INVESTIGATION OF MATERIALS FOR THE REDUCTION AND PREVENTION OF CORROSION ON HIGHWAY MAINTENANCE EQUIPMENT

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16. Abstract

The issue of corrosion of winter maintenance equipment is becoming of greater concern because of the increased use of liquid solutions of ice control chemicals, as opposed to their application in solid form. Being in liquid form, the ice control chemicals can more easily penetrate into the nooks and crannies on equipment and avoid being cleansed from the vehicle.

Given this enhanced corrosive ability, methods must be found to minimize corrosion. The methods may include coatings, additives, cleansing techniques, other methods, and may also include doing nothing, and accepting a reduced equipment lifetime as a valid (perhaps) trade off with the enhanced benefits of using liquid ice control chemicals. In reality, some combination of these methods may prove to be optimal. Whatever solutions are selected, they must be relatively cheap and durable. The latter point is critical because of the environment in which maintenance trucks operate, in which scrapes, scratches and dents are facts of life. Protection methods that are not robust simply will not work.

The purpose of this study is to determine how corrosion occurs on maintenance trucks, to find methods that would minimize the major corrosion mechanisms, and to suggest a mode of analysis to determine the optimal combination of approaches for a given maintenance situation.

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1. INTRODUCTION

Estimates suggest (Verink, 2000) that over $220 billion are lost in the United States each year due to corrosion. The same report estimates that 15% of this loss is avoidable. In winter maintenance, the chemicals used for ice control can be very corrosive, thus there is a potential need for steps to be taken to minimize the impacts of corrosion that results from the use of these ice control chemicals. However, determining what these steps are is a complex process, because so many different components, made of different materials, may be impacted by the ice control chemicals used. Thus, we have to consider not just steel, but also the various "soft metals" that can be found in the wiring and elsewhere on the fleet. Specifically, copper, aluminum, chrome and brass all need to be considered/protected as well as steel. The issue is further complicated because the materials are used in different configurations. Copper, for example, is often used in wiring, and in that use is often enclosed in a plastic sheath to provide insulation. If that sheath is broken, corrosion may occur very rapidly due to the creation of a galvanic cell, with the practical outcome that a wire which appears to be operational, is in fact almost totally corroded away within its insulating sheath.

The issue of corrosion of winter maintenance equipment is becoming of greater concern because of the increased use of liquid solutions of ice control chemicals, as opposed to their application in solid form. Of course, when a solid material such as rock salt is applied to the road, it goes into solution to become liquid, but when salt brine is being used directly, there is a lot more of it around the truck and other equipment in the ideal form to create rapid corrosion.

Being in liquid form, the ice control chemicals can more easily penetrate into the nooks and crannies on equipment and avoid being cleansed from the vehicle. The use of liquid brine brings significant benefits in winter maintenance activities, but if as a result vehicles are subject to much higher rates of corrosion, the benefits will be somewhat offset.

Given this enhanced corrosive ability, methods must be found to minimize corrosion. The methods may include coatings, additives, cleansing techniques, other

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methods, and may also include doing nothing, and accepting a reduced equipment lifetime as a valid (perhaps) trade off with the enhanced benefits of using liquid ice control chemicals. In reality, some combination of these methods may prove to be optimal. Whatever solutions are selected, they must be relatively cheap and durable. The latter point is critical because of the environment in which maintenance trucks operate, in which scrapes, scratches and dents are facts of life. Protection methods that are not robust simply will not work.

The purpose of this study is to determine how corrosion occurs on maintenance truck, to find methods that would minimize the major corrosion mechanisms, and to suggest a mode of analysis to determine the optimal combination of approaches for a given maintenance situation.

2. LITERATURE REVIEW

The review considers the literature relating to corrosion of winter maintenance equipment in three parts. First, general ways in which corrosion occurs, that are pertinent to winter maintenance environments, are considered. Then, the corrosion specification developed by the Pacific Northwest Snowfighters is considered. Finally, some reports that are specific to and particularly pertinent to corrosion in winter maintenance environments are considered.

2.1 Mechanisms of Corrosion

The basic mechanisms of corrosion are well documented and understood. For example, Schweitzer (2003) defines corrosion as the destructive attack of a metal by chemical or electrochemical reaction, and identifies nine basic forms of corrosion as follows.

1. Uniform Corrosion: In these cases, exposure of metal to air results in the formation of a passive film on the surface of the metal. This film (provided it maintains structural integrity) then protects the underlying metal from further corrosion. Clearly, the formation of such a passive film can be beneficial.

2. Inter-Granular Corrosion: This form of corrosion attacks the grain boundaries within a metal preferentially, and can be rapid and progress deeply into the material, reducing both the strength and the ductility of the metal very rapidly.

3. Galvanic Corrosion: This occurs when two different metallic materials are electrically connected, and in contact with a conductive solution. One of the metals will become the anode, and will corrode, while the other becomes the cathode and is protected. Provided the correct metal is the cathode, galvanic corrosion can be a means of protection. Tables of metals (sometimes called galvanic series) are available (see e.g. Table 2.2 in Schweitzer, 2003) that list metals from the anodic to the cathodic. If protection is being sought for a given material, then the sacrificial anode must be made of something that is higher or more anodic in the galvanic series.

4. Crevice Corrosion: As indicated by the name, this sort of corrosion occurs within or adjacent to narrow gaps or opening between metal-to-metal or metal-to-nonmetal interfaces. Such locations tend to have lower oxygen concentrations than elsewhere on a body or component, so when small amounts of liquid collect there, the differences in oxygen concentration may give rise to corrosion. Unfortunately in a winter maintenance context, crevice corrosion is more intense when chlorides are present.

5. Pitting Corrosion: This form of corrosion is localized. Pitting starts when the protective film on the surface of the metal is broken down, creating a small cavity. The typically small size of the pit allows a difference in concentration of either oxygen or salt concentration in liquids to develop, and this allows for the creation of a galvanic cell. If the metal is anodic in respect to the surface coating, then corrosion under such circumstances can be rapid.

6. Erosion Corrosion: In order for erosion corrosion to occur, a corrosive fluid must be moving over the surface of the corroding metal. The fluid motion causes a breakdown in the surface protective layer, and thus continually exposes new metal to the corrosive liquid. This form of corrosion can be particularly prevalent under circumstances where cavitation may be occurring.

7. Stress Corrosion Cracking: This form of corrosion failure is limited to certain alloys or alloy systems under certain environmental conditions. It occurs when cracks form in a material or component under stress, and if environmental conditions are right, the crack may grow rapidly due to corrosion within the cracked region. The stress appears to enhance the rate of corrosion in a way not fully understood. This form of corrosion can be particularly pernicious, since the main surface of the metal or component may show now signs of corrosion. Unfortunately, a number of alloy systems are prone to stress corrosion cracking in the presence of chlorides. These include some alloys with either aluminum or magnesium bases, martensitic and austenitic stainless steels, and titanium.

8. Biological Corrosion: Living organisms may under certain circumstances impact the anodic and cathodic reaction processes. This means that their presence may significantly accelerate corrosion, or even enable it to occur under circumstances in which, absent the organisms, corrosion would not have occurred. Biological corrosion often appears very similar to pitting, so if pitting is observed it may be necessary to test for the presence of micro-organisms to determine the true cause of the pitting (and thus develop an appropriate countermeasure).

9. Selective Leaching: The removal or corrosion of a single element in an alloy is known as selective leaching or dealloying (or, if the element being removed is zinc, dezincification). Typical conditions for such corrosion include high temperatures, a stagnant, acidic environment, and the formation of a porous scale on the surface of the alloy or component. This is not likely to occur in a winter maintenance context. Typically, this form of corrosion can be avoided by selecting a different alloy for a given component.

Clearly, not all of the above mechanisms are likely to be of major concern in winter maintenance conditions, but a number of them are particularly prevalent. In general, when using chlorides as an ice control chemical, any protective film that might otherwise form on the surface of a metal is disrupted. In particular, ions destroy the protective oxide films on the metal surface, and this increases the corrosion rate substantially (Chance, 1974).

The presence of chlorides exacerbates the situation further because the chloride ions help the formation of an electrochemical cell, in which the metal is the anode (and is thus corroded). Additionally, the conductivity of a chloride solution is better than that of water, so there is an increased flow of electrons, or a higher corrosion current. As noted by Minsk (1998), the corrosion rate is directly proportional to the corrosion current.

When using liquids as ice control materials, the corrosion rate can be enhanced in a number of ways. First, a wet environment allows for easier creation of galvanic cells. Second, corrosion current will be high in the presence of liquids. Third, liquids can penetrate into areas not accessible by solids. Fourth, liquids may result in differential aeration (Trethewey and Chamberlain, 1995), in which circumstances the location with lower levels of oxygen serves as the anode (and is corroded). Fifth, the presence of liquids may enhance the presence of micro-organisms, thus giving rise to biological corrosion. The most prominent cause for this type of localized corrosion is the presence of sulfate-reducing bacteria, Desulfovibrio desulfuricans (Uhlig and Revie, 1985). Taken collectively, these factors might be read as being highly negative of the use of liquids in winter maintenance, but in reality, any time any ice control chemical, whether liquid or solid, is placed on the road and goes into solution, a liquid chemical will be present. The quantity of liquid may be greater when liquids are applied directly, and certainly anecdotal reports would seem to suggest higher likelihood of corrosion when using liquids directly, but that does not mean that corrosion can be avoided by the use of solids chemicals only.

Other factors that influence corrosion rates in a winter maintenance environment include the fact that dissimilar metals may be found in many locations on trucks, and these can easily give rise to a galvanic cell, leading to corrosion of the metal that is serving as the anode. Under certain circumstances, low pH levels (in general, pH < 4, an acidic region) may give rise to increased corrosion (Uhlig and Revie, 1985), especially if the pH is sufficiently low to dissolve or break down any passive coatings. Conversely, highly alkali regions (pH > 10) may be beneficial, since Iron, for example, becomes passive under such conditions. Also, given that the frame of a truck (along with other

components) is under load in normal circumstances, stress corrosion cracking may be of concern (Trethewey and Chamberlain, 1995).

Clearly, the environment on a snow plow in winter conditions that is applying ice control chemicals (and indeed various other components around a garage at such times) is one in which corrosion is a definite possibility. Preventing this corrosion will require a number of different approaches, depending on how the corrosion is occurring, and what parts on the truck (or elsewhere) are corroding. The damage of critical components (whether load bearing, electrical systems, brake systems, or whatever) is obviously of greater concern than cosmetic damage. Nonetheless, even cosmetic corrosion may be an indication that more damaging corrosion is occurring elsewhere.

2.2 Corrosion Control Standards

The Pacific Northwest Snowfighters[1] (PNS) are a collection of states and provinces[2] that have worked together to develop common specifications for ice control chemicals. One area in which they have produced a specification is that of corrosion[3]. These specifications state that:

> *No bid will be accepted on any corrosion inhibited product that has not successfully completed the National Association of Corrosion Engineers (NACE) Standard TM0169-95, as modified by the PNS, and found to have a Corrosion Value of at least 70% less than that of Sodium Chloride (salt).*

The specifications describe further how NACE TM0169-95 is to be modified. The specifications identify eight different product categories, with particular requirements for each category (typical categories would include corrosion inhibited sodium chloride, or corrosion inhibited liquid calcium chloride). There is a ninth category termed "PNS Experimental Category" to accommodate any novel chemicals that may be presented for consideration by the members of the PNS.

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[1] PNS has a web site at: http://www.wsdot.wa.gov/partners/pns/default.htm (accessed 12/29/08)
[2] Current membership includes Washington, Oregon, Montana, Idaho, Colorado, and the Province of British Columbia.
[3] See http://www.wsdot.wa.gov/partners/pns/pdf/4-06FinalPNSSPECS.pdf (accessed 12/29/08)

A complete description of NACE TM0169-95 is given in Chapter 3 below, but the test as modified by the PNS requires the use of a steel washer of a particular type (specifically the coupons must meet ASTM F 436, Type 1, with a Rockwell Hardness of C 38-45. All testing for the PNS is comparative, and any chemical product solution being tested must be tested at the same time as distilled water and sodium chloride control standards. The weight loss of the coupons tested in the chemical product solution is then compared with the weight loss of the coupons tested in the sodium chloride control solution. In order to pass the test the coupons tested in the chemical product solution must show 70% less weight loss than those tested in the sodium chloride control solution.

The corrosion test itself involves dipping the coupons into the solution for a period of 10 minutes every hour, for a total duration of 72 hours. The rest of the time (when not in the solution) the test coupons remain in the flask containing the solution. After the 72 hour period, the coupons are cleaned and weighed, and the amount of corrosion is thus determined.

One aspect of specification tests is that they be sufficiently well defined that any time the test is performed essentially the same results are obtained when testing the same materials. This has the significant benefit of providing an objective standard, but it has the limitation that it can only test certain conditions. In the matter of corrosion, any specification test is necessarily limited. In this case, the NACE test, as modified by the PNS, is limited in a number of ways. First, and most importantly, it tests the performance of steel only (and a particular type of steel at that). Obviously, there is concern about corrosion of metals other than steel (e.g. copper or aluminum), and of steels other than that used in the specification test. Second, the test only addresses a particular set of circumstances in which corrosion may occur, specifically when a component is subjected in a cyclic manner to immersion in a liquid, followed by drying of that liquid. In other circumstances, different modes of corrosion (see 2.1 above) may dominate in which case the specification test will not provide reliable information.

Nonetheless, specification tests of this sort are regularly used in a number of different fields. A primary reason for this is that it is not economically feasible to test all the different materials that may be subject to corrosion by an ice control chemical and to

test also all the different modes in which that chemical might cause corrosion. For the purposes of specification, a single, limited, test must be used. However, it should be borne in mind that the results of such tests are necessarily incomplete with regard to the full range of corrosive behavior that may result from the use of the chemical being tested.

2.3 Reports Specific to Winter Maintenance

Section 2.1 considered ways in which corrosion occurs in general. The specifics of the winter maintenance environment allows this broad range of behaviors to be narrowed somewhat, and two reports in particular are helpful in this regard. The first is a laboratory study conducted for Colorado Department of Transportation (Xi and Xie, 2002) which considered how Magnesium Chloride and Sodium Chloride caused corrosion on automobile components. The second is a report of the Washington DOT Salt Pilot Project (Baroga, 2004), a field test conducted along I-90 in Eastern Washington.

2.3.1 Laboratory Study by Xi and Xie.

In this study four different materials were tested using three different types of corrosion tests. The four materials tested were two steels and two aluminum alloys. The steels were 304L, a stainless steel with relatively high levels of Chromium (18.1%) and Nickel (8.05%), and 410, a stainless steel with no measurable Nickel, and only 2.5% Chromium. The two aluminum alloys tested were Al 2024 with relatively low levels of Magnesium (0.25-0.5%) and Al 5086 with relatively high levels of Magnesium (3.5-4.5%). These four test materials thus represent a fairly wide span of possible steels and aluminums, although there is no guarantee that for example, an aluminum alloy with Magnesium levels between those in Al 2024 and Al 5086 would perform at a level between that observed in the two alloys tested herein.

Testing was initially conducted using two protocols – the SAE J2334 method (a cyclic exposure test) and the ASTM B117 spray test. Tests were conducted using both pure reagent chemicals and ice control chemicals as supplied by Colorado DOT. The SAE J2334 method required that samples be cycled from a high temperature high humidity environment to a higher temperature lower humidity environment, and back. Each cycle lasted one day, and the total testing lasted two months. The ASTM B117

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spray test involves spraying the test coupons continuously with a 4% solution of the ice control chemicals, for a period of 800 hours.

In the SAE J2334 tests neither the 304L steel nor the Al 5086 Aluminum alloy experienced any significant corrosion. For the other two materials, both experienced significantly more corrosion due to Magnesium Chloride than to Sodium Chloride. This was especially true for the 410 steel which corroded at rates between 5 and 13 times faster in the Magnesium Chloride than in the Sodium Chloride.

In contrast, in the spray test (ASTM B117) the 410 steel corroded approximately four times as fast in the Sodium Chloride as in the Magnesium Chloride. The Al 2024 corroded at approximately the same rate in both chemicals, while the Al 5086 corroded at similar rates, in general, to the Al 2024 (in contrast to the SAE J2334 test results) with slightly more corrosion in the Magnesium Chloride than in the Sodium Chloride. Again, the 304L steel showed almost no corrosion in the spray test. Given these somewhat conflicting results, it was decided to extend the study into Phase II, and examine how the modified NACE test used by PNS would perform. However, because the NACE test is only of short (72 hour) duration, none of the first batch of materials could be tested, since they would likely show no significant corrosion in the test time. Thus the PNS specified washer (see above) was tested, along with an A36 steel coupon. A36 is a carbon steel, and is not a stainless steel. It contains no significant levels of Chromium. In this test both the washer and the A36 steel coupon corroded more in the Sodium Chloride than in the Magnesium Chloride, by a factor of between two and three times. It is of interest that subsequent testing under the SAE J2334 protocol of these two materials showed very similar corrosion rates for both Magnesium Chloride and Sodium Chloride. For the A36 steel and the washer, the corrosion rates in the SAE J2334 tests were about ten times higher than the highest rates for the other materials.

These test results are very troubling. It is clear that the different test techniques attempt to capture different environments. It is also apparent that the NACE test is limited practically to materials that exhibit rapid corrosion, and may tell us very little about the performance of materials that are even mildly corrosion resistant. The authors concluded that the primary difference in the results came from the behavior of the

Magnesium Chloride in high humidity conditions. It appears that in the SAE J2334 test, during the very high humidity portion of the test, the Magnesium Chloride, which had previously dried out, would re-hydrate into a liquid very rapidly. This meant it was in a liquid (i.e. more corrosive) form much longer than the Sodium Chloride, and as a result gave rise to a much higher rate of corrosion. Unfortunately, it is less than clear whether the high humidity conditions of the SAE J2334 protocol are more or less realistic of field environments than the immersion conditions of either the NACE test or the ASTM B117 spray test.

2.3.2 Field Study by Baroga

For a number of years, the Washington State DOT has been conducting a field trial of various ice control chemicals along the I-90 corridor in Eastern Washington (Baroga, 2004) termed the Salt Pilot Project. The purpose of this project has been to determine whether corrosion rates in the field mirror those observed in the NACE test method used by the PNS. Specifically, the PNS Specification requires that ice control chemicals be 70% less corrosive than salt, and a primary goal of this study was to determine whether chemicals that met this requirement in the laboratory performed equally well in the field. In addition, the study aimed to compare snow and ice control costs when using Sodium Chloride with those costs when using corrosion-inhibited chemicals; to compare the road conditions obtained when using salt with those obtained when using corrosion-inhibited chemicals; and to compare chloride levels in roadside soils, surface water, and underlying groundwater in areas using salt with chloride levels in areas using corrosion-inhibited chemicals.

Four segments of I-90 were selected and defined for the test between milepost (MP) 111.00 and 299.82. In two of the segments (MP 111.00 to MP 136.50 – the SC salt segment, and MP 191.89 to MP 255.29 – the Eastern salt segment) rock salt and salt brine were used as the primary ice control materials. In a third segment (MP 136.50 to MP 191.89 – the NC segment) liquid calcium chloride and corrosion-inhibited rock salt were used, while in the fourth segment (MP 255.29 to MP 299.82 – the Eastern corrosion-inhibited segment) liquid magnesium chloride and corrosion-inhibited rock salt were used.

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In all four of the test segments, a level of service rating (as measured by the DOT Maintenance Accountability Program) of A (the highest possible) was achieved. In terms of costs per lane mile, the segments using salt rather than other inhibited materials exhibited lower costs, although care must be taken with such comparisons since the severity of storms and of the winter season may not be exactly comparable in all four segments.

The corrosion testing made use of 4 inch by 6 inch coupons of three materials – a mild steel, a sheet aluminum alloy (Al 5182) and a cast aluminum alloy (Al A356). These were selected because they are often used in car and truck parts. Two of each coupon were mounted on a test rack, which was in turn mounted to a vehicle. In total 31 maintenance trucks had these test racks mounted, as did four supervisor trucks. In addition, one set of coupons was also fitted onto guardrail posts at select locations in each of the segments.

Weight loss measurements from the coupons were obtained by averaging the losses for each material type from each project section. A first result was that weight loss in the steel coupons was approximately an order of magnitude higher than in either of the two aluminum coupons tested.

As noted above, the specification test used by Washington DOT requires that corrosion-inhibited ice control chemicals be 70% less corrosive than salt. However, in none of the field test results was this level of improvement obtained. Comparing the first salt region (SC salt) with the first corrosion-inhibited region (NC segment) the steel coupons on the maintenance trucks corroded 53% less in the NC segment than in the SC segment. Those on the supervisor trucks corroded 60% less, while those on the guardrail corroded 17% more. The sheet aluminum coupons corroded more in the corrosion-inhibited segment (NC) for all three locations (180%, 13% and 100% respectively), while the cast aluminum coupons corroded less for the maintenance (25%) and supervisor trucks (32%) in the corrosion-inhibited segment, and corroded more on the guardrails (143%).

A similar result, in general, was found when comparing the straight salt segment and corrosion-inhibited segment in the Eastern region. For the steel coupons,

maintenance trucks (30%) and supervisor trucks (27%) showed less corrosion from the corrosion-inhibited material, while the guardrail showed more (9%). The sheet aluminum coupons corroded more in the corrosion-inhibited region for the maintenance (140%) and supervisor trucks (160%), but less for the guardrail coupons (50%). The cast aluminum coupons corroded more in the corrosion-inhibited segment for the maintenance (14%) and supervisor trucks (53%) and less for the guardrail coupons (47%).

Clearly the corrosion mechanism being tested in the PNS specification test is not what is regularly experienced in the field. This is not to say that the modified NACE TM0169-95 test is incorrect, but merely that it cannot address all modes of corrosion experienced in the field.

3. LABORATORY EXPERIMENTS AND RESULTS

One of the issues raised by Xi and Xie (2002) but not fully addressed was how much the concentration of a chemical solution would impact the corrosion caused by that chemical, and whether chemicals that were particularly corrosive at one concentration would be less so at another. In order to test for this possible factor, it was decided to conduct a series of experiments, using the modified PNS NACE TM0169-95 method using a variety of ice control products at three different concentrations. In this chapter, the test method used and the results obtained are described.

3.1 Test Method

This testing followed the method described by the PNS in their modified use of the NACE TM0169-95 standard test method, with the exception that each of the test chemicals used was tested at three different concentrations (1.5%, 3%, and 6%) instead of at just one concentration (3%). The concentrations were achieved by mixing the as-supplied ice control products with distilled water so that the ice control product comprised 3% (or 1.5 or 6%, as appropriate) by weight of the final solution.

3.1.1 Equipment

The testing was conducted using an AD-TEK Corrosion Testing Machine Model CTM10-10/50 (see Figure 3.1). The device can test up to ten samples simultaneously, each sample being tested in its own flask, containing its own fluid. The device suspends

the test coupons from a rotating bar that is controlled to allow for 10 minutes immersion in the fluid being tested, followed by 50 minutes suspension (still in the flask) above the fluid. This cycle is repeated for a total time of 72 hours (implying 72 separate cycles).

The test coupons used were cylindrical flat steel washers (the steel met ASTM F 436 Type 1, with a Rockwell Hardness of C38-45) with an outer diameter of approximately 1.38 inch, an inner diameter of approximately 0.56 inch, and a thickness of approximately 0.11 inch. Each test coupon was measured prior to testing, and was also weighed twice. In all cases, the two weights measured for a given coupon were within 0.0005 g of each other.
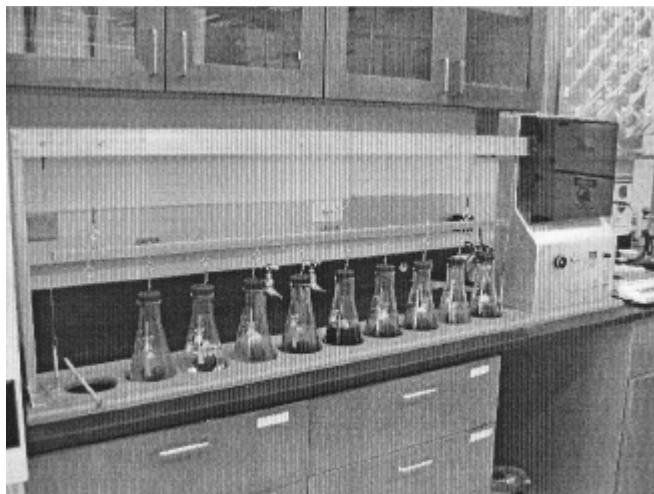

Figure 3.1: Corrosion Testing Apparatus

3.1.2 Test Process

Coupons are prepared by first degreasing them, then acid etching with Hydrochloric acid for 2 to 3 minutes (in a fume hood). They are then quickly rinsed with tap water, distilled water, wiped dried and placed in chloroform. Next, they are air dried for 15 minutes. The coupons were then measured as specified in the NACE standard, and weighed.

Eight ice control products, obtained from DOTs around the Midwest, were tested: salt brine, CMA, mineral brine, calcium chloride, Geomelt, a mixture of 20% Ice Ban Ultra and 80% salt brine, Caliber M-1000, and potassium acetate. In each test run, all eight chemicals were tested, together with distilled water. Note that in the PNS test,

comparison is made with a reagent grade salt brine, whereas in these tests comparison was made with the salt brine (supplied from the Oakdale garage) used by Iowa DOT.

Three test coupons were placed inside each flask, attached to the machine so that they would be immersed in the fluid for 10 minutes and suspended above it for 50 minutes in a repeating cycle. The tests were run for 72 hours (and thus 72 cycles). One set of tests (i.e. three coupons for each chemical) was run using 1.5% solutions. Three sets of tests were run using 3% solutions, but in the first two of these the distilled water used to dilute the solutions was contaminated and thus erroneous results were obtained. Three sets of tests were run using 6% solutions.

After the 72 hour test was completed, coupons were removed from the flasks and cleaned by placing in a glass beaker containing hydrochloric acid, stannous chloride, and antimony trichloride (in a fume hood) for 15 minutes. They are then removed from the cleaning acid, rinsed with tap water and distilled water, and wiped with a cloth to clean off any deposits. The cleaning procedure (in acid, followed by rinsing) is then repeated. The coupons are weighed (twice, to within 0.0005 g) and the final weights recorded.

After weighing, the weight loss for each coupon can be expressed in a more standard form for corrosion rate, as MPY or mils penetration per year. The formula used to calculate this is:

$$MPY = \frac{WL \times 534}{A \times t \times \rho} \tag{3.1}$$

Where WL is weight loss in milligrams, A is area (in square inches), t is time (in hours), and ρ is the density of the steel coupon (7.85 g/cm^3).

3.2 Test Results

Figure 3.2 shows the results from the set of tests conducted using the 1.5% 4solutions of chemicals. Somewhat surprisingly, salt brine is about as corrosive as CMA, and only marginally more corrosive than the 20/80 mix of Ice Ban and Salt Brine. Potassium Acetate is very non-corrosive, and the mineral brine and the calcium chloride mixture are the two most corrosive materials.

Corrosion Rates for 1.5% Solutions
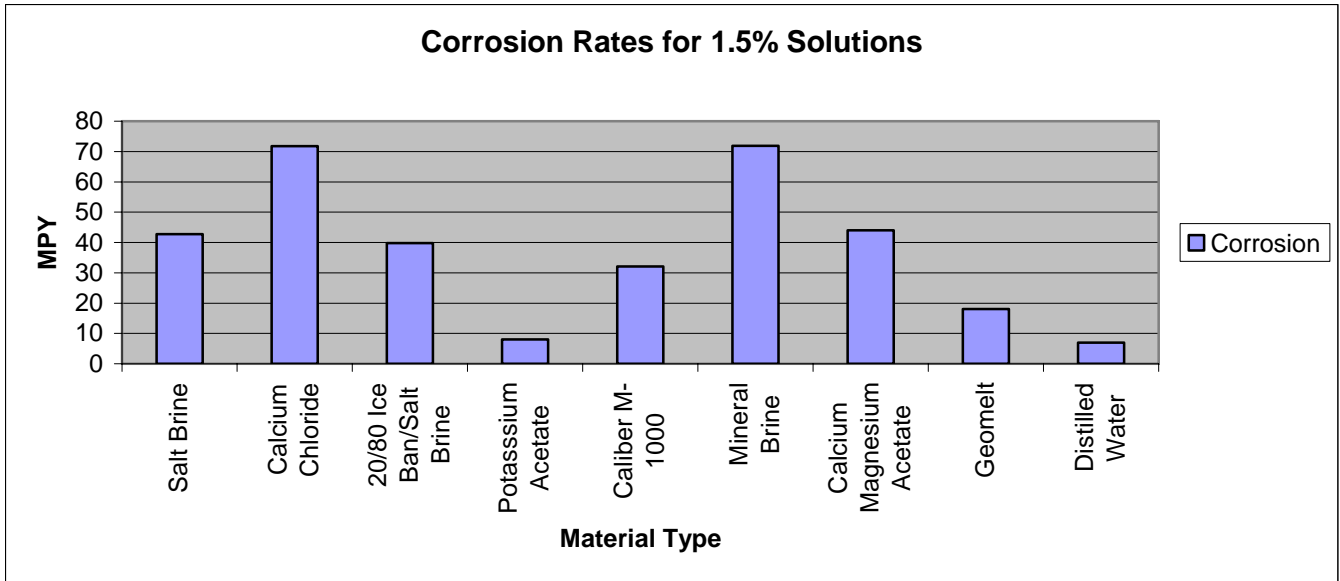
Figure 3.2: Corrosion Rates for 1.5% Solutions (MPY)

Figure 3.3 shows the corrosion rates for tests conducted with 3% solutions of chemicals. Again the calcium chloride and the mineral brine are the most corrosive, and the potassium acetate is the least corrosive, but the 20/80 Ice Ban and Salt Brine mixture is now more corrosive than the salt brine itself, and the Geomelt is now more corrosive than the Caliber M-1000. Also, the CMA is now clearly less corrosive than the salt brine.
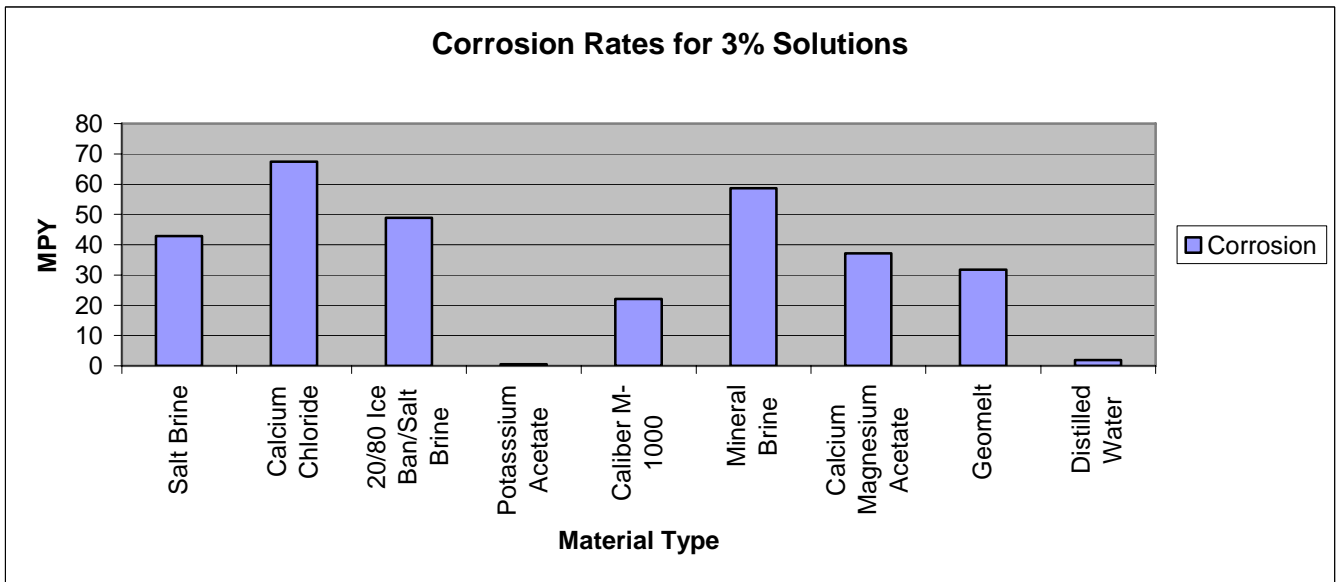
Corrosion Rates for 3% Solutions

Figure 3.3: Corrosion Rates for 3% Solutions (MPY)

Figure 3.4 shows the corrosion rates observed for the 6% solutions. The 20/80 Ice Ban and Salt Brine mixture is now the most corrosive and the mineral brine is now less corrosive than the salt brine. Other than that, the order, in terms of relative corrosivity, remains unchanged.

Corrosion Rates for 6% Solutions
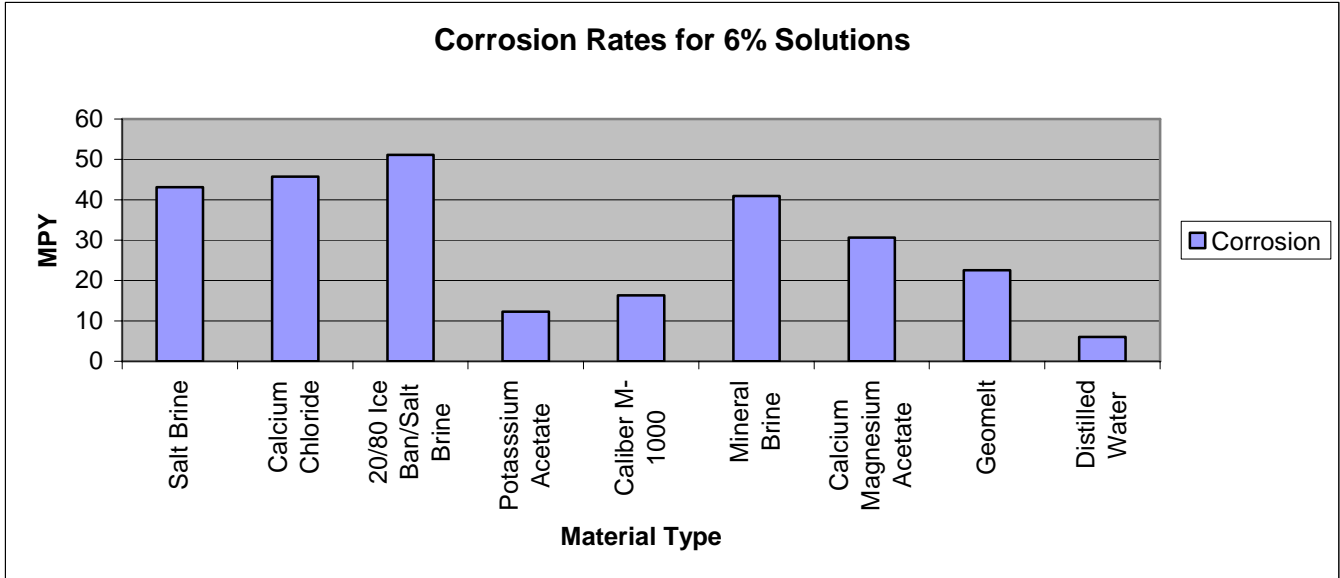
Figure 3.4: Corrosion Rates for 6% Solutions (MPY)

Variations in the relative degree of corrosion between the various chemicals is more clearly seen in figure 3.5 which shows results for all three solutions. The variation in the degree of corrosion for some of the materials is striking. Calcium chloride, mineral brine, CMA, and Caliber M-1000 all show a monotonic decrease in corrosion as the concentration of the material increases. In contrast, the 20/80 Ice Ban salt brine mixture increases in corrosion with an increase in concentration, while salt brine itself is relatively unchanged, and potassium acetate and Geomelt show no clear trends.
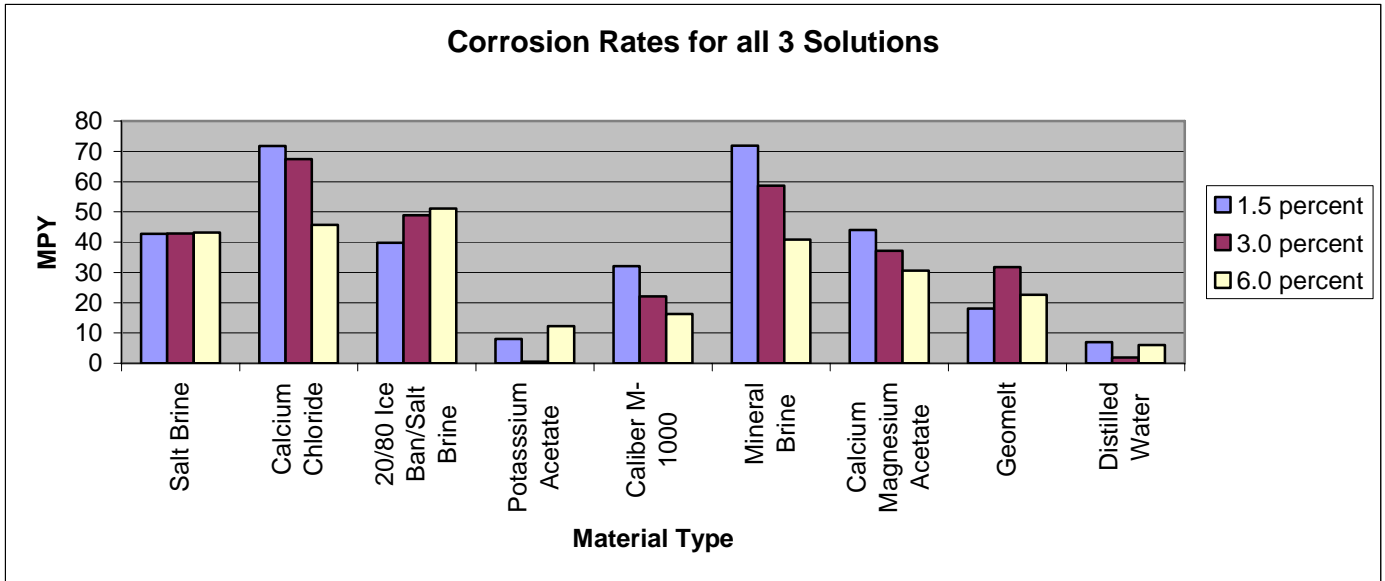
Figure 3.5: Corrosion Rates for All Three Solutions (MPY)

This result can be presented in a tabular form, if the materials are ranked from least corrosive (rank of 1) to most corrosive (rank of 8) for the three solutions. This is shown in Table 3.1. While potassium acetate is the least corrosive for all three concentrations, the situation thereafter is more complex. Clearly Geomelt and Caliber M-1000 are also not very corrosive, but thereafter the rankings are not particularly consistent. This indicates clearly that for many chemicals a test at one level of concentration will not necessarily place that chemical definitively in comparison to other materials with regard to its degree of corrosivity.

Table 3.1: Relative Ranking of Material Types at Different Concentrations.

Material Type	Ranking		
	1.5%	3%	6%
Potassium Acetate	1	1	1
Geomelt	2	3	3
Caliber M-1000	3	2	2
20/80 Ice Ban/Salt Brine	4	6	8
Salt Brine	5	5	6
Calcium Magnesium Acetate	6	4	4
Calcium Chloride	7	8	7
Mineral Brine	8	7	5

The implication of these results is not positive from the viewpoint of finding a specification test that can cover many different field situations. In a field application of chemicals, the concentration of chemicals on a truck or other piece of equipment will vary all the way from full strength down to less than 1% of full strength, as dilution occurs over time. If corrosion rates vary significantly with concentration, and relative corrosion also varies, then the specification test used by the PNS (and indeed any such test) is even less able to provide a comprehensive picture of corrosion. Recall that the PNS test is limited to a single coupon material, whereas in reality many different types of metals are subject to corrosion in field situations, and the situation becomes even more complex. The reality is perhaps that no specification test can ever provide a complete or near complete picture, but that such tests can identify very poor (and possibly very good) performers from the viewpoint of corrosion, and might thus be of use as a screening type of test (which is how PNS uses this test at present).

4. POTENTIAL SOLUTIONS TO CORROSION IN THE FIELD

In this chapter various conceptual methods for reducing corrosion in field applications will be considered, together with reports from the field on corrosion prevention methods that have either been proven useful, or may have the potential to be useful.

4.1 Conceptual Solutions

As clearly seen in chapter 3, some ice control products are in general less corrosive than others. One reason for this may be that some chemicals provide fewer charged particles or ions for the corrosion current. For example, sodium chloride, calcium chloride, and magnesium chloride contain more ions while calcium magnesium acetate, sodium formate, and urea contain fewer ions (Minsk, 1998). One might thus expect the latter chemicals to be less corrosive than the former. However, issues of cost and availability may limit an agency's options when it comes to selection of an ice control product, thus it may not always be possible to select a chemical that has minimal corrosion impact.

Another family of methods that can be effective may be classed as surface protection. If some sort of barrier can be placed over any metal surfaces, then the corrosive chemicals can never make contact with the metal surface, and thus corrosion cannot occur. This can be achieved in a number of different ways. First, surface treatments such as applying a coat of paint reduce the contact between the metal and moisture thereby preventing corrosion. Passivation of the surface may also be considered but the use of this approach is limited to those materials for which passivation is a possibility (Kruger, 2000).

In the area of component or equipment design, there are a number of possible approaches. One simple approach is to prevent the intrusion and retention of liquids on the metal surface either by introducing a barrier to the migration of water to the metal surface or by adjusting detailed design so that surfaces on which liquids may aggregate are minimized (Minsk, 1998). Related to this is the avoidance of differential aeration, by ensuring that oxygen levels between anode and cathode are at a minimum. This can best be achieved by avoiding closed or confined areas in equipment in which oxygen concentrations might differ from the rest of the equipment. Or if such closed areas must exist, they must be made in such a way that they are airtight and liquids cannot get in. This latter cannot be a half hearted measure, since if corrosive liquids do get into a confined space, they will likely cause very rapid corrosion. Another design factor that can reduce corrosion is to ensure that no electrical paths can form between any dissimilar

metals on the piece of equipment under consideration. If such paths can form then an electrochemical cell will be created giving rise to rapid corrosion. Related to this, methods of inspection and maintenance must be such that they do not create electrochemical cells. One example of a poor maintenance procedure in this regard is the checking of wiring by poking a probe through the insulation on the wiring. Doing this creates a potential electrochemical cell which can corrode out a wire very rapidly indeed.

An active defense that is used in a number of other equipment fields is the use of sacrificial anodes also known as cathodic protection (Fitzgerald, 2000). Cathodic protection requires that a current is applied from the anode through the liquid causing corrosion, to the surface being protected. The anode is then corroded, while the cathodic surface is protected. This approach has the benefit of low maintenance and easy installation, but is not always a feasible solution. Nonetheless, it may merit investigation.

An alternative approach is to limit the potential for corrosion by inhibiting the corrosive properties of the ice control chemical. A number of readily available ice control chemicals include inhibitors (e.g. Geomelt) and in some cases these appear to work reasonably well. However, as the results from the Washington Salt Pilot Study indicated (see chapter 2) these inhibitors do not always provide the protection in the field that results in the laboratory might suggest. One concern is that if the inhibitor is mixed with the ice control chemical (rather than in some way being chemically bound to it) then at some point after application of the chemical the inhibitor may become separated from the chemical, and thus its inhibitive benefits will no longer apply. The issue of the fate of inhibitors is currently undergoing investigation by the PNS[4].

4.2 Field Experiences

In this section information from two sources will be presented. First, a request was posted on the snow and ice list-serve asking for feedback on methods used to prevent corrosion that had worked in the field. Second, a search for such products was conducted to determine what possible solutions might also be available. Clearly, data found in the

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[4] See the latest progress report at:
http://www.wsdot.wa.gov/partners/pns/pdf/PNS_Inhibitor_Longevity_Progress-Oct_final2.pdf accessed 12/30/08.

second way are in general presentation from the vendor viewpoint, while those obtained from the list-serve are in general from the user viewpoint.

While relatively few responses (8 in total) were obtained to the request posted on the snow and ice list-serve, they do provide a fair overview of the various options. Seven of the eight responses mention the primary role that washing of vehicles should play in corrosion prevention practices. One noted:

Anodes, protective coatings, etc haven't done nearly as much for our fleet as a good old fashioned shot of hot water with soap.

Another response said:

Post storm washing and lubrication is the foundation to effective preventative maintenance.

And another noted:

Our DOT bought each garage low volume high pressure washers. Then we adopted a policy on washing equipment after each event.

Figure 4.1 shows a dedicated truck washing facility owned and operated by Minnesota DOT in the Twin Cities area.

Figure 4.1: Dedicated Snow Plow Washing Facility, Minnesota DOT.

While such facilities are likely expensive to build they certainly simplify the process of cleaning the truck after plowing and applying chemicals. Because they make it easy to perform this task, they in turn make it more likely to happen and thus aid significantly in reducing corrosion in winter maintenance equipment. However, such facilities pose a number of challenges. The water used in these facilities is likely to become contaminated with a number of chemicals and other products (e.g. engine oil, diesel, ice control chemicals) and thus special arrangements for water disposal will likely be required (adding to the overall cost). To the authors' knowledge, no cost benefit analysis of such facilities has yet been conducted.

Three responses mentioned some form of coating that can be applied to the truck to provide protection. One noted:

We use a product called LubraSeal. It is an encapsulant that coats our equipment with a black anti-corrosive film. It also has some lubricating qualities. It's not pretty and we do not apply it to the vehicle bodies. We do apply it to our hopper

type spreaders inside and out. We also coat our tailgate spreaders with is. We have been using it for approximately 6 years and have had good success.

Another noted:

Ziebarted undercarriage always...Rhomar LubraSeal and encapsulant helps to break down chlorides during washing.

And another noted:

We have also found that at the end of the season we have been using Neutro Wash.

In terms of design changes, three responses mentioned a variety of approaches that had, in their experience, limited corrosion. One respondent noted:

Regarding wiring, we use weather tight electrical connections. We position wiring to reduce damage to the outside casing of wires. We do not probe the wires to test for continuity and we use dielectric silicone for sealing damaged areas or connections.

Another respondent said:

Buying stainless steel truck boxes and stainless steel pre-wetting tanks has worked well for our county highway department. They are also buying stainless steel sanders.

And the third respondent to address design issues made a number of comments:

Worst areas undercarriages, suspension/threaded bolts, inside pillars on dump boxes, open them and try to flush out... Opening up helps...Welds help so it isn't working into gaps. Prior to painting use caulk to seal welds. On the lighting, no paint on rubber around light. That was one trouble area. Make sure everything is painted. Proper preparation of equipment before painting.

In terms of searching for products, the primary findings were of coatings for equipment. Table 4.1 lists the companies, their products, and website information for those companies that have been identified as providing possible solutions to the winter maintenance corrosion problem. Inclusion of a product in the list does not in any way

imply endorsement of that product, and to the authors' knowledge no formal tests by government agencies of these products and their benefits have been conducted to date.

Table 4.1: Products to Prevent Corrosion of Equipment

Company Name	Products	Web site or Contact Information
Road Solutions Inc.	Molycor System, Clion-X, Arrest, Molycor 20	www.roadsolutionsinc.com
Magnet Paint and Shellac Co., Inc.	Chassis Saver	www.magnetpaints.com
Rhomar Industries Inc.	LubraSeal, Neutro Wash	www.rhomar.com
Corrosion Control Products Company	Hold*Blast	http://www.farwestcorrosion.com/
Paradigm Chemical LLC	Tectyl 812	303-986-7871

Of course, in addition to coatings there are a number of additives to ice control chemicals (inhibitors) that may be beneficial. In the survey of list-serve members, two of the eight responses mentioned inhibitors, but neither response provided any specific details as to which inhibitors worked best.

4.3 Conclusions

On the basis of the information presented in this chapter, it seems there are four primary ways in which the impact of corrosion on winter maintenance equipment can be reduced. These are as follows:

- Add some sort of inhibitor to the ice control chemicals being used.

- Provide a mechanism to wash vehicles thoroughly and often after use, so as to remove corrosive chemicals from contact with corrodible components.

- Ensure that equipment is designed and maintained in such a way as to minimize opportunities for corrosion.

- Coat all exposed metal parts so as to prevent corrosive liquids from coming into contact with metal surfaces.

5. DEVELOPING A METHODOLOGY TO MINIMIZE CORROSION

It is clear from the above material that there is no single "magic bullet" that will reduce or stop corrosion on winter maintenance equipment. Any steps to minimize corrosion will of necessity involve all four of the approaches outlined at the end of chapter 4. At issue is what combination of these four approaches will provide the best (as in most efficient and effective) combined approach. In determining this approach, the concepts of efficiency and effectiveness must first be defined.

Efficiency in this case refers to the cost of the action. The more expensive the actions taken, the less efficient they are. However, this requires some adaptation because in that simple form, doing nothing would be the most efficient (because least expensive) action. Clearly this is not the case, and the cost of replacing a corroded piece of equipment (whether it be some part of a truck or the whole truck) must be included in the notion of efficiency.

Efficiency must therefore take into account the service lifetime of the truck if nothing is done to prevent corrosion from occurring. Presumably, taking some action or combination of actions will then result in an extension of that service lifetime. This can be translated (see below) into an annual saving. This saving, or benefit, can then be compared with the annual cost of taking the action or combination of actions that resulted in the service life extension of the truck. For an action to be of benefit, the annual savings obtained through life extension must exceed the annual costs of taking the action. Further, the optimal combination of actions can be found by comparing how much different actions or combinations of actions save annually compared with how much they cost – in short, a benefit – cost analysis is performed and the action combination that provides the highest benefit – cost ratio is the optimal methodology to minimize corrosion.

The equation relating the initial cost of a truck (or other piece of equipment) with the equivalent annual cost for that truck is given as:

$$A = P\left[\frac{i(1+i)^n}{(1+i)^n - 1}\right] \qquad (5.1)$$

Where A is the annual cost, P is the initial cost of the truck, n is the lifetime of the truck in years, and i is the annual interest rate. The annual interest rate for a government agency (or indeed for any entity) can be taken as the interest rate that agency would pay to borrow money – thus for a city or state it might be the bond rate for that entity.

Putting numbers to this equation may help to clarify the proposed process. Suppose that a fully equipped truck has an initial cost (complete with spreader, plow, and related equipment) of $100,000 and a service lifetime of 7 years without any significant measures to prevent corrosion. If prevention measures are taken, the lifetime can be extended to 10 years. Taking an interest rate of 5% (note that all numbers here are approximate), the annual cost without any prevention is $17,281.98. If the lifetime is extended to 10 years, the annual cost is $12,950.46. Thus the prevention measures taken result in annual savings of $4,331.52. If the annual cost of the prevention measures for that truck is less than this, then the measures are worth taking. Note that these figures are of course highly dependent on the input values used.

The four measures identified at the end of chapter 4 will now be considered in the context of this methodology. At this time there is insufficient information available to allow for actual calculations in regard to the specific measures, but as further work is conducted (see chapter 6 for recommendations in this regard) the data needed for these calculations will become available.

5.1 Adding Inhibitors to Ice Control Chemicals

There are a number of issues that remain to be resolved regarding this approach in order to ascertain the degree to which this measure is efficient and effective. As discussed above, tests measuring the corrosivity of various chemicals, with and without inhibitors, provide very different results depending on the test used, the concentration of the chemical tested, and whether the test is conducted in the laboratory or the field. There are some practitioners who are firmly convinced that inhibitors reduce corrosion in maintenance equipment, and others who do not believe they are effective at all. No consensus exists as to how much the use of such inhibitors extends the service life of equipment thus making any calculation of benefit – cost ratios currently impossible.

There are also other factors that must be considered in this regard. If an agency decides to use an inhibited calcium chloride liquid (e.g. Geomelt) rather than uninhibited salt brine, they may be doing this to reduce corrosion or to obtain the enhanced low temperature performance that the calcium chloride based product provides compared to the salt brine. How much of the extra cost of the calcium chloride product should be considered to be spent to reduce corrosion?

The testing reported to date in the literature regarding the corrosive effects of ice control chemicals has focused to date on measuring what might be termed typical corrosion rates (as in mils penetration per year). No studies have yet been published considering the impact of ice control chemicals on equipment service life, and these studies would be needed to obtain suitable benefit – cost information. A current ongoing study (see footnote 4 above) is investigating the long term performance of inhibitors, and it would be prudent to see what results this study brings (the final report is due in September 2010) before investigating this issue further.

5.2 Developing High Efficiency Washing Systems for Equipment

There does seem to be a consensus that vehicle washing is a very effective way to reduce equipment corrosion. At least in concept, the options for a washing program would seem to range from a rag and bucket through to a fully automated system such as that used by Minnesota DOT. However, in practice an effective wash program would require at least some sort of low volume high pressure system[5]. Fully automated systems are likely to cost in the range of $1 to 5 million (depending on site details) but some of that cost is associated with disposal of the wash water. The disposal system must handle issues such as oil and grease in the water, and ensure that in appropriate contaminants do not get passed into the stormwater system. Of course, any wash system, whether in a fully automated stand alone facility or using a low volume high pressure system needs to include appropriate waste water disposal facilities, so that part of the cost is common to all wash systems. Nonetheless, it is clear that a fully automated system is very expensive. Assuming a twenty year life, annual savings generated by such a system over and above

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[5] Information can be found at sites like: http://www.dcs1.com/articles/choosing_a_pressure_washer.html which notes that prices for such systems are typically less than $10,000.

other simpler wash systems would have to be of the order of $100,000 to 500,000. Clearly such systems make more sense at locations where many vehicles are stored, since this reduces the per-vehicle savings needed significantly, but such systems are unlikely to be viable at locations with less than 20 vehicles. However, such automated systems may offer savings over and above life extension savings. It may take considerably less time to move a truck through an automated wash facility than to wash it with a low volume high pressure system by hand, for example, and that reduced time translates into potentially significant labor savings.

At present, there is insufficient information available to compute the benefit-cost ratios for different wash systems, but the consensus indicates that some sort of reliable and relatively easy to use wash system is a critical part of any processes designed to reduce equipment corrosion in winter maintenance fleets.

5.3 Design and Operational Changes

As noted above, there are a number of ways in which the basic construction and assembly of a winter maintenance truck can be altered so as to minimize opportunities for damage due to corrosion. These include designs specific to the wiring:

- Use weather tight electrical connections;

- 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.

They also include a variety of detailed design changes in the truck body itself:

- 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;

- Consider buying stainless steel truck boxes, pre-wetting tanks, and sanders.

There are almost certainly additional ways in which trucks can be protected against corrosion by design changes, and it would be useful to investigate this further (see below). Such design changes will of course add to the cost of a truck and related equipment, and perhaps substantially so (e.g. stainless steel truck boxes) but they have the potential to generate significant savings by increasing the truck life, and would likely have a high benefit-cost ratio.

5.4 Use of Coatings

There are clearly a number of coatings available that may be very effective at minimizing corrosion on winter maintenance equipment. There is an extensive literature on the performance of coatings. A search of TRIS using the terms "corrosion" and "coating" generated nearly 1,000 references, but none of these pertained directly to winter maintenance equipment. Areas within these references included coatings for bridges, for ships and marine structures, for pipelines, and for railroad cars, and certainly some of the information in these references has some general relevance for winter maintenance equipment. However, no studies are available that deal directly with the use of coatings on winter maintenance equipment.

Further to this, even if field studies on the effectiveness of coatings were to be conducted on winter maintenance vehicles (using, for example, SAE J1293 test standard for under-vehicle coupon testing) these studies would not provide direct information regarding the extent to which such coating would increase the effective service life of winter maintenance equipment. In order to determine that degree of information, a series of comparative trials must be made using different coatings on different vehicles over several years.

5.5 Conclusions

A methodology exists whereby the benefit of various corrosion mitigation activities can be calculated in terms of how much a given activity extends the service life of a piece of equipment. Of course, this approach is in some ways artificial, because a given agency may not in fact keep vehicles in service for longer but may still offer them for resale after a fixed period of time. In such cases a piece of equipment with less corrosion is likely to have greater residual value than a more corroded one, but it is not

clear how much. Using a process of annualized costs over the lifetime of the equipment provides an objective method of comparing different corrosion prevention techniques in terms of increased service lifetime.

Unfortunately the data to use this methodology do not yet exist. Where data have been collected they have typically considered corrosion rates rather than increases in lifetime of equipment. While there is no doubt a link between corrosion rate and service lifetime, this link is not particularly straightforward or evident. However, as discussed below, some field testing could provide this information relatively quickly.

6. RECOMMENDATIONS AND CONCLUSIONS

The recommendations and conclusions are presented in the context of the four methods previously identified as having potential to minimize corrosion in winter maintenance equipment.

6.1 Use of Inhibitors in Ice Control Chemicals

Considerable uncertainty exists at present as to the effectiveness of inhibitors at reducing corrosion in winter maintenance equipment. Laboratory based specification tests show clear benefits for the use of these inhibitors, but field tests, using the same sorts of chemicals, did not show equivalent benefits. Further, laboratory tests have shown that while a given chemical may perform well for one type of material under one concentration of chemical, it may perform poorly with different materials and at different concentrations.

Additionally, it is unknown at present how long inhibitors "stay with" the ice control chemicals with which they are mixed once they have been deployed in the field. This is a critical issue of performance and is being studied currently (see footnote 4) by the PNS. Until such time as these results are available, nothing definitive can be said about inhibitor longevity in the field.

Given these factors, it is recommended that ice control chemicals not be chosen on the basis of their potential to reduce corrosion due to inhibitors. There is insufficient information at present to determine how such inhibitors impact the service life of

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equipment, and thus no way to know whether the premium price paid for an inhibited chemical gives a net benefit. There may well be other reasons for selecting a corrosion-inhibited ice control chemical (for example, superior performance at very low pavement temperatures) but corrosion prevention should not be the basis for their selection.

6.2 Use of Washing Systems

Clearly washing of winter maintenance equipment after exposure to ice control chemicals is seen by practitioners to provide significant service lifetime extension for that equipment. However, what form that washing of equipment should best take has not yet been determined. One way in which this determination could be achieved would be by a comparative test of two different wash methods. Given the potential benefits that more effective washing would present, it is recommended that the Iowa DOT consider setting up a comparative study between two garages. In one garage, a fully automated wash system (similar to that in Minnesota) would be constructed. In the other, comparison garage, operators would be provided with a suitable low volume high pressure wash system, established in a location with a suitable wash water treatment system. Any difference in truck lifetimes under the two systems would be apparent after a five year period, and if detailed records of expenses and time are maintained during the five years then a full comparison of the two washing methods can be performed. This would then allow the optimal method to be developed for use statewide.

6.3 Use of Design Changes

The use of design changes has the capability of bringing about greatly improved resistance to corrosion at relatively little increase in cost. It is recommended that the Iowa DOT bring together a working group of district maintenance engineers or their delegates to examine existing trucks in the DOT fleet, identify locations and design features on those trucks that appear to be particularly prone to corrosion, and having done this, develop possible design changes that would reduce the likelihood of corrosion in those locations. The most promising changes should be introduced into new truck specifications as soon as is reasonably practicable.

6.4 Use of Coatings

The use of coatings to provide a barrier between bare metal and any corrosive liquid has significant potential. Other areas of transportation (e.g. bridges, pipelines, railroad cars) make extensive use of such coatings with significant success. This would seem to suggest that significant benefits in terms of reducing corrosion might be achievable by the use of the right sort of coating.

Determining which coatings will provide the best protection can be done in two ways. First, a coupon test could be run in which coupons of various base materials (typical of those used in winter maintenance equipment) would be coated with various coating systems and suspended beneath trucks in service during one winter. The protocol for this sort of testing is set out in SAE J1293). At the end of the winter season, the coupons are compared and thus the best performing coating system can be determined. This process is an effective one, but it treats each material on the equipment as a separate part, whereas in some circumstances the very presence of dissimilar metals on a piece of equipment may be what gives rise to corrosion. Further, it may be necessary to extend this study over a number of winters to be able to draw definitive distinctions between the different coating types.

An alternative test would be to conduct comparative studies of the coatings applied to trucks. In this case, a number of garages would be selected equal to the number of coating types to be tested. Then in each garage, four trucks of similar age, type, and usage would be chosen. Two of these trucks would receive one of the coating treatments, while the other two would be control trucks. The performance of the test and control trucks from the viewpoint of corrosion would be tracked and compared annually through the remaining life of the trucks. Those coatings that are most effective will become apparent over time, while less effective coatings will quickly be seen to be less effective. In this way, a full test of the coatings can be performed in the actual circumstances of their eventual use.

6.5 Conclusions

Corrosion is an extremely complex set of phenomena and has multiple causes and cures. No single test can hope to determine whether a procedure will be fully effective in

the field at minimizing corrosion for a given piece of equipment. Given this, the most suitable way to determine effective and efficient corrosion prevention techniques is to conduct full scale field trials. While these are expensive, and also may take a number of years, they are the only way of obtaining objective and unambiguous data on the basis of which a corrosion prevention program can be built. A number of such field tests have been proposed herein, on the basis of which a set of optimal procedures can be developed to minimize corrosion in winter maintenance equipment.

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