Section 5.5, Chapter 5, An update of current corrosion-prevention methods used by DOTs

Manual of Best Practices for the Prevention of Corrosion on Vehicles and Equipment Used by Transportation Agencies for Snow and Ice Control

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Top corrosion protection coatings currently used by DOTs

The Clear Roads project fund CR 21-02 supported the research work (2023-2024) which found the commonly used paints, sealants, and lubricants used by several US DOTs in the past 5 to 10 years as corrosion protection coatings for their snow management vehicles and equipment. Some of the top choices were selected to be tested in the laboratory here at WSU Pullman WA for their corrosion resistance in saline environments, hardness, and adhesion strength. The tests performed included electrochemical impedance spectroscopy (EIS), a cyclic salt spray test based on SAE J2334 (SAE International, 2016), adhesion test ASTM D4541 (ASTM International, 2017) that is used to test pull-off strength of coatings, pencil hardness test ASTM D3363 (ASTM International, 2022) that is used for finding film hardness, and micro Vickers hardness test used to find surface hardness for relatively harder coatings. Both EIS and SAE J2334 are regarded as accelerated tests. For EIS, two salt blends were used to test the coatings. One of the two had a corrosion inhibitor, Beet Juice, which is commonly used by several DOTs according to Task 1 (Survey Analysis) results. The details of two salt blends were provided in the final report of CR 21-02.

The products selected are provided in Table 7.

Table 7. Selected coatings for different materials for the CR 21-02 research project

Materials		Selected coatings	Manufacturer
Steel	1.	Lubra Seal ®	Rhomar Industries, Inc.
	2.	Fluid Film ®	Eureka Chemical Company
	3.	Aquapon ® | 97-670 series (zinc-rich epoxy)	Pittsburgh Plate Glass (PPG) Industries, Inc.
Stainless Steel	1.	Armour Seal ®	Rhomar Industries, Inc.
	2.	Lubra Seal ®	Rhomar Industries, Inc.
Aluminum	1.	Fluid Film ®	Eureka Chemical Company
	2.	Armour Seal ®	Rhomar Industries, Inc.
Copper	1.	Di-electric Grease	Permatex ®
	2.	DeoxIT ®	Caig Laboratories, Inc.

Table 8. Abbreviations used for material-coating combinations for all tests, in CR 21-02 project

Materials	Material – Coating combinations	Material – Coating abbreviations
Steel	Steel – Lubra Seal	S-LS
	Steel – Fluid Film	S-FF
	Steel - Aquapon	S-AP
Stainless steel	Stainless steel – Armour Seal	SS-LS
	Stainless steel – Lubra Seal	SS-AS

Materials	Material – Coating combinations	Material – Coating abbreviations
Aluminum	Aluminum – Armour Seal	Al-AS
	Allunimum – Fluid Film	Al-FF
Copper	Copper – Copper-dielectric grease	Cu-DG
	Copper – Deox IT	Cu-DO

An update to best corrosion protection coatings for DOTs

Based on the findings of the research and the test results, comparison charts were developed for the final report of the project. In this chapter, a brief update on the coatings that are currently available and are used by several DOTs is made. The update reflects the data from the most recent tests that were conducted on selected coatings. The information on those selected coatings was obtained from the surveys, specifically the Market Analysis survey as Task 2 of the CR 21-02 project. An overall picture of the results obtained from the EIS test (in both salt blends), and salt spray test (SAE J2334) is shown in Figures 41, 42, and Table 7.

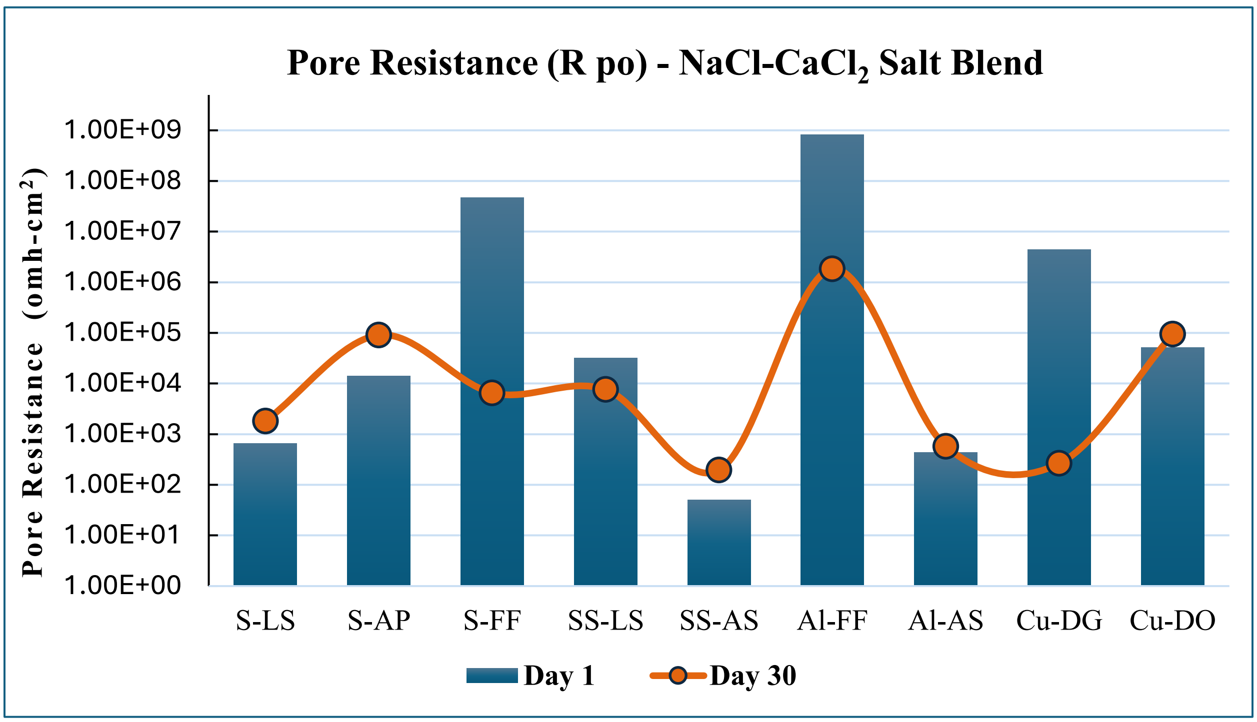

Figure 41. EIS test results for coating's resistance against NaCl-$CaCl_2$ salt blend – CR 21-02

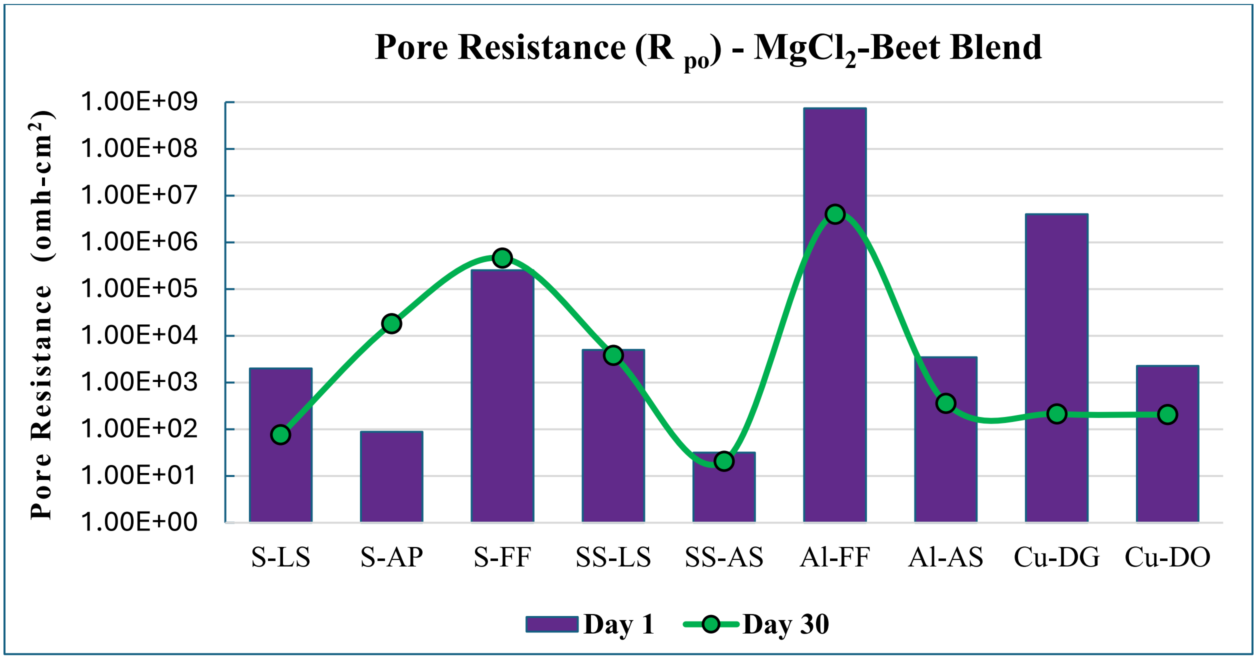

Figure 42. EIS test results for coating's resistance against $MgCl_2$-Beet blend – CR 21-02

Table 9. Combinations that passed and failed the salt spray test – CR 21-02

SAE J2334 – Cyclic Salt Spray Test					
Passed Combinations					
S-AP	S-FF	SS-LS	SS-AS	Al-FF	Al-AS
Failed Combinations					
S-LS		Cu-DO		Cu-DG	

Best coatings for carbon steel

Initially, 4 products were selected for carbon steel (A1008, cold rolled), but due to the unavailability of one of the products in the US, the number was reduced to 3. The three products (shown in Table …) selected for steel included a sealant (Lubra Seal®), a lubricant (Fluid Film®), and a metal-based coating (zinc-rich epoxy primer called Aquapon®) that can also be regarded as galvanizing for steel.

EIS test results

Based on EIS results, when the NaCl-$CaCl_2$ salt blend was used without any inhibitor, Aquapon® proved to be the best choice in terms of corrosion protection for steel and for minimizing the transportation of corrosive ions from the electrolyte through the coating to the metal surface. This was evident from the higher pore resistance (also known as coating resistance) of Aquapon after 30 days of accelerated EIS test. Compared to Aquapon®, Fluid Film® showed higher resistance to migration of corrosive ions through the film on day 1 of testing, but it decreased significantly after 30 days of testing. Lubra Seal® showed the least promising results for protecting steel against corrosion in aqueous saline media.

In the other blend ($MgCl_2$-Beet Juice), Fluid Film remained the best choice for A1008 plain carbon steel, in terms of corrosion protection and sealing its surface in aqueous media. For steel, Fluid Film showed the highest pore resistance on day 1 and day 30, compared to Aquapon and Lubra Seal. However, Aquapon (galvanizing) also showed remarkable performance and its resistance to corrosion and the property of creating a barrier against corrosive ions increased as expected after 30 days of testing.

Salt spray test (SAE J2334) results

From the cyclic salt spray test (SAE J2334), both Fluid Film® and Aquapon® passed the 60 cycles which are equivalent to 5 years of real-life exposure in saline-laden corrosive environments, whereas Lubra Seal® failed the test after only 12 cycles. However, this test does not guarantee that Fluid Film when applied on steel, will remain adhered to and protect it in conditions like heavy rainfall and after an event of washing. Therefore, by careful regular monitoring, it must be re-applied whenever necessary.

Adhesion and hardness test results

Based on the adhesion and hardness tests, the zinc-rich epoxy primer showed the highest adhesion strength and hardness when applied to steel as well. It was expected as the other candidates were not paints and did not adhere very well to the steel's surface. The sealant (Lubra Seal®) had negligible hardness and no concrete results for its adhesion strength on steel could be determined as well. It will not provide adequate resistance to scratch, wear, indentations, and abrasion and will also come off the material easily. Fluid Film is a lubricant with no adhesion whatsoever on any surface, but its tenacious oily characteristic was good enough for it to stay on the test coupons till the end of EIS and salt spray tests. It may be removed in a heavy rain exposure or after a washing event, with negligible resistance to indentation as well. Aquapon® however should remain adhered to the surface for 5 years, even in severe weather and abrasive conditions.

Best coatings for stainless steel

EIS test results

From the EIS test findings, for stainless steel (type 430), Lubra Seal® showed better results compared to Armour Seal® in both salt blends. However, the LS-SS combination in the NaCl-$CaCl_2$ blend showed better performance compared to when the $MgCl_2$-Beet blend was used.

From a technical point of view, stainless steel and aluminum generally do not require any coating protection to minimize corrosion, but in severe conditions and very corrosion environments such as the ones surrounding the DOT vehicles and equipment some form of protection would be beneficial.

Salt spray test (SAE J2334) results

SAE J2334 test showed that both Lubra Seal® and Armour Seal® showed no signs of failing as there was no evidence of rust, pitting, blistering, and any other coating failure as visible to the naked eye, after 60 cycles (2 months). Once again, this could also be because stainless steel has a self-protecting characteristic known as passivity which is referred to as the natural formation of a chromium oxide (Cr_2O_3, chromium dioxide) layer on its surface. Stainless steel has at least 12 wt. % of chromium in it. For SAE J2334, S.S. type 316 was used.

Adhesion and hardness test results

Based on adhesion and hardness tests, Armour Seal showed adequate results for adhesion strength on stainless steel, but the strength was lower than compared to the Steel-Aquapon combination. Lubra Seal, however, did not show any reasonable readings, and the results were discarded. This happened for both steel and stainless steel, perhaps due to the shiny surface of the sealant, the glue did not stick to the test dollies resulting in glue failures for all tested coupons. The surfaces were mildly sanded as well as part of the ASTM D4541 test procedure (ASTM International, 2017), but still, the adhesion between the glue and Lubra Seal was not adequate to carry on the test.

Best coatings for aluminum alloys

EIS test results

The EIS test done in both salt blends ($NaCl$-$CaCl_2$ and $MgCl_2$-Beet Juice) showed that Fluid Film showed much higher potential in corrosion protection of aluminum alloy 6061-T6 compared to Armour Seal®. The pore resistance of Fluid Film® after 30 days of testing was 10,000 times higher in the $MgCl_2$-Beet blend and 1.3 million times higher in the $NaCl$-$CaCl_2$ salt blend than Armour Seal on the aluminum alloy.

Salt spray test (SAE J2334) results

SAE J2334 salt spray test showed that both coatings passed the 60 test cycles successfully. Again, this could also be supported by the self-protecting ability of aluminum alone which naturally creates an oxide layer on its surface.

Adhesion and hardness test results

Adhesion and hardness tests were only conducted for the aluminum-Armour Seal combination, as for Al-Fluid Film these tests were not feasible. Armour Seal® showed satisfactory adhesion strength on Aluminum, as it was 3 times lower than the steel-Aquapon combination and 1.1 times lower than the stainless steel-Armour Seal combination.

Best coatings for copper

EIS test results

EIS test results for the $NaCl$-$CaCl_2$ salt blend showed that di-electric grease though initially performing better than Deox-IT®, ended up as runner-up by a good margin at the end of 30 days of testing. When applied to copper (C11000), the pore resistance of Deox-IT® was 355 times higher than di-electric grease, in the $NaCl$-$CaCl_2$ salt blend. In the $MgCl_2$-Beet Juice blend, both products showed similar results after 30 days of testing.

Salt spray test (SAE J2334) results

Both products could not pass the 60-cycle accelerated salt spray test and started to fail (showing signs of corrosion and color changing) after only 20 cycles. If cycles are converted to years based on the 5-year real-life projection of this test, then the life of these products on copper would be between 1 and 2 years.

Adhesion and hardness test results

No adhesion and hardness tests were performed for these products.

Overall performance of coatings

Coatings for steel

Overall, the use of both Fluid Film® and zinc-based spray coating is feasible for steel, however, there are pros and cons of using these products. One is heavier than the other but can be used for the long term due to its higher adhesion strength, abrasion resistance, and hardness. Heavier coatings on vehicles may increase their weight, ultimately increasing fuel consumption. A rough estimate for that is every 100 pounds of weight increment results in a 2 % increase in fuel consumption. Zinc is a heavy metal and in galvanizing paints, it is often added as zinc dust up to at least 90 wt. %.

Though it may last only for a short term (6 months to a year) without washing and will require re-application after each washing event; Fluid Film® however, is versatile as well. It can be applied on steel, stainless steel, and aluminum. Its application cost including the labor cost would be lower too, compared to galvanizing. It is a single-component product and needs minimum mixing before application. Whereas galvanizing treatments rely on professional spraying kits and the paints are often 2 to 3-component kits, which require careful mixing. Nevertheless, for peace of mind and longer uninterrupted protection (up to 5 years), protection like galvanizing should be preferred.

Other metallic coatings could be used to protect steel from corrosion such as aluminum and cadmium-based coatings, though cadmium coatings offer better protection for steel in marine environments, given equal coating thickness (Harper, 2001). Cadmium also does not form bulky corrosion products that can contaminate or interfere with equipment mechanisms. However, cadmium is extremely toxic and presents process, environmental, and ecological concerns. Compared to zinc, cadmium, and its compounds are highly toxic. Cadmium sacrificial corrosion products are often dusted to which personnel should never be exposed (Harper, 2001). Therefore, cadmium coatings are not recommended based on their highly toxic nature.

Coatings for stainless steel and aluminum

For stainless steel and aluminum generally, coatings are not necessary, but since both are susceptible to pitting corrosion, protecting their surface with some corrosion resistance coating would be beneficial. Once again, the sealants vs lubricants debate for these materials would end up in lightweight and longer-lasting products.

Bituminous paints (sealants) have very low water permeability (ASM Handbook Committee & ASM International, 1978). While both sealants passed the 60 cycles of salt spray testing, Lubra Seal showed better performance in the EIS test for stainless steel. Whereas for Aluminum, Fluid Film resulted in much higher corrosion protection than Armour Seal. Fluid Film may also be used for stainless steel, but it might require frequent re-applications within a year. Therefore, Lubra Seal due to being lightweight compared to Armour Seal and lasting longer than Fluid Film, is a better choice for stainless steel. For Aluminum, though long-lasting, Armour Seal is a heavy coating in comparison with Fluid Film and may or may not be used for aluminum alloys, depending on cost analysis and the ease of re-application.

An update to surface preparation methods

Even the best coatings will not perform their function if they are not applied on properly prepared substrates. For this reason, surfaces must first be cleaned to remove oily soils, corrosion products, and particulates, and then pretreated before applying any coatings and finishes (Harper, 2001).

Some of the metal surface cleaning techniques are abrasive cleaning, solvent cleaning, alkaline cleaning, and vapor degreasing. All of these remove oily soils and some corrosion products, whereas abrasive cleaning (such as sandblasting) is specifically helpful in the removal of rust and corrosion products (Harper, 2001).

Surface preparation requirement for lubricants

There are no mandatory surface preparation requirements for Fluid Film® in its technical data sheet (TDS). It can be applied on a mildly rusted surface as well. The surface should be dry though before applying it. However, it is always recommended that for superior performance, the flash rust from steel should be removed by grit blasting, or simply sanding, followed by degreasing. Generally, it is better to apply any lubricant on a corrosion-free, degreased, cleaned, and dry metal surface. This practice is also recommended for Deox-IT® and di-electric grease on copper.

Surface preparation requirement for galvanizing

When it comes to galvanizing, there are special surface preparation requirements that must be followed before applying zinc-rich rust protective paint on steel. These are usually NACE requirements, wanting the users to prepare a specific surface profile by sandblasting the steel. Paints then must be applied as soon as possible to avoid flash rust developing on the steel surface. Surfaces must also be cleaned of grease, oil, or dirt and dry before paint application. In this research, a primer coat (Aquapon®) was applied and tested, which does not need a topcoat when used as a rust protective coating. Aquapon® is a three-component (paint, epoxy, and zinc-dust) epoxy paint primer, which requires careful proportional mixing before application. Primers provide adhesion, corrosion protection, passivation, and solvent resistance to substrates. Topcoats usually provide weather, chemical, and physical resistance and generally determine the performance characteristics of finish paint systems (Harper, 2001).

Surface preparation requirement for sealants

For sealants, no special surface preparation requirements are mentioned in their TDS. However, before applying them surfaces should be washed (with salt neutralizers if exposed to salt), cleaned, and must be dried. They can also be applied over mildly rusted surfaces, but the research team would recommend applying any product on steel after the removal of rust, grease, dirt, and oil. Generally, sandblasting for steel is a good practice and should be followed before applying any corrosion-protective coating on it.

For stainless steel and aluminum, since they are mostly clear of rust and corrosion, it would be preferable just to clean their surfaces with any chemical mode. Mechanical cleaning (blasting) may not be required for them in most cases. In case sandblasting is required for stainless steel and aluminum, guidelines from the applied product's TDS must be followed.

An update to modes of application

Coatings are applied to most industrial products by spraying, typically in an industrial spray booth. In 1890, Joseph Binks invented the cold-water paint spraying machine, the first airless sprayer, which was used to apply whitewash to barns and other building interiors (Harper, 2001).

Method of application for lubricants

For Fluid Film® an airless sprayer is recommended, which would apply a uniform layer and may also result in a slightly higher lubricant-to-surface bond.

For Deox-IT® and the di-electric grease application, manufacturers' guidelines should be followed. For this research, a paintbrush for di-electric grease and the pre-provided spray tip with the can for Deox-IT was used.

Method of application for galvanizing

When spraying any galvanizing paint on steel, a pressurized spray system is recommended which can also constantly stir the mixed epoxy paint while spraying is done. A pressure pot with a stirrer would be a suitable choice if spraying is adopted. However, galvanizing may also be applied by modes other than spraying. A conventional spray gun capable of sustaining 60 psi of gun pressure, and a minimum of 16 CFM compressor will be required with the setup of a pressure pot.

Method of application for sealants

For sealants their TDS were followed, which led to the use of a pistol-grip spray gun for Armour Seal®. Initially, it was decided to buy Rhomar's Heavy Duty Public Works Applicator for Lubra Seal®, but after discussing with a Rhomar representative over the phone, the pistol grip gun was used for it as well. However, the TDS of Lubra Seal recommends the use of Rhomar's Heavy Duty Public Works Applicator.

An update to the use of corrosion inhibitors

For the EIS test, the second salt blend had the corrosion inhibitor (Beet Juice) in it. Moreover, $MgCl_2$ is also not as corrosive to ferrous alloys as NaCl. It was evident from the coated coupons, particularly Steel-Lubra Seal (S-LS), after 30 days of EIS testing, that corrosion of base metal mostly occurred in the NaCl-$CaCl_2$ salt blend compared to the $MgCl_2$-Beet blend. Figure 43 shows the condition of S-LS coupons in both blends after 30 days of EIS testing, including the wet/dry stress cycles.

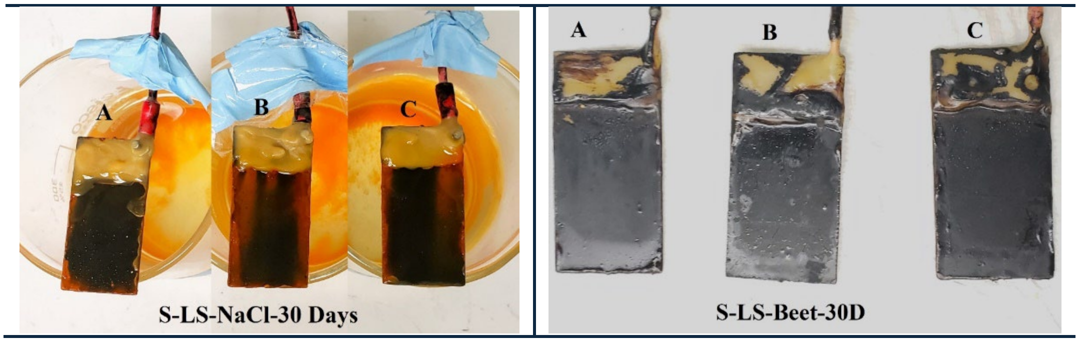

Figure 43. EIS test coupons after 30 days of testing: (left) Steel-Lubra Seal tested in NaCl-$CaCl_2$ salt blend and (right) Steel-Lubra Seal tested in $MgCl_2$-Beet blend

Moreover, similar visual results were observed for copper-dielectric grease (Cu-DG) as well as copper-Deox-IT (Cu-DO) coupons, as shown in Figure 44. Corrosion products developed on Cu-DO and Cu-DG coupons in NaCl-CaCl2 salt blend, but not in $MgCl_2$-Beet blend for the EIS test after 30 days.

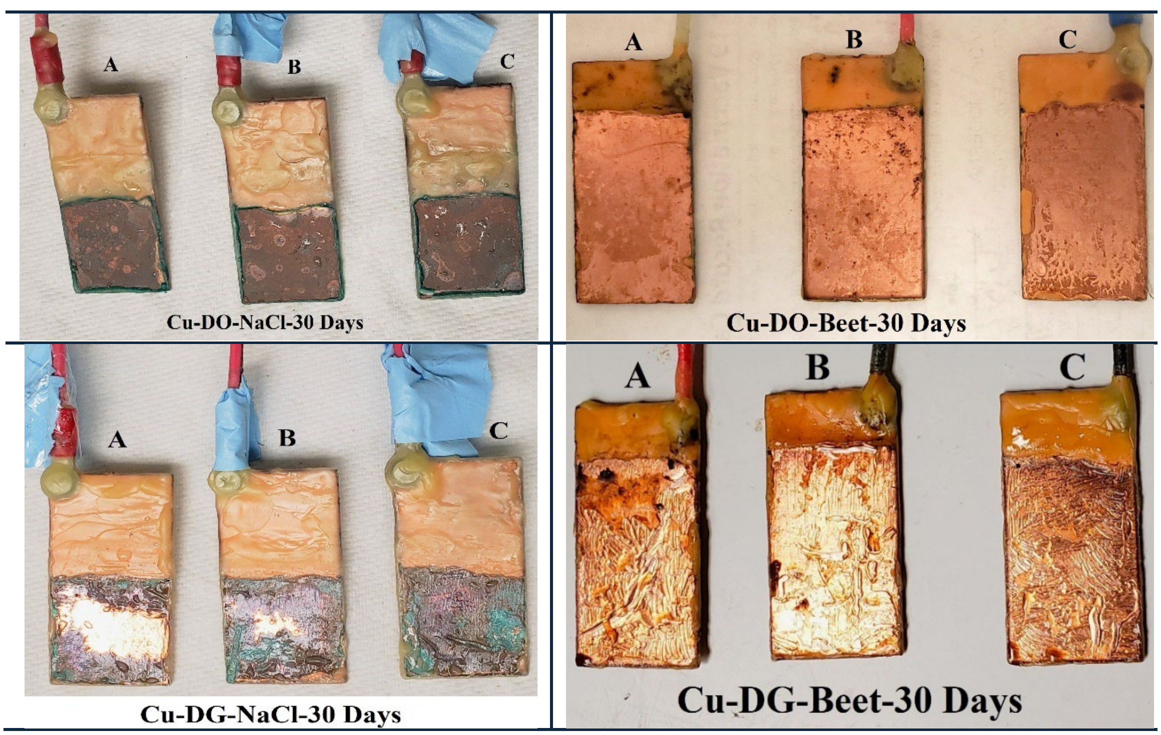

Figure 44. EIS test coupons after 30 days of testing: (top) Cu-DO coupons tested in NaCl-$CaCl_2$ salt blend on the left and Cu-DO coupons tested in $MgCl_2$-Beet blend on the right (bottom) Cu-DG coupons tested in NaCl-$CaCl_2$ salt blend on the left and Cu-DG coupons tested in $MgCl_2$-Beet blend on the right

Furthermore, in the final report of CR 21-02, figures of Steel-Aquapon (S-AP) coupons after 30 days of testing in both salt blends also indicate that $MgCl_2$-Beet proved to be less harmful for metal-coating combinations tested in the EIS test. Therefore, the use of corrosion inhibitors in chloride salt deicers is highly recommended whenever possible.

Comments on washing and drying of DOT vehicles & equipment

An update on washing practice

From the responses to the survey analysis (Task 1), it was deduced that some of the DOTs were using treated water and water from nearby wells with higher salinity and mineral content. While it is a good practice to use treated water which can lower the risk of corrosion attack, particularly for steels; a better way to identify the characteristics of water is to have it tested before being used for washing. Regarding water, several factors contribute to corrosion acceleration for ferrous alloys (steel and stainless steel) including pH, hardness, salinity, mineral content, dissolved carbon dioxide, and oxygen (Roberge, 2000). After washing if the water is not dried off, it may leave puddles on certain areas of the vehicle body, resulting in a localized corrosion attack (ASM Handbook Committee & ASM International, 1978; Roberge, 2000). Therefore, it is recommended to use water that is safe for washing DOT vehicles.

An update on drying practice

From the Task 1 survey responses, it was also concluded that most of the DOTs are not drying their vehicles after an event of washing rainfall or exposure to moist conditions. Technically, the vehicles must be dried after being in contact with water or aqueous saline environments especially when they are not in use for a good amount of time.

Role of moisture in corrosion of ferrous and non-ferrous alloys

The trucks may be self-dried when driven on the roads, but in case they are parked and not in use, that is the time when localized corrosion attack can aggravate in areas with mini puddles and pools of water present on wet vehicles. Those small puddles act as anodes and the rest of the body surface turns into a cathode, which creates an ideal situation for uniform as well localized corrosion and starts eating away the smaller area anodes very quickly. This is generally discussed under anodic-cathodic protection. Any area with oxygen depletion acts like an anode and the surface surrounding it would turn into a cathode. In the theory of corrosion, the anode would start rusting (for ferrous alloys) or corroding. To stop that from happening, often anodic/cathodic protections are provided depending on the areas of anode and cathode and the type of corrosion.

Wet corrosion that is the corrosion in water, brine, acids, or alkalis, is much more complicated and cannot be captured by rate equations with simple constants (Harper, 2001). Water is much more ominous to metal surfaces and plays a bigger role in conjuring corrosion attacks than salts. Salts containing chlorides result in aggravating the corrosion attack that is already started by water.

Remedies to stop the spread of localized, uniform, and galvanic corrosion

Though there should be drying stations for drying DOT vehicles that are washed after each storm and then are not used for a while, if drying of thousands of vehicles is not feasible, thorough and regular inspection of vehicles must be done to ensure rust/corrosion is not initiated anywhere on the main body of the vehicle. If any rust or corrosion is spotted it should be dealt with quickly by cleaning the corrosion products and applying any temporary corrosion protection coating in that area. If the affected area is bigger, a proper surface cleaning method must be adopted, and the surface must be protected with a longer-lasting coating afterward.

Although general corrosion is relatively easy to evaluate and monitor, localized corrosion (pitting, crevice corrosion, etc.) is harder to scale and monitor, and materials selection is difficult. Localized corrosion is insidious and often results in failure or even total destruction of equipment without warning (ASM Handbook Committee & ASM International, 1978).

In the case of galvanic coupling (contact of dissimilar metals/alloys), protective barrier coatings can be used with an important provision (i.e., coating the anodic material only is not recommended) because it can have disastrous consequences in practice. At defects, which are invariably present in such coatings, extremely rapid corrosion penetration will occur under a very unfavorable area ratio. It is much better practice to coat the cathodic surface in the galvanic couple (Roberge, 2000).

Material selection plays an important role in reducing the risk of pitting corrosion. For instance, the resistance to chloride-induced pitting in austenitic stainless steels is improved in alloys with higher molybdenum contents (Roberge, 2000).

Generally, the risk of pitting corrosion is increased under stagnant conditions, where corrosive microenvironments are established on the surface. Drying and ventilation can prevent this accumulation of stagnant electrolyte (Roberge, 2000). This is true for the DOT snow management vehicles (SMVs) and equipment after they are either exposed to moisture (outdoors) or washed and then not dried properly. Environmental modifications such as deaeration, chloride ion removal, and the addition of corrosion inhibitors can reduce the risk of pitting. Cathodic protection can be effective in preventing crevice corrosion, but anodic protection is generally unsuitable (Roberge, 2000). In the case of DOTs, deaeration and chloride ion removal can be done for the water that is used for the washing, however, the addition of corrosion inhibitors can be done for both – the water used in the washing and the chemical deicers used.

An update to material design

Materials considered for the project CR21-02 included plain carbon steel, stainless steel, aluminum, alloys, and copper. Material design considerations are important and are often prioritized over choosing more advanced and therefore expensive coatings. Prevention of corrosion damage can be done in the following ways (Roberge, 2000):

a) Change to a more suitable material
b) Modifications to the environment
c) Use of protective coatings
d) The application of cathodic or anodic protection
e) Design modifications to the system or component

The application of protective coatings, cathodic protection, material selection, and the use of corrosion inhibitors usually serve to control uniform corrosion (Roberge, 2000).

Plain carbon and alloy steels

The corrosion of carbon steel in seawater is controlled by the availability of oxygen to the metal surface. Thus, under static conditions, carbon steel corrodes at between 100 and 200 mils/year, reflecting the oxygen level and temperature variations in different locations. As velocity causes a mass flow of oxygen to the surface, corrosion is very dependent on flow rate and can increase by a factor of 100 in moving from static or zero velocity to velocity as high as 40 ms^{-1}. Galvanizing confers only limited benefit under flow conditions, as corrosion of zinc also increases with velocity (Roberge, 2000). This means that compared to stationary vehicle, if a DOT truck is moving at any given velocity the brine from deicers and melted snow can cause an accelerated corrosion attack on carbon steels.

Interestingly, natural waters, if they are reasonably free from aggressive ions, such as chloride and acidic species, are noncorrosive and have been handled satisfactorily by mild steel for many years (Roberge, 2000). Such hard waters have calcium and magnesium salts as impurities, which rather form a hard carbonate protective scale on the exposed steel surface. On the other hand, chemically pure, distilled water is, in fact, corrosive, and when the concentration of these salts is low, the corrosion of steel must be controlled by reducing the oxygen present in the water by chemical treatment or by cathodic protection (Roberge, 2000). Therefore, the DOT members were questioned about the type of water used in the washing and even preparing the salt brine.

Alloy steels should be used whenever possible in place of ordinary carbon steels because certain alloying additions can make them better corrosion-resistant materials. Those alloying additions are often vanadium (Vd), chromium (Cr), copper (Cu), nickel (Ni), manganese (Mn), aluminum (Al), and titanium (Ti).

Stainless steels

Stainless steel (S.S.) is a generic name for a series of more than 30 different alloys (Fontana, 2005), containing 11.5 to 30 wt. % Chromium (Cr), 0 to 22 wt. % Nickle (Ni), and some other alloy additions. A common misconception about S.S. is that they resist all forms of corrosive conditions better than ordinary structural steels. Stainless steels are less resistant to corrosion in chloride-containing mediums and stressed structures compared to common steels. These alloys are also more susceptible to localized corrosion pitting, and stress-corrosion cracking than ordinary steels (Fontana, 2005).

Use of stainless steels in waters

Stainless steels are not subject to impingement attack but are prone to pitting and crevice corrosion under low-velocity conditions, and this must be taken into consideration when these alloys are used in seawater (Roberge, 2000). This is important in the case of DOTs that operate their SMVs in wet salt-laden environments. According to the Handbook of Corrosion Engineering (Roberge, 2000), attempts to build seawater systems from standard grades of stainless steel, such as Type 316, have proved unsuccessful. In recent years, grades of stainless steel with high resistance to pitting and crevice corrosion have been developed. The first successful major use of stainless steel for seawater systems was in the Gullfaks oilfield in the Norwegian offshore sector where Avesta 254SMO (21% Cr, 18% Ni, 6% Mo, 0.2% N) was adopted (Roberge, 2000). For this study CR 21-02, types 316 (austenitic) and 430 (ferritic) were used.

Aluminum alloys

Because aluminum exhibits a naturally protected phenomenon by forming an oxide layer on its surface, it is often used without any protective coating. For some applications, the metal may be protected with a coating. An example is anodizing, a process that accelerates the formation of the protective oxide layer (Harper, 2001).

Anodizing is the conversion of the aluminum surface to aluminum oxide while the part is the anode in an electrolytic cell. During anodizing, the part is immersed in an acid solution that serves as the electrolyte at a controlled temperature and time while an electric current is introduced (Harper, 2001). Exterior automotive parts (bright trim, and bumpers) made of anodized aluminum show good resistance to deicing salts despite the limited thickness applied to maintain brightness and image clarity (Harper, 2001). An example of how good aluminum is against corrosion is the cap made of aluminum that was placed at the top of the Washington Monument in 1884 and is still there today in 2024.

Some of the aluminum alloy series show better corrosion resistance than others. The 5xxx series is produced by adding magnesium, resulting in strong, corrosion-resistant, high-welded-strength alloys.

Many of the 5xxx series alloys have general corrosion resistance as good as commercially pure aluminum and are more resistant to salt water, so are useful in marine applications (Harper, 2001)

Aluminum alloys in the 6xxx series contain magnesium and silicon in proportions that form magnesium silicide (Mg_2Si). These alloys have a good balance of corrosion resistance and strength. 6061 is one of the most popular of all aluminum alloys, and it has a yield strength comparable to mild carbon steel (Harper, 2001). For this study, CR 21-02, both 5xxx and 6xxx series of aluminum alloys (5052-H32 and 6061-T6) were selected after reviewing a report by Colorado DOT (Xi & Olsgard, 2000).

Moreover, the fatigue strength of aluminum in corrosive environments such as salt spray can be considerably less than the fatigue strength in laboratory air. This may be because corrosion sites such as pits act as points of initiation for cracks, much like flaws such as dents or scratches. The more corrosion-resistant alloys of the 5xxx and 6xxx series suffer less reduction in fatigue strength in corrosive environments than the less corrosion-resistant alloys such as those of the 2xxx and 7xxx series (Harper, 2001).

Use of aluminum in waters

When it comes to the use of aluminum in water, only a small amount of aluminum is dissolved by high-purity water at room temperatures, and, after a few days, an oxide film on the aluminum prevents further oxidation (Harper, 2001). In the natural fresh waters, the corrosion-resistant aluminum alloys (1xxx, 3xxx, 5xxx, and 6xxx series) are compatible and have been widely used in boats. The pitting that may occur is a function of the presence of dissolved minerals in the water, such as chlorides, sulfates, bicarbonates, and heavy metals, and the water temperature and pH. However, chlorine, in the levels used for potable water, has a negligible effect on aluminum (Harper, 2001). Therefore, for DOTs water treatment could be useful to reduce the dissolved minerals in it.

In seawater**,** extensive experience with the 1xxx, 3xxx, 5xxx, and 6xxx wrought alloy series and 356.0 and 514.0 castings in marine environments has been good, including partial, intermittent, and total immersion conditions. The 5xxx and 3xxx alloys are preferred; corrosion is of the pitting type and the corrosion rate based on weight loss is less than 0.2 mils/year, about 5% that of uncoated carbon steel. The 6xxx series alloys are slightly less resistant and suffer a corrosion rate of about two to three times that of the 3xxx and 5xxx series (Harper, 2001). Therefore, for DOTs, when choosing aluminum alloys for any of the components of their vehicles, the 5xxx series could be most beneficial.

Additional notes – Titanium alloys and non-metallics

The high affinity of titanium metal with oxygen increases its corrosion resistance, by enabling the formation of a stable, continuous adherent oxide film. It is therefore recommended for mildly reducing to quite highly oxidizing atmospheres, and it is excellent in marine and general industrial environments. However, if the oxidizing atmosphere is too strong (or in the absence of moisture), the oxide film is not protective, and titanium and oxygen can react violently (Harper, 2001). However, in the case of DOTs, the environment in which their SMVs operate is wet 99% of the time. Titanium alloys are also adversely affected by hot, concentrated chloride salts and all acidic solutions that are reducing in nature (Harper, 2001), which is also not the case for the US DOTs.

The only issue with the use of titanium or its alloys is that they are much more costly than steel, aluminum, and even stainless steels.

The use of non-metallics such as ceramics, composites, plastics (polymers), and rubbers (elastomers) whenever possible could also save money as well as provide adequate corrosion resistance for a good amount of time.

Plastics do not corrode and therefore there are polymeric coatings to protect the surfaces of metals. Moreover, their use would also eliminate the galvanic coupling. Composite materials can be used in tanks and pipes and can provide corrosion resistance to industrial chemicals including deicer salts (Harper, 2001).

Costs associated with corrosion control

From survey responses, it was noted that there is no cost-benefit analysis data available, when it comes to corrosion control of DOT vehicles and equipment. Such cost analysis can only be done when the costs of corrosion losses or damages are known or estimated. So that the cost of any corrosion control remedy implication can be compared to the costs of corrosion losses. If there is a benefit foreseen, it must be implemented to save dollars. A few comparisons can be made by DOTs to benefit from the most effective and affordable corrosion control remedies.

Cost-benefit analysis for the right material selection

The following material selections can be considered:

Carbon steel vs alloy steel

Alloy steels if replaced with regular plain carbon or mild steel, can provide better corrosion resistance. Several alloying additions (Cr, Mn, Vd, Ti, Cu, and Ni) to steel can improve its corrosion resistance. Some of these alloying additions work better in reducing the corrosion rate for steel when they are added in combinations. If a cost-benefit analysis is done for choosing alloy steel vs plain carbon steel, to minimize the corrosion attacks, it could be beneficial. This might save some dollars for selecting alloy steel over stainless steel.

Ordinary steel vs stainless steel, and aluminum alloys

From the Task 1 (Survey Analysis) results, it was found that several DOTs have replaced steel with stainless steel to deal with the corrosion problem for their vehicles. This is a good example of adopting one of the corrosion control remedies, by changing to a more suitable material. However, there is a need to conduct a cost-benefit analysis for choosing stainless steel over ordinary steel, alloy steel, and aluminum. Only then, a better suggestions on the use of specific stainless steel types or alloy steels be provided.

When choosing aluminum over steel, strength-to-weight ratios could play an important role. However, often aluminum alloys may not provide sufficient strength compared to steels and may still have higher strength-to-weight ratios due to very low density.

Cost-benefit analysis for using drying stations

Perhaps one of the most important tools to minimize corrosion for SMVs in the case of DOTs, is making sure the vehicles and equipment do not have areas of high and low moisture contents. The use of drying stations for a fleet of thousands of vehicles could be cumbersome, but until the costs are unknown of bringing such a change it cannot be overlooked. Since, DOT SMVs are mostly used in wet conditions, and this update has provided a good narrative on how moisture can cause corrosion attacks; keeping them dried when not in use is a very important aspect of this study.

Cost-benefit analysis for using galvanizing

Protecting steel surfaces with zinc-rich primer paints or coatings has been proven the best method in $NaCl$-$CaCl_2$ salt-like environments. There is a need to do a cost-benefit analysis for implementing such a change, by equipping DOTs with spray booths, and adequate modes of surface cleaning and applications.

Several counties or perhaps one entire state (if it is a smaller one, Maryland, Delaware, Rhode Island, Connecticut, as examples) can be covered by just one such setup providing blasting, cleaning, and spray painting, facilities. Vehicles can then be galvanized in such a facility and transported to their designated counties. Such a setup can also help in applications of any other coatings that require surface cleaning and spraying. Because the metallic coatings last very long (5 to 10 years), if applied properly, there must be some considerations made for the overall cost analysis associated with them.

Conclusions

The decision of which corrosion protective coatings and factors related to material design for combating corrosion will perform better than the other depends on several estimates. Table 8 sums up some of those estimates.

Table 8. Necessary information required for estimating corrosion performance (Roberge, 2000)

Corrodent Variables
Main constituents (identity and amount)
Impurities (identity and amount)
Temperature
pH
Degree of aeration
Velocity or agitation
Pressure
Estimated range of each variable
Type of application
What is the function of the part or equipment?
What effect will uniform corrosion have on serviceability?
Are size changes, appearance, or corrosion products a problem?
What effect will localized corrosion have on usefulness?
Will there be stresses present?
Is stress-corrosion cracking (SCC) a possibility?
Is the design compatible with the corrosion characteristics of the material?
What is the desired service life?
Experience
Has the material been used in an identical situation?
With what specific results?
If equipment is still in operation, has it been inspected?
Has the material been used in similar situations?
What are the differences in performance between the old and new situations?
Any pilot-plant experience?
Any plant corrosion-test data?
Have laboratory corrosion tests been run?
Are there any available reports?

The following conclusions can be drawn from the discussion made on the update of the most recent corrosion preventive practices for DOTs:

1. Zinc-rich primer paints (galvanizing paints) must be considered to protect steel in NaCl-$CaCl_2$-based aqueous environments, with no added corrosion inhibitors. Though such metallic coatings

are heavy and can increase fuel consumption as well as are costly, these are very long-lasting solutions with minimum re-application and maintenance costs.

2. Steel surfaces protected with lubricants like Fluid Film®, must be regularly inspected for that they can easily be washed away, leaving the metal in jeopardy.
3. Any coatings must be applied in conjunction with the technical data sheet (TDS) provided by the manufacturer, especially following the surface cleaning and mode of application.
4. Sealants should be avoided to protect the steel surfaces. If used, keep in mind that they may only last for 6 months and therefore steel surfaces protected by sealants must be regularly inspected during those 6 months and re-application by following their TDS should be done whenever necessary.
5. Aluminum (anodized) and stainless steels generally do not require protective coatings, but if coatings are used they must be applied by following proper surface cleaning and the mode of application indicated in their TDS.
6. The Aluminum 5xxx series should be used when choosing aluminum alloys, followed by the 6xxx series; to provide maximum corrosion resistance benefits.
7. Not all stainless steel types will provide corrosion resistance and therefore stainless steels suitable for salt-laden wet environments must be used.
8. Lubricants and any lightweight sealants can be used for stainless steel protection, provided that regular inspection is done for the protected surfaces.
9. To protect copper, the use of di-electric grease or any other lubricant may prove suitable but only for 6 months to 1 year. Therefore, when protected with such products, copper surfaces must be regularly inspected for any signs of corrosion products. When re-applying them, the copper surfaces must be cleaned following their TDS.
10. The type of water used for washing DOT snow management vehicles and equipment as well as in brine making must be selected based on its corrosion rating for steels, stainless steels, aluminum alloys, and copper.
11. Tests must be conducted for the water used in making brine and for washing to understand its dissolved oxygen and carbon dioxide levels, pH, hardness, and dissolved mineral content. If the water already used is not fit to use in terms of corrosion mitigation (especially for ferrous alloys), any industrial water treatment procedure must be followed.
12. Tap water with chloride ion concentration equal to that of potable water should be used instead of well water and water that is high in mineral content.
13. Drying of vehicles can make a significant difference in controlling corrosion, particularly localized corrosion attack; and therefore must be considered by DOTs.
14. Cost-benefit analysis must be made whenever necessary to implement any new corrosion control remedy, by first estimating the costs involved in corrosion losses for any DOT.

References

ASM Handbook Committee & ASM International (Eds.). (1978). *Metals handbook* (9th ed, Vol. 13). American Society for Metals.

ASTM International. (2017). *Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers* (D4541 − 17). ASTM International. https://doi.org/10.1520/D4541-17

ASTM International. (2022). *Test Method for Film Hardness by Pencil Test* (D3363 − 22). ASTM International. https://doi.org/10.1520/D3363-22

Fontana, M. G. (2005). *Corrosion engineering* (3rd ed). Tata McGraw-Hill.

Harper, C. A. (Ed.). (2001). *Handbook of materials for product design* (3rd ed). McGraw-Hill.

Roberge, P. R. (2000). *Handbook of corrosion engineering*. McGraw-Hill.

SAE International. (2016). *Laboratory Cyclic Corrosion Test* (J2334_201604). SAE International. https://doi.org/10.4271/J2334_201604

Xi, Y., & Olsgard, P. J. (2000). *Effects of De-Icing Agents (Magnesium Chloride and Sodium Chloride) on Corrosion of Truck Components* (CDOT-DTD-R-OO-IO). Colorado Department of Transportation.