

EROSION-CORROSION IN DISTURBED LIQUID/PARTICLE FLOW

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**ABSTRACT**

Erosion-corrosion occurs in pipelines that transport both corrosive liquids and erosive solid particles. This study has tested the erosion-corrosion behavior of mild carbon steel under conditions where there is no protective iron carbonate film. High and low NaCl concentrations were studied in order to determine the effect of salt concentration on the erosion-corrosion process as well as the individual pure corrosion and pure erosion processes.

The effect of erosion-corrosion on mild steel was tested under disturbed flow by using a specially designed test section consisting of three flow alterations: a flow constriction, protrusion, and expansion. Under the tested conditions it was found that there is no synergistic effect between erosion and corrosion and that for an unprotected base metal the rate of metal loss is equal to the sum of erosion loss and corrosion loss. The higher salt concentration led to a lower corrosion rate and erosion rate but did not affect the interaction between erosion and corrosion.

Keywords: erosion, corrosion, sand, synergy, disturbance, salt, carbon steel

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\* Currently employed with Nalco Energy Services

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## INTRODUCTION

Material degradation in industrial pipelines occurs through two main processes: *corrosion* and *erosion*. If both erosion and corrosion occur at the same time there is a chance that a synergistic effect may cause the amount of metal loss to be greater than the sum of metal loss due to erosion and corrosion. Typically, this synergistic effect is observed where there is a protective film covering the metal surface which can be from a corrosion inhibitor or from protective scale formation. For highly used industrial materials such as carbon steel it is important to know how the material will wear in erosion-corrosion environments as there may be interactions between the two mechanisms leading to a synergistic effect. The goal of this study was to determine the effect of erosion-corrosion on carbon steel.

## EXPERIMENTAL PROCEDURE

### *Experimental Testing Equipment*

The approach used in this research was to monitor erosion and corrosion in a five foot acrylic test section with fifty-eight concentric coupons mounted in a recirculating flow loop. The coupons were made from 4" (10.2 cm) and 2 ½" (6.4 cm) diameter 1018 carbon steel pipe which were cut into ¾" (1.9 cm) wide rings. Surface areas tested ranged from 5.98 in<sup>2</sup> (38.6 cm<sup>2</sup>) to 9.49 in<sup>2</sup> (61.2 cm<sup>2</sup>). These rings were machined so that the outer diameter fit tightly into an acrylic tube. The test section consisted of five individual acrylic tubes which were flanged so they could be bolted together once the rings were in place. The rings were isolated from each other using 1/8" (0.32 cm) o-rings which also provided sealing to prevent the outer surface of the rings from contacting solution. The stress applied by bolting the acrylic flanges together created the proper amount of compression on the o-rings. Stainless steel machine screws through helicoil inserts in the acrylic pipe wall made electrical contact with each individual ring for external measurements. The test section consisted of a six inch section of 4" (10.2 cm) rings, a constriction from 4" (10.2 cm) to 2 ½" (6.4 cm), halfway between the 25 inches of 2 ½" (6.4 cm) pipe section was a 2" (5.1 cm) protrusion, and then an expansion from 2 ½" to 4" with another 25 inches of 4" pipe after the expansion. Weight loss and electrochemical analysis could also be performed on the constriction because it was a flat circular plate of 1018 carbon steel which was made to fit in a recess on the 6" acrylic test section. Figure 1 shows a cutaway view of the test section.

### *Corrosion Coupon Preparation*

The coupon preparation procedures used in this study were derived from NACE Standard RP0775-2005<sup>1</sup>. Coupons were prepared by initially bead-blasting all of the coupons to remove any corrosion product that was formed on the surface. The outer parts of the coupons were also bead blasted to avoid rust on the outer surface. The bead-blasting process ensured a repeatable surface and made hand polishing quicker and easier. The coupons were then polished by hand with 400 grit sandpaper to remove any dimples or irregularities caused by bead-blasting. Polishing with sandpaper provided a smoother more repeatable finish than just sandblasting. After polishing with sandpaper the coupons were rinsed with isopropyl alcohol and dried. Once the coupons were dry they were weighed to an accuracy of 0.1 mg. The coupons were then placed in the test section.

### *Setting System Parameters*

For every test, the flow loop was filled with approximately 180 gallons (680 liters) of water and then salt was added for the desired weight percent. For pure corrosion and erosion-corrosion tests the system was then purged with carbon dioxide overnight and for pure erosion the system was purged with

nitrogen. For erosion and erosion-corrosion tests sand was added to the desired weight percent and the sand concentration was measured using a flow diversion tube and by sampling. The concentration of oxygen was measured before the test to ensure the concentration of dissolved oxygen was less than 10 ppb.

Before the test began the pH of the system was checked and adjusted if necessary. For pure corrosion and erosion-corrosion tests the pH was set to 4 and for pure erosion tests the pH was set to 7. The temperature was set to 35°C and controlled using heating pads located on the tank. The test section was then placed in the bypass section and purged with the appropriate gas to eliminate any oxygen in this area. The bypass section allowed the conditions to be set while the flow loop was running. The bypass section was then opened to the test section and testing began.

### *Monitoring During Testing*

During testing electrochemical measurements were made on each coupon to acquire the *in situ* corrosion rate using linear polarization resistance. The solution resistance was measured using electrochemical impedance spectroscopy. Additionally, weight loss analysis was performed on the coupons after the test was complete.

## **RESULTS AND DISCUSSION**

Each of the tests shown below were repeated and the error bars given are the minimum and maximum metal loss rates for the two experiments. For the pure erosion results the average electrochemically measured corrosion rate has been subtracted from the weight loss rate in order to obtain the pure erosion rate. The magnitude of corrosion under the pure erosion conditions was always less than 0.2 mm/yr and this rate was consistent down the entire length of the test section.

Pure erosion conditions were set by purging the system with nitrogen and adjusting the pH to 7. Pure corrosion conditions were set by purging the system with carbon dioxide and adjusting the pH to 4. Erosion-corrosion conditions were the same as pure corrosion except for the addition of sand. The sand used had an average particle size of 275 micron.

The velocity in each section was determined using a flow modeling software. The calculated velocity in the 4" (10.2 cm) pipe section was 2 m/s and in the 2 1/2" (6.4 cm) section the velocity was 4.5 m/s.

### *Results at 1 wt% NaCl*

The results at 1 wt% sand and 1 wt% NaCl are shown in Figure 2. Under these conditions there was no significant erosion and only corrosion lead to a significant metal loss. This is obvious since the erosion-corrosion weight loss results overlay the pure corrosion results. The pure erosion results also showed insignificant erosion down the entire length of the test section.

Figure 3 shows the combined analysis for 2 wt% sand and 1 wt% NaCl. These results show that there is only a significant erosion rate in the 2.5" (6.4 cm) area of the test section and the erosion rate approximately doubles in the area past the protrusion. The erosion-corrosion and pure corrosion results show no significant difference in the 4" (10.2 cm) areas of the test section which is also consistent with the pure erosion results which show no significant erosion in these areas of the test section.

Figure 4 shows the sum of pure erosion and pure corrosion plotted with the erosion-corrosion results for 2 wt% sand and 1 wt% NaCl. These plots show no significant difference meaning there is no synergistic effect under these conditions.

#### *Comparison between Pure Corrosion Results at 1 wt% and 10 wt % NaCl*

Figure 5 shows the comparison between pure corrosion at 1 wt% and 10 wt% NaCl. The corrosion rates decrease by one half when going from 1 wt% to 10 wt% NaCl. The reason for this comes from changes in both the chemical and mass transfer reactions as well as changes in the charge transfer reactions as postulated by Fang et al.<sup>2</sup>. High concentrations of NaCl affect the chemical and charge transfer reactions by increasing the fluid density (1009 kg/m<sup>3</sup> at 1 wt% and 1113 kg/m<sup>3</sup> at 10 wt%) and the fluid viscosity (0.0009 kg/m-s at 1 wt% and 0.0011 kg/m-s at 10 wt%). This affects the mass transfer limiting current by increasing the boundary layer through which the cathodic reaction occurs. The high NaCl concentration also increases the ionic strength which reduces the amount of dissolved CO<sub>2</sub> present in the system at the same partial pressure. Fang et al.<sup>2</sup> found that these changes alone did not add up to the reduction in corrosion rate and postulated that there is also chemical adsorption of Cl<sup>-</sup> onto the metal surface which affects the charge transfer reactions.

#### *Comparison between Pure Erosion Results at 1 wt% and 10 wt % NaCl*

Figure 6 and Figure 7 show the comparison between pure erosion results at 1 wt% sand and 1 and 10 wt% NaCl. The results show that there is no change in the erosion rate profile when going from 1 to 10 wt% salt. Under these conditions there is still only a significant amount of erosion just past the protrusion leading to erosion rates around 1 mm/yr.

Figure 8 and Figure 9 show the comparison between pure erosion results at 2 wt% sand and 1 and 10 wt% NaCl. The results show that the erosion rates are significantly lower past the constriction and the protrusion at 10 wt% NaCl. There is no significant difference in the erosion rates in the larger 4" (10.2 cm) sections due to the low amount of erosion loss in these areas. The reason the erosion rate is lower in the smaller 2.5" (6.4 cm) section is due to the increase in fluid density and viscosity which decreases the turbulence in these areas.

It was known by visual observation as well as sampling that the tests performed in this study were near the erosional velocity limit. It could be observed through clear acrylic pipe sections located before the test section that there was sand being dragged along the bottom of the flow for both 1 and 10 wt% salt. Sampling ports were placed on the top and bottom of one of the 4" (10.2 cm) pipe sections located on the flow loop. Sampling showed that at 1 wt% NaCl and 2 wt % sand the top sampling port yielded a sample with a sand concentration of 1 wt% sand and the bottom sample had a sand concentration of 3 wt% which shows that there was more sand flowing along the bottom of the pipe than at the top. The average sand concentration as measured by the flow diversion tube was 2 wt% which makes sense since this was the average sand concentration of the entire flow. At 10 wt% salt and 2 wt% sand the top sample port yielded a sample with 0.75 wt% sand and the bottom sand concentration was 3.5 wt%. Once again the average sand concentration measured by the flow diversion tube was 2 wt% which is close to the average of the top and bottom sand concentration measurements. This shows that at 10 wt% NaCl there is less sand entrained since the sand concentration at the top of the pipe was lower and at the bottom of the pipe was higher.

The combination of the reduction in turbulence which is responsible for the reduction in sand entrainment can be used to explain the difference between the erosion rates between 1 and 10 wt% NaCl at 2 wt% sand. This reduction in sand entrainment comes from the change in fluid density and viscosity which cause more drag force on the sand and less turbulence to entrain the sand.

Figure 10 shows the comparison between pure erosion results at 1 and 2 wt% sand and 10 wt% NaCl. The results show that the magnitudes of erosion rates are similar under both conditions. The sampling port at 1 wt% sand yielded a sand concentration at the top of the pipe of 0.5 wt% and at the bottom the sand concentration was 1.5 wt% which gives an average sand concentration of 1 wt% which is what was measured by the flow diversion tube. Comparing these results with the results at 2 wt% sand it can be seen that the sand concentration at the top of the pipe is the same for both 1 and 2 wt% sand and this suggests that the amount of entrained sand is also equal. This explains why these results are of similar magnitudes.

#### *Erosion-Corrosion Results at 1 and 2 wt% Sand and 10 wt% NaCl*

Figure 11 shows the comparison between erosion-corrosion results at 1 and 2 wt% sand. As expected from the previous pure erosion results these two results are not significantly different since the magnitude of erosion is similar for both 1 and 2 wt% sand at 10 wt% NaCl.

#### *Results Analysis at 10 wt% NaCl*

Increasing the concentration of NaCl from 1 wt% to 10 wt% salt not only affected the pure corrosion rate, but also caused the pure erosion rate to decrease. At 10 wt% salt the pure erosion rates are similar for both 1 wt% and 2 wt% sand. This is due to the increase in density and viscosity which causes the solution to have the same erosivity despite the increase in the sand concentration. Figure 12 and Figure 13 show the combined analysis of results for 1 wt% and 2 wt% sand, respectively, at 10 wt% NaCl. It can be seen from these graphs that the erosion-corrosion rates are significantly lower or equal to the pure corrosion rates.

Figure 14 and Figure 15 show that the sum of pure erosion and pure corrosion are significantly higher than the erosion-corrosion results in some areas of the test section for both 1 wt% and 2 wt% sand, respectively. It is important to remember that under these conditions for both 1 and 2 wt% sand erosion does not lead to significant metal loss. There may be some affect of the addition of sand on the pure corrosion rates since it has been shown that additional sand above 1 wt% simply increases the amount of sand flowing along the bottom of the pipe and does not increase the amount of entrained sand. The sand flowing along the bottom could be interfering with the pure corrosion by acting as another barrier for the corrosive species to travel through. Any sand barrier along the bottom of the pipe would also interfere with the erosion rates since sand particles cannot impact the surface directly.

## **CONCLUSIONS**

The results from the current study has shown higher salt concentration reduces the magnitude of corrosion when going from 1 wt% to 10 wt% NaCl. This effect has been found in other studies<sup>2</sup> and it has been concluded the reduction in the corrosion rates at higher concentrations of NaCl comes from the changes in density and viscosity which affect the mass transfer reactions, from an increase in ionic strength which reduces the amount of dissolved CO<sub>2</sub>, and from chloride ion adsorption onto the metal surface.

Furthermore this study has found that increasing the concentration of NaCl also affects the erosion rates. The erosion rates at 1 and 2 wt% sand and 10 wt% NaCl are not significantly different. At 1 wt% NaCl, however, erosion rates at 1 wt% sand are significantly lower than at 2 wt% sand. This reduction in the erosion rate comes from the increase in fluid density and viscosity. Increasing the density and viscosity causes more drag force on the particle and also reduces the turbulence of the flow. These changes decrease the amount of sand entrained. Only 1 wt% sand can be entrained at 10 wt% NaCl and

any additional sand added rolls along the bottom of the pipe and does not lead to erosion. Therefore the erosion rates at 1 wt% sand are the maximum erosion rates that can be obtained under the tested conditions at 10 wt% NaCl.

### **ACKNOWLEDGMENTS**

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2. Fang, Haitao, "Low Temperature and High Salt Concentration Effects on General CO<sub>2</sub> Corrosion for Carbon Steel" November 2006, Ohio University Institute for Corrosion and Multiphase Technology, Thesis for Master's of Science in Chemical Engineering.
3. ASTM Standard G 119-04 "Standard Guide for Determining Synergism between Wear and Corrosion" Copyright by ASTM International, 2004.

# FIGURES

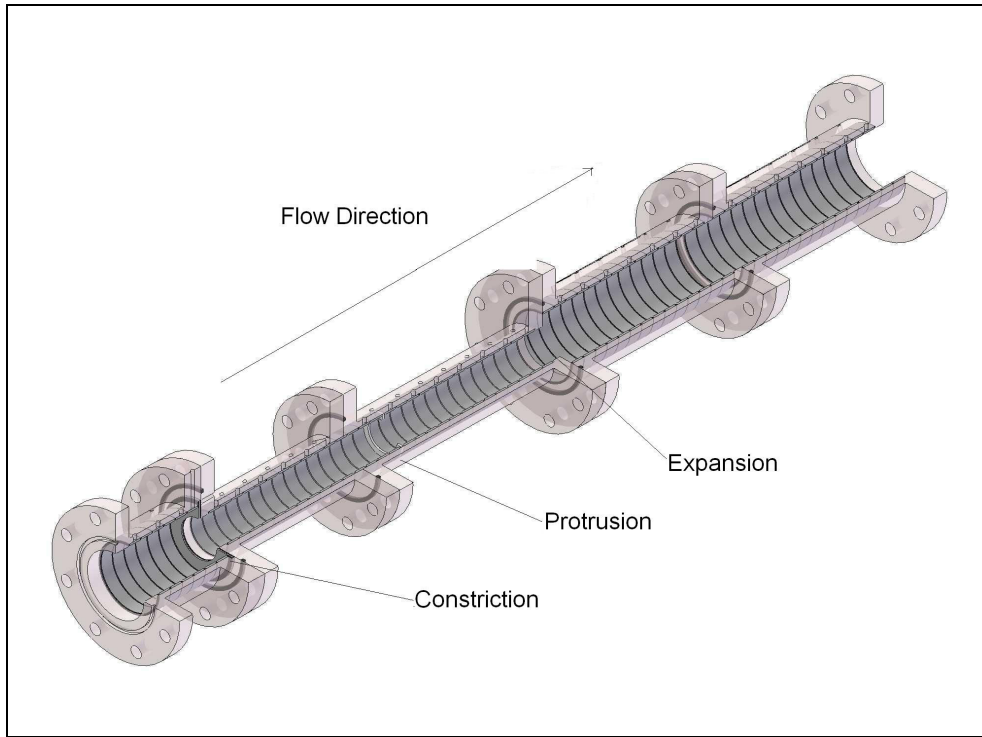


Figure 1: Cutaway view of test section showing the flow disturbances.

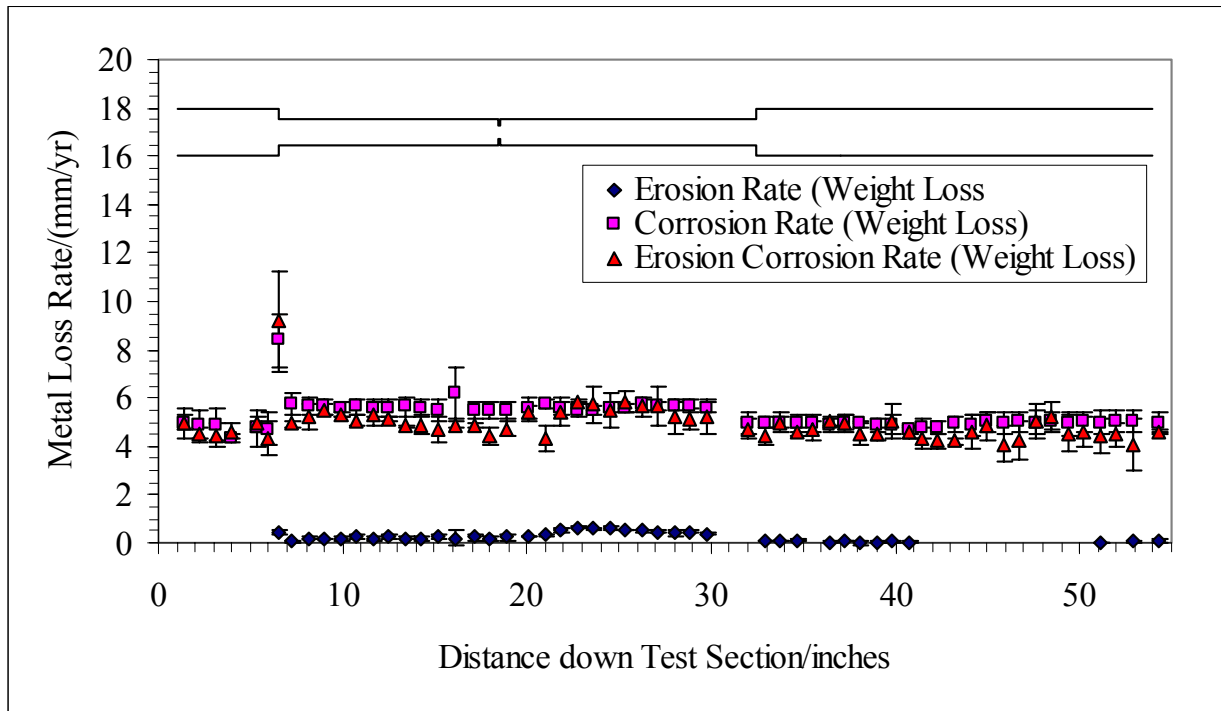


Figure 2: Analysis of results at 1 wt% NaCl and 1 wt% sand.

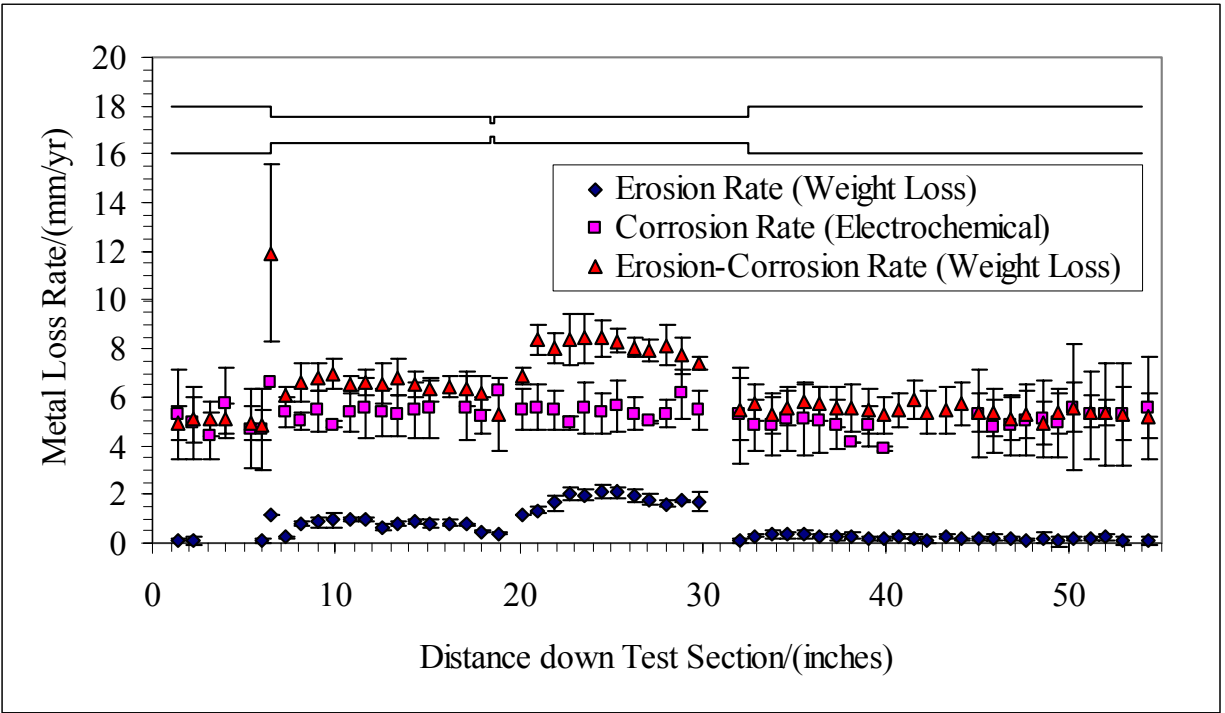


Figure 3: Analysis of results at 1 wt% NaCl and 2 wt% sand.

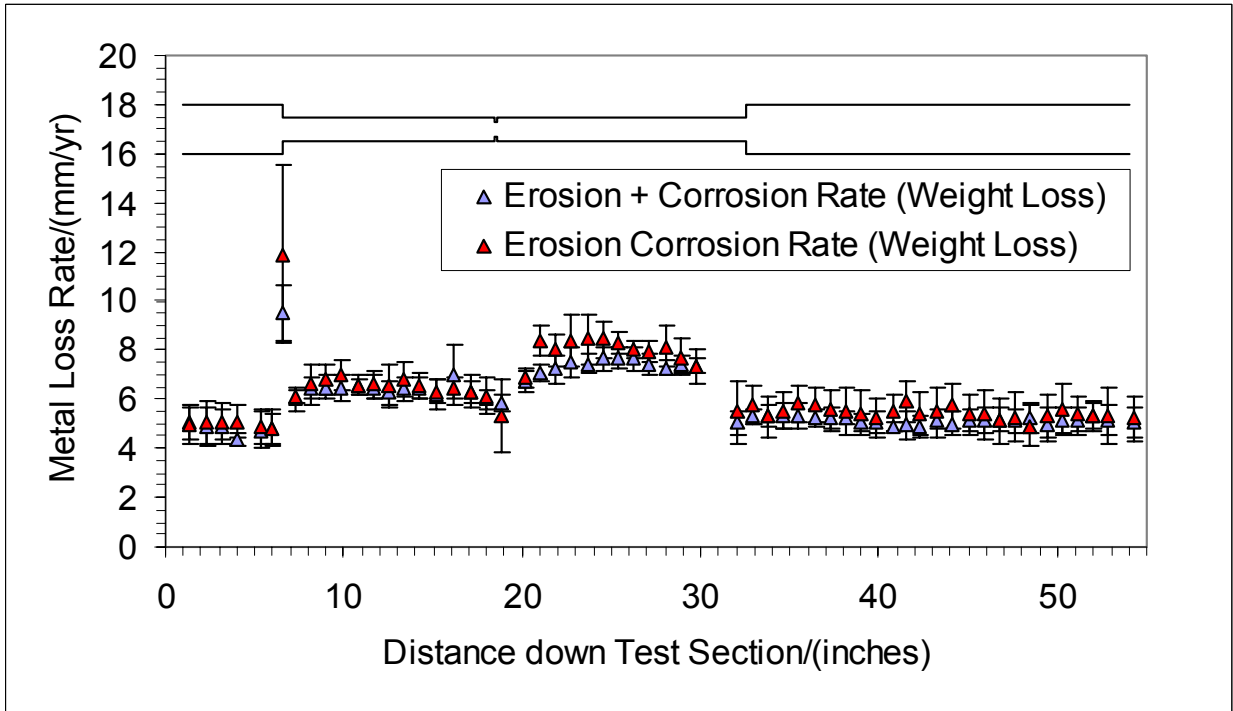


Figure 4: Sum of pure erosion and pure corrosion for 1 wt% NaCl and 2 wt% sand.



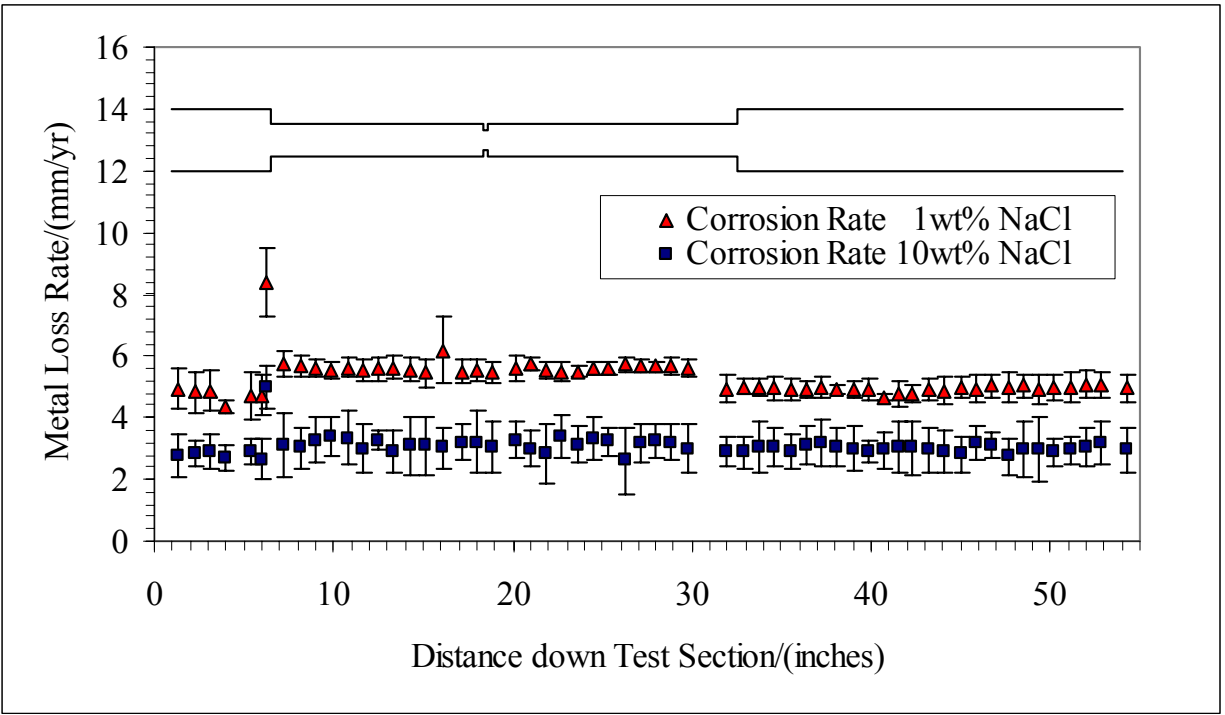


Figure 5: Pure corrosion comparison between 1 and 10 wt% NaCl.

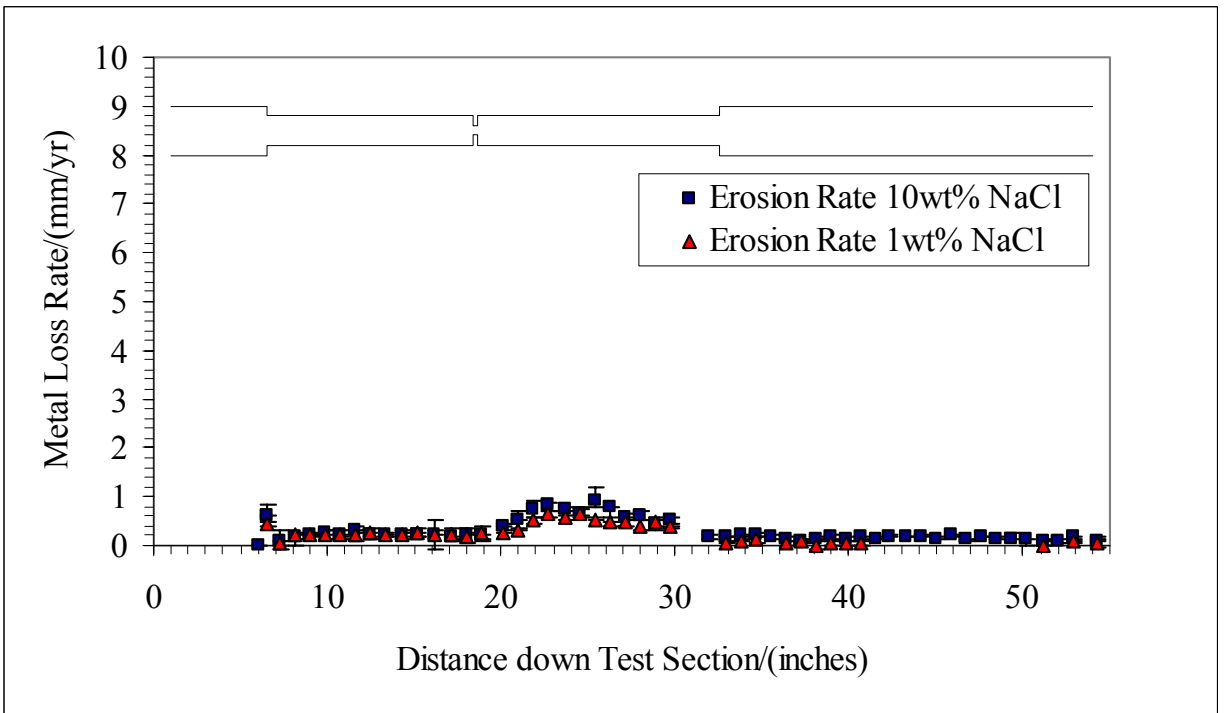


Figure 6: Comparison between pure erosion weight loss results at 1 and 10 wt% NaCl at 1 wt% sand. The erosion rate is unchanged when going from 1wt% to 10 wt% NaCl at 1 wt% sand.

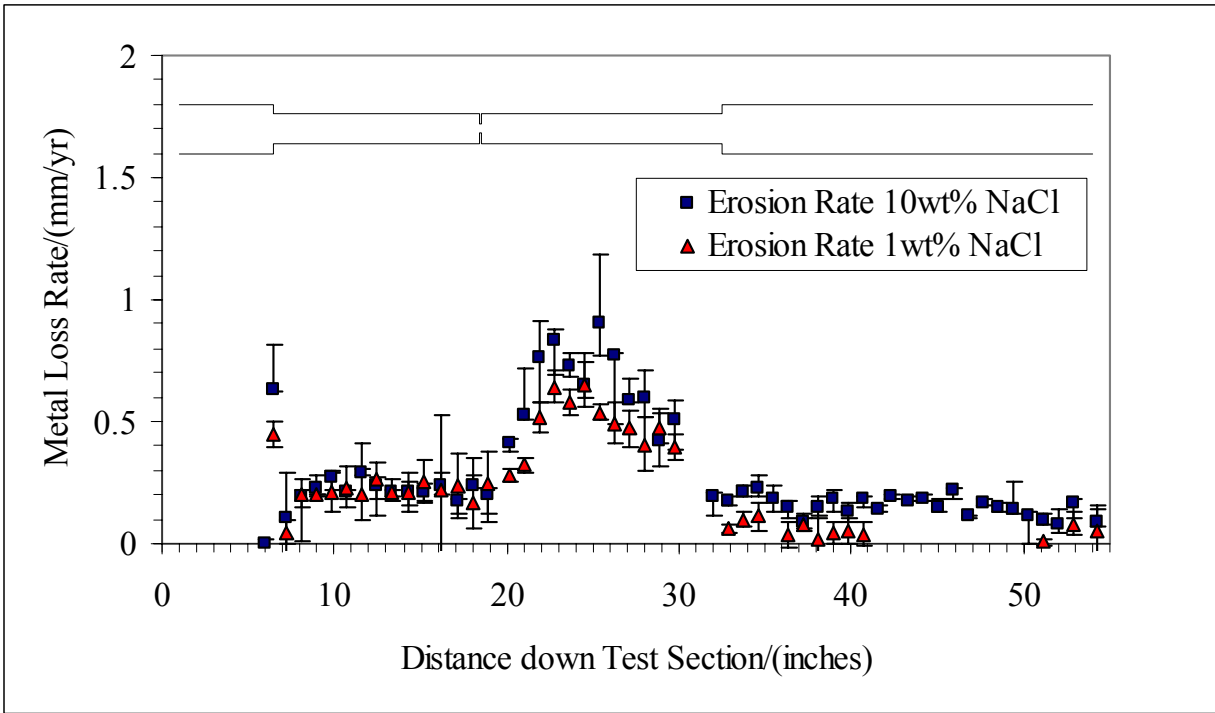


Figure 7: Comparison between pure erosion weight loss results at 1 and 10 wt% NaCl at 1 wt% sand on a smaller scale range to show more detail in the results.

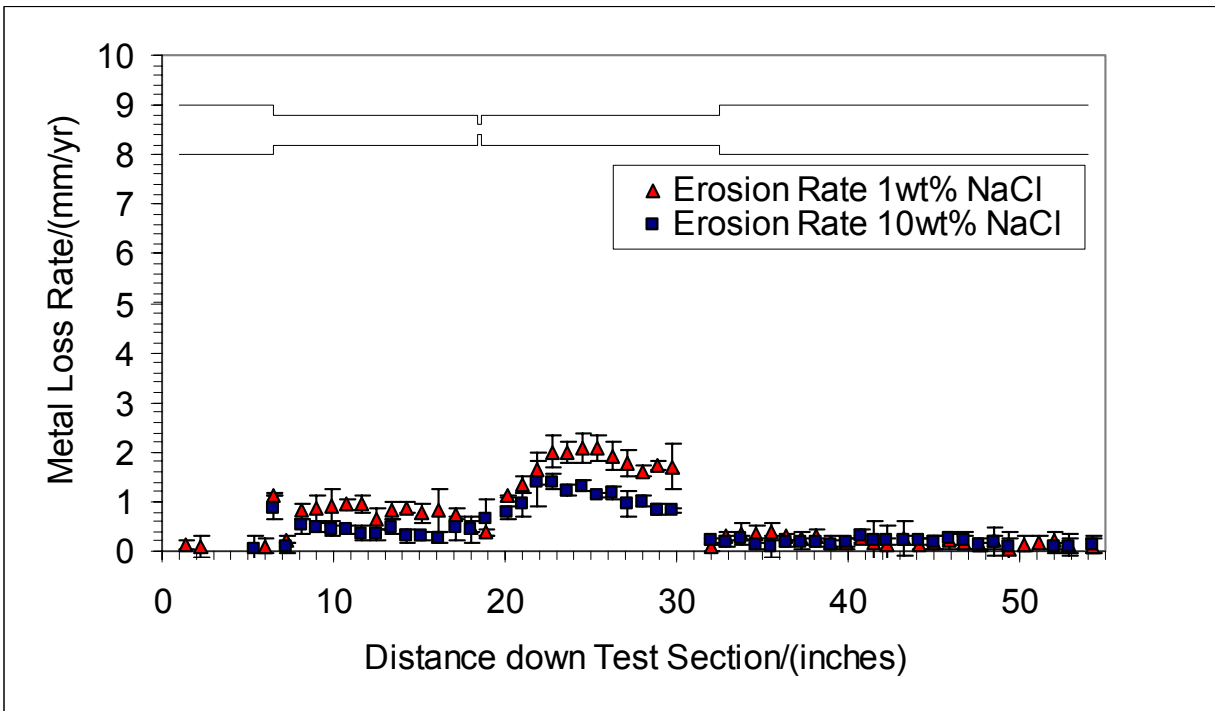


Figure 8: Comparison between pure erosion weight loss results at 1 and 10 wt% NaCl at 2 wt% sand.

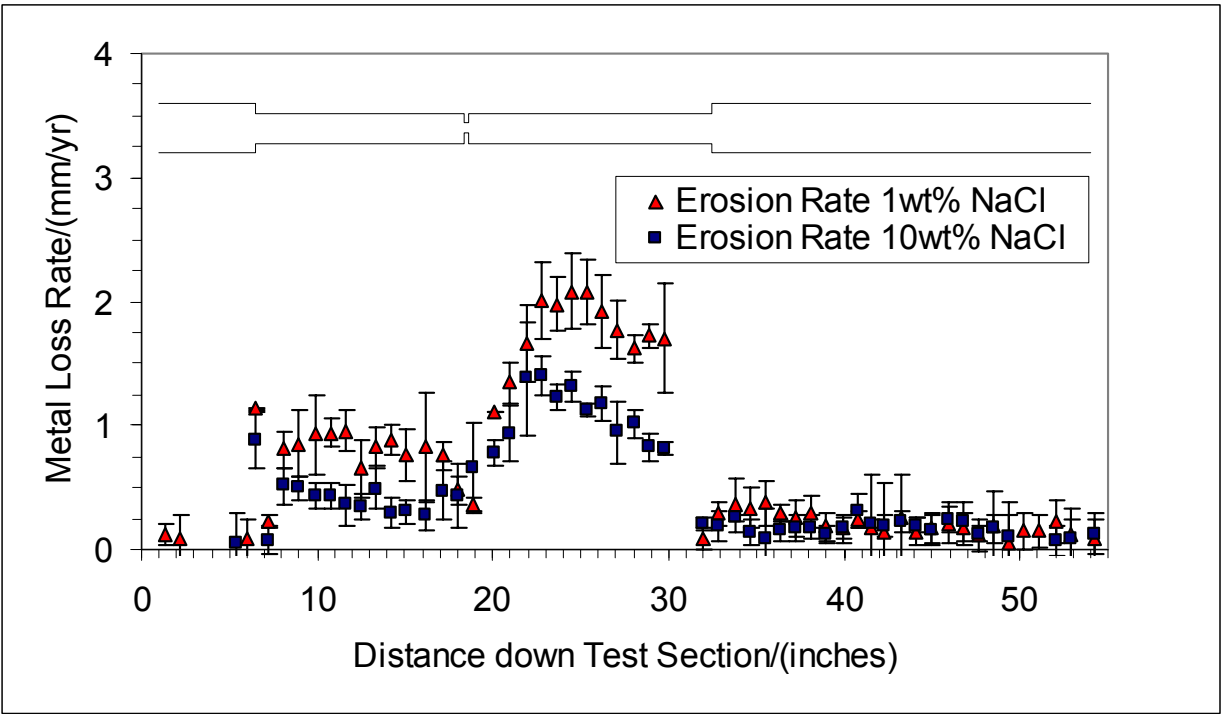


Figure 9: Comparison between pure erosion weight loss results at 1 and 10 wt% NaCl at 2 wt% sand on a smaller scale range to show more detail.

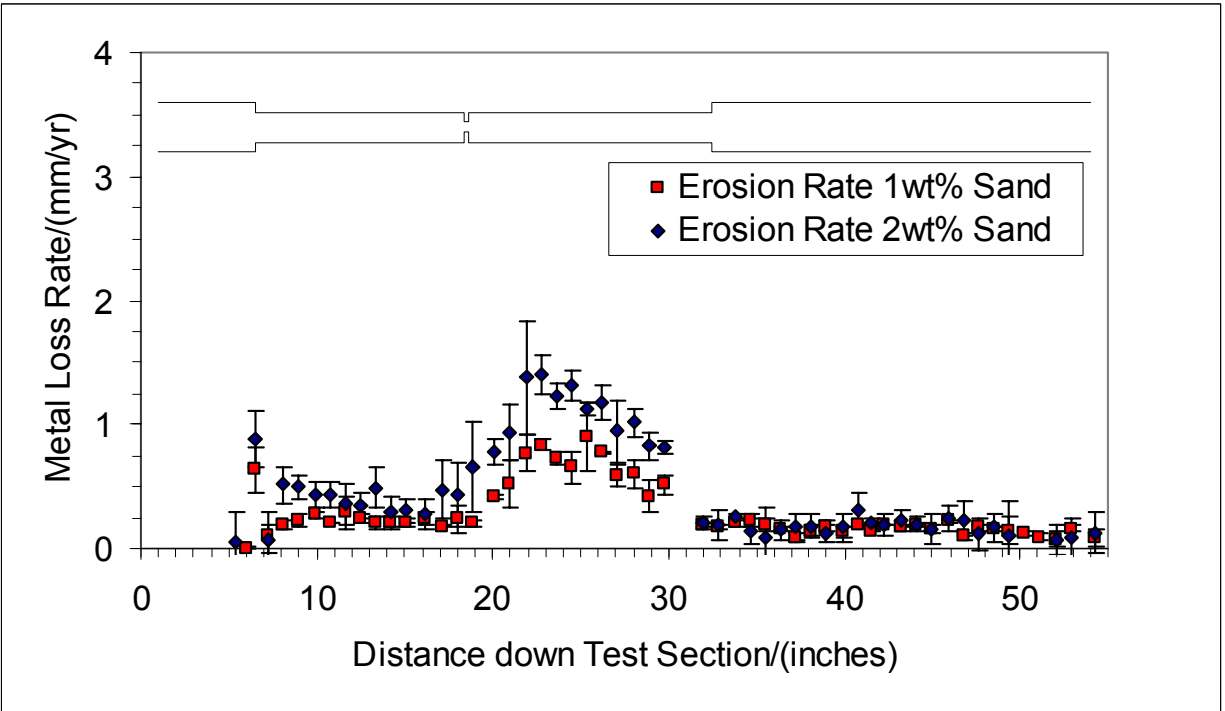


Figure 10: Comparison between pure erosion results at 1 and 2 wt% sand at 10 wt% NaCl.

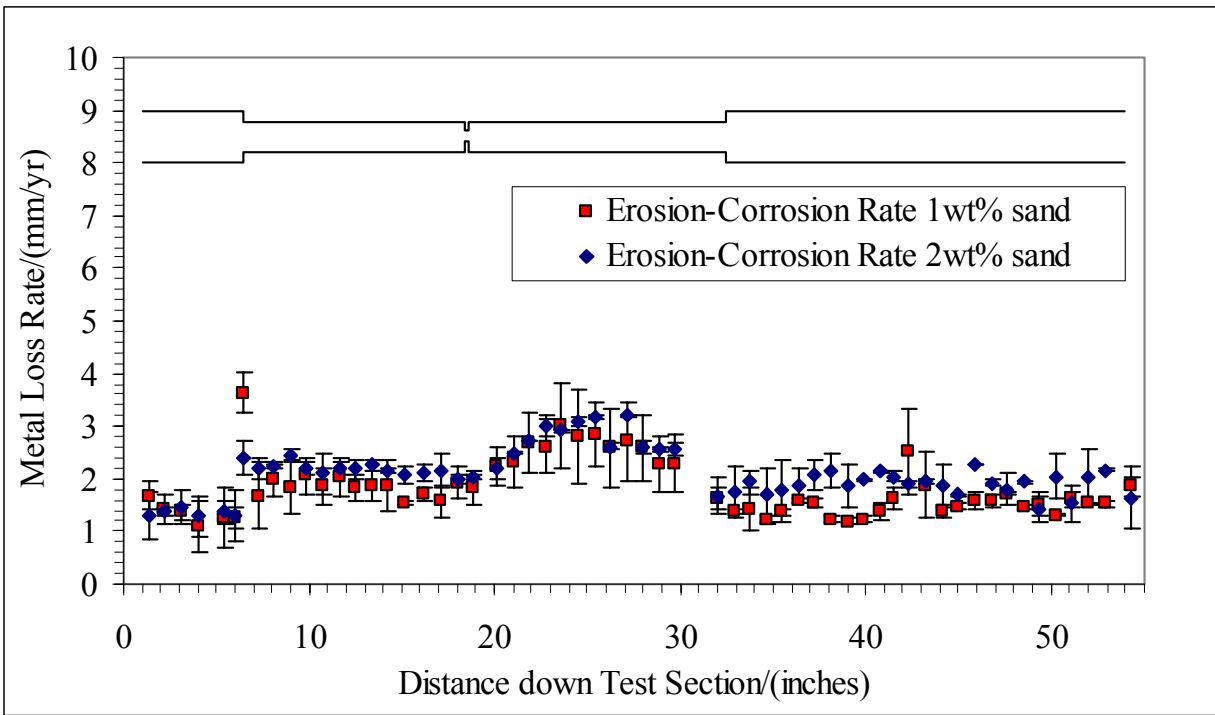


Figure 11: Erosion-corrosion results comparison at 1 and 2 wt% sand at 10 wt% NaCl.

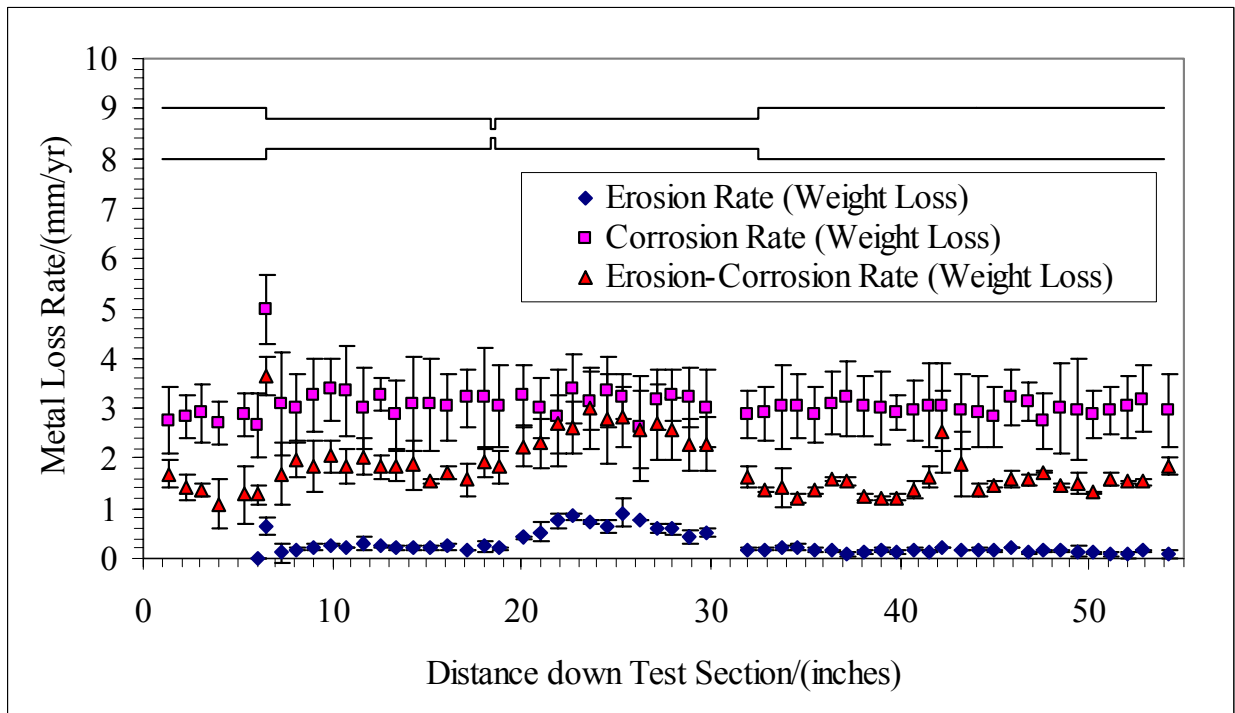


Figure 12: Combined analysis for 1 wt% sand and 10 wt% NaCl.

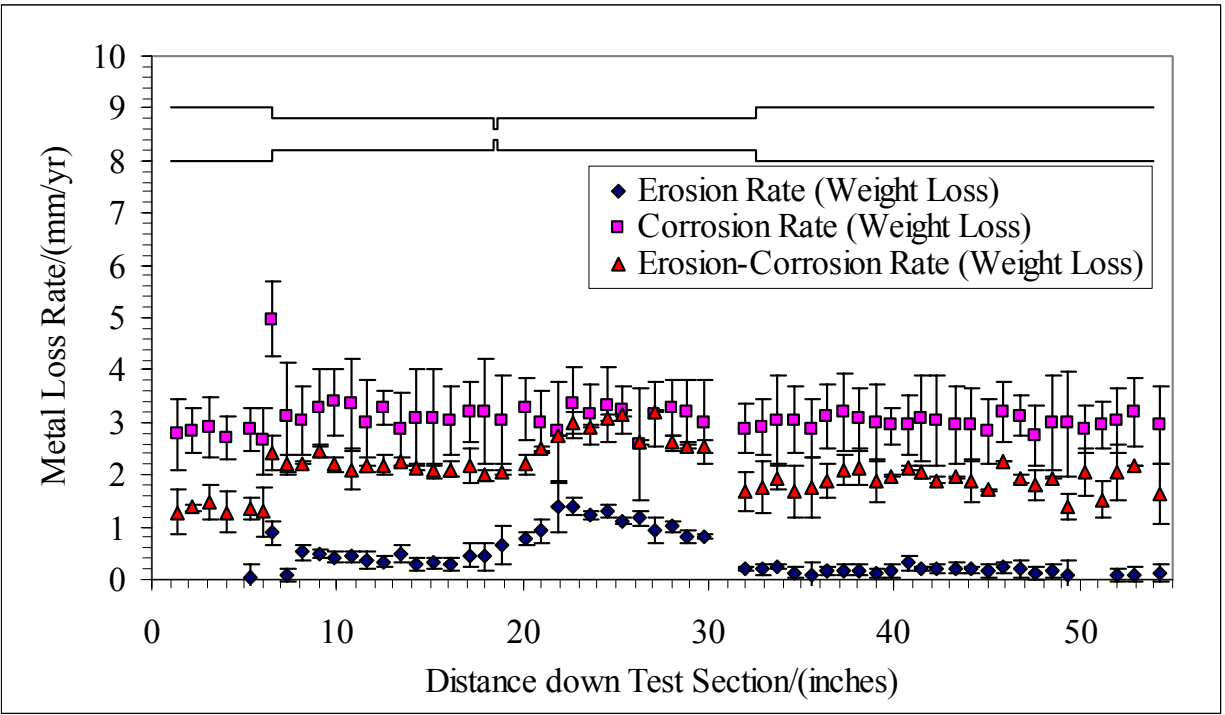


Figure 13: Combined analysis for 2 wt% sand and 10 wt% NaCl.

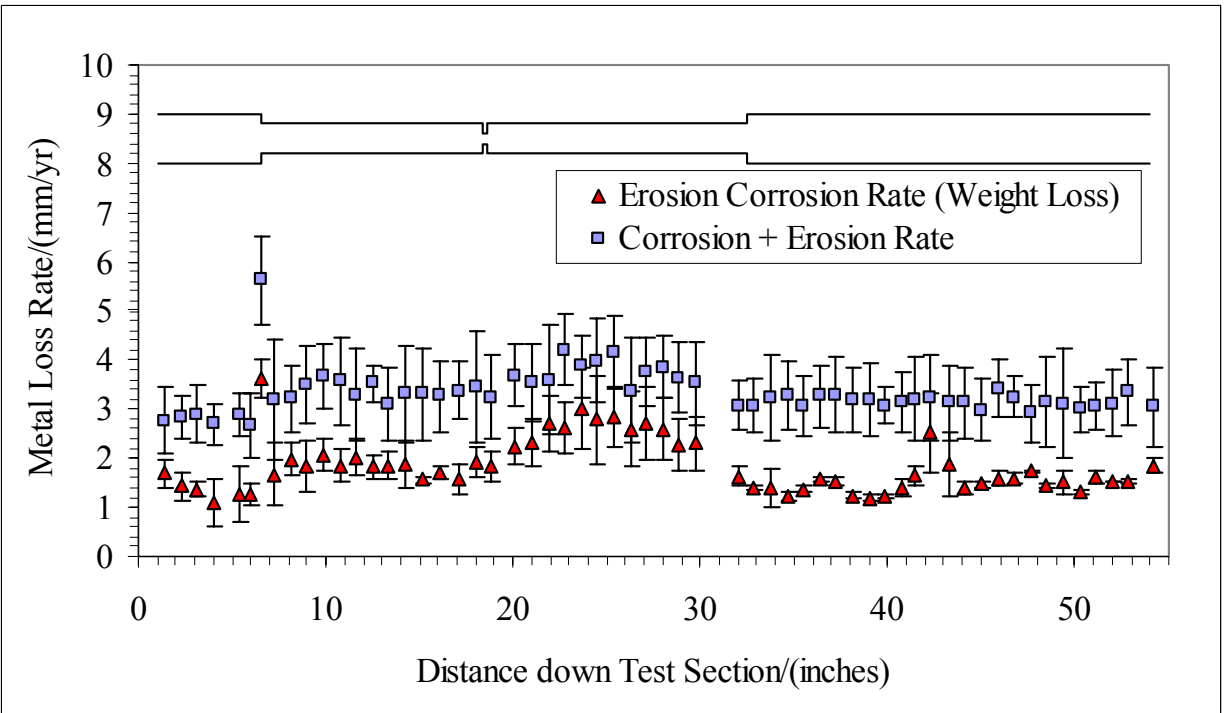


Figure 14: Sum of erosion and corrosion rates plotted with the erosion-corrosion rate for 1 wt% sand and 10 wt% NaCl.

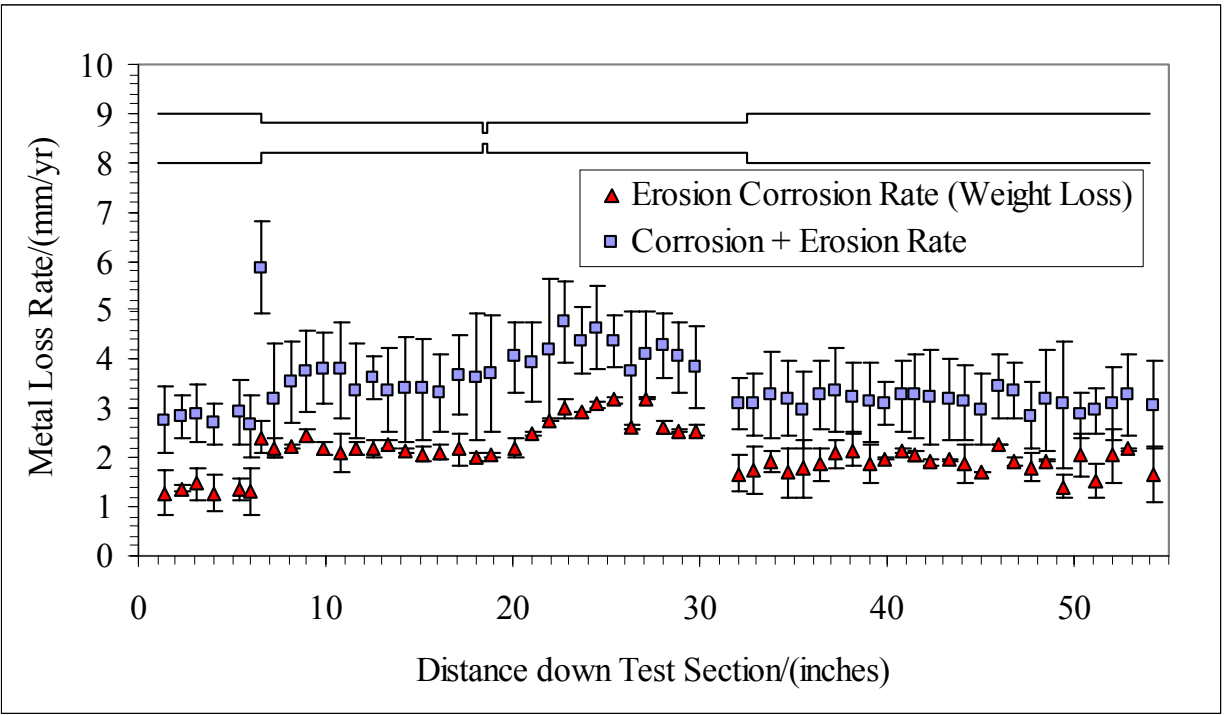


Figure 15: Sum of erosion and corrosion rates plotted with the erosion-corrosion rate for 2 wt% sand and 10 wt% NaCl.