Selected Publications and Abstracts on Multielectrode Array Sensors for Corrosion Monitoring

2007

1. **"Coupled Multielectrode Array Systems and Sensors" in "Corrosion Inspection and Monitoring", Pierre R. Roberge, Section 4.3.3.3.3, Hoboken, NJ: John Wiley &Sons. Inc, pp.207-209, 2007.**

2. **"Electronic system for multielectrode sensors and electrochemical devices", Xiaodong Sun Yang, US Patent, #7,180,309 (United States Patent and Trademark Office, 2007).**

3. **"Multielectrode Penetration Sensor for Monitoring Localized and General Corrosion", Xiaodong Sun and Lietai Yang, CORROSION/2007, paper no. 07391 (Houston, TX: NACE, 2006).**

4 **"Measurement of Cumulative Localized Corrosion Rate Using Coupled Multielectrode Array Sensors," Lietai Yang and Xiaodong Sun, CORROSION/2007, paper no. 07378 (Houston, TX: NACE, 2007).**

5. **"Development of Crevice-Free Multielectrode Sensors for Elevated Temperature Applications", Kuang-Tsan Kenneth Chiang and Lietai Yang, CORROSION/2007, paper no. 07376 (Houston, TX: NACE, 2007).**

6. **"Laboratory and Field Studies of Localized and General Corrosion Inhibiting Behaviors of Silica in Zero Liquid Discharge (High TDS Cooling Water) using Real Time Corrosion Monitoring Techniques" Dan Duke, Lietai Yang, CORROSION/2007, paper no. 07626 (Houston, TX: NACE, 2007).**

2006

1. **"Coupled Multielectrode Array Systems And Sensors for Real-Time Corrosion Monitoring - A Review", L. Yang and N. Sridhar, CORROSION/2006, paper no. 06681 (Houston, TX: NACE, 2006).**

2. **"Real-time Measurement of Crevice Corrosion with Coupled Multielectrode Array Sensors", X. Sun and L. Yang, CORROSION/2006, paper no. 06679 (Houston, TX: NACE, 2006).**

3. **"Real-Time Monitoring of Localized and General Corrosion Rates in Simulated Marine Environments Using Coupled Multielectrode Array Sensors", X. Sun and L. Yang, CORROSION/2006, paper no. 06284 (Houston, TX: NACE, 2006).**

4. **"Real-Time Monitoring of Localized and General Corrosion Rates in Drinking Water Utilizing Coupled Multielectrode Array Sensors", X. Sun and L. Yang, CORROSION/2006, paper no. 06094 (Houston, TX: NACE, 2006).**

5. **"Monitoring Corrosion Behavior of a Cu-Cr-Nb Alloy by Multielectrode Sensors", K. Chiang and L. Yang, CORROSION/2006, paper no. 06676 (Houston, TX: NACE, 2006).**

6. **“Application of Multielectrode Array to Study Dewpoint Corrosion in High Pressure Natural Gas Pipeline Environments”, N. Sridhar, L. Yang and F. Song, CORROSION/2006, paper no. 06673 (Houston, TX: NACE, 2006).**

7. **“Use of the Multiple-Array-Sensor to Determine the Effect of Environmental Parameters on Microbial Activity and Corrosion Rates”. P. Angell, CORROSION/2006, paper no. 06671 (Houston, TX: NACE, 2006).**

2005

1 **“Evaluation of the coupled multielectrode array sensor as a real-time corrosion monitor”, Lietai Yang, Narasi Sridhar, C. Sean Brossia, Darrell S. Dunn, Corrosion Science, 47 (2005), p.1794-1809.**
Coupled multielectrode array sensors made of carbon steel and stainless steels were evaluated and compared with electrochemical noise (EN) sensors. Good correlations between sensor signals and solution corrosivity were observed for all multielectrode array sensors. Some correlation between the average pit index and solution corrosivity was observed for the carbon steel EN sensors, but not for the stainless steel EN sensors. The time-average noise resistances from the stainless steel EN sensors correlate well with solution corrosivity. There were, however, large random fluctuations and drifting for all EN signals, which make the EN sensors unreliable as real-time monitors.

2 **“Online Monitoring of Undercoating Corrosion Using Coupled Multielectrode Sensors", X. Sun, Materials Performance, 44(3), March (2005), pp. 28-32.**
Online monitoring of carbon steel corrosion under different commercial coatings was conducted utilizing coupled multielectrode sensors. The experimental results showed that the coupled multielectrode sensor is an effective tool for detecting initial defects and real-time degradation of coatings. Because of their high sensitivity, the coupled multielectrode sensors may also be used as a quick and convenient tool for optimizing the selection of proper coatings for different applications.

3 **"Online and Real-Time Monitoring of Carbon Steel Corrosion in Concrete, Using Coupled Multielectrode Sensors,” X. Sun, CORROSION/2005, paper no. 05267 (Houston, TX: NACE International, 2005).**
Real-time corrosion monitoring of carbon steel rebar materials in concrete was conducted utilizing coupled multielectrode sensors. It was demonstrated that the coupled multielectrode sensor is a quantitative and real-time tool for the monitoring localized corrosion rates in concrete. The coupled multielectrode sensor also provided real-time indications for the effectiveness of cathodic protection in concrete.

4 **“Real-Time Corrosion Monitoring in Soil with Coupled Multielectrode Sensors,” X. Sun, CORROSION/2005, paper no. 05381 (Houston, TX: NACE International, 2005).**
Real-time corrosion monitoring for carbon steel materials in soil was conducted utilizing coupled multielectrode sensors. It was demonstrated that the coupled multielectrode sensor is an effective realtime tool for monitoring the corrosion rate in soil. The steady state corrosion rate measured in water saturated soil was found to be approximately 2 to15 μm/year. However, the corrosion rate in a space filled with water was several orders of magnitude higher than those found in the densely packed soil saturated with water. The coupled multielectrode sensor also provided real-time indications for the effectiveness of cathodic protection in soil.

5 **"Laboratory Evaluation of a Multi-Array Sensor for Detection of Under Deposit Corrosion and/or Microbiologically Influenced Corrosion", M. H. Dorsey, D.R. Demarco, G. A. Fisher, and B. J. Saldanha, CORROSION/2005, paper no. 05371 (Houston, TX: NACE International, 2005).**
Real-time coupled multielectrode array sensors (MAS) and other monitoring tools were used to evaluate the corrosion of carbon steel and stainless steel in a laboratory based recirculating flow loop simulating an industrial cooling water system. The design and implementation of the monitoring system and results are discussed in this paper. Characterization of the degree and depth of attack from the MAS probe showed good correlation with characterization of under deposit attack on corrosion coupons that were exposed simultaneously with the MAS probe. In addition, sensor response was altered in the presence of microorganisms suggesting the possible influence of biofilm and/or microbial products on corrosion rates and sensor signals.

6 **"An Improved Method for Real-Time and Online Corrosion Monitoring, Using Coupled Multielectrode Array Sensors," L. Yang, D. S. Dunn, and G. A. Cragnolino,**

CORROSION/2005, paper no. 05379 (Houston, TX: NACE International, 2005).
Coupled multielectrode array sensors (MAS) may underestimate non-uniform corrosion rates in cases where the environment is not significantly corrosive because of possible internal electron lows on the most corroding electrode. An improved method was developed to derive the lower and upper bounding values for the non-uniform corrosion rate measured with the MAS probes. The lower boundary was measured when the electrodes of the MAS probe were at the natural coupling potential. The upper boundary was measured when the coupling potential of the MAS probe was raised to a value at which all electrodes are likely to be anodic. Under such raised coupling potential, possible internal electron flows within the most anodic electrode were stopped and their effects on the measured corrosion rate were eliminated.

7 **"Real-Time Monitoring of Carbon Steel Corrosion in Crude Oil and Salt Water Mixtures Using Coupled Multielectrode Sensors," L. Yang, Y-M. Pan, D.S. Dunn, and N. Sridhar, CORROSION/2005, paper no. 05293 (Houston, TX: NACE International, 2005).**
A real-time coupled multielectrode array sensor was used to measure the non-uniform corrosion of carbon steel material in a crude oil containing different amounts of brine solutions. Parallel immersion tests with carbon steel specimens in the crude oil were also conducted. The measurement results from the sensor and the results from immersion tests show that the crude-brine mixtures were not corrosive if there was no segregated phase of brine or water formed. However, the crude-brine mixture was highly corrosive when a segregated brine phase was present even in a small quantity. The measured results also show that, once initiated by even a small amount of suspended brine particulates, it took a long time for the corrosion to stop after the brine was homogeneously mixed with the crude oil.

8 **"Validation of a Localized Corrosion Model Using Real-Time Corrosion Monitoring in a Chemical Plant", A. Anderko, N. Sridhar1 and L. Yang, S.L. Grise, B.J. Saldanha, and M.H. Dorsey, Corrosion Engineering, Science and Technology (formerly British corrosion J.), Vol 40, August, 2005, pp.33-42.**

2004

1 **"Monitoring Localized Corrosion", by M.V. Veazey, Materials Performance, August (2004): p.12.**
Engineers at Southwest Research Institute (SwRI) (San Antonio, Texas) have developed a sensor technology that reportedly can perform real-time monitoring of localized corrosion in structures such as bridges, chemical plants, pipelines, refineries, and aircraft. "The Multielectrode Array Sensor System [MASS] can be tailored to meet the process needs of a variety of industries," says Narasi Sridhar, Program Director in SwRI's Mechanical and Materials Engineering Division. According to SwRI, MASS uses multiple miniature electrodes composed of materials identical to the component being tested as the sensing electrode. The electrodes are coupled together by connecting each to a common joint through independent small resistors. Each electrode simulates part of a corroding metal. The voltage drop across the resistors produces anodic and cathodic currents, which signal localized corrosion…..

2\. **"What's New in the Water Industry?", by Arthur J. Freedman, Materials Performance, May (2004): p.8.**
….In another field study of under deposit corrosion, arrays of microelectrodes were used to simulate anodes and cathodes on metal surfaces. The results accurately simulated microbiologically influenced corrosion observed on carbon steel exposed in contaminated surface water. These techniques and others may someday become practical tools for monitoring under deposit corrosion in cooling water systems…..

3 **"Online Monitoring of Undercoating Corrosions Utilizing Coupled Multielectrode Sensors", by X. Sun, CORROSION/2004, paper no. 04033, (Houston, TX: NACE International, 2004).**
Abstract: Online monitoring of carbon steel corrosion under different commercial coatings was conducted, utilizing coupled multielectrode sensors. The experimental results showed that the coupled multielectrode corrosion sensor is an effective tool for detecting initial defects and real-time degradation of the coatings. Because of their high sensitivity, the coupled multielectrode sensors may also be used as a quick and convenient tool for optimizing the selection of proper coatings for different applications.

4 **"Online Monitoring of Corrosion under Cathodic Protection Conditions Utilizing Coupled Multielectrode Sensors", by X. Sun, CORROSION/2004, paper no. 04094, (Houston, TX: NACE International, 2004).**
Abstract: Real-time corrosion monitoring for carbon steel materials in simulated seawater under cathodic protection conditions was conducted, utilizing coupled multielectrode sensors. It was demonstrated that the coupled multielectrode sensor is an effective real-time tool for monitoring the effectiveness of cathodic protection and for

measurement of the threshold value of the protection potential for specific equipment.

5 **"Cooling Water Monitoring Using Coupled Multielectrode Array Sensors and Other On-line Tools", by M. H. Dorsey, L. Yang and N. Sridhar, CORROSION/2004, paper no. 04077, (Houston, TX: NACE International, 2004).**

Abstract: Real-time coupled multielectrode array sensors (MAS) and other monitoring tools were used to evaluate a complex corrosion phenomenon on carbon steel in a large industrial cooling water system. The design and implementation of the monitoring system, and monitoring results are discussed in this paper. Characterization of the degree and depth of attack from the MAS probe showed excellent correlation with characterization of under deposit attack on corrosion coupons that were exposed simultaneously with the MAS probe.

6 **"Real-Time Corrosion Monitoring in a Process Stream of a Chemical Plant Using Coupled Multielectrode Array Sensors", by L. Yang and N. Sridhar, S. L. Grise, B. J. Saldanha, M.H. Dorsey, H. J. Shore and A. Smith, CORROSION/2004, paper no. 04440, (Houston, TX: NACE International, 2004).**

Abstract: Coupled multielectrode array sensors made of Type 316L stainless steel, AL6XN and Alloy C-276 alloys were used as real time-sensors to monitor localized corrosion in a side loop of a process stream in a chemical plant. The pitting corrosion rates measured from the probes made of stainless steel and nickel-chromium alloys are consistent with the pitting resistance equivalent numbers of the alloys and with the plant experience. The pitting rate obtained from the long-term measurement is in good agreement with the actual corrosion rate obtained from the posttest surface examination of the probes.

7 **"Laboratory Comparison of Coupled Multielectrode Array Sensors with Electrochemical Noise Sensors for Real-Time Corrosion Monitoring", by L. Yang, N. Sridhar, D. S. Dunn and C. S. Brossia, CORROSION/2004, paper no. 04033, (Houston, TX: NACE International, 2004).**

Abstract: The performance of the electrochemical noise sensors made of carbon steel and stainless steels were tested and compared with the coupled multielectrode array sensors made of the same materials as real-time corrosion sensors. No correlation was observed between the pit index signals for localized corrosion from the electrochemical noise sensors and the corrosivity of the solution. The noise resistance signals for general corrosion that were averaged over long time intervals appeared to correlate with the corrosivity of the solutions However, the fluctuation of noise resistance signals was significant and often overwhelmed the measured signals. Averaging over long time intervals were required to obtain meaningful noise resistance signals for the electrochemical noise (EN) sensors. Thus the EN sensors may not be reliable for real-time measurement of localized corrosion. It may be used for real-time measurement of general corrosion. The responses of the coupled multielectrode array sensors to the localized corrosivity of the solutions were excellent.

8 **"Sensor Array and Method for Electrochemical Corrosion Monitoring", L. Yang and N. Sridhar, U.S. Patent No. 6,683,463 (2004).**

9 **"Studies on The Corrosion Behavior of Stainless Steels in Chloride Solutions in the Presence of Sulfate Reducing Bacteria", by L. Yang and G. A. Cragnolino, CORROSION/2004, paper no. 04598, (Houston, TX: NACE International, 2004).**

2003

1 **Monitoring of Localized Corrosion", by L. Yang and N. Sridhar, in ASM Handbook, Volume 13A-Corroson: Fundamentals, Testing, and Protection, Stephen. D. Crammer and Bernard S. Covino, Jr. Eds, ASM International, Materials Park, Ohio, 2003, pp 519-524.**

2 **"Coupled Multielectrode Online Corrosion Sensor", L. Yang and N. Sridhar, Materials Performance, 42(9) September (2003): p.48-52.**

This article describes the development, application, and validation of a new sensor to monitor nonuniform and localized corrosion in many different applications. The main advantage of this sensor is its ability to monitor localized corrosion in real-time

3 **"Studies of Microbiologically Influenced Corrosion Using a Coupled Multielectrode Array Sensor", by C. Sean Brossia and Lietai Yang, ‚CORROSION/2003, paper no. 03575, (Houston, TX: NACE International, 2003).**

Abstract: A newly developed multielectrode array sensor (MASS) was used to conduct a series of abiotic and biotic tests to determine if the probe can detect corrosion induced by microbial activity. The probe was able to determine the maximum corrosion rate in the presence of sulfate reducing bacteria (SRB) and showed that this rate was at least a factor of 10 greater than in the absence of SRBs. In addition, the corrosion rates obtained using the probe were much higher than those determined using linear polarization resistance further demonstrating its inherent better sensitivity to localized corrosion.

4 **"The Study of Atmospheric Corrosion of Carbon Steel and Aluminum under Salt Deposit Using Coupled Multielectrode Array Sensors", by L. Yang, Roberto T. Pabalan and Darrell S. Dunn, the 204th Meeting of the Electrochemical Society, Abstract #465, Extended Abstract Volume 2003-II (Pennington, NJ: Electrochemical Society, 2003).**

http://www2.electrochem.org/cgi-bin/abs?mtg=204&abs=0465

5 **"Development of Sensors for Waste Package Testing and Monitoring in the Long Term Repository Environments", V. Jain, S. Brossia, D. Dunn, and L. Yang, Ceramic Transactions, Vol. 143, pp. 283-290, 2003, American Ceramic Society, Westerville, OH**

6 **"Corrosion Behavior of Carbon Steel and Stainless Steel Materials under Salt Deposits in Simulated Dry Repository Environments", by L. Yang, R. T. Pabalan, L. Browning and D.S. Dunn,, 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.**

Abstract: *In-situ* coupled multielectrode array sensors were used to measure the non-uniform corrosion of carbon steel and stainless steel materials under KCl salt deposit in simulated dry repository environments. It was found that the initiation of non-uniform corrosion occurs at a relative humidity that is 14% lower than the deliquescence relative humidity of the chloride salt. It was found also that once significant corrosion had occurred, the non-uniform corrosion process for the carbon steel material under the salt deposit continues at relative humidities as low as 27%.

7 "Measurement of Corrosion in Saturated Solutions under Salt Deposits Using Coupled Multielectrode Array Sensors", by L. Yang, R. T. Pabalan, L. Browning, and G. A. Cragnolino, CORROSION/2003, paper no. 03426, (Houston, TX: NACE International, 2003).

Abstract: The corrosion rates of type 1010 carbon steel, and types 304 and 316 stainless steels in saturated solutions under salt deposits were measured using coupled multielectrode sensors. The measurements were carried out in the presence of the following salts: KCl, NaCl, NaNO3, MgCl2, NiCl2, FeCl3, FeCl2, CuCl2, and a NaCl+NaNO3 mixture.
The results indicate that the corrosiveness of the salts increased in the following order:
KCl ~ NaCl ~ NaNO3 ~ NaCl+NaNO3 ~ MgCl2 < NiCl2 < FeCl3 < FeCl2 < CuCl2
for carbon steel, and
KCl ~ NaCl ~ MgCl2 ~ NiCl2 ~ NaCl+NaNO3 < FeCl3 ~ FeCl2 ~ CuCl2
for type 304 stainless steel. Some inhibition of corrosion of type 316 stainless steel by NaNO3 was observed in a mixture of NaCl+NaNO3, but not in pure NaNO3 solution.

8 **"An Electrochemical Approach to Predicting and Monitoring Localized Corrosion in Chemical Process Streams", by A. Anderko, N. Sridhar, C. S. Brossia, D. S. Dunn, L.T. Yang, B.J. Saldanha, S.L. Grise, and M.H. Dorsey, CORROSION/2003, paper no. 03375, (Houston, TX: NACE International, 2003).**

Abstract: A general model for predicting the occurrence of localized corrosion in chemical process streams is described. The model predicts the repassivation and corrosion potentials based on input chemistry of a system. The model predictions are compared to experimental data. Initial data from a validation study using a multielectrode array sensor at a process plant is described.

2002

1 **"Evaluation of Corrosion Inhibitors in Cooling Water Systems Using a Coupled Multielectrode Array Sensor", by L. Yang, and D. S. Dunn, CORROSION/2002, paper no. 02004, (Houston, TX: NACE International, 2002).**

Abstract: A multielectrode localized corrosion sensor has been developed for evaluating the performance of corrosion inhibitors for carbon steel in cooling water. Experimental results indicate that the coupled multielectrode sensor provided instantaneous measurement of corrosion currents and a rapid real-time response to the addition of inhibitors. Evaluation of several inhibitors showed that the sensor was able to distinguish between inhibitor type and concentration. It was also demonstrated that the sensor has a detection limit of 5x10-11A with respect to current measurement. The capabilities of the sensor may be suitable for online monitoring of corrosion in a variety of applications where real-time

monitoring is required.

2 **"Comparison of Localized Corrosion of Fe-Ni-Cr-Mo Alloys in Concentrated Brine Solutions Using a Coupled Multielectrode Array Sensor", by L. Yang, N. Sridhar, and G. Cragnolino, CORROSION/2002, paper no. 545, Houston, TX: NACE International, 2002).**

Abstract: A multielectrode localized corrosion sensor was developed and used for comparing localized corrosion of Fe-Ni-Cr-Mo alloys in chloride solutions. Experimental results indicated that the coupled multielectrode sensor provides a rapid real-time response to changes in temperature and salt concentration. It was demonstrated that the sensor has a lower detection limit of 5×10^{-11} A with respect to corrosion current and 2×10^{-8} A/cm^2 with respect to the corrosion current density for the miniature electrodes used in the sensors.

3 **"An In-situ Galvanically Coupled Multielectrode Array Sensor for Localized Corrosion", by L. Yang, N. Sridhar, O. Pensado, and D. S. Dunn, Corrosion, 58 (2002): p.1004-1014.**

Abstract: A localized corrosion sensor consisting of multiple, corrodible, miniature electrodes was tested in different chemical environments. The miniature electrodes were coupled together by connecting each of them to a common joint through independent resistors, with each electrode simulating an area of a corroding metal. In a localized corrosion environment, anodic currents flow into the more corroding electrode, and cathodic currents flow out of the less or noncorroding electrodes. These currents are measured from the voltages across the resistors. The variation among the galvanic currents measured from the miniature electrodes responded well to changes of the environment with respect to localized corrosion. It was demonstrated that statistical parameters derived from the currents flowing through the miniature electrodes, such as the standard deviation or the 90th percentile anodic value, can be used as effective indictors for localized corrosion. Measurement has shown the following order of corrosiveness of the environment for UNS S30400 stainless steel:

deionized water < saturated KCl < 1 M $NaNO_3$ + 0.25 M $FeCl_3$ < 0.0025 M $FeCl_3$ < 0.25 M $FeCl_3$.

It was also shown that the penetration rate of localized corrosion may be estimated from either the measured maximum or the standard deviation of the anodic current densities, and the cumulative penetration may be estimated from either the measured maximum or the standard deviation of the cumulative anodic charges through the electrodes.

4 **"Corrosion Sensing and Monitoring", by C.S. Brossia, L. Yang, D.S. Dunn, N. Sridhar, in Proceedings of Tri-Service Corrosion Conference, Jan. 14-18, 2002, San Antonio, TX.**

2001

"Development of a Multielectrode Array Sensor for Monitoring Localized Corrosion", by L. Yang, N. Sridhar, and O. Pensado, Presented at the 199th Meeting of the Electrochemical Society, Abstract #182, Extended Abstract Volume I, (Pennington, NJ: Electrochemical Society, 2001).