

MEASUREMENT OF CUMULATIVE LOCALIZED CORROSION RATE USING COUPLED MULTIELECTRODE ARRAY SENSORS

Lietai Yang and Xiaodong Sun
Corr Instruments, LLC
San Antonio, TX, USA

ABSTRACT

Cumulative localized corrosion rate and cumulative maximum localized corrosion rate factors are introduced for corrosion monitoring using coupled multielectrode array sensor probes. Maximum localized corrosion rate is the corrosion rate on any of the electrodes of a probe that has the highest corrosion rate at a given moment of time. Cumulative maximum localized corrosion rate is the corrosion rate of the electrode that has been corroded the most in a given time period. The cumulative maximum localized corrosion rate is directly related to the corrosion damage (maximum localized corrosion depth); the maximum localized corrosion depth equals the integration of the cumulative maximum localized corrosion rate. Maximum localized corrosion rate should be used for process control purposes, but cumulative maximum localized corrosion rate should be used to evaluate the localized corrosion effect on metal damage.

Keywords: Corrosion monitoring, corrosion sensor, localized corrosion, online sensor, crevice corrosion, corrosion probe, real-time sensor, multielectrode sensor, coupled multielectrode.

INTRODUCTION

Coupled multielectrode array concept has been extensively used in electrochemical studies of metal dissolution behaviors.¹⁻¹⁰ Coupled multielectrode array sensors (CMAS) have been recently used as *in situ* and online monitors for localized corrosion in cooling water pipes of chemical plants,¹¹⁻¹⁴ and other laboratory and field systems.¹⁴⁻³⁴ Some of the CMAS applications include quantitative and real-time localized corrosion monitoring for cathodically protected systems,²¹ coated metal components,^{22,27} metals in concrete,²³ metals in soil,²⁶ metals in low conductivity waters,²⁸ and carbon steel in H₂S environments³². The coupled multielectrode sensor probes were also used as real-time corrosion monitors for crevice corrosion of stainless steels, copper and carbon steel in simulated seawater.³⁰

MAXIMUM LOCALIZED CORROSION RATE AND MAXIMUM CORROSION DEPTH

The maximum anodic current has been used to derive the localized corrosion rate (the maximum penetration rate).^{15-17,24} The following equation has been used to calculate the maximum localized corrosion rate from maximum anodic current, I_{\max} :

$$CR_{\max} = (1/\varepsilon)I_{\max} W_e / (F\rho A) \quad (1)$$

where CR_{\max} is the calculated maximum penetration rate (cm/s), ε is the current distribution factor (fraction of the electrons produced on the most corroding electrode that flow to the other electrodes through the coupling circuit), F is the Faraday constant (96485 C/mol), A is the surface area of the electrode (cm²), ρ is the density of the alloy or electrode (g/cm³), W_e is the equivalent weight (g/mol). The values of ε is unity, if the most corroding electrode is significantly different from the other electrodes in the coupled multielectrode sensor probe, and close to zero, if very few of the electrons flow externally to the other electrodes.²⁴

The maximum localized corrosion depth or penetration is related to the total damage accumulated in a given time period. The corrosion depth of the i^{th} electrode may be derived from the cumulative charge that can be obtained by integrating the corrosion current through the electrode from time zero to time t :

$$Q = \int I_i(t) dt \quad (2)$$

where Q_i is the cumulative charge of the i^{th} electrode. Similar to the maximum localized corrosion rate, the following equation has been used to calculate the maximum cumulative localized corrosion depth or penetration (cm):

$$CD_{\max} = (1/\varepsilon)Q_{\max} W_e / (F\rho A) \quad (3)$$

where Q_{\max} is the maximum of the cumulative charges (coulomb) from all the electrodes. The cumulative charge of each electrode is calculated individually using Equation (2).

Because the maximum localized corrosion rate may not always take place at the electrode that is most corroded, the corrosion depth calculated by integrating Equation (1) is generally higher than the maximum localized corrosion depth as shown in Equation (3). The present paper presents a method on how to derive a more realistic rate for localized corrosion that agrees with the corrosion rate derived from Equation (3)

Figure 1 shows typical currents measured from a stainless steel coupled multielectrode array sensor probe in simulated seawater (3%wt sea salt in distilled water). The coupled multielectrode instrument used in the measurement was a nanoCorr^{*} Model S-50 analyzer, manufactured by Corr Instruments (San Antonio, TX, USA). The probe had 16 electrodes made of annealed Type 316L (UNS31603) stainless steel wire. The size of the wire was 1 mm in diameter and the surface area of each electrode was 0.785 mm². In Figure 1, the maximum anodic current was due to the current from a single electrode (Electrode #4). The anodic charges corresponding to Figure 1 are shown in Figure 2. By applying Equations (1) through (3) to the data shown in Figures 1 and 2, the maximum localized

* nanoCorr and CorrVisual are trademarks of Corr Instruments, LLC

corrosion rate and maximum corrosion depth were obtained and shown in Figure 3. In Figure 3, the maximum localized corrosion depth curve is the integration of the maximum localized corrosion rate curve. Because the maximum localized corrosion rate curve in Figure 3 was from one electrode, the maximum localized corrosion rate curve and the maximum localized corrosion depth curve are directly related to each other.

Figure 4 shows typical currents measured from an aluminum coupled multielectrode array sensor probe in simulated seawater using the same analyzer as mentioned above. The aluminum probe had 16 electrodes made of annealed Type 3003 (UNS A93003) aluminum wire. The size of the wire was 1 mm in diameter and the surface area of each electrode was 0.785 mm². In Figure 4, the maximum anodic current was from different electrodes (Electrodes #5, #13, #12, and #16) at different times. The anodic charges corresponding to Figure 4 are shown in Figure 5. Applying Equations (1) through (3) to the data shown in Figures 4 and 5, the maximum localized corrosion rate and the maximum localized corrosion depth were obtained and are shown in Figure 6. Unlike Figure 3, the maximum localized corrosion depth curve is not the direct integration of the maximum localized corrosion rate curve in Figure 6. The integration of the maximum localized corrosion curves would produce a much higher depth than the true maximum localized corrosion penetration depth as shown in Figure 6 (dashed line). Therefore, there is no direct relationship between the maximum localized corrosion rate and the maximum localized corrosion penetration depth.

CUMULATIVE MAXIMUM LOCALIZED CORROSION RATE

To solve the problem of discrepancy between the maximum localized corrosion rate and maximum localized corrosion depth, as shown in Figure 6, a new parameter called cumulative maximum localized corrosion rate, CR_{cmax} , is introduced in this paper. It is defined as the derivative of the maximum localized corrosion depth curve:

$$CR_{cmax}(t) = d[CD_{max}(t)] / dt \quad (4)$$

The maximum localized corrosion depth, $CD_{max}(t)$, is proportional to the maximum anodic charge, Q_{max} , as shown in Figure 5 [see Equation (3)]. The maximum anodic charge in Figure 5 was obtained by integrating the currents from the electrodes that had the maximum anodic charge since time zero (or had been corroded the most at time t). Therefore, the derivative of $CD_{max}(t)$ is simply a function of the current from the electrode that has the highest anodic charge at time t , I_{max_charge} :

$$CR_{cmax}(t) = (1/\epsilon) I_{max_charge} W_e / (F\rho A) \quad (5)$$

The CR_{cmax} values for the data shown in Figures 4 and 5 are calculated and shown in Figure 7. The maximum localized corrosion depth, CD_{max} , and the calculated corrosion rates for the electrodes that exhibited the highest corrosion currents at certain times during the test (see Figure 4) are also plotted in Figure 7. In the specified three time periods, the maximum localized corrosion depth was the values measured from Electrodes #5, #13, and #12 respectively (see Figure 5). Therefore, the cumulative maximum localized corrosion rate, CR_{cmax} , was equal to the corrosion rates of these three electrodes during the different corresponding time intervals. Another way to look at the cumulative maximum localized corrosion rate is that it is the corrosion rate of the cumulatively most corroded electrode at any given time (or the electrode with the deepest pit, if the mode of localized corrosion is pitting corrosion). Because of the nature of localized corrosion, the deepest pit may be repassivated under certain conditions and the corrosion rate in this pit may drop to zero. The zero value of CR_{cmax} in the second time interval indicates that the most corroded electrode (Electrode #13) was repassivated, and the corrosion on it was stopped from approximately 5:20 to 6:20 a.m.

Because the cumulative maximum localized corrosion rate is simply the corrosion rate of the electrode that passed the maximum amount of charge, a sorting algorithm may be built into a real-time corrosion monitoring software* to track the most corroded electrode and obtain the cumulative maximum localized corrosion rate. The software may give the maximum localized corrosion rate, the cumulative maximum localized corrosion rate and the average corrosion rate, CR_{avg} , which is calculated from the average of the anodic currents. The average corrosion rate may be used to represent the general corrosion rate.²⁹ Figure 8 shows the maximum localized corrosion rate, cumulative localized corrosion rate and average corrosion rate calculated by the software.

Because the cumulative maximum localized corrosion rate is defined as the derivative of the maximum localized corrosion depth, the CR_{cmax} and CD_{max} values are directly related to each other. One can solve for CR_{cmax} from CD_{max} by differentiation, or solve for CD_{max} from CR_{cmax} by integration. Unlike the maximum localized corrosion rate, CR_{max} , whose integration would produce an imaginary number that may be higher than the actual maximum localized corrosion depth, the integration of the cumulative maximum localized corrosion rate would produce exactly the maximum localized corrosion depth.

CUMULATIVE LOCALIZED CORROSION RATE AND DEPTH FACTORS

Localized corrosion rate factor and localized corrosion depth factor were introduced to indicate how much higher the corrosion rate on the most corroding electrode is than the average corrosion rate, and how much higher the corrosion depth on the most corroded electrode is than the average corrosion depth.²⁹ Similarly, cumulative localized corrosion rate factor, f_{crate} , is defined here to indicate how much higher or lower the cumulative maximum localized corrosion rate is than the average corrosion rate:

$$f_{crate} = CR_{cmax} / CR_{avg} \quad (6)$$

Figure 9 shows the cumulative localized corrosion rate factor, maximum localized corrosion rate factor and localized corrosion depth factor for the data shown in Figures 4 and 5.

Although the cumulative maximum localized corrosion rate as shown in Figures 7 and 8 reflects the true corrosion process of the most corroded electrode, it is not a continuous function. Sometimes it may be extremely high, but other times it may be zero. When it is equal to zero, it may mislead people to think that localized corrosion is not happening. To avoid the tendency of misleading people by the cumulative maximum localized corrosion rate, other alternatives may be used to approximate the cumulative maximum localized corrosion rate. Examples of the approximation are:

$$CR'_{cmax} = \frac{1}{t} \sum CR_{cmax}(t_i) \Delta t_i, \quad i \text{ from } 1 \text{ to } n \quad (7)$$

$$CR'_{cmax} = \frac{1}{t} \int_0^t CR_{cmax}(t) dt \quad (8)$$

and,

$$CR''_{cmax} = f_{depth} CR_{avg} \quad (9)$$

* Patent pending

$$f_{\text{depth}} = CD_{\text{max}}/CD_{\text{avg}} \quad (10)$$

where CD_{avg} is the average corrosion depth and f_{depth} is the localized corrosion depth factor. Hence, CR'_{cmax} represents the cumulative maximum localized corrosion rate averaged over a time period from time zero to time t and CR''_{cmax} represents the average corrosion rate multiplied by the localized corrosion depth factor. Both CR'_{cmax} and CR''_{cmax} are plotted, along with CR_{max} , CR_{cmax} , and CR_{avg} , in Figure 10. It should be noted that neither the integration of the CR'_{cmax} nor the integration of CR''_{cmax} will produce a value that would correspond to the maximum localized corrosion depth.

CUMULATIVE AVERAGE CORROSION RATE

As mentioned above, the cumulative maximum corrosion rate is significantly different from the maximum localized corrosion rate, if the maximum localized corrosion rate is not due to the same electrode. However, the cumulative average corrosion rate and the average corrosion rate is the same.

Based on the definition of the cumulative maximum corrosion rate, the cumulative average corrosion rate, CR_{cavg} , may be written as:

$$CR_{\text{cavg}}(t) = dCD_{\text{avg}}(t) / dt \quad (11)$$

$$CR_{\text{cavg}}(t) = d\left[\int CR_{\text{avg}}(t)dt\right] / dt \quad (12)$$

$$CR_{\text{cavg}}(t) = CR_{\text{avg}}(t) \quad (13)$$

APPLICATIONS OF MAXIMUM LOCALIZED CORROSION RATE AND CUMULATIVE MAXIMUM LOCALIZED CORROSION RATES

Maximum localized corrosion rate is a measure of localized corrosion rate at a given moment of time. Cumulative localized corrosion rate is a measure that relates to the cumulative damage of localized corrosion to a metal. If the maximum localized corrosion rate is high, but the cumulative maximum localized corrosion rate is low, the corrosion rate at one electrode is high at one time, but remains low at other times and there is always one electrode that has a high corrosion rate. The cumulative effect of this kind of high maximum localized corrosion rate in a given time period is a high general corrosion rate, (i.e., every electrode is significantly corroded after a given period of time). When the maximum localized corrosion rate is significantly different from the cumulative maximum localized corrosion rate, the cumulative maximum localized corrosion rate should be used to evaluate the persistence of localized corrosion.

Because the cumulative maximum localized corrosion rate is the corrosion rate on the most corroded electrode and the corrosion rate on the most corroded electrode may be lower than the corrosion rate taking place on the most corroding electrode (the maximum localized corrosion rate) at certain times, the cumulative maximum localized corrosion rate is always lower than the maximum localized corrosion rate:

$$CR_{\text{cmax}} \leq CR_{\text{max}} \quad (14)$$

Therefore, for process control applications (i.e., inhibitor dose control), the maximum localized corrosion rate, CR_{max} , should be used. However, for the evaluation of the effect of localized corrosion on the cumulative damage to a metal component, the cumulative maximum localized corrosion rate should be used. It should be noted that in a certain environment, the cumulative maximum localized corrosion rate may be very low, even zero, but the maximum localized corrosion rate may still be very high. This means that the localized corrosion on the most corroded electrode has stopped, but the localized corrosion on the other electrodes may still be high.

CONCLUSION

Cumulative maximum localized corrosion rate and maximum localized corrosion rate factors are important parameters for corrosion monitoring using coupled multielectrode array sensor probes. Maximum localized corrosion rate is the corrosion rate on any of the electrodes of a probe that has the highest corrosion rate at a given moment of time. The cumulative maximum localized corrosion rate is the corrosion rate of the electrode that has been corroded the most in a given time period. The cumulative maximum localized corrosion rate is directly related to the corrosion damage (maximum localized corrosion depth); the maximum localized corrosion depth equals the integration of the cumulative maximum localized corrosion rate. In many cases, such as stainless steel in seawater, the maximum localized corrosion rate often equals the cumulative maximum localized corrosion rate. In other cases, such as aluminum in seawater, however, the maximum localized corrosion rate is not the same as the cumulative maximum localized corrosion rate, because the corrosion rates on the different electrodes constantly change relative one to another. Maximum localized corrosion rate is always higher than the cumulative maximum localized corrosion rate. The maximum localized corrosion rate should be used for process control purposes, but the cumulative maximum localized corrosion rate should be used to evaluate the localized corrosion effect on metal damage in a given time.

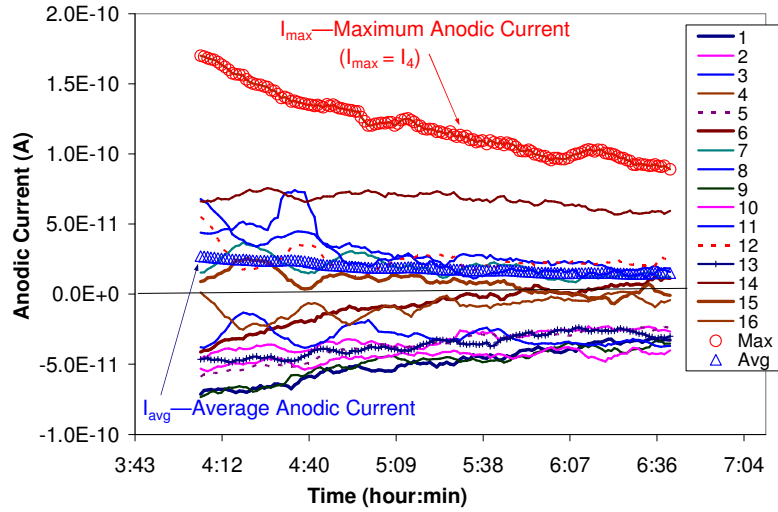


Figure 1. Typical currents measured from a stainless steel coupled multielectrode array sensor probe in simulated seawater. Maximum anodic current was due to one electrode (Electrode #4) throughout the measurement period and maximum localized corrosion rate can be directly calculated from the maximum anodic current. Note: the numbers in the legend indicate the IDs of the probe electrodes; a negative value of the anodic current means that the current is actually cathodic.

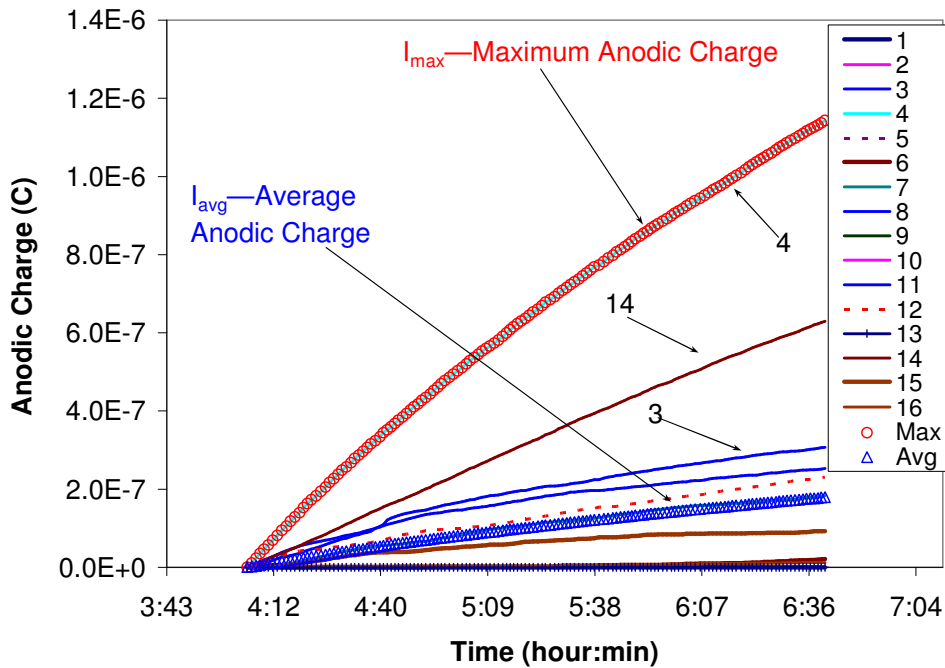


Figure 2. Anodic charges obtained from the data in Figure 1. Maximum anodic charge is the integration of the current from one electrode (Electrode #4).

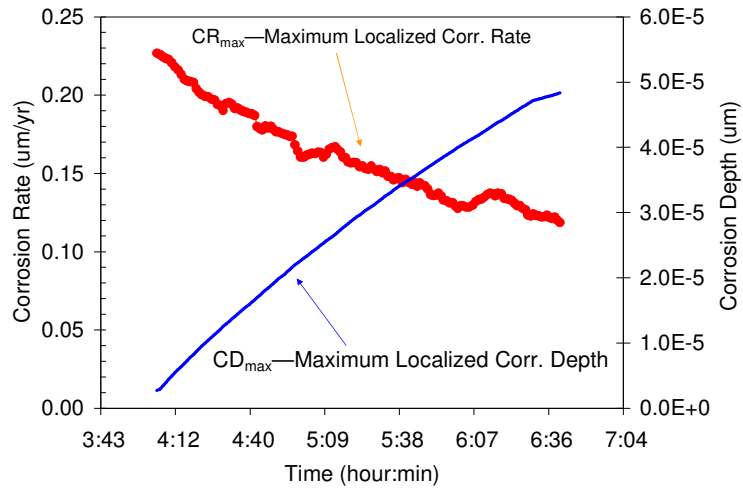


Figure 3. Maximum localized corrosion rate and maximum localized corrosion depth (penetration) for the data shown in Figures 1 and 2. The maximum localized corrosion depth is a direct integration of the maximum localized corrosion rate.

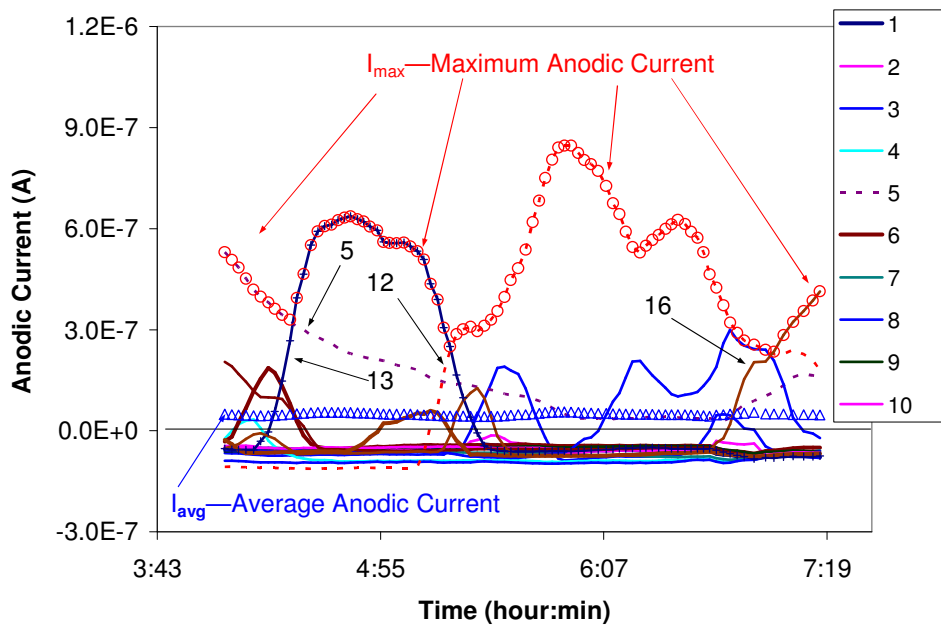


Figure 4. Typical currents measured from an aluminum coupled multielectrode array sensor probe in simulated seawater. Maximum anodic current was due to different electrodes (Electrodes #5, #13, #12, and #16) at different times and cumulative localized corrosion rate cannot be directly calculated from the maximum anodic current.

Note: the numbers in the legend and figure indicate the identifications of the probe electrodes; a negative value of the anodic current means that the current is actually cathodic.

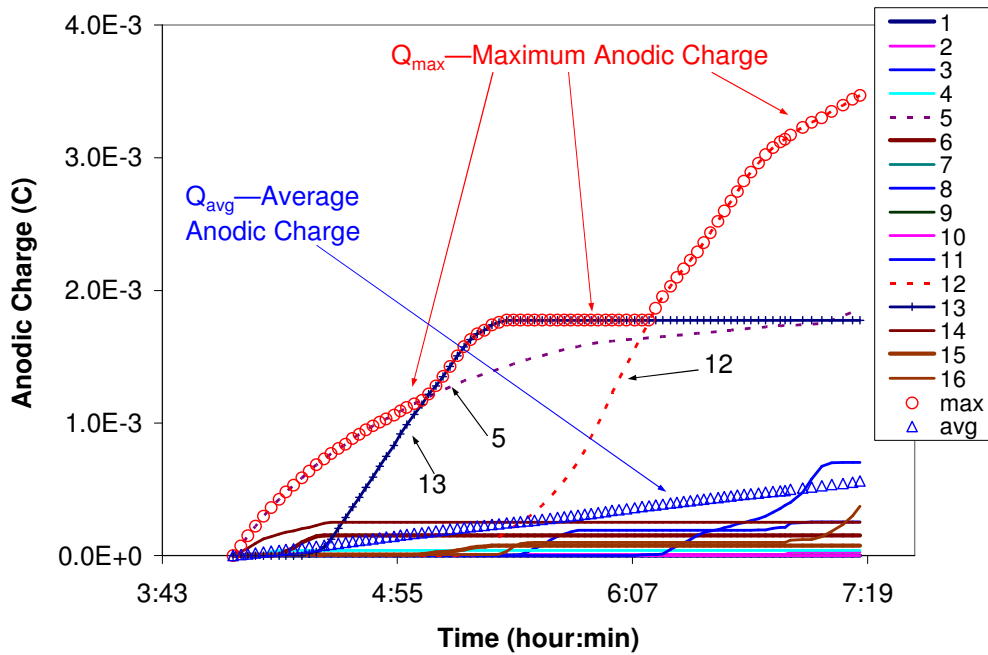


Figure 5. Anodic charges corresponding to Figure 4. Maximum anodic charge is the integration of the currents from different electrodes (Electrode #5, #13, and #12).

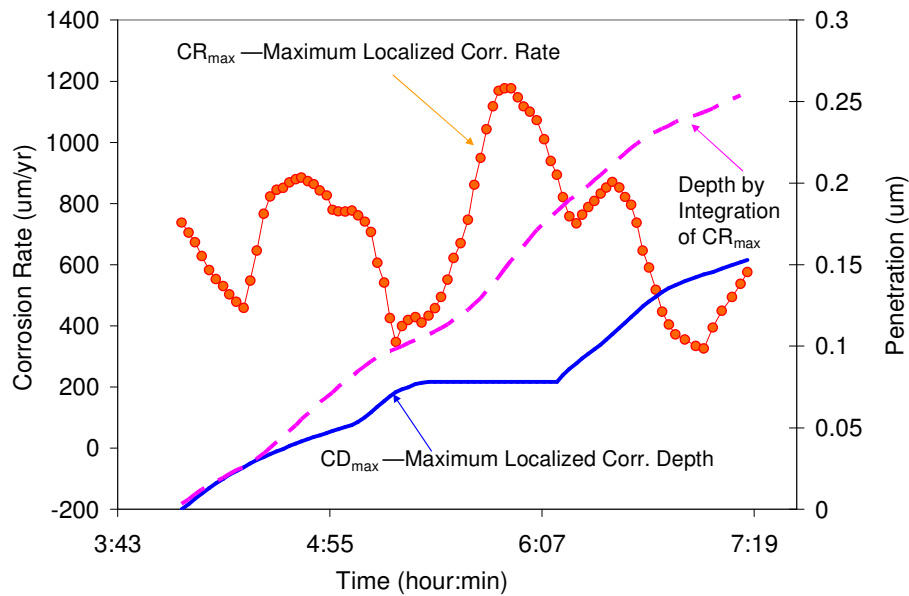


Figure 6. Maximum corrosion rate and maximum localized corrosion depth for the data shown in Figures 4 and 5. The dashed line was obtained by integrating the maximum localized corrosion rate, CR_{max} , and is much higher than the actual maximum localized corrosion depth, CD_{max} .

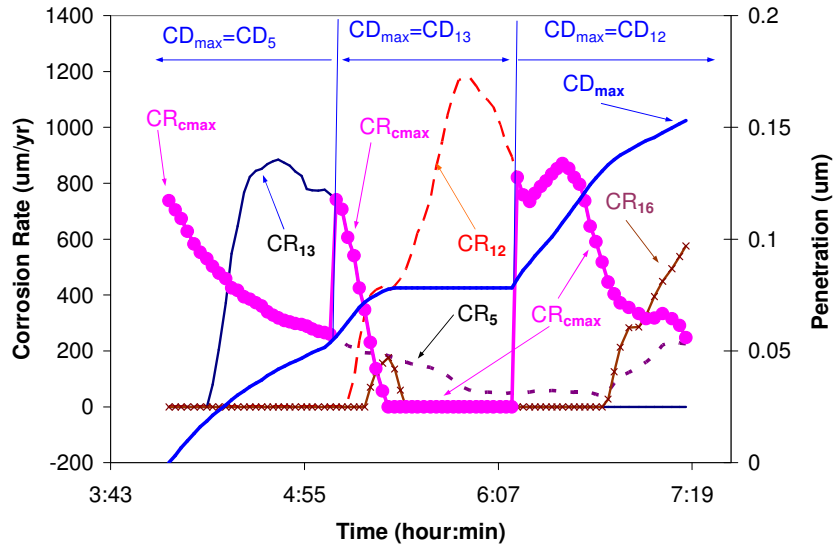


Figure 7. Cumulative maximum localized corrosion rate, maximum localized corrosion rate, and maximum localized corrosion penetration depth measured from the AL 3003 probe in simulated seawater.

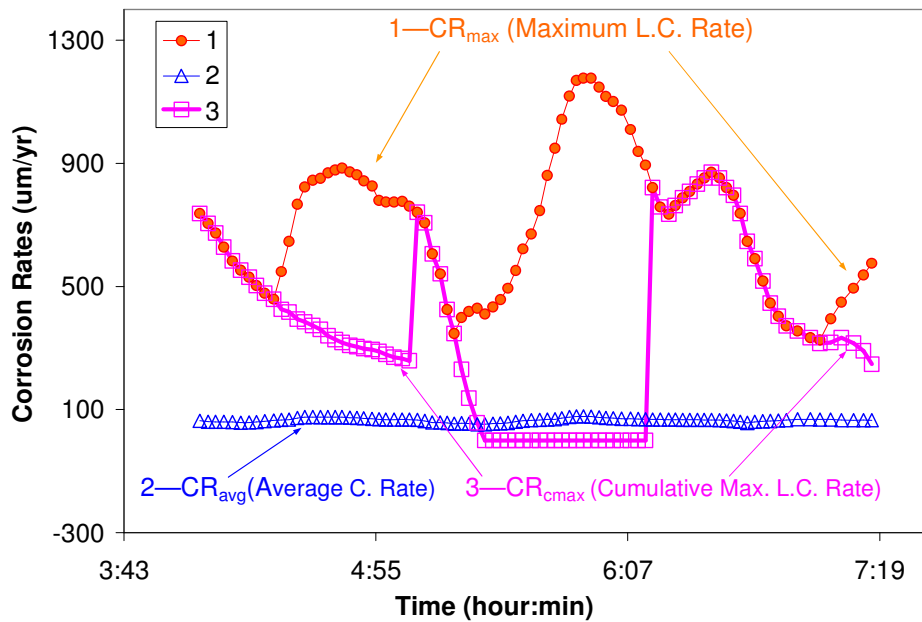


Figure 8. Maximum localized corrosion rate (CR_{max}), cumulative maximum localized corrosion rate (CR_{cmax}), and average corrosion rate (CR_{avg}) for the data shown in Figure 4. Patent pending.

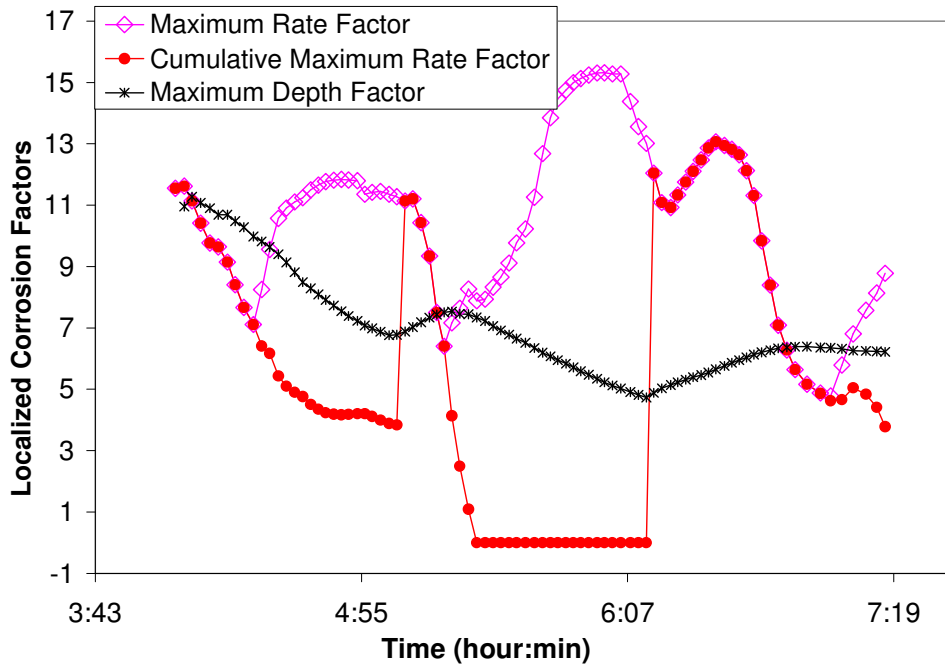


Figure 9. Maximum, cumulative localized corrosion rate factors, and maximum localized corrosion depth factor for the data shown in Figures 4 and 5.

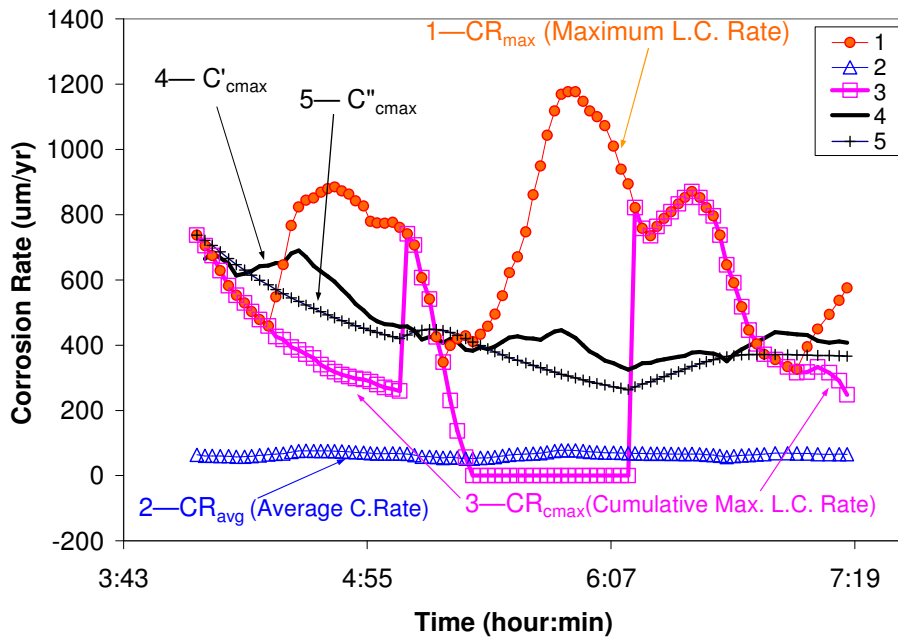


Figure 10. Alternative representations of localized corrosion rate by the localized corrosion depth factor multiplied by average corrosion rate (C'_{cmax}) or by time-averaged cumulative maximum localized corrosion rate (C''_{cmax}).

REFERENCES

1. Z. Fei, R. G. Kelly, and J. L. Hudson, "Spatiotemporal Patterns on Electrode Arrays," *J. Phys. Chem.*, 100, (1996): p. 18986-18991.
2. T.T. Lunt, J.R. Scully, V. Brusamarello, A.S. Mikhailov, and J.L. Hudson, "Spatial interactions among localized corrosion sites: experiments and modeling," *J. Electrochemical Soc.* 149, 5, B163-B173 (2002).
3. N.D. Budiansky, J.L. Hudson, J.R. Scully, "Origins of Persistent Interaction among Localized Corrosion Sites on Stainless Steel *Journal of the Electrochemical Society* (2004), 151(4), B233-B243].
4. Y.J. Tan, "Monitoring Localized Corrosion Processes and Estimating Localized Corrosion Rates Using a Wire-beam Electrode," *Corrosion*, Vol 54 (No. 5), 1998, p403-413.
5. Y.J. Tan, "Wire Beam Electrode: A New Tool for Studying Localized Corrosion and Other Inheterogeneity Electrochemical Processes," *Corrosion Science*, Vol 41 (No. 2), 1999, 229-247.
6. N. D. Budiansky, F. Bocher, H. Cong, M. F. Hurley, and J. R. Scully, "Use of Coupled Multi-Electrode Arrays to Advance the Understanding of Selected Corrosion Phenomena," *CORROSION/2006*, paper no. 06677 (Houston, TX: NACE, 2006).
7. Michael F. Hurley, John R. Scully, "Candidate Corrosion Resistant Reinforcement Materials for Concrete Structures: Corrosion Propagation Behavior," *CORROSION/2006*, paper no. 06340 (Houston, TX: NACE, 2006).
8. F. Doug Wall, "Applications of Multi-Electrode Techniques to Aqueous and Atmospheric Corrosion Testing," *CORROSION/2006*, paper no. 06672 (Houston, TX: NACE, 2006).
9. N. N. Aung, Y.J. Tan, "A New Method of Studying Buried Steel Corrosion and Its Inhibition Using the Wire Beam Electrode," *Corrosion Science*, 46, (2004), pp.3057-3067.
10. Y. J. Tan, "An Experimental Comparison of Three Wire Beam Electrode Based Methods for Determining Corrosion Rates and Patterns," *Corrosion Science*, 47 (2005) 1653–1665.
11. M. H. Dorsey, L. Yang and N. Sridhar, "Cooling Water Monitoring Using Coupled Multielectrode Array Sensors and Other On-line Tools," *CORROSION/2004*, paper no. 04077, (Houston, TX: NACE International, 2004).
12. Michael H. Dorsey, Daniel R. Demarco, Brian J. Saldanha, George A. Fisher, Lietai Yang and Narasi Sridhar, "Laboratory Evaluation of a Multi-Array Sensor for Detection of Underdeposit Corrosion and/or Microbially Influenced Corrosion," *CORROSION/2005*, paper no. 05371 (Houston, TX: NACE, 2005).
13. A. Anderko, N. Sridhar¹ and L. Yang, S.L. Grise, B.J. Saldanha, and M.H. Dorsey, "Validation of a Localized Corrosion Model Using Real-Time Corrosion Monitoring in a Chemical Plant,"

Corrosion Engineering, Science and Technology (formerly British corrosion J.), Vol. 40, pp.33-42, August, 2005

14. L. Yang and N. Sridhar, "Coupled Multielectrode Array Systems And Sensors for Real-Time Corrosion Monitoring - A Review," CORROSION/2006, paper no. 06681 (Houston, TX: NACE, 2006).
15. L. Yang and N. Sridhar, "Monitoring of Localized Corrosion ASM Handbook," Volume 13A-Corrosion: Fundamentals, Testing, and Protection, Stephen. D. Crammer and Bernard S. Covino, Jr., Eds., ASM International, Materials Park, Ohio, 2003, pp 519-524.
16. L. Yang, N. Sridhar, O. Pensado, and D.S. Dunn, *Corrosion*, 58 (2002), p.1004.
17. L. Yang and N. Sridhar, "Coupled Multielectrode Online Corrosion Sensor," *Materials Performance*, 42 (9), pp 48-52 (2003).
18. L. Yang, R.T. Pabalan, L. Browning, and G.C. Cragnolino, "Measurement of Corrosion in Saturated Solutions under Salt Deposits Using Coupled Multielectrode Array Sensors," CORROSION/2003, paper no. 426 (Houston, TX: NACE, 2003).
19. L. Yang, R. T. Pabalan, L. Browning and D.S. Dunn, "Corrosion Behavior of Carbon Steel and Stainless Steel Materials under Salt Deposits in Simulated Dry Repository Environments," in *Scientific Basis for Nuclear Waste Management XXVI* R. J. Finch and D. B. Bullen, Eds., Warrendale, PA: Materials Research Society, M.R.S. Symposium Proceedings Vol. 757, pp.791-797, 2003.
20. C.S. Brossia and L. Yang, "Studies of Microbiologically Induced Corrosion Using a Coupled Multielectrode Array Sensor," CORROSION/2003, paper no. 575 (Houston, TX: NACE, 2003).
21. X. Sun, Xiaodong Sun, "Online Monitoring of Corrosion under Cathodic Protection Conditions Utilizing Coupled Multielectrode Sensors," CORROSION/2004, paper no. 04094, (Houston, TX: NACE International, 2004).
22. X. Sun, "Online Monitoring of Undercoating Corrosions Utilizing Coupled Multielectrode Sensors," CORROSION/2004, paper no.04033 (Houston, TX: NACE, 2004).
23. X. Sun, "Online and Real-Time Monitoring of Carbon Steel Corrosion in Concrete Using Coupled Multielectrode Sensors," CORROSION/2005, paper no.05267 (Houston, TX: NACE, 2005).
24. Lietai Yang, Darrell Dun and Gustavo Cragnolino, "An Improved Method for Real-time and Online Corrosion Monitoring Using Coupled Multielectrode Array Sensors," CORROSION/2005, paper no. 05379, (Houston, TX: NACE International, 2005).
25. Lietai Yang, Darrell Dun, Yi-Ming Pan and Narasi Sridhar, "Real-time Monitoring of Carbon Steel Corrosion in Crude Oil and Salt Water Mixtures Using Coupled Multielectrode Sensors," CORROSION/2005, paper no. 05293, (Houston, TX: NACE International, 2005).

26. Xiaodong Sun, "Real-Time Corrosion Monitoring in Soil with Coupled Multielectrode Sensors," CORROSION/2005, paper no.05381 (Houston, TX: NACE, 2005).
27. Xiaodong Sun, "Online Monitoring of Undercoating Corrosion Using Coupled Multielectrode Sensors," Materials Performance, 44 (2), p28-32 (2005).
28. Xiaodong Sun and Lietai Yang, "Real-Time Monitoring of Localized Corrosion in Drinking Water Utilizing Coupled Multielectrode Array Sensors," CORROSION/2006, paper no. 06094, (Houston, TX: NACE International, 2006).
29. Xiaodong Sun and Lietai Yang, "Real-Time Monitoring of Localized and General Corrosion Rates in Simulated Marine Environments Using Coupled Multielectrode Array Sensors," CORROSION/2006, paper no. 06284 (Houston, TX: NACE, 2006).
30. Xiaodong Sun and Lietai Yang, "Real-time Measurement of Crevice Corrosion with Coupled Multielectrode Array Sensors," CORROSION/2006, paper no. 06679 (Houston, TX: NACE, 2006).
31. K. Chiang and L. Yang, "Monitoring Corrosion Behavior of a Cu-Cr-Nb Alloy by Multielectrode Sensors," CORROSION/2006, paper no. 06676 (Houston, TX: NACE, 2006).
32. N. Sridhar, L. Yang and F. Song, "Application of Multielectrode Array to Study Dewpoint Corrosion in High Pressure Natural Gas Pipeline Environments," CORROSION/2006, paper no. 06673 (Houston, TX: NACE, 2006).
33. Peter Angell, "Use of the Multiple-Array-Sensor to Determine the Effect of Environmental Parameters on Microbial Activity and Corrosion Rates," CORROSION/2006, paper no. 06671 (Houston, TX: NACE, 2006)
34. Lietai Yang, Narasi Sridhar, C. Sean Brossia, Darrell S. Dunn, "Evaluation of the Coupled Multielectrode Array Sensor as a Real-time Corrosion Monitor," Corrosion Science, 47 (2005), p.1794-1809.