**Report No. CDOT-DTD-R-2000-10**
**Final Report**

# Effects of De-Icing Agents (Magnesium Chloride and Sodium Chloride) on Corrosion of Truck Components

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**Patricia J. Olsgard**

DOT
DEPARTMENT OF TRANSPORTATION
RESEARCH

**November 2000**

**COLORADO DEPARTMENT OF TRANSPORTATION**
**RESEARCH BRANCH**

# Effects of De-Icing Agents (Magnesium Chloride and Sodium Chloride) on Corrosion of Truck Components

by

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**16. Abstract**

Colorado DOT has been using $MgCl_2$ for anti-icing and deicing for several years. Some concerns have surfaced that the chemicals may affect various components of cars and trucks. In this experimental study carried out at the Materials Laboratory at CU-Boulder, representative metals were selected from the automobile industry to compare their corrosion behaviors under exposures to deicing salts NaCl and $MgCl_2$. Both reagent grade $MgCl_2$ and the $MgCl_2$ used by CDOT (which contains a corrosion inhibitor) were used in the testing process. Two testing methods were applied to the selected metals: SAE J2334 (an accelerated cyclic test); and, ASTM B117 (a continuous spraying test). The testing environment of SAE J2334 provided cyclic exposure, which is a better simulation of actual service conditions.

While CDOT specifications state that magnesium chloride must be 70% less corrosive than sodium chloride, experimental results obtained by SAE J2334 indicated that $MgCl_2$ is more corrosive than NaCl to the bare metals tested. Corrosion varied from only slight differences for some metals to 13 time more corrosion for SS410. The experimental results from ASTM B117 showed inconsistencies when compared with the results of SAE J2334, especially for the stainless steel SS410, for which NaCl is more corrosive than $MgCl_2$. The experiment also indicated that the mixture of $MgCl_2$ and NaCl caused slightly more corrosion to the metals than either single salt (either $MgCl_2$ or NaCl) on three of the four metals tested does. This implies that there are coupling effects between the two chlorides to the corrosion of the metals.

**Implementation**

Deicers provided by vendors should be monitored independently by CDOT for chemical characteristics. Any significant changes in processing or source material should be disclosed by the vendor. Colorado-based specifications, specifically with respect to corrosion inhibitors must be strictly adhered to. Because mild steel was not included in this research study, further implementation of findings from this report will be delayed until an additional study on the corrosive effects of magnesium chloride on mild steel is completed.

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## Abstract

Colorado DOT has been using $MgCl_2$ for anti-icing and deicing for several years. Some concerns have surfaced that the chemicals may affect various components of cars and trucks. In this experimental study carried out at the Materials Laboratory at CU-Boulder, representative metals were selected from the automobile industry to compare their corrosion behaviors under exposures to deicing salts NaCl and $MgCl_2$. Both reagent grade $MgCl_2$ and the $MgCl_2$ used by CDOT (which contains a corrosion inhibitor) were used in the testing process. Two testing methods were applied to the selected metals: SAE J2334 (an accelerated cyclic test); and, ASTM B117 (a continuous spraying test). The testing environment of SAE J2334 provided cyclic exposure, which is a better simulation of actual service conditions.

Experimental results obtained by SAE J2334 indicated that $MgCl_2$ is more corrosive than NaCl to the bare metals tested. The experimental results from ASTM B117 showed inconsistencies when compared with the results of SAE J2334, especially for the stainless steel SS410, for which NaCl is more corrosive than $MgCl_2$. The experiment also indicated that the mixture of $MgCl_2$ and NaCl caused more severe corrosion to the metals than any single salt (either $MgCl_2$ or NaCl) does. This implies that there are coupling effects between the two chlorides to the corrosion of the metals.

## Executive Summary

The Colorado Department of Transportation (CDOT) uses liquid magnesium chloride ($MgCl_2$) in several areas of Colorado as both an anti-icing and a deicing agent. Magnesium chloride is used in the Denver metro area, I-70 west through Glenwood Springs and a few other spots where meeting air-born particulate standards is a problem. In conjunction with, and instead of magnesium chloride, CDOT also uses a dry mixture of sodium chloride (NaCl) and sand (5-10%). The sand salt mixture is used when it is too cold for magnesium chloride to effectively melt snow and ice.

Trucking companies expressed concern that the use of magnesium chloride has caused increased vehicle maintenance costs. Because of the nature of the industry, trucks often travel the same route on a daily basis, and subsequently encounter a high level of chemical deicers. To investigate whether the perception that magnesium chloride damages trucks is widespread, a survey was sent to over 150 Colorado trucking companies. Seventy-two percent of the respondents reported noticing increased wear on their equipment since Colorado began using magnesium chloride. Companies reported the most damage to chrome, tractor or trailer bodies, aluminum parts, wheels, hoses and connectors, and electrical parts. The specific type of damage mentioned most often included corrosion, pitting, staining/tarnishing, discoloration, drying/cracking (hoses), and accelerated rust.

The project started with an extensive literature review on the relevant information. Based on the collected information, two experimental methods and several types of metal specimens were selected for the experimental program. Then, an experimental study was performed in the Materials Laboratory at CU-Boulder. Some of the specimens were also placed on trucks traveling in the state of Colorado.

In this experimental study, representative metals were selected from the automobile industry to compare their corrosion behaviors under exposures to deicing salts NaCl and $MgCl_2$. Both reagent grade $MgCl_2$ and the $MgCl_2$ used by CDOT which contains a corrosion inhibitor were used to test the metals. The metals tested included stainless steel 410 and 4L, aluminum 2024 and 5086. In addition to the metal coupons, coated coupons from automobile body sheets were also tested. Two testing methods were applied to the selected metals. One is SAE

J2334, which is an accelerated cyclic corrosion test representing the in-service environments; and the other is ASTM B117, which is a continuous spraying test representing a different corrosive environment and mechanism. For each of the two selected testing methods, two salts (i.e., sodium chloride and magnesium chloride) were used as the corrosive medium, respectively. In order to examine the corrosiveness of the deicing salts to electrical components, an electrochemical test unit was devised, in which the difference in the corrosion potential of the copper specimens in the two chloride solutions were measured.

The in-service exposure test was carried out on Colorado highways during the winter of 1999 to verify the results from the laboratory experiments. Five metal coupons, identical to those used in the laboratory tests, were bolted to a Plexiglas sheet approximately the size of a license plate. Ten of these Plexiglas plates were mounted on trucks for exposure on the highway starting the first week of November 1999. The plates were removed from the various trucks and returned to CU-Boulder for analysis in May 2000.

Experimental results obtained by SAE J2334 indicate that $MgCl_2$ is more corrosive than NaCl for the bare metals tested. The rate of corrosion varies from metal to metal. For stainless steel SS410, the corrosion rate due to $MgCl_2$ is 5 to 13 times higher than that due to NaCl. For aluminum AL2024, the corrosion rate by $MgCl_2$ is one to two times higher. Experimental results obtained by ASTM B117 showed inconsistencies when compared with the results of SAE J2334, especially for the stainless steel SS410, for which NaCl is more corrosive than $MgCl_2$.

It was found that a mixture of $MgCl_2$ and NaCl causes more severe corrosion than any single salt (either $MgCl_2$ or NaCl) does. This implies that there are coupling effects between the two chlorides with respect to the corrosion of the metals. On the other hand, higher chrome content in stainless steels and higher magnesium content in aluminum alloys seems to increase corrosion resistance of the metals under the attack of $MgCl_2$ or NaCl solution. The coated automobile body panels with the treatment of electroplating or hot-dip alloying exhibited very strong corrosion resistance. No significant corrosion products were observed on the coupons even if the panels were scratched and the outer coating was damaged.

However, the coated cold roll sheets showed poor corrosion resistance. $MgCl_2$ is more corrosive than NaCl to electronic components made of copper.

In many ways this study has raised more questions than it has answered. Additional work needs to be done in order to address the identified problems and develop solutions to limit corrosion caused by $MgCl_2$. For example, the trucking and automotive industry should consider:

- If there any specific undercoating or plating techniques that can be used on trucks to mitigate the corrosive effects of magnesium chloride.
- If there are sealants or other protective measures trucking companies can take to protect electrical components from deicing chemicals.
- Whether different formulations of aluminum and stainless steel that are more resistant to corrosion can be used in truck and trailer manufacturing. For example, stainless steel with higher chromium content is more resistant to corrosion.
- If there are more effective windshield fluid solutions and truck wash methods that can be employed.

Additional testing is currently being conducted by CDOT and the University of Colorado to determine if the $MgCl_2$ product CDOT uses meets their corrosion specifications. Further study and/or operating procedures should be investigated by CDOT to determine:

- Whether CDOT should re-examine and/or alter its policy of pre-wetting roads with magnesium chloride prior to storms.
- The effect a third salt (calcium chloride) that is also widely used a deicer has on corrosion. A test involving all three common deicers would provide valuable information to CDOT and other states.
- A study to identify the optimal combination (percentage weight) of magnesium and sodium chloride solutions that may limit corrosion while maximizing effectiveness.
- Whether other deicing chemicals are available that are cost effective and less corrosive.
- If the optimal the type and amount of corrosion inhibitor is being used in the $MgCl_2$ solution.

# Section I: Introduction

## 1.1 Background

The Colorado Department of Transportation (CDOT) has chosen what they consider to be the most effective and cost efficient chemical deicer, magnesium chloride ($MgCl_2$), to apply on Colorado's roads and highways. In conjunction with magnesium chloride, CDOT also uses a dry mixture of sodium chloride and sand in certain areas of the state. Liquid magnesium chloride is used as both an anti-icing and a deicing agent. Some trucking companies believe the use of magnesium chloride has led to increased vehicle maintenance costs and may cause an increased risk to vehicle safety. Because of the nature of the industry and customer demands, trucks are counted on to deliver freight regardless of road and weather conditions. Additionally, trucks often travel the same route on a daily basis, and subsequently encounter a higher level of chemical deicers than many passenger cars.

Anecdotal information provided by Colorado trucking companies revealed widespread belief that magnesium chloride is responsible for excessive pitting and corrosion, increased vehicle maintenance and cleaning costs, accelerated metal component wear, breakdown of electrical systems, and increased safety risks due to loss of visibility, wet highways, and affected brake systems.

In response to those concerns, the CDOT Research Division agreed to sponsor this study to investigate the effect (if any) liquid magnesium chloride has on vehicles in Colorado. It is hoped the private sector will benefit from the identification of causal factors, costs, and solutions regarding the use of liquid deicers. The public sector will benefit from testing, under laboratory and real-world conditions, the impact upon vehicle components caused by current deicing methods. Additional benefits include the opportunity for industry and government to work together toward creating solutions and building a viable partnership for the future.

## 1.2 Overview of Study

The American Trucking Associations Foundation (ATAF) and the University of Colorado (CU) were contracted by the CDOT Research Division to investigate the impacts of deicers on commercial vehicles. This study included both qualitative research conducted by the ATAF, and laboratory analysis, which was conducted by the University of Colorado Materials Laboratory. The Research Team (ATAF and CU) also worked with the trucking industry to identify specific concerns and perceptions from the use of magnesium chloride.

The goals of the study were to conduct experimental testing of the effect of magnesium chloride on the metals most commonly used in manufacturing trucks. Representative metals were selected from the automobile industry to compare corrosion behaviors after exposure to two deicing salts, sodium chloride (NaCl) and magnesium chloride ($MgCl_2$). Metals were selected from conventional coupons used in automobile and steel industries, which do not include mild steel. The main concern was the corrosion behavior of alloy steel (especially stainless steel) and various coatings. Additional information was collected from CDOT and other state transportation departments in the Western U.S. to further investigate deicing procedures and methods. Information was also collected directly from trucking companies to determine perceptions and opinions on whether the use of magnesium chloride affects trucks and trucking operations in Colorado. The issues addressed in the study included:

- How stainless steel is affected;
- If $MgCl_2$ attacks Cr (chrome) components;
- What the affect of $MgCl_2$ is on Al (aluminum);
- Whether there is a chemical reaction between the $MgCl_2$ and NaCl;
- How $MgCl_2$ affects electrical components;
- Identifying the concerns/problems trucking companies attribute to deicer use;
- Documenting and analyzing the costs and benefits to the trucking industry from the use of deicers;
- Identifying the costs and benefits of various deicers used by CDOT;
- Identifying and evaluating possible alternatives to current deicers and evaluating possible alternatives to current application methods and processes.

## 1.3 Theory of Metal Corrosion

Pure metals and their alloys tend to enter into chemical union with the elements of a corrosive medium to form stable compounds similar to those found in nature. When metal loss occurs in this way, the compound formed is referred to as the **corrosion product**, and the metal surface is spoken of as being **corroded**.

Corrosion is a complex phenomenon that may take any one or more of several forms. It is usually confined to the metal surface, and this is called **general corrosion**. But it sometimes occurs along grain boundaries or other lines of weakness because of a difference in resistance to attack or local electrolytic action, this is called **localized corrosion** (Perry and Chilton 1973).

Localized corrosion includes:
*Intergranular Corrosion*: Selective corrosion in the grain boundaries of a metal or an alloy without appreciable attack on the grains or crystal. Austenitic stainless steels and some aluminum alloys, when improperly heated, become susceptible to intergranular corrosion because of the precipitation of intergranular compounds.

*Stress Corrosion*: Corrosion can be accelerated by the applied stresses.

*Galvanic Corrosion*: A corrosion rate that is faster than usual, which is associated with the flow of current to a less active metal (cathode) in contact with a more active metal (anode) in the same environment.

*Crevice Corrosion*: It occurs within or adjacent to a crevice formed by contact with another piece of the same or another metal or with a non-metallic material. This form of corrosion can result because of a deficiency of oxygen in the crevice, acidity changes in the crevice, buildup of ions in the crevice, or depletion of an inhibitor.

*Pitting Corrosion*: It develops in highly localized areas on a metal surface.

## 1.4 Mechanisms of the Corrosion of Metallic Materials Caused by Deicing Salts

It is generally considered that the corrosion of metallic material caused by deicing salts is an electrochemical process. According to the electrochemical theory, a complete corrosion reaction is divided into an anodic portion and a cathodic portion, occurring simultaneously at discrete points on metallic surfaces. The flow of electricity from the anodic to the cathodic areas may be generated by local cells set up either on a single metallic surface (because of local point-to-point differences on the surface) or between dissimilar metals. When a solution exists, electrons are captured by the cation in the solution, which causes the movement of electrons to continue. The active metal gradually becomes ionic and dissolves into the solution. By this time, we consider that the metal is corroded. Taking the corrosion of iron as an example, the following are the chemical reactions involved in the corrosion process:

1). At anode, iron ions enter solution in the form:

$$2Fe \rightarrow 2Fe^{2+} + 4e \qquad (1)$$

2). At cathode, the hydrogen ions in water accept electrons:

$$4H^{+} + O_2 + 4e \rightarrow 2H_2O \qquad (2)$$

3). Ions of iron combine with OH ions in water to form $Fe(OH)_2$:

$$2Fe^{2+} + 4OH^{-} \rightarrow 2Fe(OH)_2 \qquad (3)$$

4). $Fe(OH)_2$ is further oxidized into $Fe(OH)_3$:

$$4Fe(OH)_2 + O_2 + 2H_2O \rightarrow 4Fe(OH)_3 \qquad (4)$$

The presence of chloride ions from the deicing salts in solution can create extensive localized attack by their adsorption on weak parts of the oxide film on the surface of metals, thus forming soluble complexes. This process can be further accelerated by several microstructural features of the alloy. The presence of other ions such as $OH^{-}$, $SO_4^{2-}$, and $CO^{2-}$ in solution and factors such as pH and temperature, can all lead to accelerated corrosion (Srivatsan et al. 1989).

## Section II: Research Procedures, Methods and Results

### 2.1 Corrosion Testing Methods Used in the Project

#### *2.1.1 SAE J2334 and ASTM B117 for metal coupons*

Based on an extensive literature review of corrosion testing methods, SAE J2334 was selected as the main test method in the project to compare the effects of different salts on the chosen metals. In order to compare test results with different corrosion mechanisms, ASTM B117 was also employed. The former is a typical cyclic corrosion test representing the in-service environments; the latter provides a different corrosive environment and mechanism. In each of the two selected testing methods, two salts (sodium chloride and magnesium chloride), were used as the corrosive medium, respectively. After the designated testing cycles or hours were reached, the difference in the corrosion of the metals caused by the two chlorides were compared.

The laboratory experiments were conducted by the following procedures:

A. Prepare (clean and dry) the coupons according to the procedures specified by ASTM G1-96 "Practice for preparing, cleaning, and evaluating corrosion test specimens." All coupons were degreased by ethanol and rinsed thoroughly with water, before being dried in the oven.

B. Weigh the coupons to a precision of ± 0.001 g.

C. Carry out corrosion experiments in accordance with SAE J2334 and ASTM B117, respectively. In each run of the tests by SAE J2334, two coupons were tested for each type of material, while in each run of the tests by ASTM B117 only one coupon was used.

The basic procedures for SAE J2334 can be seen in Figure 1. The ASTM B117 test is a continuous spray test lasting for 800 hours at a temperature of 38°C. A few modifications were made to SAE J2334 when the test was conducted. One of the modifications was the tests were not interrupted during weekends and holidays in order to provide a constant and continuous environment to the coupons. Another modification was the concentrations of the salt solutions were increased to 1.0%, instead of 0.5%, as specified in the standard. The magnesium chloride was obtained from CDOT's Region 6 maintenance facility. The chemical analysis showed that the concentration of the sample solution was 22 wt.%. Based on that concentration, the solutions for the corrosion test was made with reduced concentrations 0.5% and 1.0%. This modification was made to accelerate the corrosion process and decrease the testing time.

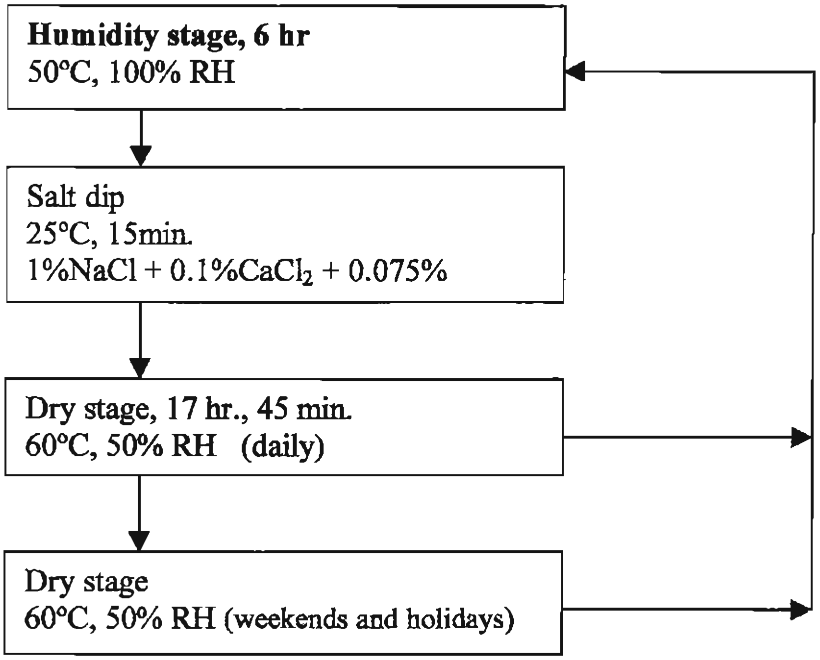


**Figure 1: Schematic of SAE J2334 (manual mode).**

D. After the designated cycles or hours were reached, the coupons were taken out for cleaning and evaluating, following the procedures specified by ASTM G1-96. Stainless steel coupons were dipped in nitric acid of 10 vol.% for 20 min. at 60°C. Aluminum coupons were dipped in nitric acid ($HNO_3$, sp gr 1.42) for 15 min. at room temperature. The coupons were rinsed with water and dried before being weighed again. All coupons were photographed at two-week intervals after the beginning of the test.

### *2.1.2 Corrosion Test for Electrical Components*

In order to examine the corrosiveness of the deicing salts to electrical components, an electrochemical test unit was devised for testing the corrosion of steel bars in concrete. The experimental setup is shown in Figure 2.

In the device, there are two electrodes, Cu/$MgCl_2$ and Cu/NaCl. According to electrochemical theory, the electrode with a higher negative potential will have a higher corrosion potential. Once they are connected to form the circuit shown in Figure 2, the electrode with higher negative potential will serve as a cathode and the other as an anode, and there will be a current flowing from the anode to the cathode. The potential difference (in milli-volts) between the two electrodes represents the relative ability to be corroded.

This electrochemical cell has not been used by other researchers and thus it is definitely not a widely accepted procedure. Our intention was that, in addition to the direct observation on the surface condition of coupons, this electrochemical cell provides more information on the change of electrode reduction potential for the same metal (i.e. copper) in different solutions, which is an indication of the driving force for the corrosion process. Specifically, when we see that the copper tube immersed in $MgCl_2$ has more and more green rust as immersion time increases, the absolute value of the potential difference also increases as shown in Fig. 15, which provides quantitative information about the corrosion process taking place in the copper tubes.

We did not use copper together with other materials in SAE J2334 and ASTM B117, because the research team spent a lot of time trying to identify a better testing approach for electronic components. After a long delay, the team did not find any viable approach and then the electrochemical cell was devised.

The test results obtained from the electrochemical cell indicate that magnesium chloride is more corrosive than sodium chloride to the electrical components made of copper. In another words, magnesium chloride may have higher potential to cause the failure of electrical components made of copper.

Two pieces of copper tube, with outer diameters of 0.4 inches, were tested by the SAE J2334 method with sodium chloride and magnesium chloride solutions as corrosive media. The concentrations of the chloride solutions were 3.0 wt.%. The two pieces of copper tube were then connected to the circuit while the corrosion potential was measured at weekly intervals.

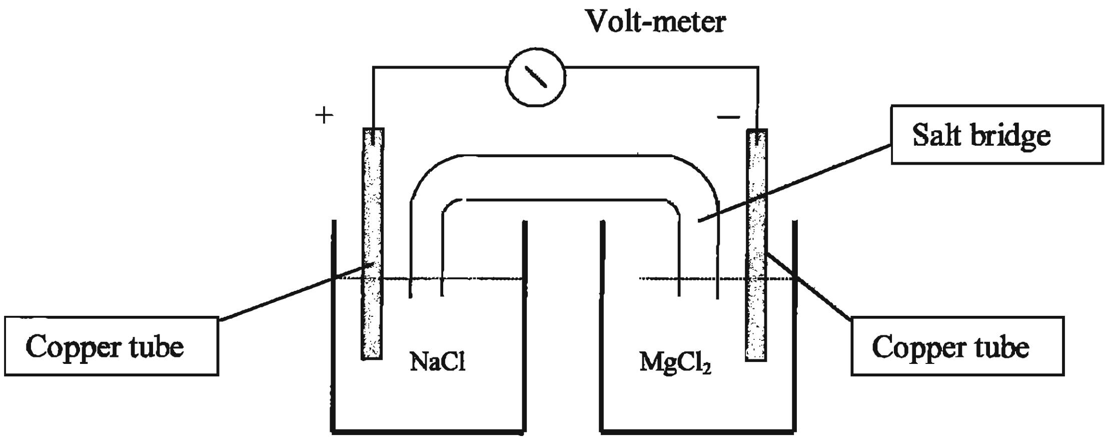


**Figure 2: The testing circuit for electrical components.**

## 2.2 Experiment Materials

The following materials were used in the project:

a. Al 2024, a representative of aluminum with low magnesium

Cr: <0.1
Cu: 1.0~2.0
Mg: 0.25~0.5
Si: <0.6
Zn: <0.25
Mn: 0.1~0.4
Fe: <0.5
Ti: <0.1

b. Al 5086, a representative of aluminum with high magnesium

Cr: 0.050/0.250
Cu: 0.100 max
Fe: 0.500 max
Al: balance
Mn: 0.200/0.700
Si: 0.400 max
Ti: 0.150 max
Mg: 3.500/4.500
Zn: 0.250

c. SS 304L, a representative of stainless steel with high chromium and nickel

C: 0.018
Cr: 18.110
Cu: 0.38
Fe: balance
Mn: 1.810
Mo: 0.350
N: 0.080
Ni: 8.050
P: 0.028
S: 0.001
Si: 0.520

d. SS 410, a representative of stainless steel with low chromium

C: 0.150 max.
Cr: 1 2.500
Fe: balance
Others: minimal

e. ACT cold roll sheet, coated, one of the standard corrosion coupons

f. ACT Zn/Fe A45, coated, one of the standard corrosion coupons

g. ACT E60 EZG, coated, one of the standard corrosion coupons

All three ACT coupons (Type e, f, and g) have the same coating system:

Ecoat: U32AD400
Primer: G27AD258 Powder
Basecoat: R164WE936 Stone white
Clearcoat: R126CG2001

**Figure 3: A photograph of the coupons.**

## 2.3 Equipment

a. Two environmental chambers (see Figure4), with a range in temperature from ambient to 65°C, and a humidity range from ambient to 100% RH;
b. Precision balance, 210± 0.001g;
c. Continuously spray unit (see Figure4), 38°C ±1°C;
d. Optical microscope of 200x with a CCD camera connected to a PC with an image grabber;
e. Digital Multimeter, Model Bel Merit DX360T;
f. Microcomputer pH meter, Model HI 8424.

**Figure 4: Experimental setups.**

## 2.4 Field Testing Procedures

The in-service exposure test was carried out on Colorado highways during the winter of 1999 to verify the results from the laboratory experiments. Five metal coupons, identical to those used in the laboratory tests, were bolted to a Plexiglas sheet approximately the size of a license plate. Ten of these Plexiglas plates were mounted on trucks for exposure on the highway starting the first week of November 1999. The plates were removed from the various trucks and returned to CU-Boulder for analysis in May 2000.

Two sets of coupons were also installed along the roadside of Interstate 70 near Georgetown on February 21, 2000. These coupons will be in place for at least one year, in order to compare corrosion results between the laboratory test and roadside conditions.

Four plates were mounted on CAST Transportation trucks; three plates were mounted on HVH Transportation trucks, and the remaining three plates were mounted on CDOT Region 6

Maintenance trucks. While both CAST and HVH have interstate operations, the participating carriers were asked to mount the plates on trucks that ran miles only in Colorado to guard against exposure to other state's deicing chemicals.

- HVH Transportation is a large for-hire trucking company that operates primarily in Colorado. Test plates were installed on two trucks that operate between Denver and Grand Junction, and one truck that operates between Pueblo and Denver.
- CAST Transportation is a large for-hire trucking company that operates primarily in Colorado. Test plates were installed on four trucks that operate mainly on the I-70 and I-25 corridors.
- Colorado Department of Transportation Region 6 Maintenance Department is responsible for Highway Maintenance along the Front Range and in the Denver metropolitan area, including C-470 and parts of I-25. Test plates were installed on two vehicles that apply magnesium chloride and one vehicle utilized by the Road Maintenance Supervisor.

Figure 5a: coupons on CDOT truck immediately prior to removal

Figure 5b: coupons on CDOT truck immediately prior to removal

Figure 5c: coupons on HVH truck immediately prior to removal

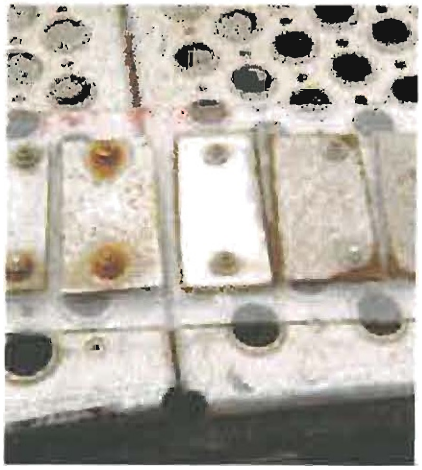


Figure 5d: coupons removed from CAST truck

Figure 5E: Coupons from Cast truck

Figure 5g: Coupons on CDOT truck

Figure 5f: Coupons on CDOT truck

Figure 5h: Coupons on HVH truck

## Section III: Experimental Results and Discussion

### 3.1 Cyclic Exposure Test by the SAE J2334 Method

The cyclic exposure test provided a severe corrosive environment in which cyclic changes in temperature, humidity and concentration of the solutions took place simultaneously. In total, six runs were conducted by the SAE J2334 method. Each run lasted for two months. Some runs were extended after two months of testing, which will be explained later. In Run 1 and Run 2, NaCl and $MgCl_2$ reagents were used, respectively. In Run 3 and Run 4, NaCl and $MgCl_2$ deicing salts were applied. In Run 5, a mixed solution of NaCl and $MgCl_2$ was used. In Run 6, a mixed solution of $MgCl_2$ and NaI was used. In the first four runs, 1.0 wt.% was the concentration for NaCl and $MgCl_2$ solutions. In Run 5, the solution contained 0.5 wt.% NaCl and 0.5 wt.% $MgCl_2$. In Run 6, the solution contains 1.0 wt.% $MgCl_2$ and 1.0 wt.% NaI, which was intended to examine whether NaI has any corrosion inhibiting effect. Fig. 6 shows the corrosion rates of various metals with the reagent $MgCl_2$ (without corrosion inhibitor). Fig. 7 shows the corrosion rates of the same metals with the real salt practically used on the road (with corrosion inhibitor). By comparing Fig. 6 and Fig. 7, one can see that the corrosion rate of AL2024 is reduced about 60% by the corrosion inhibitor (from 0.1987 down to 0.0783), however, the corrosion rate of SS410 is increased more than three times (from 0.4356 up to 1.3819).

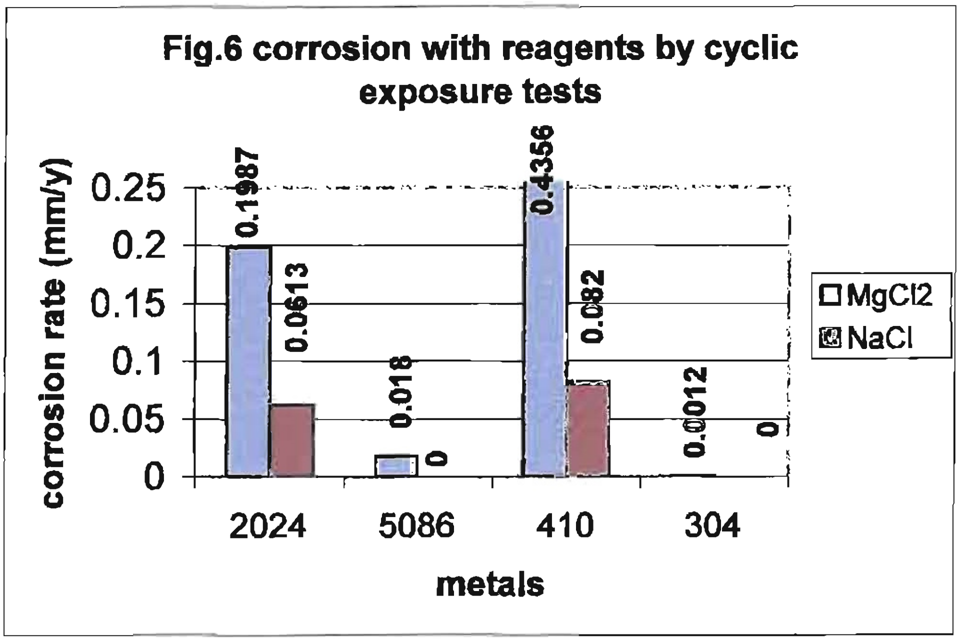


Fig.6 corrosion with reagents by cyclic exposure tests

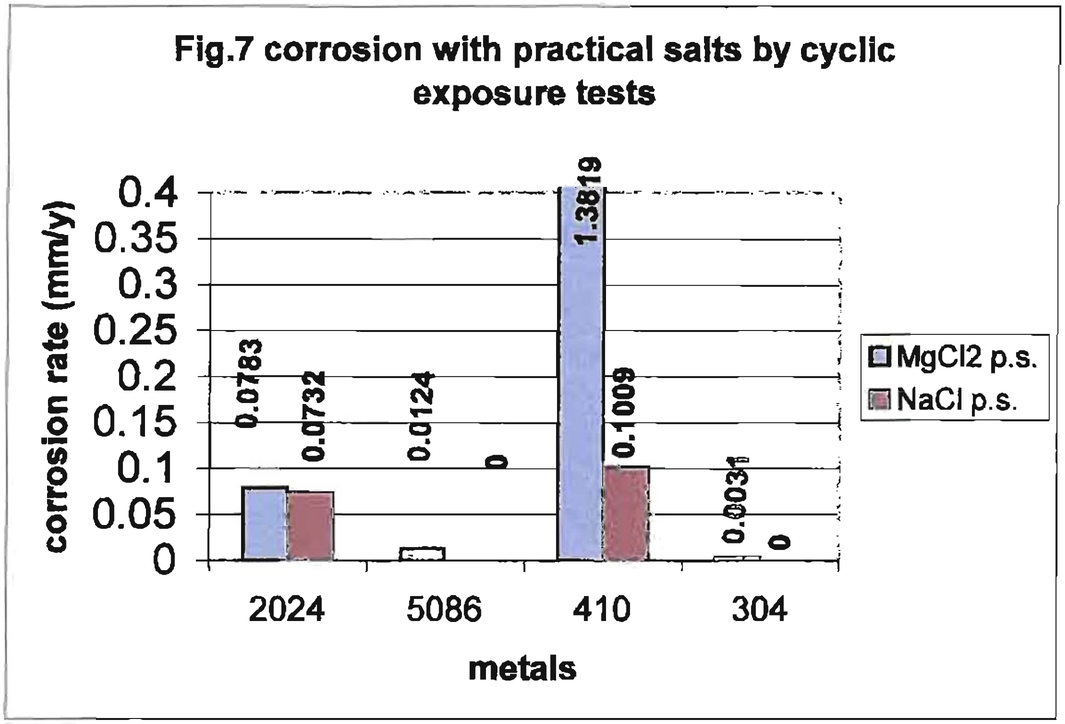


Fig.7 corrosion with practical salts by cyclic exposure tests

Among the metals tested, SS410 has less corrosion resistance as compared to SS304L. Similarly, Al2024 has less corrosion resistance compared to Al5086. We noticed that SS410 contains less chrome than SS304L and Al2024 contains less magnesium than Al5086. These may be among the reasons for the different corrosion resistances.

Figure 6 and Figure 7 show the test results by reagents and road salts, respectively. In the figures, the corrosion rate is shown in mm/y and is calculated following procedures outlined by the ASTM G28 standard. According to this standard, the corrosion rate is given by the following formula:

$$\text{Corrosion Rate} = \frac{K \times W}{A \times T \times D}$$

where:

$K$ = a constant

T = time of exposure, in hours

A = area in $\text{cm}^2$

$W$ = mass lost in grams

D = density in $\text{g/cm}^3$

The experimental results of the cyclic test with mixed NaCl and $MgCl_2$ (Run 5) are given in Table 8 (Appendix 1). The experimental results of the cyclic test with mixed NaI and $MgCl_2$ (Run 6) are given in Table 9 (Appendix 1). In theory, the mixed solution of NaCl and $MgCl_2$ would be less corrosive than $MgCl_2$ alone, since NaCl (less corrosive) is added to the solution. However, comparison of Table 6 and Table 8 (Appendix 1) shows that the mixed solution of NaCl and $MgCl_2$ is more corrosive than the $MgCl_2$ solution for the three metals. This indicates that there exists a coupling effect between the two chlorides in terms of the corrosiveness. Comparing Figures 6 and 7 with Figure 8, we can easily see that the coupling effect is a dominant one, because the absolute corrosion rates under the mixed salt attack are much higher than those induced by the single salt. The reason for the coupling effect is not clear, but we can rule out the possible chemical reactions between the two chlorides.

The addition of NaI did not result in any inhibiting effect. To the contrary, it increases the corrosiveness of the solution to a great extent. A comparison of the corrosion results caused by the three solutions 1wt.% $MgCl_2$, 0.5 wt.% $MgCl_2$+0.5wt.% NaCl, and 1.0wt.% $MgCl_2$ + 1.0 wt.% NaI is given in Figure 8.

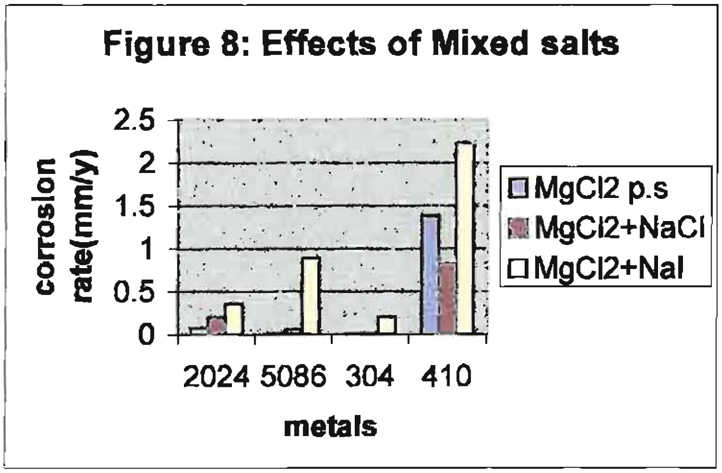


**Figure 8: Effects of Mixed salts**

For ACT coupons (i.e. ACT cold roll sheets, ACT Zn/Fe A45, and ACT E60 EZG), different chlorides used in the cyclic tests did not lead to any significant difference in the corrosion damage, as shown in Figure 9. The cold roll sheet was corroded by both NaCl and $MgCl_2$ to the same extent. However, no corrosion occurred to the other two ACT sheet materials, (ACT Zn/Fe

A45 and ACT E60 EZG) even after the cyclic tests were extended from two months to four months. One should notice that a scratch which penetrated the coating layer was made on every ACT coupon. Previous research showed that the scratches help accelerate the corrosion of the metals. The tests indicate that the treatments of electroplating or the hot-dip alloying during the manufacturing of the coupons enable the two ACT coupons to withstand cyclic chloride corrosion.

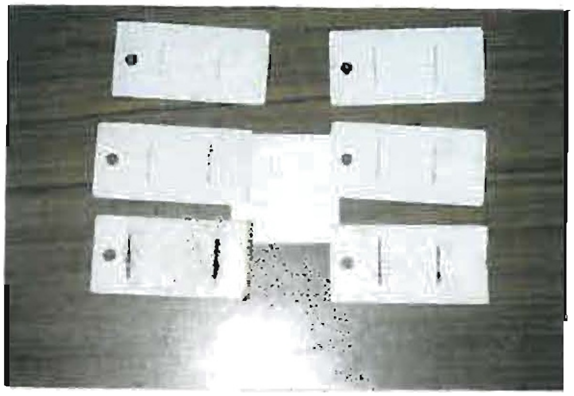


**Figure 9: Coupons Corroded by NaCl and $MgCl_2$**

Figures 10 and 11 are photographs of the corroded coupons at different stages caused by reagents and practical salts, respectively.

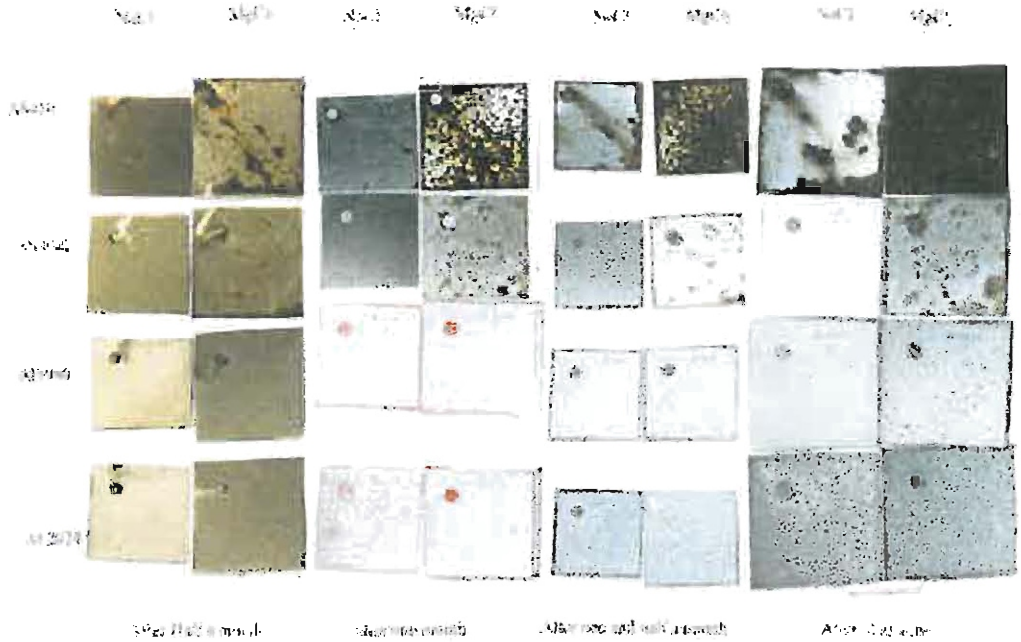


**Figure 10: Coupons after testing by SAE J2334 (with reagents)**

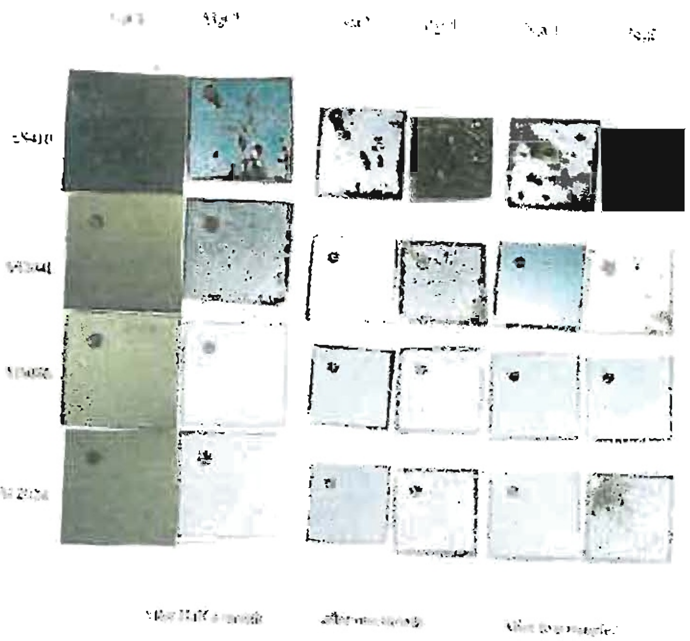


**Figure 11: Coupons corroded by practical salts**

### 3.2 Continuous Spray Test by the ASTM B117 Method

For the continuous spray test (ASTM B117), two runs were carried out with 4.0 wt.% solution of NaCl and $MgCl_2$, respectively. There were a total of 800 hours of continuous spray for each run. We originally considered extending the spray time from 800 hours to 1600 hours. However, the spray test was terminated after 800 hours because too much chloride gas was accumulated in the laboratory. The detailed test results are given in Table 10 and Table 11 (Appendix 1) and are also

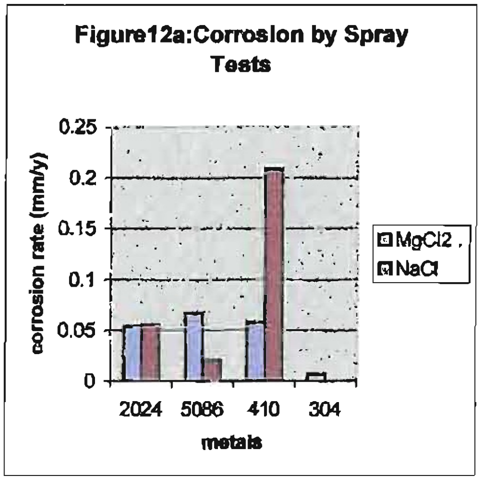


Figure12a:Corrosion by Spray Tests

shown in Figure 12a. The photos for the samples of the continuous spray test are shown in Figure 12b.

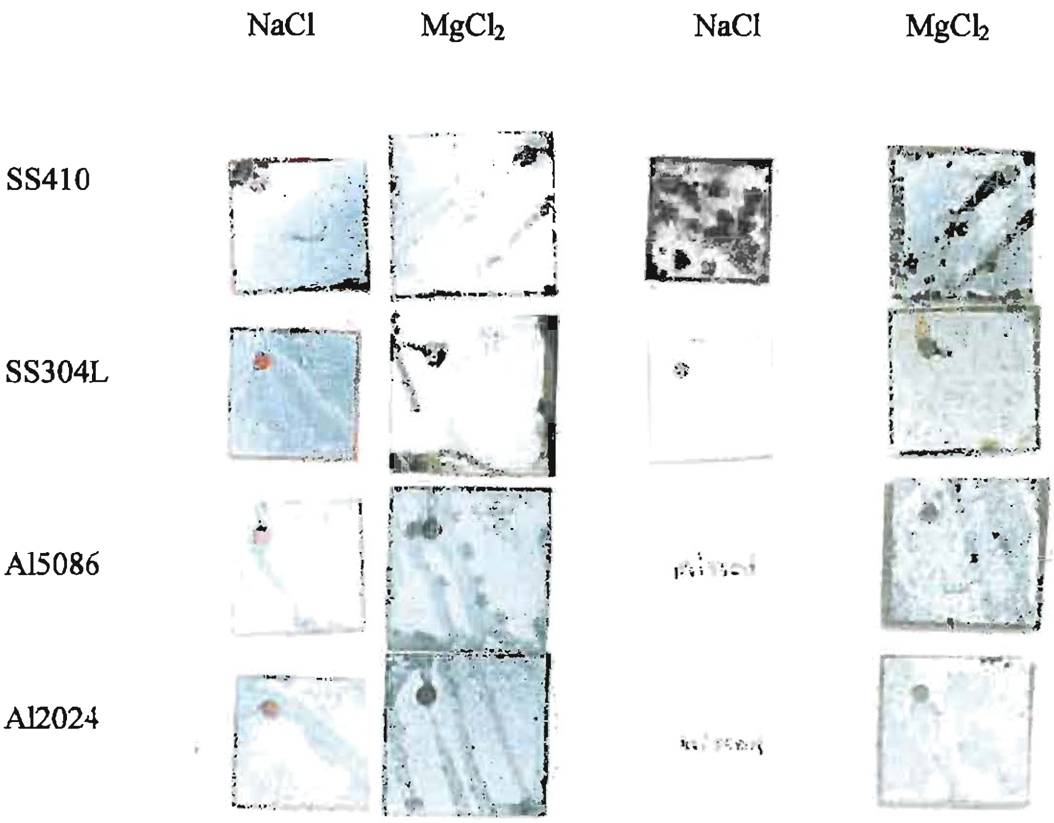


**Figure 12b: The test samples of the continuous spray test (ASTM B117).**

### 3.3 Comparison of the Cyclic Exposure Test and the Continuous Spray Test

Comparing the results shown in Figures 6, 7, 8, and 12a one can see that the absolute corrosion rates obtained from the cyclic exposure test are higher than those from the continuous spray test. This may be due to the fact that in the spray test the coupons are rested in a nearly closed environment. A mixture of salt fog and a small fraction of air are blown into the chamber. The oxygen concentration in the chamber is very low. In this circumstance, the electrochemical corrosion process is impeded, just as in the case when the coupons are immersed in the salt solutions.

In order to confirm the role of oxygen in the electrochemical corrosion process, another experiment was performed, in which SS410 and copper wires were immersed in 30% NaCl solution and 30% $MgCl_2$ solutions for two months, respectively. Although the two materials suffered severe corrosion under other test environments, hardly any corrosion occurred in the immersion test (Figure13). This indicates the importance of oxygen in the corrosion process.

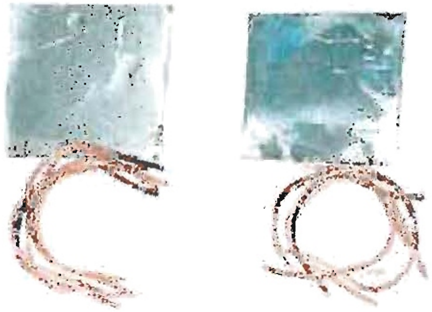


**Figure 13: Immersion tests of SS410 and copper wires.**

## 3.4 The Corrosion of Copper Tubes

The corrosion test for copper tubes by SAE J2334 lasted one month. Two different chloride solutions were used in the test with the same concentration (3.0 wt.%). Different corrosion damages were observed. The results are given in Figures 14a and 14b. Copper wire specimens experienced same test and the corroded wires are seen as in Figure 14c. All these photos indicate that $MgCl_2$ causes more severe corrosion to the copper specimens than NaCl.

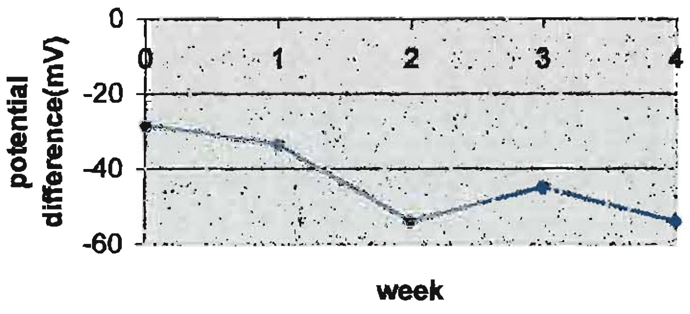
**Figure 14a: Copper coupons prior to the test of SAE J2334**

Figure 14b: Copper coupons after SAE J2334 testing

Figure 14c: Corroded copper wires after SAE J2334 testing

It was found that the tube subjected to the $MgCl_2$ solution had a higher negative potential than the one subjected to NaCl. The potential differences varied from -30 to -57 mV. According to electrochemistry theory, this difference in potential could result in a significant difference in the corrosion rates in the two cases. Figure 15 is a comparison of the corroded copper tubes after the one-month test. The coupons subjected to the $MgCl_2$ solution had more green rust (CuO) on the corroded surface than the corrosion caused by NaCl.

Figure 15: Corrosion Potential Difference of Copper



## 3.5 In-service Tests

The coupons mounted on the trucks of CDOT, HVH, and CAST were sent back to CU-Boulder for laboratory testing after being exposed for one winter (1999). The results are given in Table 12 (Appendix 1) and shown in Figure 16a, b, c, and d. It appears trucks #295, #1169, #1159, #1166, #1158, #1576, and #3066 had been exposed to a more severe corrosion environment than the others.

Coupons 3088, 3067, and 3066 were mounted on HVH trucks. Trucks 3066 and 3088 ran 5-6 days each week on I-70 between Denver and Grand Junction. Truck 3066 ran six nights per week and was driven a total of 81,305 miles while the test coupons were installed. Truck 3088 ran five days per week from Grand Junction to Denver and was driven a total of 78,986 miles. Truck 3067 ran 2 trips per day, five days per week from Pueblo to Denver and was driven a total of 70,254 miles during the test period. Based on testing completed by CU-Boulder, the trucks driven between Denver and Grand Junction (3066 and 3088) suffered more corrosion damage than the truck driven between Denver and Pueblo.

Coupons 1169, 1159, 1158, and 1166 were installed on trucks driven by CAST Transportation. Truck 1158 was driven throughout the Colorado during the testing period and was driven a total of 60,459 miles. Truck 1159 and 1166 operated between Denver and Grand Junction and were driven 98,313 and 39,826 miles. Truck 1169 operated between Denver and Climax and was driven 37, 236 miles during the test period.

**Fig.16a Corrosion of SS304L**

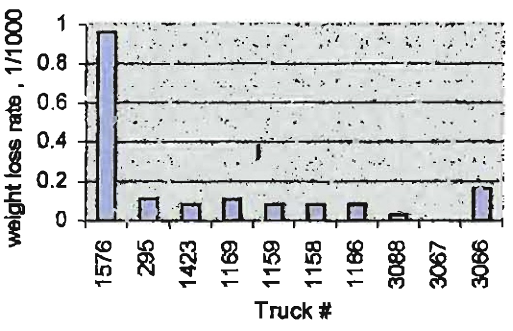


**Fig.16b Corrosion of SS410**

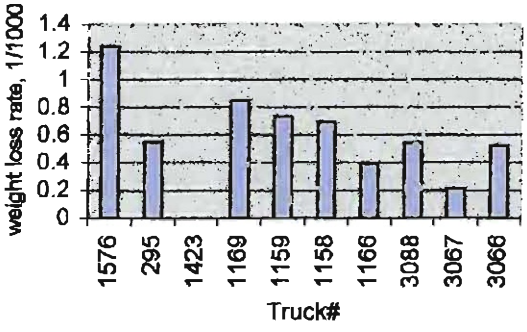


**Fig. 16c Corrosion of Al2024**

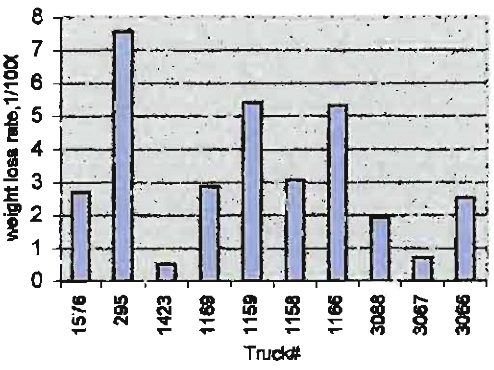
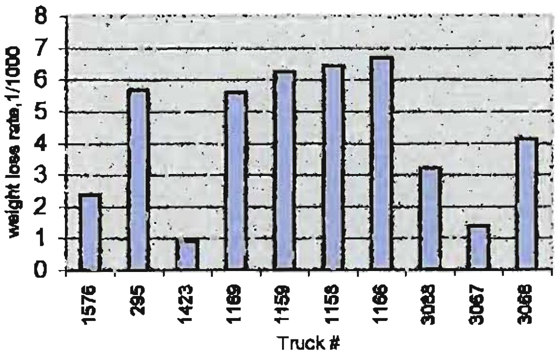


**Fig.16d Corrosion of Al5086**



### 3.6 Chemical and Microscopic Analyses

In order to understand and further explain some of the test results, chemical and microscopic analyses were performed. Figure 17a through Figure 17h are the microscope photographs of the corroded coupons subjected to the cyclic exposure corrosion test. It can be seen that regardless of the corrosion medium used, the same morphological feature of the corrosion products is observed for the same metal. Different amounts of the corrosion products can be seen for different metals under attacks by different chlorides. All corrosion products are in amorphous or glass states.

**Figures 17a-h: Microscope photographs of the corroded coupons subjected to the cyclic exposure corrosion test.**

**Figure 17a**

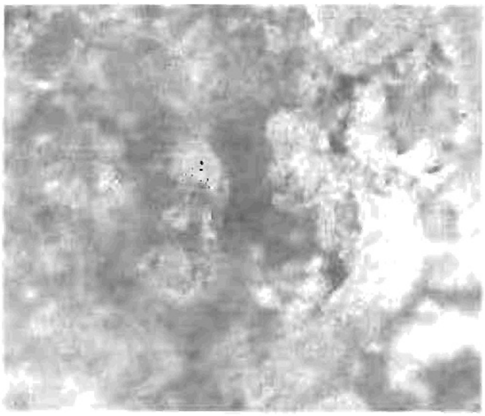


**Figure 17b**

**Figure 17c**

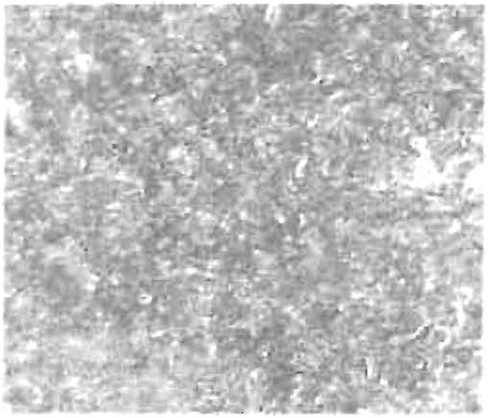


**Figure 17d**

**Figure 17e**

**Figure 17f**

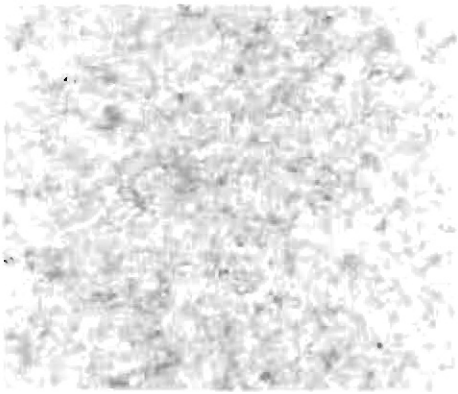


**Figure 17g**

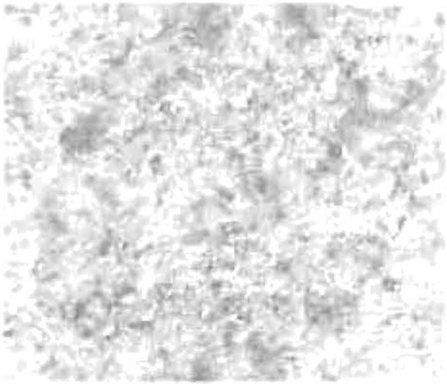


**Figure 17h**

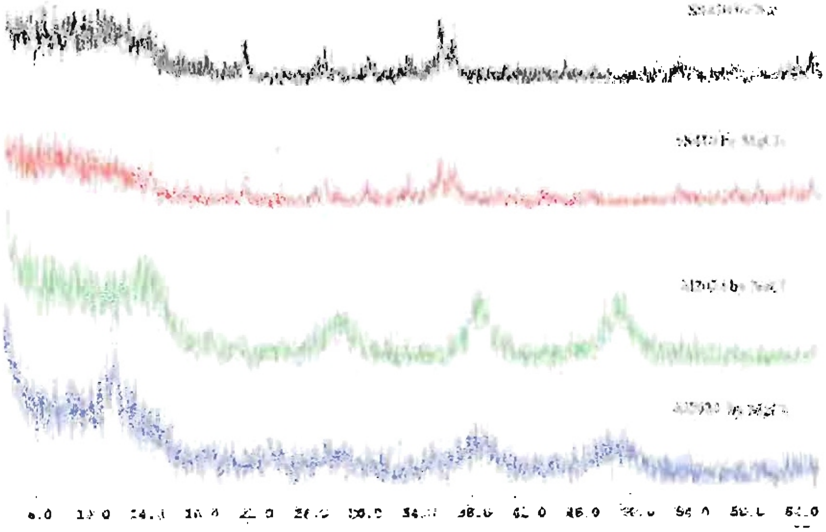


Figure 18: Corrosion products collected from coupons in SAE J2334 test, analyzed by XRD

The corrosion products collected from those coupons in SAE J2334 test were analyzed by X-ray diffraction (XRD) (see Figure 18). The XRD results show these corrosion products are aluminum oxide hydroxide (bohmite) for the aluminum, and a mixture of iron oxide (magnetite) and iron oxide hydroxide (lepidocrocite) for the steel. These corrosion products are in low crystallinity, without incorporation of chloride. Our results agree with the study by Kajiyama and his colleague (1995), who studied the chemical composition of the corrosion products of steel on vehicles used in North America, as well as the growth mechanism of the corrosion products. Quantitative analyses of the crystalline compositions were performed on the rust formed on the outer panel surface and in the crevice of the lapped portion on the vehicles. Characteristic regions of the rust compositions were found in the $\alpha$-FeOOH/($Fe_3O_4$ + $\gamma$-FeOOH)/($\beta$-FeOOH + amorphous rust) ternary diagram. The rust from the crevice in the lapped portion contained more ($\gamma$-FeOOH + $Fe_3O_4$) than that from the outer steel panel.

All these observations and analyses suggest that the corrosions of the bare metals including iron, aluminum and copper under cyclic exposure to deicing salts are typical electrochemical corrosion processes, rather than a direct chemical reaction between the metal and chloride. At the anode areas the following reactions take place:

| | | |
|---|---|---|
| Steel: | $Fe \rightarrow Fe^{2+} + 2e$ | (5) |
| Aluminum: | $Al \rightarrow Al^{3+} + 3e$ | (6) |
| Copper: | $Cu \rightarrow Cu^{2+} + 2e$ | (7) |

At the cathode areas, the hydrogen ions in water accept electrons:

$$4H^{+} + O_2 + 4e \rightarrow 2H_2O \qquad (8)$$

Ions of the metals may further combine with OH ions in water to form hydroxides,

$$2Fe^{2+} + 4OH^{-} \rightarrow 2Fe(OH)_2 \qquad (9)$$

and $Fe(OH)_2$ is further oxidized into $Fe(OH)_3$:

$$4Fe(OH)_2 + O_2 + 2H_2O \rightarrow 4Fe(OH)_3 \qquad (10)$$

## 3.7 Corrosion induced by $MgCl_2$

It is thought that there are two factors leading $MgCl_2$ to have higher corrosiveness than NaCl. One is its lower pH value and the other is its relatively higher chloride concentration in the solution.

With the same concentration level, the $MgCl_2$ solution has lower pH values than the NaCl solution. This is because $MgCl_2$ can hydrolyze according to $MgCl_2 + H_2O \rightarrow Mg(OH)Cl + HCl$ (Silcock,1979). This means there are more hydrogen ions in the corrosion medium when $MgCl_2$ is used as the road salt. Since higher concentrations of hydrogen ions can promote the cathode reaction (see Equation 8), the metals subjected to the $MgCl_2$ solution have a higher corrosion rate.

Chloride ions do not chemically react with the metals. Chloride ions only assume a role as a medium or catalyst in the electrochemical process. Chloride anions in the solution could help to remove the metal cations accumulated on the anode by forming soluble compounds, and this contributes to an accelerated anodic reaction and thus faster rusting of the metals. This hypothesis is supported by the research of Ambat and Dwarakadasa (1993), who found the concentration of chloride had great effect on the corrosion rate of aluminum alloys in the region of neutral pH. They considered that the strong dependence of the corrosion rate of aluminum on chloride ion concentration in a neutral environment might be explained by taking into account the adherent oxide film that is present on the surface of the alloy. In such cases, the presence of chloride ions can accelerate the corrosion by retarding film repair. At the film/solution interface, chloride ions lead to a local thinning of the passive layer and to pitting corrosion.

Since the oxide film on the surface of the aluminum is soluble in both low and high pH solutions, the change of pH has a great influence on aluminum corrosion. This influence is profound because the solutions of NaCl, $CaCl_2$, $MgCl_2$ and so on have different pH values even with same weight percentage concentration.

In practice, the applied concentration of $MgCl_2$ is much higher than NaCl, in order to acquire the equivalent deicing effect to NaCl, e.g. 8.1% $MgCl_2$ solution is the deicing equivalent of the 3.5%

NaCl solution (McCrum, 1989). Calculations show that even though they have the same weight percentage concentration, $MgCl_2$ will contain 22.5% more chloride ions in the solution. Therefore, in practice, the harmfulness of $MgCl_2$ is much greater than NaCl of the equivalent deicing effect.

### 3.8 Conclusions from Experimental Testing

1. Experimental results obtained by the cyclic exposure test (SAE J2334) indicate that $MgCl_2$ is more corrosive than NaCl to the bare metals tested. The rate of corrosion varies from metal to metal. For stainless steel SS410, the corrosion rate caused by $MgCl_2$ is 5 to 13 times higher than by NaCl; for aluminum AL2024, the corrosion rate caused by $MgCl_2$ is one to two times higher.

2. Experimental results obtained by the continuous spray test (ASTM B117) show inconsistencies when compared with the results of the SAE J2334 test, especially for the stainless steel SS410, for which NaCl is more corrosive than $MgCl_2$.

3. The corrosion rates obtained by the SAE J2334 test are higher than the corrosion rates obtained by the ASTM B117 test. Experimental results from our immersion test indicate this may be due to the different oxygen concentrations in the two testing procedures. The coupons were placed in an atmosphere with reduced oxygen concentration in ASTM B117, which resulted in the lower corrosion rates. From a practical point of view, the testing environment of ASTM B117 may not be a realistic simulation of the actual conditions on the road. On the other hand, the testing environment in SAE J2334 provides cyclic exposure from dry to wet, from cold to hot, and from concentrated salt solution to diluted salt solution, which is much closer to the actual service condition.

4. Mixtures of $MgCl_2$ and NaCl cause more severe corrosion to the metals than does any single salt (either $MgCl_2$ or NaCl). This implies there are coupling effects between the two chlorides. However, we can rule out the chemical reaction between the two salts.

5. Corrosion of metals caused by deicing salts are electrochemical processes instead of direct chemical reactions. Therefore, hydrogen ion and oxygen concentrations play important roles.

6. Two factors may lead to the higher corrosion rate of $MgCl_2$. One is its lower pH value, and the other is its higher chloride concentration in the solution, compared to NaCl of the same weight percentage concentration.

7. Higher chrome content in stainless steels and higher magnesium content in aluminum alloys seems to increase corrosion resistance of the metals under the attack of $MgCl_2$ or NaCl solutions.

8. The coated automobile body panels with the treatment of electroplating or hot-dip alloying exhibit very high corrosion resistance. No significant corrosion products were observed on the coupons even when the panels were scratched and the outer coating was damaged. However, the coated cold roll sheets show poor corrosion resistance.

9. $MgCl_2$ is more corrosive than NaCl to electronic components made of copper.

## Section IV: Survey of Colorado Trucking Companies

### 4.1 Overview of Survey

The American Trucking Associations Foundation developed a two-page survey to determine the level of concern among the trucking industry regarding the use of magnesium chloride on Colorado's highways. The survey was pilot tested and refined prior to being faxed to more than 150 trucking companies with operations in Colorado. These companies were asked to provide information relating to costs, safety issues and general opinions/attitudes concerning Colorado's use of magnesium chloride.

Trucking companies were identified from two main sources: the membership of Colorado Motor Carriers Association, and the National Motor Carrier Directory. Fifty-three surveys were returned, providing a response rate of 34.8%. This response rate is very acceptable for a single mailing, voluntary response survey.

The survey was divided into three sections: company information; vehicle wear attributed to magnesium chloride; and general questions regarding Colorado's use of magnesium chloride. A copy of the survey is included in Appendix 3.

### 4.2 Survey Results

Of the companies that responded to the survey, 80% were for-hire companies (hired to carry freight). Private trucking companies (haul primarily company goods) represented the remaining 20% of the respondents. Companies reported an average of 62% of total fleet miles was driven within Colorado. While many of the companies were interstate carriers, 33 of the respondents reported being intrastate or pickup/delivery carriers. Additionally, the trucking companies that responded operate in all areas of the state, with a concentration on the I-25/front range corridor.

Seventy-two percent of the respondents reported noticing increased wear on their equipment since Colorado began using magnesium chloride. Twenty-eight percent reported no problems associated with the use of magnesium chloride.

Companies reported the most damage to chrome, tractor or trailer bodies, aluminum parts, wheels, hoses and connectors, and electrical parts. The specific type of damage mentioned most often included corrosion, pitting, staining/tarnishing, discoloration, drying/cracking (hoses), and accelerated rust.

Chrome, aluminum parts, and electrical wiring were reported to have received heavy damage requiring replacement. However, 25% of respondents reported no damage to electrical wiring or chrome, indicating certain types of wiring/connections and chrome may be more susceptible than others to damage.

Fifty-three percent of the companies reported they have not changed their procedures to limit vehicle damage caused by magnesium chloride or other deicing methods. Those companies that have implemented changes to their operations to limit or repair damage caused by deicing primarily increased the frequency of vehicle washing. On average, these companies increased the frequency of truck washing by 28% in the months that magnesium chloride is used. In addition to increasing the number of washings, 62% of companies reported magnesium chloride was difficult to remove requiring more labor, additional brushing, and stronger cleaning chemicals to eliminate the residue.

General attitudes about the benefits of magnesium chloride were mixed. A narrow majority of respondents do *not* believe that the use of magnesium chloride has made truck driving less safe or affected the safety of their equipment. Companies which disagreed cited such reasons as: magnesium chloride sticks to the highway even when there is no snow so the highways are continually wet; magnesium chloride creates a film on the windshield that is difficult to remove and impairs visibility; and magnesium chloride corrodes electrical connections which lead to electrical failures. Eight respondents reported that increased electrical failures affected vehicle safety.

The majority of respondents (62%) believe that magnesium chloride has *not* reduced the number of winter road closures in Colorado. A similar majority also prefers previous methods of deicing (primarily salt/sand mixtures) to the current methods used by CDOT.

Companies were asked to quantify the costs they associated with the use of magnesium chloride. Eighteen companies detailed costs relating to increased maintenance, accelerated parts/wiring replacement, etc. The total annual cost associated with those 18 companies was over $260,000, with an average annual cost per company of $14,500. Twenty-five companies detailed annual costs associated with additional truck washing (including different/extra chemicals, additional labor, etc.) totaling nearly $200,000, with an average annual cost per company of $8,000.

Thirteen companies further detailed costs relating to the use of magnesium chloride. The average cost per company per year is presented as a general reference to the types of costs motor carriers are attributing to the use of magnesium chloride, associated with various truck components.

| | |
|---|---|
| Paint: | $13,000 |
| Chrome: | $48,000 |
| Tractor/Trailer body: | $ 6,950 |
| Aluminum parts: | $ 7,050 |
| Other metal parts: | $ 1,890 |
| Lights: | $ 4,546 |
| Windshield: | $ 682 |
| Tires: | $ 2,000 |
| Wheels: | $ 6,850 |
| Hoses: | $ 1,080 |
| Wiring: | $ 4,244 |

# Section V: Literature Review and Secondary Information

## 5.1 Information from Other States

Interviews were conducted with winter road maintenance departments in twelve western states. Information was collected about winter road maintenance, deicing/anti-icing procedures, application methods, budgets, research plans and other topics regarding magnesium chloride. The results of those interviews are summarized below.

*The information below reflects statements made by DOT employees in other states, and many include opinions. The statements were not substantiated through this research project, and do not reflect the opinions of the Research Team.*

*Colorado:*

We use magnesium chloride with a low thermal inhibitor because it lasts 30% longer than the salt/sand method and is more environmentally friendly. It reduces the air and water pollution and it helps prevent road closures. We use about four million gallons statewide per year, and we are cutting back on using sand. Magnesium chloride is the most cost effective at 30 cents a gallon.

Colorado uses a mixture of 27–30% magnesium chloride and 70–73% water. Magnesium chloride is a trade off—it causes sloppy messes but we do not have the ice buildup on roads we used to have. We do have to continually monitor and clean road signs because the magnesium chloride causes a build-up of grime. Magnesium chloride "locks" down fine materials, whereas road-sanding produces dust particulates, affecting the environment and causing pollution. Rock salt used in sand mixes with the magnesium chloride and is more corrosive.

We are experimenting with "Ice Slicer", which is a granular product. It involves using 1/3 less product and requires no sweeping. It is very expensive ($75 per ton) but keeps the roads wet. We used Ice Ban for a while. It worked well, but it costs two to two and one-half times more than magnesium chloride. It also has a high phosphorous level, which caused higher algae growth. We are now testing Calabran M 1000 (an alcohol-based solution), which works better than magnesium chloride in colder weather and is less corrosive. However, it is two to two and one half times more expensive than magnesium chloride, at a cost of about 75 cents per gallon. CDOT's average annual maintenance budget is $2.5 million. In 1999, CDOT spent $627,000 on salt/sand and $300,000 on magnesium chloride.

CDOT used to have a lot of chipped paint and windshield damage complaints when we used the salt/sand mixture. The biggest complaint we hear with the magnesium chloride is the continual water spray from wet highways and that it is hard to clean off vehicles. We have a training manual for our maintenance crews. We stress safety and customer service. We use PowerPoint slides as a learning tool. One of the things we teach is that we don't anti-ice on curved highways because of the difference in skid resistance.

*California:*

Most of the products we use are for anti-icing and anti-frosting. We use magnesium chloride, rock salt and salt brine, depending on the area. Once we explained to the public that the magnesium chloride had reduced the number of accidents, the public was more receptive. We use 28-38 gallons per lane mile. We make our own tanks and we spread it based on gear speed. We have 15 spray tanks to cover 1,700 miles of road.

Our magnesium chloride costs 50 cents per gallon. It is supposed to be equal in corrosion to salt/sand but the mist from magnesium chloride is more noticeable since it covers the entire vehicle. We do not use magnesium chloride as a bond breaker. With magnesium chloride we'll go 5 to 7 days between applications, compared to daily applications of rock salt.

We also use a lot of salt brine since it is much cheaper (6 cents a gallon). We purchased two salt brine-mixing machines and mix it ourselves. We are presently experimenting with Freeze Guard and PCI—both products have a corrosion inhibitor.

*Idaho:*

Magnesium chloride is our primary anti- and deicer but we also use a sand/salt mixture (5% salt). We have been using magnesium chloride for a few years and it is working well. We wanted more of an anti-icing product than we got with salt/sand, so we switched to magnesium chloride. It is a growing program as we are adding more roads to our deicing system, and magnesium chloride seems to be more cost effective.

We have had some complaints about our deicers pitting and corroding aluminum parts, sticking to the windshields and being difficult to remove. We have also had complaints that when magnesium chloride with an inhibitor was first applied at the beginning of the season, it created slick conditions on the highways. We are researching this using a skid meter. Additionally, we are researching to see if different structured highways and traffic volumes make a difference when magnesium chloride is put down. Our annual road maintenance budget is around $50 million, $13 million of which is our anti/deicing budget.

*Kansas:*

We use salt, pre-wetted salt and salt brine for both anti- and deicing. We use magnesium chloride with a corrosion inhibitor only in the Kansas City Metro area where there is heavy traffic volume and large structures. Kansas has an abundance of salt so it is more cost effective (less than 3 cents a gallon) than any other deicers on the market. In some instances we use pure salt, but other times we mix three parts sand to one part salt.

We did try Ice Ban with a corrosion inhibitor along with the salt brine but we had a lot of complaints about how slimy it was and how it stuck to the vehicles. Our staff did not like using it either because of the offensive odor. Lab tests showed Ice Ban did reduce corrosion of the salt but it did not drop the effective temperature of the salt. Ice Ban is also more costly per gallon.

*Montana:*

Magnesium chloride is used in the urban areas, and a combination of magnesium chloride and salt/sand is used elsewhere. We use 2 ½-5% salt in stockpiles to provide traction. We use approximately 2 ½ million gallons of magnesium chloride by winter's end. Magnesium chloride is a trade-off between cosmetics and traction. It could save lives, which is invaluable. We have been using magnesium chloride since 1993 and most of our complaints are about corrosion of "after market" items that are not clear coated. Aluminum wheel damage seems to be the biggest complaint.

Our sand trucks are equipped with side tanks filled with liquid chemical. We inject the sand with this liquid chemical. The abrasive, wetted down with the liquid chemical, keeps the sand from being thrown to the side of the track—making a sandpaper effect. It isn't thrown from the wheel path, reducing both windshield damage and dust/pollution.

We quit using salt/sand mixtures because of environmental issues. Magnesium chloride provides better air quality and performance. Anything we use has to be 70% less corrosive than salt. We use salt brine on steel for testing and comparison purposes. We found calcium chloride to be more corrosive than the other products we have used.

*Nebraska:*

Our Road Maintenance Department uses salt brine (sodium chloride), magnesium chloride and Ice Ban for our deicing program. We were a test state for Ice Ban. We use an estimated 80,000 gallons of Ice Ban liquid a year. Ice Ban is not fool proof and it is somewhat expensive. It is reddish in color and smells like syrup. We use it on our new concrete highways because it is non-corrosive, but when the temperature reaches below 24 degrees, Ice Ban becomes a skating rink.

Temperature and humidity dictate what product we will use on any given day. We use a lot of pre-wetted salt. Some salt/sand (aggregate) is used but we are using it less often as it creates a major clean-up problem and we get better results with the chemical deicers. The salt brine is cheap to use and any new deicer product would have to be equal or less costly, in order for us to change.

We have not had many complaints with our deicers. Vehicle manufacturers are doing a better job of zinc coating, which prevents a lot of the corrosion.

*Nevada:*

We use magnesium chloride and salt grind tanks as winter road storm control. We use the magnesium chloride as an anti-icer and salt/sand mixture during and after the storm. Both methods work well. We haven't used enough of the magnesium chloride to have complaints from the public. We did use magnesium chloride on a parking lot to keep the dust down and had a lot of complaints about corrosion. Ten to fifteen percent of our overall road maintenance budget is used for anti-deicing.

In the mountains near Reno we use brine as an anti-icing agent to prevent snow and ice buildup. We send out sand trucks with liquid tanks on the sides, to monitor an area in case of changing conditions. The problem with magnesium chloride (PCI inhibitor) is the high cost and spotty availability of the product. Salt water is cheaper and less corrosive.

We used to be in the top 10 most polluted areas when we used salt/sand. We now use harder sand (standard is 5 parts sand to 1 part salt), and we check it every 500 yards on the highways.

We also use road sensors to monitor temperatures. A DTM (Doppler radar system) is used to help in controlling winter driving conditions. This gives the Department opportunities to utilize alternate de-icing chemicals, make optimal use of materials and staff, and practice anti-icing techniques developed through years of research.

*North Dakota:*

We have never tried the magnesium chloride. We use rock salt for anti and deicing. We have salt brine makers all over the state and make it as needed. Until two years ago we did not use an anti-icer, but now, we use the salt brine for that purpose as well. We like the price of rock salt.

*Oregon:*

We have been using CMA (Calcium Magnesium Acetate, a vinegar-like product) for three to four years. CF2 (potassium), a combination of CMA and DF2 magnesium chloride with an inhibitor. CMA is used prior to a storm and works best at 24 degrees and above. We never use salt, but do use a lot of sand. In some areas of the state, we have used rock salt without a corrosive inhibitor and have received no complaints.

We believe magnesium chloride is a better anti-icer and breaks up the ice better than CMA during and after a storm. It is also cheaper to use than the others we have tried. It is more environmentally safe since it does not get in the water.

*South Dakota:*

We use abrasive materials--anywhere from 15 to 70% salt/sand. We use about 20 tons of salt a year. We put down both pre-wetted salt/sand, as well as dry sand that we wet after application. We also use magnesium/chloride as an anti-icer, as well as a deicer. We use a corrosion inhibitor with it. We like it because our pavement returns to bare pavement days earlier than when we use the salt/sand method and it is easier to clean up after a storm.

Next year we are testing Ice Ban as a pre-wetting for abrasive materials under limited application. We are developing a deicer of our own that is neutral in pH factor. It is a dry pellet and manufacturing it is not yet economical.

*Utah:*

We use sodium chloride (NaCl) 50/50 sand/salt mix as a deicer. We mix the NaCl ourselves. We have the usual complaints when using NaCl of pitting windshields. We are now pre-wetting with brine solution (20-23 % sodium chloride) as an anti-icer, and are using all liquid trucks. We just plow if it gets below 20 degrees and freezes.

We have been experimenting with magnesium chloride and calcium chloride. Calcium magnesium acetate is less corrosive but more expensive to use. We were told that it works with temperatures as low as –60 degrees. We have High Performance Salt that is mined in Utah and absorbs energy from the sun. There is also Morton Salt that is white and we add dye to it. We are running lab tests to see what effect, if any, white, red or blue sand has on our deicer program.

*Washington:*

We use magnesium chloride with Ice Ban as an inhibitor in most areas. We also use CMA and calcium chloride. Magnesium chloride is the least expensive. CMA works the best and it doesn't corrode, but is far more expensive. Calcium chloride does the most damage to aluminum. We use 10-15 gallons of magnesium chloride per mile as an anti-icer. In extreme conditions, we will also use salt/sand. We do not use pre-wetted salt or sand. We used to use granular products for both anti and deicing (urea and salt/sand), but we stopped using the salt/sand method when it became an environmental issue.

Our biggest concern in anti/deicing is the uniformity both in training and application. Road surfaces vary, therefore, you cannot treat a new highway with anti-icing and deicers the same way you treat an older highway that has had a lot of use, dirt and oil on it. Human factors of over applying or not knowing when and how much to apply are a lot of the problems associated with deicers. Anti/deicing is an ongoing learning process in our state. We have had some complaints about the magnesium chloride and Ice Ban being corrosive and hard to remove. We advise people to wash their vehicles as often as possible.

We are a member of Pacific Northwest States (PNS) that sets the anti/deicer criteria in many states. They set the specification for what is used. They plan to try other methods, especially if the cost is right. FHWA reported CMA is coming out with a cheese whey by-product that may work as good as the original but not nearly as costly.

Ice Ban is really good as a buffer for the chloride but its smell and color are objectionable to humans, although it is not a toxic product. The Ice Ban is a by-product of beer and is a real hazard where animals are concerned as they get out on the highways to lick it and sometimes get hit by vehicles.

## 5.2 Research on Automotive Corrosion/ Literature Review

Statistics showed that road salt costs about $55 per ton, and its use results in more than $1543/ ton worth of damage to vehicles, bridges, and the environment (Hudson, 1987). As early as the

1960's, Jameston (Cargill Inc. 1968) investigated the effect of inhibited deicing salt on corrosion rates of metals used in automobiles by performing tests under driving conditions.

Koyama and Sakauchi (Australia 1982) proposed a test method for evaluating the chipping resistance of outer panels, which affords superior accuracy and repeatability as well as excellent applicability for quantitative evaluation of the corrosion resistance.

Gluszek and Nitsch (1982) determined the susceptibility to stress cracking corrosion and pitting corrosion of 304L steel in boiling NaCl, $CaCl_2$ and $MgCl_2$ solutions at 5N concentration. They found the order of corrosiveness of the solutions was NaCl > $CaCl_2$ > $MgCl_2$, with pHs of 7.0, 6.3 and 5.4, respectively. This conclusion, however, cannot be applied to other occasions, since in the condition of boiling the role of oxygen in the corrosion process will be greatly reduced. For the corrosion of automobile metals, oxidization of steel should be the first mechanism and chloride is only one of the participators in the electrochemical process.

In 1990, the Society of Automotive Engineers (SAE) published a standard road test procedure (SAE J1293) for comparing the corrosion resistance of both coated and uncoated sheet steels in an undervehicle deicing salt environment.

Tarutani et al. (Sumitomo Metal Industries 1991) studied the performance of ferritic stainless steels for automobile muffler corrosion. They examined the corrosion behavior of ferritic stainless steel (409L and 410L) in artificial exhaust gas condensates containing corrosive ions such as $Cl^-$ and $SO_4^{2-}$. The test results clarified that Type 436L ferritic stainless steel, the material for the automobile muffler, exhibited acceptable corrosion resistance.

Whitton (Ford Motor 1995) presented a report on their research results on vehicle component corrosion resistant coatings and test methods comparison. The corrosion resistance of the coating was evaluated on automobile automatic transmission oil pans. Three test methods, including salt spray, accelerated corrosion test track testing and customer vehicles, were evaluated. The most informative and most severe test method was found to be the accelerated corrosion test track method.

Androsch (Voest-Alpine 1995) investigated the corrosion behavior of various coating systems in different types of automotive corrosion tests. He found that for the same site, test and coating type, the creepage results could differ significantly, depending on which season the exposure began.

Bednar et al (AK Steel Corp. 1995) researched the corrosion behavior of automotive body panels in normal vehicle service under severe conditions of intense deicing salt usage. The study included, in addition to visual evaluation and rating of doors, a metallographic investigation of the manner of paint coating failure on steel and zinc/zinc-alloy coating substrates and the corrosion behavior of metallic coatings.

Altmayer (Scientific Control Laboratories 1996) provided guidelines to assist in choosing the most appropriate accelerated corrosion test for a given application. Simpson et al. (Bethlehem Steel 1998) introduced US automotive corrosion trends over the past decade. The paper reported the results of five surveys conducted to date. The surveys, consisting of closed car parking lot surveys checking for perforation, blisters, and surface rust, were carried out in the Detroit, Michigan area. More recently, the research group published another article on a license plate corrosion test (Townsend et al. 1999). They mounted coupons on the vehicles, and the conditions of the scribe creep of the coupons are given in Table 1.

**Table 1: Scribe Creep Results in Canada On-vehicle Tests (mm).**

| Materials | 1 year | 2 years | 3 years | 4 years | 5 years |
|---|---|---|---|---|---|
| EG30 | 0.8 | 1.4 | 2.2 | 3.7 | 5.4 |
| EG70 | 0.7 | 0.8 | 1.1 | 1.2 | 1.9 |
| GA67 | 1.0 | 1.0 | 1.0 | 1.4 | 1.6 |
| Zn44 | 1.5 | 1.7 | 2.0 | 2.4 | 3.2 |
| CRSB | 3.0 | 8.6 | 12.5 | 17.4 | 23.4 |

The corrosiveness of deicing salts to the automobile was studied mainly based on commonly used NaCl and $CaCl_2$. Other salts were hardly investigated in experiments. We found that the only research dealing with different deicing salts in automobile industry was by McCrum (1989). In the study CMA, sodium chloride and magnesium chloride were used in highway and bridge structures. The corrosiveness of these salts was compared. He found that CMA was definitely less corrosive than NaCl or $MgCl_2$, and rust inhibitor mix could also provide superior (less) corrosion performance over distilled water.

We can also find some useful data regarding the corrosiveness of $MgCl_2$ and NaCl to the metal materials. The data in Table 2 is from the *Chemical Engineers' Handbook (5th Edition)*. This data, obtained from unidentified test procedures, indicate that there is no obvious difference between the corrosiveness of the two chlorides to the materials.

**Table 2: Corrosiveness of $MgCl_2$ and NaCl to some materials (inch/year).**

| **Materials** | **$MgCl_2$** | **NaCl** |
|---|---|---|
| Al | **<0.005**<br>(10%, 75°F) | **<0.005**<br>(10%, 75°F) |
| Copper, Al Bronze, Tin Bronze | **<0.02**<br>(10%, 75°F) | **<0.02**<br>(10%, 75°F) |
| Stainless Steel (12% Cr) | **<0.02**<br>(10%, 75°F) | **<0.02**<br>(10%, 75°F) |
| Stainless Steel (17% Cr) | **0.02~0.05**<br>(10%, 75°F) | **<0.02**<br>(10%, 75°F) |
| Glass | **<0.005**<br>(25%, 225°F) | **<0.005**<br>(30%, 225°F) |
| Polyethylene | Complete resistance<br>(50%, 150°F) | Complete resistance<br>(25%, 125°F) |
| Polyvinyl Chloride, unplasticized | Complete resistance<br>(25%, 150°F) | Complete resistance<br>(25%, 125°F) |
| Butyl Rubber | Satisfactory<br>(25%, 75°F) | Satisfactory<br>(25%, 75°F) |

### 5.3 Research Summary on Deicer Studies

Recent studies on the nature of liquid magnesium chloride as an anti-icer for winter highway maintenance is a topic of great interest throughout the United States, Canada and Europe. Major themes in the literature center around the benefits of using liquid magnesium chloride for winter road use versus other forms of materials such as rock salt.[1] The benefits listed in most of the research on liquid magnesium chloride include its efficiency in use, lower maintenance costs to state and federal authorities, and the assurance of a better method of protecting our fragile environment. Other products currently in use have been known to cause considerable harm to the environment.

The Department of Geological and Atmospheric Sciences at Iowa State University verified the contribution of rock salt deicers as a corrosive material on highways and a cause of groundwater contamination.[2] The study conducted by the Center for Transportation Research and Education (CTRE) noted a "considerable interest in new deicers, especially magnesium chloride because of its anti-icing properties and its effectiveness at lower temperatures than rock salt, and calcium magnesium acetate (CMA) because it reduces steel corrosion and groundwater chloride contamination."[3]

Other important benefits reflected in the most recent research include effects on air quality. "Another stimulus for switching to liquid deicers are new air quality guidelines in the U.S. which regulate the level of fine particulates in the air. This restricts the use of sand/salt mixtures which tend to increase the level of airborne particulates."[4] This is vital for states such as Colorado that use sand and other abrasives which contribute to "20% of Denver's persistent winter air quality problems."[5]

Evidence of the stimulus of state governmental agencies to work closely with federal agencies to further investigate snow and ice control on roadways are visible in various case studies developed by the Strategic Highway Research Program (SHRP).[6] The Strategic Highway

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[1] A basic summary of safety, chemical analysis, costs, applications and safety can be found in The Magnesium Chloride Project Summary prepared by Thunder Sword Resources, Inc. (1988). The report can be accessed at <http://www.thundersword.com/mc.htm>.

[2] Robert D. Cody, Anita M. Cody, Paul G. Spry, and Guo-Liang Gan. "Concrete Deterioration by Deicing Salts: An Experimental Study," Center For Transportation Research and Education <http://www.ctre.iastate.edu/pubs/semiseq/session1/cody/> No date given.

[3] Ibid., p. 4.

[4] Thundersword Resources, p.11.

[5] Federal Highway Administration, More Efficient Winter Operation, <//www.ota.fhwa.dot.gov/roadsrv/icebro.htm>

[6] Federal Highway Administration. Roadsaver case studies. Publication no. FHWA-SA-96-045 (1998).

Program is a project established by Congress in 1987 to develop and evaluate innovative technologies for roadway construction, maintenance, and operations in cooperation with the Federal Highway Administration.[7] Some of the states conducting research on anti-icing techniques include Colorado, Kansas, Iowa, Washington, Missouri, and Oregon.[8] The University of Nevada-Reno prepared summary reports of the findings of the SHRP/FHWA anti-icing studies based on a benefits-versus-cost analysis developed by the Texas Transportation Institute, of the research completed on this particular project.[9] Similar to a majority of the studies conducted by various state and federal agencies, the main focus of the research is to highlight the benefits of liquid magnesium chloride coupled with a road weather information system. Little is mentioned in the reports of the effects of corrosivity on the roadways or other chemical problems associated with the use of the product.

The Federal Highway Administration's field evaluation tests on liquid magnesium chloride performed by the U.S. Army Corps of Engineers Cold Regions Research and Engineering laboratory also provided positive results concerning this product as a deicer and non-corrosive agent.[10] This study is vital because the research eventually led to the publication of the Federal Highway Administration's Manual of Practices for an Effective Highway Anti-Icing Program.[11] Private companies in Canada also contributed to the literature by conducting studies on accident occurrences using liquid magnesium chloride compared to traditional salting and sand.[12] The findings state that new methods of deicing had reduced the number of road accidents by 75%.[13]

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[7] Roadsavers world-wide website, http://www.ota.fhwa.dot.gtov/roadsvr/

[8] The cases are as follows with the case number indicated. Washington, A Preemptive Strike on Ice (CS010); Colorado, Antiicing Saves Time and Money (CS024); Kansas, Anti-icing Improves Road Safety (CS026); Iowa, Snow and Ice Control: The New Generation (CS027); Missouri, Anti-icing Techniques Key to Safer Roads (CS028); Oregon, Saving Money and the Environment (CS092). The date on this list is 1997.

[9] Federal Highway Administration, Summary of SHRP Research and Economic Benefits of Snow and Ice Control (1998). <http://www.ota.fhwa.dot.gov/roadsvr/detlinfo.htm>

[10] U.S. Army Cold Regions Research and Engineering Laboratory, FHWA Test and Evaluation Project No. 28, "Anti-icing Technology" Field Evaluation Report. Hanover, New Hampshire, 1996.

[11] Federal Highway Administration, Manual of Effective Highway Anti-Icing Program, Roads and Bridges, 1997.

[12] Insurance Corporation of British Columbia, Kamloops – PACM Research Services, G.D. Hamilton Associates Consulting Ltd., 1998.

[13] Thundersword Resources, p.14.

Other important studies conducted were developed by the SALT Institute. Although somewhat dated, the Snowfighter's Handbook is still considered a viable source for studies in relation to snow and ice control.[14]

We can look to the future of the research to be a focus on environmental concerns. A consortium was developed between Washington, Oregon, Montana, Idaho, and British Columbia to "develop specifications for chemicals related to snow and ice control"[15] and also address environmental issues based on public interest.

## 5.4 ASTM Standards on Corrosion Testing

In general, the objective of an accelerated test is to create the degradation phenomena in a period of time shorter than the natural period, without changing the failure mechanisms. In particular, for metal corrosion the acceleration can be accomplished using various electrochemical techniques. Different accelerated testing methods have been developed, such as simple immersion tests, cabinet tests, simulated service tests, and in situ field service tests. The ability to predict actual service performance based on test results of a specific testing method increases with the length and the degree of complexity of the test.

The oldest and the most widely used standard laboratory corrosion test is the ASTM Method of Salt Spray (Fog) Testing (B117), which was originally approved in the early 1990's. According to this standard, specimens are exposed to a constant mist/spray of aerated, neutral pH, 5% NaCl solution. Specimens are exposed for several hundred hours.

In addition to ASTM B117, several other ASTM testing methods have been developed for corrosion resistance of metals, which can be divided into the following categories:

(1) General corrosion practice, (e.g. ASTM G1 "Practice for preparing, cleaning, and evaluating corrosion test specimens").

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[14] SALT Institute, The Snowfighter's Handbook (Alexandria, VA: 1991).
[15] Thundersword Resources, p. 17.

(2) Specific immersion tests, which have been developed to determine the susceptibility of particular alloys to a specific form of corrosion. They are predictors of actual service performance because results have been correlated with the occurrence of the form of corrosion in actual environments (Haynes 1990).

(3) Cabinet tests, which were originally developed for the automotive industry to rank steels under conditions which retard the formation of a protective type of rust, and should not be directly used for simulating general atmospheric exposure.

## 5.5 Accelerated Corrosion Test Methods in the Automobile Industry

Corrosion testing is an important part in the development, selection, and qualification of coated metal sheet products for corrosion-resistant automobiles. Although most of the reliable corrosion data comes from long-term monitoring of the performance of road-driven vehicles, the time and cost for these long-term tests are very high. On the other hand, laboratory accelerated corrosion tests are relatively quick and inexpensive, but are often of questionable reliability. For example, test results from the salt spray test (ASTM B117) have shown poor correlation with service performance of steel sheets. This is because the corrosion mechanisms occurring in a continuously wet salt-spray cabinet are significantly different from those taking place in the wet and dry conditions experienced by road-driven vehicles (Doppke, and Bryant, 1983; Money, and Kain,, 1988).

In the last two decades, much effort has been made to develop a laboratory test method for cosmetic corrosion of painted panels that can realistically simulate the in-service exposure. Various multi-stage cyclic testing methods (e.g., alternating salt and humidity exposures) have been developed and compared to the salt spray method (ASTM B117).

In the early 1980's, The American Iron and Steel Institute (AISI) formed a special task force for the development of accelerated corrosion testing methods to simulate the automotive corrosion environment. The AISI Task Force is made up of representatives from leading automotive manufacturers and steel companies, whose objective is "to develop a widely-accepted, standard laboratory accelerated test for cosmetic corrosion resistance that will provide an accurate representation of on-vehicle field performance of automotive steel sheet products" (Roudabush et al. 1995).

The AISI Task Force includes representatives from: Armco Steel company, Dofasco Inc., Chrysler Corporation, Metal Coating International Inc., Nissan Research & Development, Stelco Inc., Ford Motor Company, Inland Steel Company, Advanced Coatings Technologies, Quality/Statistics, M&T Harshaw, GM Corporation, BASF, Henkel Corporation, U.S. Steel Group, Armco Inc., National Steel Corporation, Chemfil Corporation, Bethlehem Steel Corporation, E.I. Dupont de Nemours & Co.

From 1990 to 1995, AISI and SAE carried out a comprehensive, cooperative research program to correlate various testing methods including ASTM standards and other methods used in the automobile industry. In the program, the accelerated and outdoor exposure tests were compared to four-year on-vehicle exposure tests from Montreal, Quebec and St. John's, Newfoundland, Canada using a variety of statistical techniques. Of the 28 test procedures compared, CCT-IV and GM9540P/B provided the best overall performances for the ten "standard" coated sheet materials, which has been widely used in corrosion studies throughout the automotive community.

CCT-IV is a cyclic testing method, consisting of three different environmental conditions: salt spray (per ASTM B117), dry-off (60°C, ambient RH), and humidity (60°C, 95%RH). Salt spray is applied for ten minutes, followed by 155 minutes of dryoff, and 75 minutes of humidity. Then, five repetitive cycles of 160 minutes dry-off and 80 minutes humidity complete the 24 hour cycle. The total exposure time is 50 cycles (five cycles per week and weekends at ambient conditions).

GM9540P/B is a GM standard, in which the first part consists of eight hours exposure to ambient conditions, with five min. salt spray period at the first four 90 minutes time intervals. Spray was applied manually using a spray bottle. The second part is a high humidity exposure (49°C, 95%RH) for eight hours. The third part provides an eight hour exposure at 60°C, and less than

30% RH. Total exposure period was 40 cycles (5 cycles per week, weekends at ambient lab conditions).

The cooperative program focused on steel substrates. Another project about accelerated laboratory testing methods conducted by Alcoa Center was about painted aluminum automotive body sheets (Moran et al. 1995). Six materials were used in this study, including aluminum alloys 2036, 2008, 6111, 5182, and steel 1008 with and without coating. The test methods used in this program involved:

- Outdoor exposure-Seacoast,
- Outdoor exposure-ATC/SS,
- In-service exposure- Highway trailers,
- In-service exposure-Passenger Vehicles,
- Lab exposure-ASTM B117,
- Lab exposure-ASTM G85,
- Lab exposure-GM9540P/A,
- Lab exposure-GM9540P/B,
- Lab exposure-CCT-IV, and
- Lab exposure SS.

The results showed that the test method which correlated best with the outdoor exposures was ASTM B117, the continuous salt spray method. This study confirmed that the two lab methods favored by SAE for evaluating steels were GM9540P/B and CCT-IV. For aluminum alloys, however, these two test methods are not optimal.

Cyclic corrosion tests involving repeated exposure to salt water, humidity, and drying conditions have been developed to overcome some of the deficiencies of the salt spray test. Many types of cyclic tests have been developed, and the results vary significantly. Moreover, the effects of the various cyclic-test parameters such as time, temperature, relative humidity, and salt composition were not well understood. Therefore, there was a pressing need for improving and standardizing the laboratory cyclic corrosion test. For this purpose, a corrosion task force was organized and funded by AISI and SAE. In 1995, funding of the Task Force was taken over by the Auto/Steel Partnership (A/SP), a consortium of North American automobile and steel producers. This joint work led to the successful development of a new cyclic cosmetic corrosion test, now designated as SAE J2334 (Townsend et al. 1998).

SAE J2334 can be run in either manual or automatic modes. The manual mode requires a minimum of inexpensive equipment, namely, an immersion tank and two static humidity chambers, but requires the daily attention of testing personnel. The automatic mode avoids the need for daily attention, but it requires a more complex and expensive automated test chamber. Either way, eight cycles (each takes one day) gives results that are comparable to five years of on-vehicle testing in North America. Based on mass losses of bare, cold-rolled steel coupons, the corrosion rates in this test are typically about 5 μm/cycle.

For developing SAE J2334, standard materials were used. All the ten materials selected in the experiment were of steel substrate. They included coated and uncoated sheets that were used in the manufacture of vehicles worldwide.

On-vehicle cosmetic corrosion tests were performed in Canada during the research program. Montreal, Quebec and St. John's, Newfoundland were chosen for on-vehicle tests since these environments are known to be among the world's most corrosive. Performance of the materials was determined after a five-year exposure by removing loose paint next to the scribed region of the panels, and measuring the extent of paint undercutting.

Many cosmetic corrosion test methods were evaluated in the research program. These test methods included laboratory, automotive proving ground, and static outdoor scab tests. To quantitatively compare the results of these tests to those obtained from the real-world, a least-squares linear regression method was adopted and the results are shown in Table 3. In the Table, R is the correlation coefficient, and $R^2$ indicates the fraction of the variation that is accounted for by the least-squares line. The closer $R^2$ is to unity, the more the lab test data and the real world experimental data agree. Another coefficient C in Table 3 is the ratio of the real creep of the tested materials to the value of creep that would be predicted by the least-squares line. An ideal test would have a $R^2$ of one and a C of one, and the sum $R^2$+C would be equal to two. From the Table, it is clear that SAE J2334 test is a significant improvement over existing tests. It is also noted that the ASTM B117 salt spray test results do not correlate well with real-world performance.

The analysis of variance revealed that a high relative humidity (50% RH) in the dry-stage is by far the most important factor in getting the correct relative performance of cold rolled steel relative to coated steel (a C-ratio of unity). It was also showed that low (0.5%) salt concentration was the most important factor in getting a good correlation with on-vehicle data for coated steels ($R^2$). It was found that some parameters are not critical, and so the choice of level could be made on the basis of other considerations, such as experimental convenience. For example, since there was little effect of wet-stage humidity, a level of 100% RH was chosen as being simpler to attain and maintain. Similarly, since the number of dry-outs per cycle was not a major factor, we can select one dry-out per cycle.

Corrosion mechanisms were analyzed by using equipment such as light microscopy, scanning electron microscopy, energy dispersive X-ray mapping, X-ray diffraction, and Mossbauer spectroscopy. The results showed a good match of the corrosion products and morphologies of attack for SAE J2334 and the on-vehicle tests, thus providing a strong fundamental basis for the correlation of the corrosion-test results. Table 3 provides a comparison of the different cosmetic corrosion test methods based on correlation coefficients $R^2$ and the C ratio.

### Table 3: Ranking of Cosmetic Corrosion Test Methods Based on Correlation Coefficients $R^2$ and the C ratio.

| Test | Duration | $R^2$ | C | Sum |
|---|---|---|---|---|
| SAE J2334 | 80 cycles | 0.96 | 0.97 | 1.93 |
| CCT | 45 cycles | 0.78 | 0.97 | 1.75 |
| CCT-IV | 35 cycles | 0.74 | 0.86 | 1.60 |
| GM9540P/B (GM) | 50 cycles | 0.84 | 0.59 | 1.43 |
| JASO M60 | 45 cycles | 0.44 | 0.98 | 1.42 |
| AISI-A | 50 cycles | 0.46 | 0.75 | 1.21 |
| AISI-C | 50 cycles | 0.74 | 0.41 | 1.15 |
| Michigan suburban | 24 months | 0.61 | 0.51 | 1.12 |
| GM9540P/B(act) | 50 cycles | 0.44 | 0.67 | 1.11 |
| Chrysler Chipping | 25 cycles | 0.54 | 0.56 | 1.10 |
| AISI-B | 70 cycles | 0.74 | 0.29 | 1.03 |
| Proving Ground 2 | 5-yr equivalent | 0.64 | 0.39 | 1.03 |
| AISI-E | 50 cycles | 0.62 | 0.38 | 1.00 |
| Proving Ground 3 | 8-yr equivalent | 0.37 | 0.59 | 0.96 |
| Hoogovens Method 1 | 20 weeks | 0.01 | 0.91 | 0.92 |
| Montreal | 24 months | 0.62 | 0.28 | 0.90 |
| Michigan Rural | 24 months | 0.68 | 0.19 | 0.87 |
| AISI-D | 70 cycles | 0.45 | 0.41 | 0.86 |
| West Virginia | 24 months | 0.58 | 0.25 | 0.83 |
| QUV-Prohesion | 12 weeks | 0.62 | 0.20 | 0.82 |
| Proving Ground 1 | 10-yr equivalent | 0.10 | 0.72 | 0.82. |
| CCT-I | 60 cycles | 0.56 | 0.21 | 0.77 |
| Michigan Urban | 24 months | 0.61 | 0.15 | 0.76 |
| South Florida | 24 months | 0.34 | 0.40 | 0.74 |
| Navistar CCT | 100 cycles | 0.49 | 0.24 | 0.73 |
| Philadelphia | 24 months | 0.49 | 0.23 | 0.72 |
| GM9511P | 20 cycles | 0.35 | 0.18 | 0.53 |
| Hoogovens Method 2 | 20 weeks | 0.02 | 0.37 | 0.39 |
| B117 Salt spray | 4 weeks | 0.19 | 0.05 | 0.24 |
| CCT-III | 960 cycles | 0.00 | 0.00 | 0.00 |

There are still a number of issues remaining that have not been well addressed in previous works. Among these are whether the results are affected by: (1) automatic vs. manual operation, (2) spray vs. immersion application of salt, and (3) steam generator vs. wet bottom and water-fog methods for achieving 100% RH. Tests are currently being conducted at A/SP to resolve these questions, and the answers will be incorporated in future revisions to the specifications. Thus, it is expected that the testing method for corrosion resistance of automobile conponents will continue to evolve.

## Section VI: Conclusions and Recommendations for Future Study

### 6.1 Conclusions

The Colorado Department of Transportation has been using magnesium chloride for anti-icing and deicing for several years with good results in snow and ice control. However, over the same period, there have surfaced some concerns that the chemicals affect various components of cars and trucks. Although the corrosion inhibitor present in the magnesium chloride used by CDOT should prevent or minimize corrosive effects, the question remains if the chemicals attack aluminum and other vehicle components. The Colorado Motor Carriers Association, in response to complaints from their members, requested a study be performed to provide objective facts to address these concerns.

The results from the industry survey show the high degree of concern, ranging from comments about tarnished and dulled paint finishes to ruined components in need of replacement. The overall cost to the industry is difficult to quantify, but could potentially reach into the thousands of dollars for each power unit or trailer. While the survey provided a great deal of information from trucking companies relating to attitudes and opinions about Colorado's deicing program, along with basic cost data attributed to the use of magnesium chloride, it could not prove magnesium chloride was corrosive. To address this important point, the University of Colorado, Boulder conducted laboratory tests.

The results of both the cyclic exposure test (SAE J2334) and the in-service field tests show that magnesium chloride is more corrosive than sodium chloride on all tested vehicle components, including copper wiring.

Results from the ASTM B117 test showed NaCl to be more corrosive on certain metals. However, the test procedure is not considered to be an accurate example of real-world conditions. In contrast, the SAE J2334 is highly representative of real operating environments. Under this test, (SAE J2334) the corrosion levels were higher on all metals tested (as compared to the Continuous Spray Test), and magnesium chloride was more corrosive than sodium chloride on all metals tested. Additionally, magnesium chloride, when combined with sodium chloride is more corrosive than either solution by itself. The laboratory tests clearly show a dominant coupling effect between the two chlorides in terms of corrosiveness.

The Colorado Department of Transportation uses magnesium chloride as both an anti-icing agent and as a deicer. However, CDOT continues to use sodium chloride (in a salt/sand mixture) on a limited basis to provide added traction to certain sections of highway throughout the state. This practice of mixing the two chemicals may be adding to the corrosion of motor vehicle components.

This study identified two factors that may lead to the higher corrosion rate of magnesium chloride. One is its lower pH value, and the other is its higher chloride concentration in the solution (compared to sodium chloride of the same weight percentage concentration). As a deicer, magnesium chloride is applied in greater concentrations than sodium chloride in order to acquire equivalent effects. The increased level of chloride ions makes magnesium chloride more harmful than sodium chloride at equivalent deicing effects.

Officials from the Colorado Department of Transportation agree that magnesium chloride is difficult to remove from vehicles and its use sustains wet highway conditions before and after snowfalls. These factors, in addition to the corrosive nature of magnesium chloride, substantiate the complaints made by the trucking industry.

## 6.2 Implementation and Recommendations for Future Study

In many ways, this study has raised more questions than it has answered. Additional work needs to be done in order to address the identified problems and develop solutions to limit corrosion caused by $MgCl_2$. For instance, are there specific undercoating or plating techniques that can be used to mitigate the corrosive effects of magnesium chloride? Should CDOT re-examine and/or alter its policy of pre-wetting roads with magnesium chloride prior to storms? Are there specific preventative maintenance techniques carriers can put into place? Is salt brine, or a sensible salting program a viable alternative which will address both Colorado's environmental and industry concerns?

While these questions are being examined, the trucking and automotive industry should consider the following long- and short-term solutions:

- Determine if there are any specific undercoating or plating techniques that can be used on trucks to mitigate the corrosive effects of magnesium chloride.
- Develop sealants or other protective measures to protect electrical components and connections from deicing chemicals.
- Examine whether different formulations of aluminum and stainless steel that are more resistant to corrosion can be used in truck and trailer manufacturing. For example, stainless steel with higher chromium content is more resistant to corrosion.
- Wash trucks more frequently. If possible, wash trucks while the deicer is still wet, as it is easier to remove before it dries. Experiment with different washing soaps and solutions.
- Test different windshield fluid solutions to find a product that is more effective in cleaning deicer residue and splashback. Experiment with different concentrations of windshield fluid.
- Seal all electrical connections. For instance, silicone or heat-shrink help shield connectors from exposure to deicers, and limit corrosion.

CDOT should take the following steps to address the identified problems:

- Re-examine and / or alter its anti-icing policy of pre-wetting roads with magnesium chloride prior to storms. Both the timing and the amount of deicer used should be studied.
- Work with the vendor which supplies magnesium chloride to determine the level and composition of corrosion inhibitor that exists in the product being used in Colorado.

- Review purchase order specifications for magnesium chloride, and change those specifications once more information is available regarding corrosion rates on mild steel.
- Continue positive dialog with the trucking industry to address on-going concerns about corrosion, safety and cost issues.

Although the experimental results of this study may show that NaCl is less corrosive than $MgCl_2$, we do not recommend immediate termination of the use of $MgCl_2$ in the state of Colorado.

Further studies are recommended to investigate:

(1) the coupling effect of magnesium chloride and sodium chloride at different concentrations since only one mix of the two salts was tested in the present study;

(2) the corrosion of mild steel caused by the two chlorides, which will be a valuable reference and will provide useful information for the corrosion of steel embedded in concrete;

(3) the behavior of coupons under the service condition. Longer testing period should be planned for the coupons installed on the trucks and roadsides. In the current study, coated coupons did not show significant corrosion damage due to the short testing period. CDOT service trucks may be used for future study so that it will be easier to record the actual road conditions experienced by the trucks.

(4) the effect of any corrosion inhibitors used in the road salts;

(5) the corrosion behavior of other widely used deicing salts such as calcium chloride;

(6) the effect of various deicing salts on durability of concrete;

(7) the optimum combination of the deicing salts, which leads to the least corrosion impact on automobile components and highway concrete.

CDOT and the University of Colorado are currently conducting further testing to determine whether the $MgCl_2$ used by CDOT meets current corrosion specifications. The corrosion specifications were developed by the Pacific Northwest Snowfighters using a 72-hour exposure test on mild steel. Additionally, the University of Colorado will also be conducting corrosion tests on the metals used in this study using the 72-hour exposure test. This is being done to correlate the various testing methods to determine which is most representative of real-world conditions.

# APPENDICES

# Appendix 1: Data References & Graphs

Table 4: Test Results with $MgCl_2$ Reagent by SAE J2334.

| Metal | Original weight (g) | Weight after test (g) | Weight loss (g) | Loss in % | Corrosion rate (mm/y) | Average rate (mm/y) |
|---|---|---|---|---|---|---|
| Al2024 | 5.698 | 5.468 | 0.23 | 4.0365 | 0.1957 | 0.1987 |
| Al2024 | 5.706 | 5.469 | 0.237 | 4.1535 | 0.2017 | |
| Al5086 | 5.426 | 5.425 | 0.001 | 0.0184 | 0.0009 | 0.0018 |
| Al5086 | 5.435 | 5.432 | 0.003 | 0.0552 | 0.0027 | |
| SS410 | 15.057 | 13.644 | 1.413 | 9.3843 | 0.4326 | 0.4356 |
| SS410 | 15.199 | 13.766 | 1.433 | 9.4283 | 0.4387 | |
| SS304L | 17.801 | 17.798 | 0.003 | 0.0168 | 0.0009 | 0.0012 |
| SS304L | 17.908 | 17.903 | 0.005 | 0.0279 | 0.0015 | |

Table 5: Test Results with NaCl reagent by SAE J2334.

| Metal | Original weight (g) | Weight after test (g) | Weight loss (g) | Loss in % | Corrosion rate (mm/y) | Average rate (mm/y) |
|---|---|---|---|---|---|---|
| Al2024 | 5.693 | 5.623 | 0.07 | 1.2296 | 0.0596 | 0.0613 |
| Al2024 | 5.713 | 5.639 | 0.074 | 1.2953 | 0.0630 | |
| Al5086 | 5.429 | 5.445 | 0 | 0 | 0 | 0 |
| Al5086 | 5.432 | 5.448 | 0 | 0 | 0 | |
| SS410 | 15.299 | 15.068 | 0.231 | 1.5099 | 0.0707 | 0.0820 |
| SS410 | 15.416 | 15.111 | 0.305 | 1.9785 | 0.0934 | |
| SS304L | 17.816 | 17.816 | 0 | 0 | 0 | 0 |
| SS304L | 17.871 | 17.871 | 0 | 0 | 0 | |

Table 6: Test Results with $MgCl_2$ practical salt by SAE J2334.

| Metal | Original weight, g | Weight after test, g | Weight loss, g | Loss % | Corrosion rate, mm/y | Average Corrosion rate, mm/y |
|---|---|---|---|---|---|---|
| Al2024 | 5.721 | 5.6333 | 0.088 | 1.5382 | 0.0749 | 0.0783 |
| Al2024 | 5.726 | 5.63 | 0.096 | 1.6766 | 0.0817 | |
| Al5086 | 5.438 | 5.42 | 0.018 | 0.3310 | 0.0159 | 0.0124 |
| Al5086 | 5.424 | 5.414 | 0.01 | 0.1844 | 0.0089 | |
| SS410 | 15.087 | 10.688 | 4.399 | 29.1576 | 1.3467 | 1.3819 |
| SS410 | 15.390 | 10.761 | 4.629 | 30.0780 | 1.4171 | |
| SS304L | 17.795 | 17.783 | 0.012 | 0.0674 | 0.0036 | 0.0031 |
| SS304L | 17.915 | 17.906 | 0.009 | 0.0502 | 0.0027 | |

Table 7: Test Results with NaCl practical salt by SAE J2334.

| Metal | Original weight, g | Weight after test, g | Weight loss, g | Loss % | Corrosion rate, mm/y | Average Corrosion rate, mm/y |
|---|---|---|---|---|---|---|
| Al2024 | 5.718 | 5.61 | 0.108 | 1.8888 | 0.0919 | 0.0732 |
| Al2024 | 5.718 | 5.654 | 0.064 | 1.1193 | 0.0545 | |
| Al5086 | 5.436 | 5.447 | 0 | 0 | 0 | 0 |
| Al5086 | 5.434 | 5.447 | 0 | 0 | 0 | |
| SS410 | 15.444 | 15.076 | 0.368 | 2.3828 | 0.1127 | 0.1009 |
| SS410 | 15.413 | 15.122 | 0.291 | 1.8880 | 0.0891 | |
| SS304L | 17.809 | 17.809 | 0 | 0 | 0 | 0 |
| SS304L | 18.354 | 18.354 | 0 | 0 | 0 | |

Table 8: Test Results with NaCl +$MgCl_2$ practical salts by SAE J2334.

| Metal | Original weight, g | Weight after test, g | Weight loss, g | Loss % | Corrosion rate, mm/y |
|---|---|---|---|---|---|
| Al2024 | 5.715 | 5.585 | 0.13 | 2.2747 | 0.1991 |
| Al5086 | 5.434 | 5.398 | 0.036 | 0.6625 | 0.0574 |
| SS304L | 17.813 | 17.789 | 0.024 | 0.1347 | 0.0128 |
| SS410 | 30.195 | 27.20 | 2.995 | 9.9189 | 0.8252 |

Table 9: Test Results with $MgCl_2$ (practical salts) + NaI( reagent) by SAE J2334.

| Metal | Original weight, g | Weight after test, g | Weight loss, g | Loss % | Corrosion rate, mm/y |
|---|---|---|---|---|---|
| Al2024 | 5.706 | 5.472 | 0.234 | 4.1009 | 0.3584 |
| Al5086 | 5.918 | 5.361 | 0.557 | 9.4120 | 0.8885 |
| SS304L | 15.306 | 14.927 | 0.379 | 2.476 | 0.2025 |
| SS410 | 31.111 | 23.02 | 8.091 | 26.0069 | 2.2293 |

Table10: Test Results with NaCl practical salt by ASTM B117.

| Metal | Original weight, g | Weight after test, g | Weight loss, g | Loss % | Corrosion rate, mm/y |
|---|---|---|---|---|---|
| Al2024 | 5.718 | 5.682 | 0.036 | 0.6296 | 0.0551 |
| Al5086 | 5.432 | 5.419 | 0.013 | 0.2393 | 0.0207 |
| SS410 | 15.306 | 14.927 | 0.379 | 2.4761 | 0.2088 |
| SS304L | 17.885 | 17.885 | 0 | 0 | 0 |

Table 11: Test Results with $MgCl_2$ practical salt by ASTM B117

| Metal | Original weight, g | Weight after test, g | Weight loss, g | Loss % | Corrosion rate, mm/y |
|---|---|---|---|---|---|
| Al2024 | 5.715 | 5.680 | 0.035 | 0.6124 | 0.0536 |
| Al5086 | 5.435 | 5.393 | 0.042 | 0.7728 | 0.0670 |
| SS410 | 15.141 | 15.036 | 0.105 | 0.6935 | 0.0579 |
| SS304L | 18.406 | 18.393 | 0.013 | 0.0706 | 0.0069 |

### Table 12: Corrosion of the metal coupons mounted on the trucks

| **Truck#** | **1576** | **295** | **1423** | **1169** | **1159** | **1158** | **1166** | **3088** | **3067** | **3066** |
|---|---|---|---|---|---|---|---|---|---|---|
| **304L** | **#1** | **#2** | **#3** | **#4** | **#5** | **#6** | **#7** | **#8** | **#9** | **#10** |
| **Orig. wt** | 35.5 | 36.652 | 36.717 | 36.818 | 36.846 | 36.446 | 36.593 | 36.228 | 36.148 | 36.69 |
| **after corr.** | 35.466 | 36.648 | 36.714 | 36.814 | 36.843 | 36.443 | 36.59 | 36.227 | 36.149 | 36.684 |
| **wt loss,g** | 0.034 | 0.004 | 0.003 | 0.004 | 0.003 | 0.003 | 0.003 | 0.001 | 0 | 0.006 |
| **loss, %** | 0.957746 | 0.109135 | 0.081706 | 0.108643 | 0.08142 | 0.082314 | 0.081983 | 0.027603 | 0 | 0.163532 |
| | | | | | | | | | | |
| **410** | | | | | | | | | | |
| **orig. wt** | 30.601 | 30.692 | 30.572 | 30.652 | 28.712 | 30.186 | 30.572 | 29.72 | 28.461 | 30.579 |
| **after corr.** | 30.563 | 30.675 | 30.581 | 30.626 | 28.691 | 30.165 | 30.56 | 29.704 | 28.455 | 30.563 |
| **wt loss,g** | 0.038 | 0.017 | 0 | 0.026 | 0.021 | 0.021 | 0.012 | 0.016 | 0.006 | 0.016 |
| **loss, %** | 1.241789 | 0.55389 | 0 | 0.848232 | 0.731402 | 0.695687 | 0.392516 | 0.538358 | 0.210815 | 0.523235 |
| | | | | | | | | | | |
| **2024** | | | | | | | | | | |
| **orig. wt** | 11.475 | 11.476 | 11.472 | 11.475 | 11.468 | 11.449 | 11.433 | 11.456 | 11.438 | 11.45 |
| **after corr.** | 11.444 | 11.389 | 11.466 | 11.442 | 11.406 | 11.414 | 11.372 | 11.434 | 11.43 | 11.421 |
| **wt loss,g** | 0.031 | 0.087 | 0.006 | 0.033 | 0.062 | 0.035 | 0.061 | 0.022 | 0.008 | 0.029 |
| **loss, %** | 2.701525 | 7.581039 | 0.523013 | 2.875817 | 5.406348 | 3.057036 | 5.335433 | 1.920391 | 0.699423 | 2.532751 |
| | | | | | | | | | | |
| **5086** | | | | | | | | | | |
| **orig. wt** | 10.908 | 10.899 | 10.902 | 10.906 | 10.896 | 10.902 | 10.899 | 10.896 | 10.899 | 10.903 |
| **after corr.** | 10.882 | 10.837 | 10.892 | 10.845 | 10.828 | 10.832 | 10.826 | 10.861 | 10.884 | 10.858 |
| **wt loss,g** | 0.026 | 0.062 | 0.01 | 0.061 | 0.068 | 0.07 | 0.073 | 0.035 | 0.015 | 0.045 |
| **loss, %** | 2.383572 | 5.688595 | 0.917263 | 5.593251 | 6.240822 | 6.42084 | 6.697862 | 3.212188 | 1.376273 | 4.127304 |

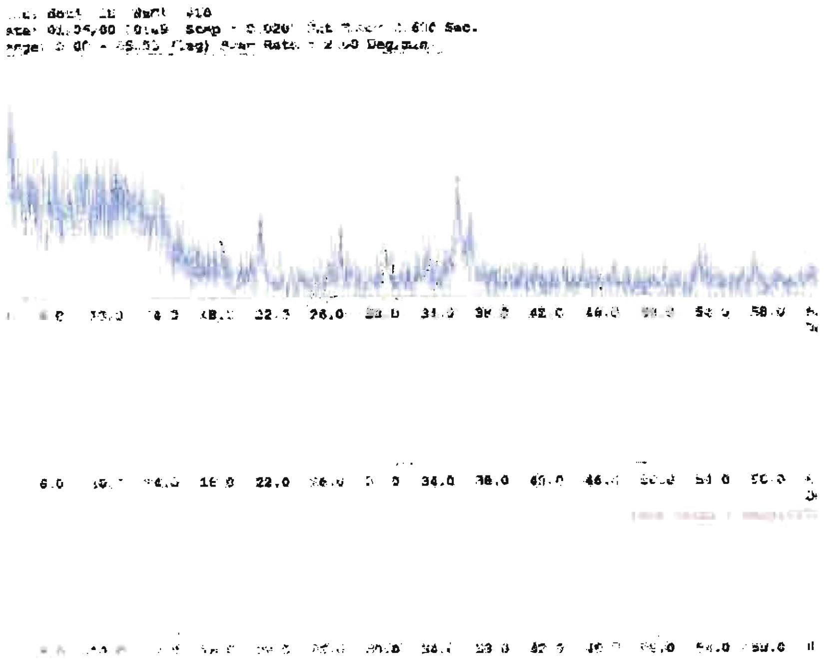

Figure 19: XRD analysis of the corrosion products on SS410 by SAE J2334 with NaCl

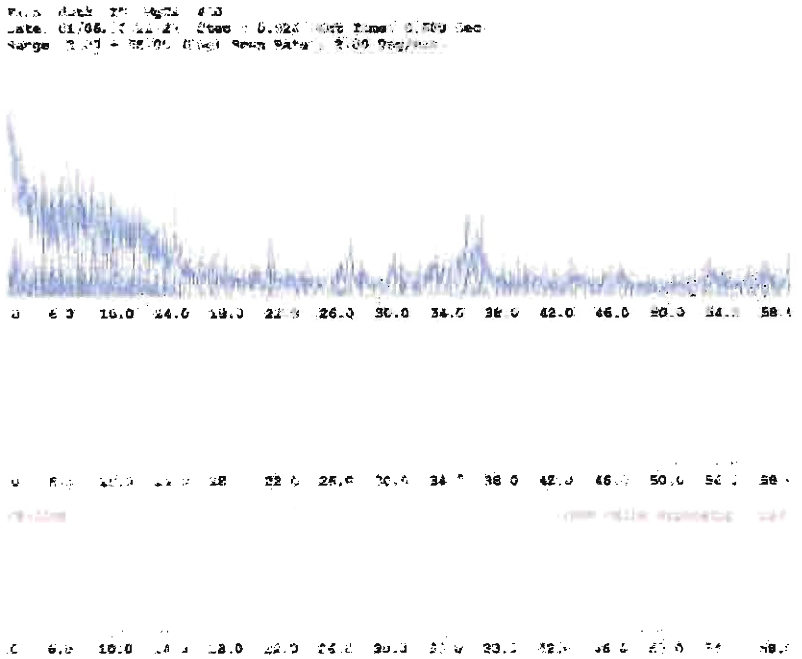

Figure 20: XRD analysis of the corrosion products on SS410 by SAE J2334 with $MgCl_2$.

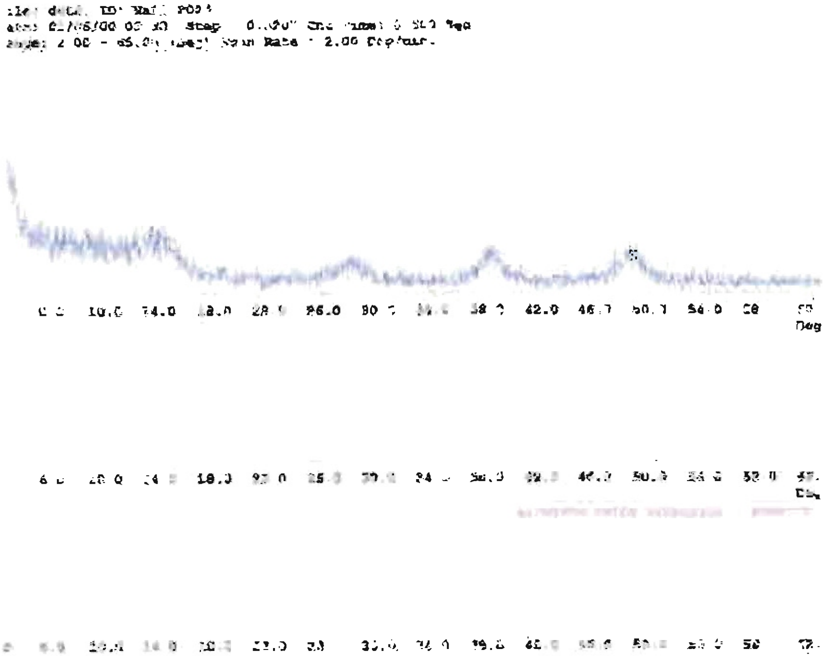

Figure 21: XRD analysis of the corrosion products on Al2024 by SAE J2334 with NaCl

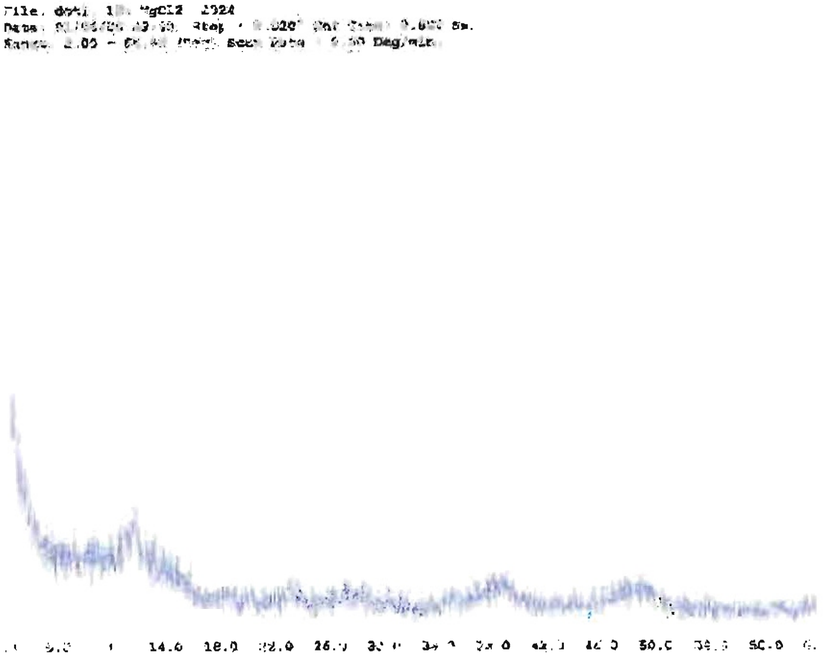

Figure 22: XRD analysis of the corrosion products on Al2024 by SAE J2334 with $MgCl_2$.

# Appendix 2: Data Collection Photographs

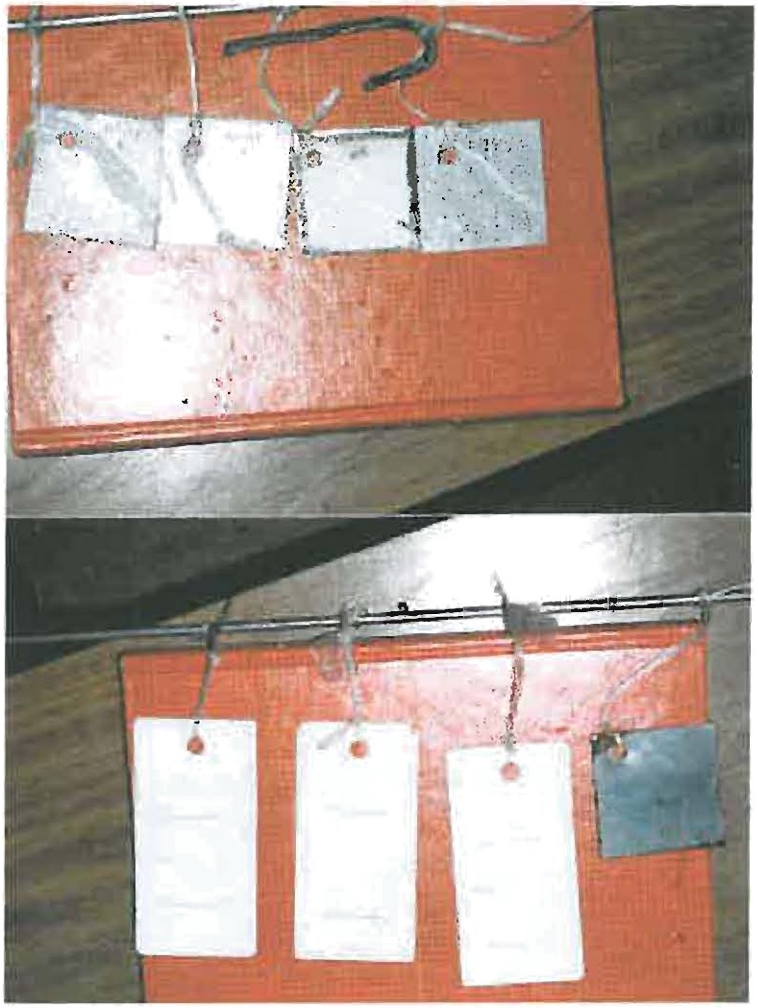

Figure 23: The coupons after the spray test for 400 hours.

**Figure 24: The coupons after the spray test for 800 hours.**

Figure 25: The coupons after the cyclic exposure test for half a month with practical salts.

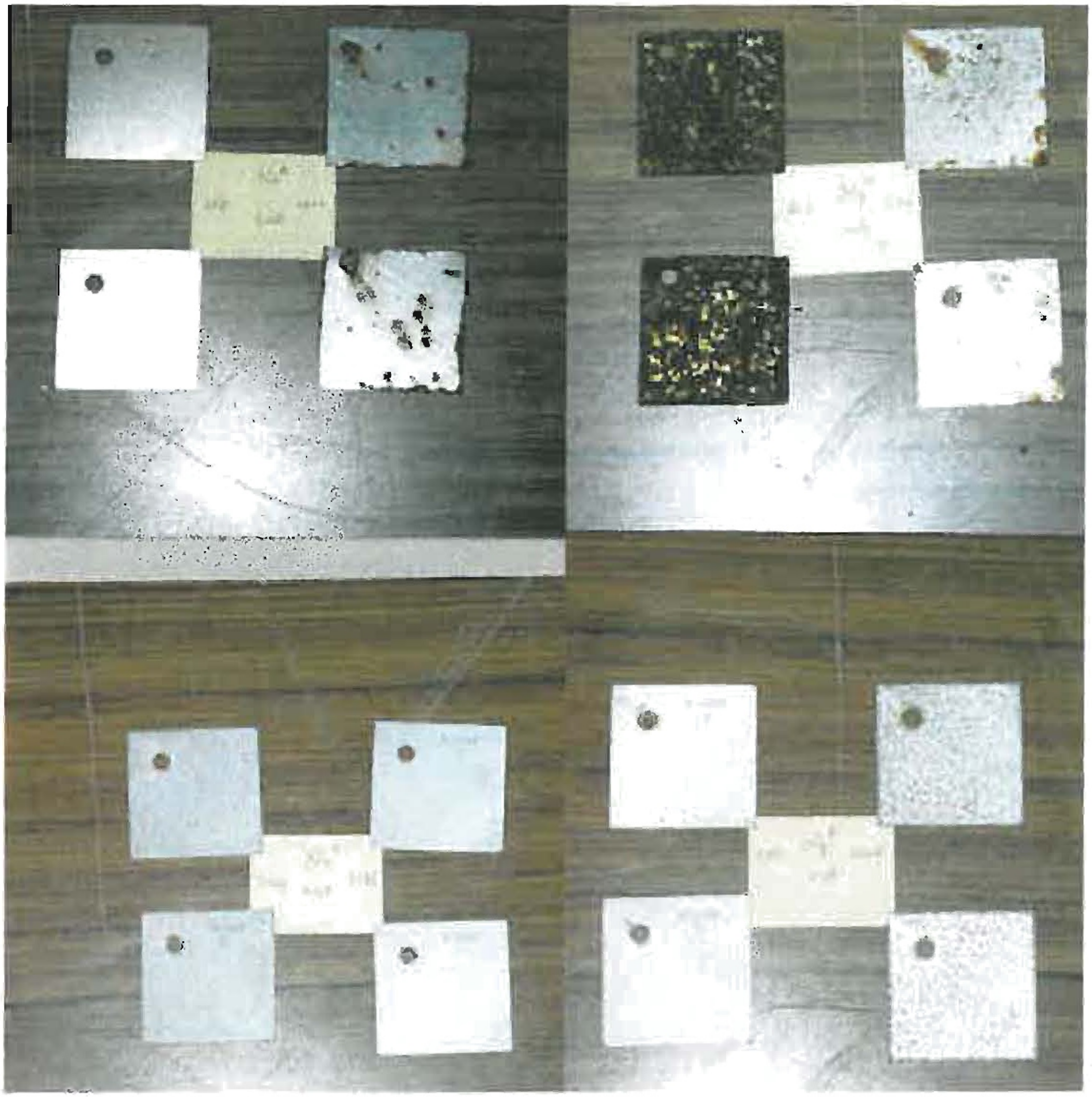

**Figure 26: The coupons after the cyclic exposure test for one month with practical salts.**

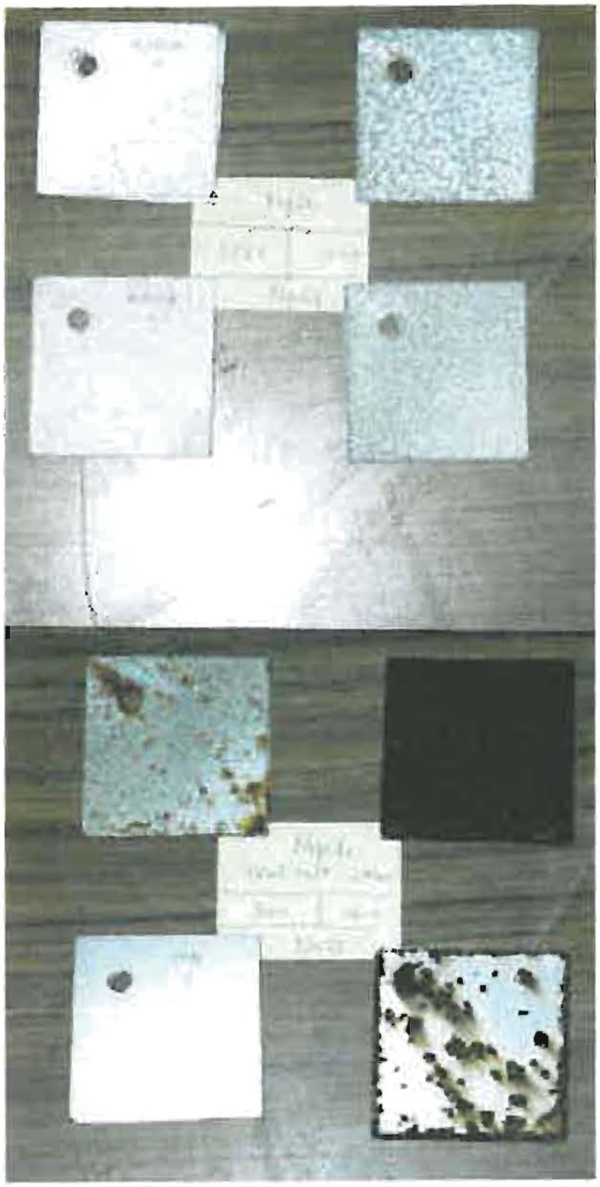

**Figure 27: The coupons after the cyclic exposure test for two months with practical salts.**

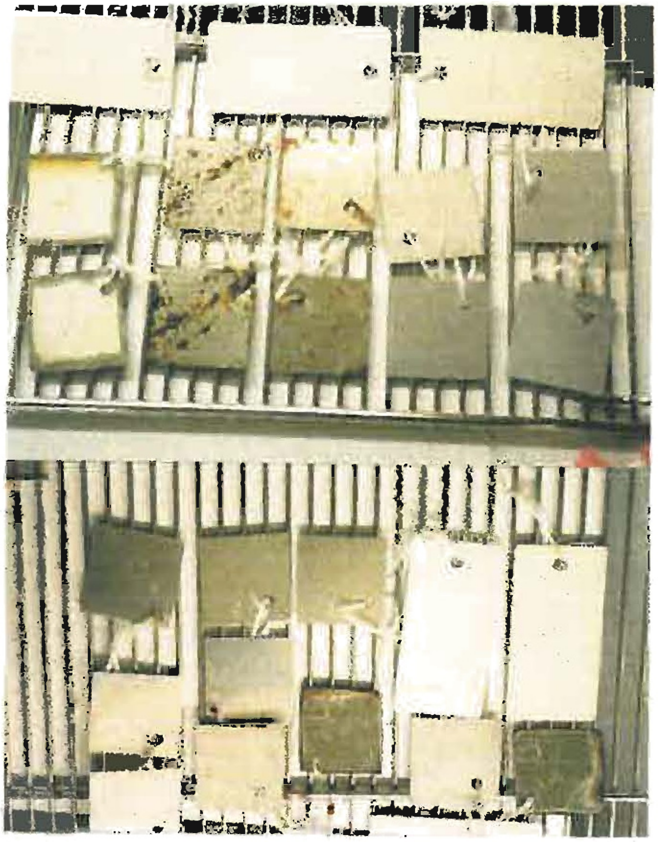

Figure 28: The coupons after the cyclic exposure test for half a month with reagents.

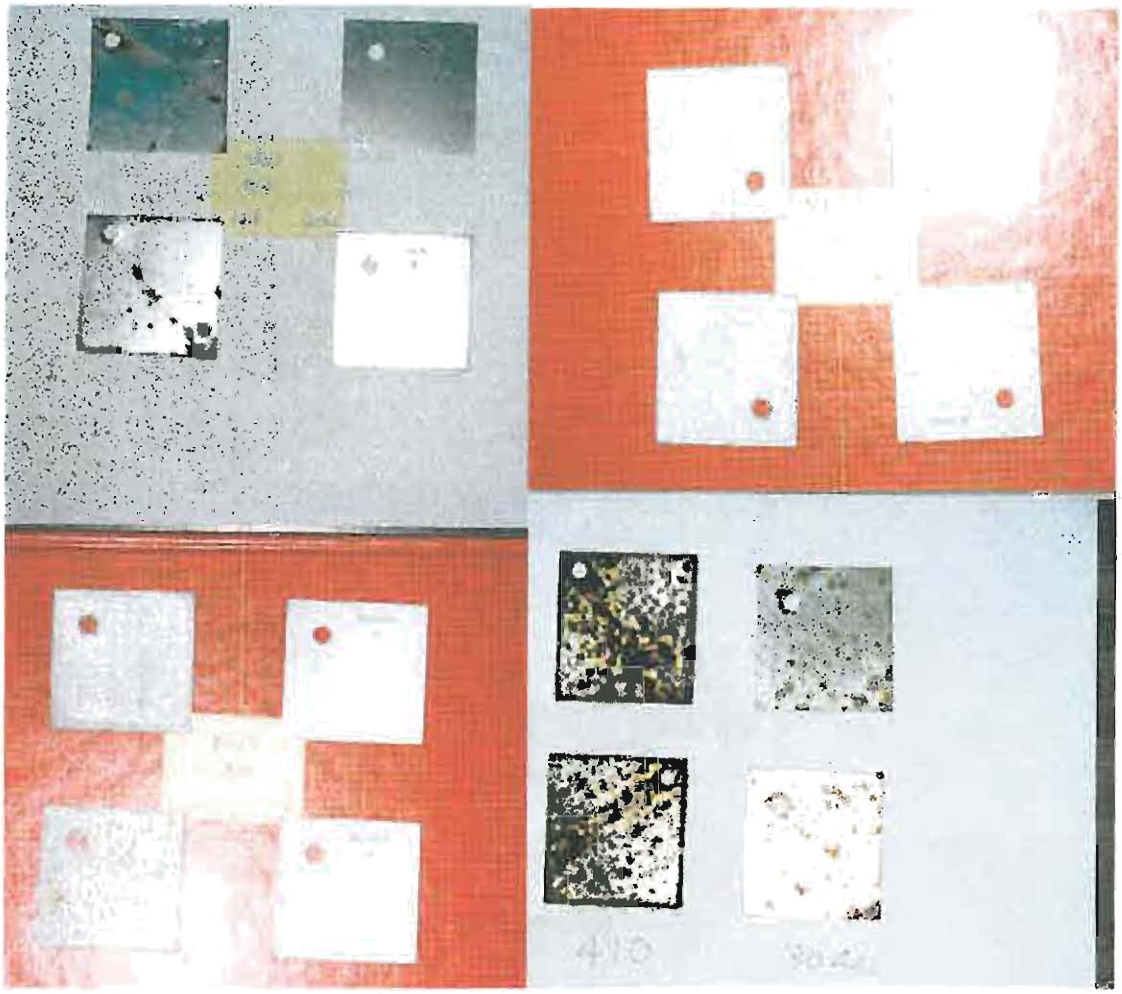

**Figure 29: The coupons after the cyclic exposure test for one month with reagents.**

Figure 30: The coupons after the cyclic exposure test for one and half a month with reagents.

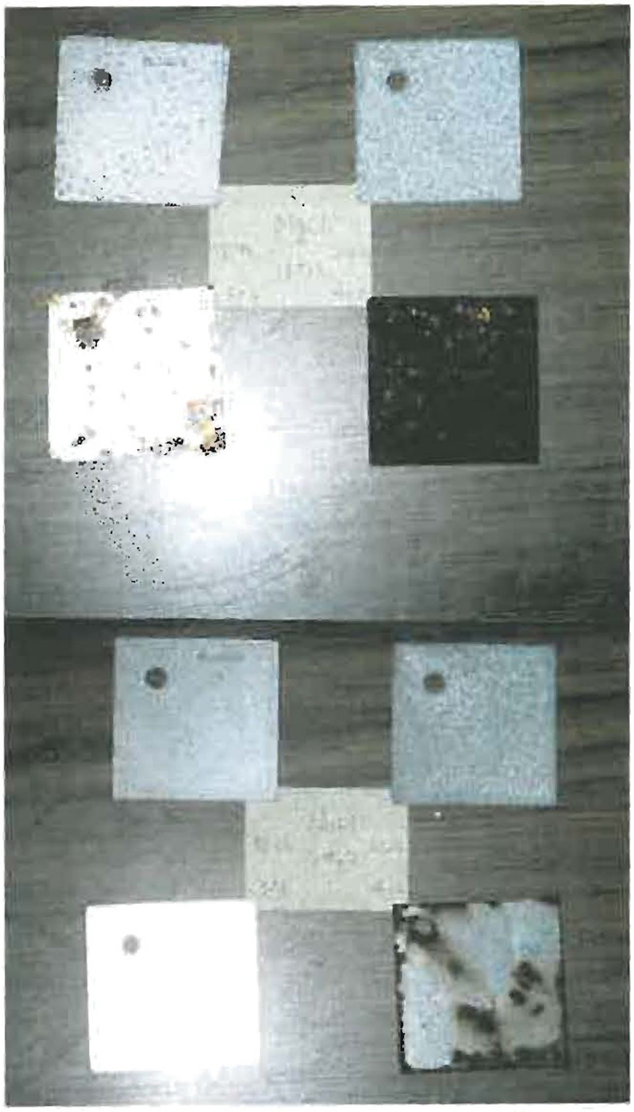

**Figure 31: The coupons after the cyclic exposure test or two months with reagents.**

**Figure 32:** The coupons after the cyclic exposure test for two months with NaCl + $MgCl_2$.

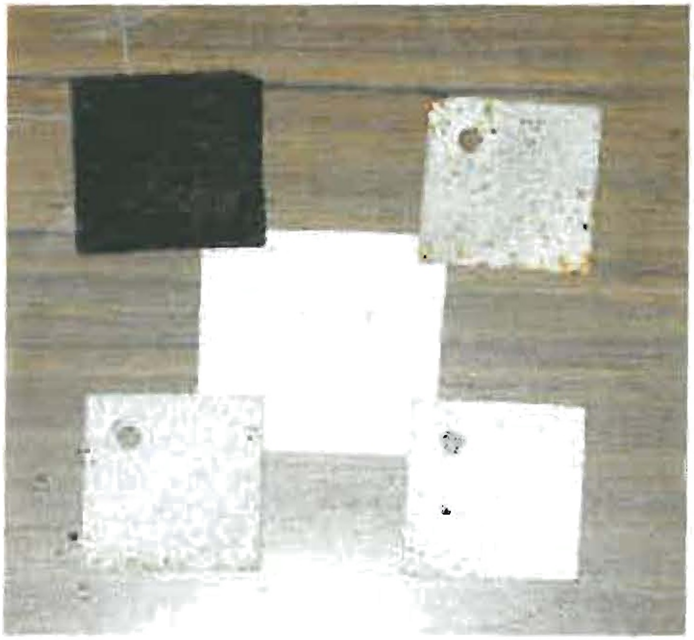

**Figure 33:** The coupons after the cyclic exposure test for two months with $MgCl_2$+ NaI.

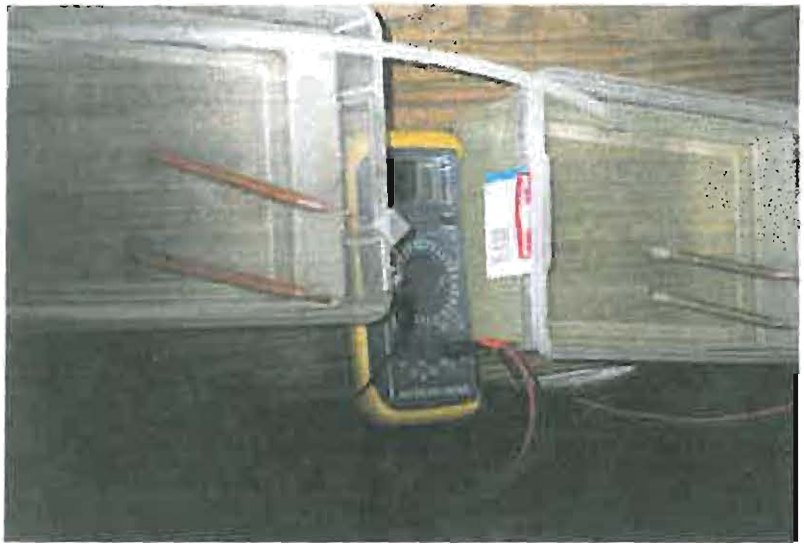

**Figure 34: The corrosion potential test unit for copper components.**

# Appendix 3: Survey sent to Colorado Trucking Companies

## Part I: Company Information

1. Your company is: Private _____ For-Hire_____

2. Your company is primarily: LTL _____ Truckload _____ Specialized _______

3. Approximately how many power units does your company own or lease? _______

4. What is your estimated percentage of fleet miles driven in Colorado? _____ %

5. Your company is primarily: Interstate_____ Intrastate ______ Local Delivery _____

6. Within Colorado, your company primarily operates (please check all that apply):
   Throughout the State _____ Western Slope___ Mountain Areas _____
   I-25 Corridor/Front-Range _____ Eastern Colorado ______

7. Do you haul magnesium chloride or similar chemicals? Yes___ No_____

## Part II: Vehicle Wear

8. Since Colorado began using magnesium chloride as a deicer, have you experienced increased wear on your equipment? Yes ___ No___

9. Please rate the specific type and level of damage, if any, on a scale of 1-5 (1- no damage, 2- some light cosmetic damage, 3- noticeable damage but generally no repair required, 4- damage requiring some repair but not replacement, 5 heavy damage requiring replacement).

| Vehicle Component | Wear/ Damage Level (1-5) | Describe Damage | Estimated Cost (including labor) |
|---|---|---|---|
| Paint | | | |
| Chrome | | | |
| Tractor/Trailer Body | | | |
| Aluminum Parts | | | |
| Other Metal Parts | | | |
| Headlights/Lights | | | |
| Windshield | | | |
| Tires | | | |
| Wheels | | | |
| Hoses/Connectors | | | |
| Electrical Wiring | | | |
| Other (please describe) | | | |

10. Are you doing anything differently to limit vehicle damage caused by magnesium chloride or other deicing methods (i.e. increased maintenance, part replacement, undercoating, different wiring)?
Yes ____ No ____
If yes, please describe:

Please estimate the additional costs, if any, your company has incurred because of these changes? $_______

Part III: Truck Washing

11. On average, how often do you wash you trucks per week?
Summer ______ average times per week Winter _____ average times per week

12. Have you noticed any difficulty in removing magnesium chloride from your trucks?
Yes ______ No _______
If yes, what specific problems have you encountered?

13. Have you adopted any new truck-wash procedures/ processes to remove magnesium chloride or other deicers (i.e. frequency of wash, different solvents)?
Yes ____ No _____
If yes, please describe:

Please estimate the additional costs, if any, your company has incurred because of increased truck-washing?
$________

Part IV: General Questions

14. Do you believe the use of magnesium chloride has made driving a truck on Colorado roads less safe?
Yes_____ No______
If yes, please describe:

15. Do you believe the use of magnesium chloride has affected the safety of your equipment?
Yes_____ No______
If yes, please describes:

16. Do you believe magnesium chloride has reduced the number of winter road closures in Colorado?
Yes____ No_____

17. Considering road closures, air quality, corrosion, and other aspects, do you prefer current deicing methods or previous procedures (primarily sand/salt mixtures)? Current_____ Previous______

Any additional comments this survey did not address?

**PLEASE FAX TO: 303-433-9780**

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