it as being a significant issue, estimated under the current level of corrosion management. Table 2 reports the deicer exposure leads to risks in six areas: an average of 17.3% depreciation in equipment value, an average of 8.5% increased equipment downtime, an average of 11.9% in reduced equipment reliability, an average of 17.3% in reduced equipment service life, an average of 19.6% in increased premature repair and replacement, and an average of 1.5% safety risk due to faulty parts on equipment. Table 3 reports the average estimated cost of equipment corrosion risks in these six areas as follows: $12,512,227, $69,167, $172,000, $1,127,750, $118,823, and $30,000, respectively. As such, the total cost of current corrosion risks related to deicer exposure is estimated to be $14,050,368 per year. For the reasons mentioned before, the coefficient of variance among the six cost items is high (averaged 125%).
Table 2. Estimated risks of equipment corrosion due to deicer exposure alone

<table>
<thead>
<tr>
<th></th>
<th>Depreciation in value</th>
<th>Increased downtime</th>
<th>Reduced reliability</th>
<th>Reduced service life</th>
<th>Increased premature repair and replacement</th>
<th>Safety risk due to faulty parts</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of Responses</td>
<td>12</td>
<td>13</td>
<td>9</td>
<td>12</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>Average</td>
<td>17.3%</td>
<td>8.5%</td>
<td>11.9%</td>
<td>17.3%</td>
<td>19.6%</td>
<td>1.5%</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>12.6%</td>
<td>8.3%</td>
<td>8.7%</td>
<td>12.6%</td>
<td>12.2%</td>
<td>1.0%</td>
</tr>
<tr>
<td>Coefficient of Variance</td>
<td>73%</td>
<td>98%</td>
<td>74%</td>
<td>73%</td>
<td>62%</td>
<td>67%</td>
</tr>
</tbody>
</table>

Table 3. Annual costs of estimated equipment corrosion risks due to deicer exposure

<table>
<thead>
<tr>
<th></th>
<th>Depreciation in value</th>
<th>Increased downtime</th>
<th>Reduced reliability</th>
<th>Reduced service life</th>
<th>Increased premature repair and replacement</th>
<th>Safety risk due to faulty parts</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of Responses</td>
<td>9</td>
<td>6</td>
<td>5</td>
<td>4</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Average</td>
<td>$12,512,227</td>
<td>$69,167</td>
<td>$172,000</td>
<td>$1,127,750</td>
<td>$139,224</td>
<td>$30,000</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>$27,053,553</td>
<td>$94,943</td>
<td>$205,597</td>
<td>$1,121,133</td>
<td>$72,729</td>
<td>NA</td>
</tr>
<tr>
<td>Coefficient of Variance</td>
<td>216%</td>
<td>137%</td>
<td>120%</td>
<td>99%</td>
<td>52%</td>
<td>NA</td>
</tr>
</tbody>
</table>

Materials Selection

Materials selection for corrosion-resistance is one critical aspect of the overall design process. Materials of construction should be economical yet provide adequate resistance to the specified service conditions. Advancements in technology have allowed for various improvements in material selection to minimize corrosion. It is well known that corrosion resistance performance greatly varies among dissimilar types of metal, which needs to be taken into consideration when selecting materials for specific applications. For instance, in natural environments, unalloyed aluminum has superior corrosion resistance properties compared to carbon steel but poor mechanical strength. Metallurgists and corrosion engineers have been attempting to improve the aluminum mechanical behavior without losing corrosion resistance properties. If a high-strength alloy is needed, it is recommended to use exfoliation resistant tempers like T76 or 7xxx alloys with copper. Copper-free alloys and alloys with low noble impurities or alloying elements contain high pitting corrosion resistance. Alloys in the 1xxx, 2xxx, 3xxx, 5xxx, and 6xxx series contain the highest corrosion resistance properties [53]. A study conducted by Uchida and Mochizuki found that the use of zinc coating on aluminum and steel sheet displayed effective anticorrosion performance. A direct relationship between corrosion and the amount of zinc coating on aluminum sheets was also observed [54]. The survey respondents were also surveyed for the corrosion-prone material seen in their agency’s equipment fleet and the results are summarized in
Table 4. From Table 4, it can be obtained that the cast irons have the most serious general or uniform corrosion (81.3%) followed by carbon steels (73.5%), composites (68.8%) and magnesium alloys (68.2%). On the other hand, aluminum alloys and stainless steels have the most serious localized corrosion (50%) followed by metallic glass (43.8%), metallic coatings (40.0%) and magnesium alloys (36.4%).

Table 4. Common types of corrosion-prone material and their respective forms of corrosion seen in respondents’ agency’s vehicles/equipment caused by exposure to chloride deicers.

<table>
<thead>
<tr>
<th>Materials</th>
<th>General or uniform corrosion</th>
<th>Localized corrosion</th>
<th>Response count(*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cast irons</td>
<td>81.3% (26)</td>
<td>21.9% (7)</td>
<td>32</td>
</tr>
<tr>
<td>Aluminum alloys</td>
<td>55.9% (19)</td>
<td>50.0% (17)</td>
<td>34</td>
</tr>
<tr>
<td>Magnesium alloys</td>
<td>68.2% (15)</td>
<td>36.4% (8)</td>
<td>22</td>
</tr>
<tr>
<td>Copper and copper alloys</td>
<td>67.9% (19)</td>
<td>35.7% (10)</td>
<td>28</td>
</tr>
<tr>
<td>Carbon steels</td>
<td>73.5% (25)</td>
<td>32.4% (11)</td>
<td>34</td>
</tr>
<tr>
<td>Stainless steels</td>
<td>50.0% (12)</td>
<td>50.0% (12)</td>
<td>24</td>
</tr>
<tr>
<td>Metallic coatings</td>
<td>64.0% (16)</td>
<td>40.0% (10)</td>
<td>25</td>
</tr>
<tr>
<td>Metallic glass</td>
<td>56.3% (9)</td>
<td>43.8% (7)</td>
<td>16</td>
</tr>
<tr>
<td>Composites</td>
<td>68.8% (11)</td>
<td>31.3% (5)</td>
<td>16</td>
</tr>
</tbody>
</table>

* Some respondents selected both forms of corrosion.

Design Improvements

Corrosion prevention and control begins with material selection, however the use of corrosion engineering principles in design can also have a significant impact. If an operating environment is considered to be corrosive, corrosion prevention designs of components need to be taken into consideration. For example, a design should be used to avoid locations where water may accumulate. Heat treatment process called Retrogression Re-Aging (RRA) is another approach to improve the corrosion resistant properties of designs. RRA treatment consists of a retrogression phase of heating at 195 °C for up to 40 minutes, quenching, and then heating at 120 °C for 24 hours, which is known as the re-aging phase. RRA has been tested by the Air Force Research Laboratory and was found to be successful for improving corrosion resistance of 7075-T6 alloy [55].

Agencies should consider corrosion-resistance requirements at the stages of materials selection and design. Existing knowledge about the anti-corrosion performance of various materials and design configurations in various deicer-laden service environments should be utilized to refine the equipment purchasing specifications developed by the transportation agencies. For instance, the zinc coating on aluminum and steel substrates can provide effective anti-corrosion performance. Structures designed for resistance to atmospheric corrosion should always provide easy drainage from all exposed surfaces. Stress corrosion...
cracking (SCC) can be prevented by substituting a more resistant alloy, removing the tensile
stress, or making the environment less aggressive. For example, in SCC of austenitic stainless
steel by chlorides, substitution of ferritic or duplex stainless steels often alleviates the problem. The
ferritic stainless steels may be subject to pitting, but the duplex grades are more resistant. Crevice
corrosion can be minimized by proper design of welded joints and gaskets that minimize
crevices. Welded joints are thus preferable to bolted and riveted joints, but the welds must be
properly designed and constructed to eliminate crevices. Gaskets must be properly sized to
minimize crevices exposed to the corrosive solution and should not use absorbent or
permeable material. Sealing compounds and inhibitive coatings on flange faces also provide
a barrier from chloride deicing chemicals. Galvanic corrosion can be avoided by using the same
type of metallic material for the same structure. If dissimilar alloys have to be used in electrical
contact with each other, galvanic corrosion can be controlled by selection of alloys that are adjacent
to each other in the galvanic series. In other unavoidable couples, the anode alloy should be larger in
area compared to the cathode and both members of a galvanic couple should be coated to avoid any
small anode area at coating defects. If feasible, dissimilar alloys should be electrically insulated from
each other at their junction. Crevices between dissimilar alloys should be avoided, under which the
corrosion is more serious than galvanic corrosion or crevice corrosion alone. Furthermore,
configuration of structures should be as simple as possible. Design should allow maximum access for
maintenance and repair painting. Box sections have poor access to coatings, collect water and debris,
and maximize possibilities of corrosion. Edges and corners are difficult to coat uniformly, and thinly
coated protrusions are susceptible to corrosion. The use of simple cylindrical structural members is
preferred since they allow for ease and uniformity of paint application as well as convenient
inspection [56].

Maintenance Practices

Winter maintenance agencies typically integrate a wide range of methods and procedures that
may involve routine washing, reapplication of coatings, grit blasting, mechanical removal of
rust, or the use of rust removers to improve the service life of equipment. Surface protection
is a common successful corrosion preventative strategy, which is achieved in various
methods. Surface treatments such as applying a coat of paint reduce the contact between the
metal and deicing agents, thereby preventing corrosion. Winter maintenance agencies have
reported various modifications of specific components to mitigate impacts of chloride deicers
to equipment. In particular, WSDOT has been actively involved in extensive corrosion
research and development projects as it has recognized the need to protect its equipment asset
from deicer corrosion. WSDOT has made substantial progress towards effective corrosion
prevention methodologies and has been very proactive with various corrosion mitigation
approaches such as appropriate deicer and corrosion inhibitor selection, equipment
modification techniques, and regular maintenance schedules.

Recent research and information collected from the Washington State Department of
Transportation (WSDOT) has identified various best practices focused on reducing impacts
to equipment from roadway deicers. These specific techniques have been an integral part of
effective reduction of corrosion rates on winter maintenance equipment and have allowed
WSDOT to achieve the recommended 12-year service life for their equipment fleet.

- Use high-quality weather-proof terminations.
• Position wiring to reduce damage to the outside casing of wires.
• Do not probe the wires to test for continuity.
• Use dielectric silicone for sealing damaged areas or connections.
• Open up closed areas (e.g. pillars) and allow them to flush out easily.
• Use welds to close and seal off certain areas that are difficult to drain.
• Caulk welds prior to painting.
• Do not apply paint to the rubber seals around lights.
• Sealed hydraulic components.
• Sealed brake canisters.
• Install modified protective cover for battery.
• Eliminate junction boxes wherever possible.
• Install modified electrical junction boxes, which are mounted inside the cab and off the floor.
• Replace original oil pans with more resistant zinc oil pans.
• Replace radiators every two years.

Some additional best practices collected from other agencies include: eliminating areas that solids and liquids may accumulate; specifying rust-proof brake shoes when rebuilding; specifying self-healing undercoats for chassis; specifying fender liners for chassis; using dielectric silicone for sealing damaged areas or connections; and avoiding any damage of wiring insulation. In addition, a general consensus of survey respondents was observed with respect to replacing certain corrosion-prone components with corrosion-resistant materials such as stainless steel or non-metallic wherever possible or be inspected and replaced on a regular basis. It has been reported by a survey respondent that stainless steel components last 25% to 100% longer than carbon steel.

Additionally, WSDOT has implemented the following best practices: consistent washing after application, regular rinsing and localized cleaning (followed by fast drying), using high-quality primers and topcoats in equipment specifications, using composite materials less susceptible to corrosion, and protecting new and replacement components prior to installation with wraps, covers, or shields. Power-wash with salt remover HoldTight or similar product to significantly enhance the anti-corrosion property of carbon steel and stainless steel parts against deicer corrosion. Once active corrosion of metals has started, power-washing should be coupled with other means, e.g., applying spray-on corrosion inhibitor (e.g., Krown T40 or Rust Oleum, 19 times per year) immediately after the equipment is washed clean and dried. Other methods of aftermarket rust-proofing may include the application of post-assembly coatings (e.g., Rust Bullet). Sharman compared the efficiency of a newly developed biodegradable rust remover and mechanical rust remover and found that this approach creates an inexpensive method of removing rust and improving the quality of the surface of the steel. Moreover, after the surface was cleaned, coating adhesion greatly improved causing an increase in performance of the coating thus increasing the service life of the material. The rust remover offers a great alternative to grit blasting and mechanical removal of rust particularly in situations where grit blasting may be prohibited or unfeasible for safety and
environmental reasons [57]. Figure 5 provides a detailed flow chart of corrosion prevention and control tasks, which can be utilized by maintenance agencies to ensure effective implementation and management of a corrosion mitigation strategy [58].

**Figure 5:** Flow of tasks for managing the corrosion of defense equipment assets [58].

**CONCLUSION**

A general overview of the mechanisms of corrosion is reported in order to gain a better understanding of the corrosion process, which will enable effective improvements to existing practices. In addition, accurate test methods and procedures play a crucial role in determining mitigation strategies through research and development. Therefore, common test methods for determining effective corrosion mitigation strategies to protect equipment are explored along with specific proactive approaches focused on reducing the impacts of chloride deicers to winter maintenance equipment.

The application of improving designs and implementing maintenance practices can combine to significantly reduce the harmful effects of corrosion and the associated costs. Research
focused on understanding and characterizing corrosion mechanisms can provide valuable insight on the corrosion process, which can be integrated into developing accurate testing methods. New corrosion prevention techniques involving advancements in materials science and engineering can be developed by supplementing knowledge gained from mechanistic studies and improved corrosion testing methods.

Online corrosion monitoring provides valuable real time corrosion information, which can effectively reduce corrosion maintenance costs, offer alternative corrosion maintenance approaches, and improve safety standards. These systems are able to provide early detection and assessment of corrosion, while being utilized to estimate service life and assess performance of corrosion inhibitors. Although many test methods and online corrosion monitoring systems have been developed, the corrosion process is complicated and it is still necessary to explore new theories, methods and technologies to address the existing problems and bridge knowledge gaps.

Through research and development several approaches to achieve better corrosion resistance and increase savings such as improving designs, modifying practices and policies, refining corrosion modeling and prediction methods will subsequently advance technology and increase education. WSDOT has made significant advancements in materials design, which have been proven to effectively mitigate corrosion impacts to winter maintenance equipment caused by roadway deicers. It is recommended for winter maintenance operations in the snowy regions of North America to integrate these techniques into standard corrosion control protocol to protect maintenance equipment, reduce costs of corrosion caused by roadway deicers, and increase equipment service life.
### Table 5: Corrosion Management Best Practices.

<table>
<thead>
<tr>
<th>Corrosion Management Best Practice</th>
<th>Highlights</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials Selection</td>
<td>Recommended to use exfoliation resistant tempers such as T76 or 7xxx alloys with copper. Alloys in the 1xxx, 2xxx, 3xxx, 5xxx, and 6xxx series contain the highest corrosion resistance properties.</td>
<td>Increased corrosion resistance and increased service life. Cost savings due to minimized corrosion. Use composite materials wherever possible.</td>
</tr>
<tr>
<td>Design Improvements</td>
<td>Structures designed for resistance to atmospheric corrosion should provide easy drainage. Properly designed welded joints to eliminate crevices are preferable to bolted and riveted joints.</td>
<td>Design should allow maximum access for maintenance and repair painting. Use of Sealing compounds and inhibitive coatings can greatly reduce effects of corrosion.</td>
</tr>
<tr>
<td>Maintenance Practices</td>
<td>Methods and procedures that involve routine washing, reapplication of coatings, grit blasting, mechanical removal of rust, or the use of rust removers. Selection of appropriate deicer and corrosion inhibitor combinations, equipment modification techniques, and regular maintenance schedules.</td>
<td>Significantly improves the service life of equipment. Recommended to seal hydraulic, electrical, and brake components and remove junction boxes. Indicate high quality coatings and materials in equipment specifications. Record and maintain detailed documentation.</td>
</tr>
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**ACKNOWLEDGEMENTS**

The authors acknowledge the financial support provided by the Washington State Department of Transportation (WSDOT) as well as the USDOT Research & Innovative Technology Administration (RITA). The authors thank their colleague Dr. Yongxin Li for editorial assistance on this manuscript and thank Greg Hansen and Monty Mills at WSDOT for providing the corrosion-related repair cost data.
REFERENCES


