Coupled Multielectrode Sensors for Real-Time Localized Corrosion Monitoring

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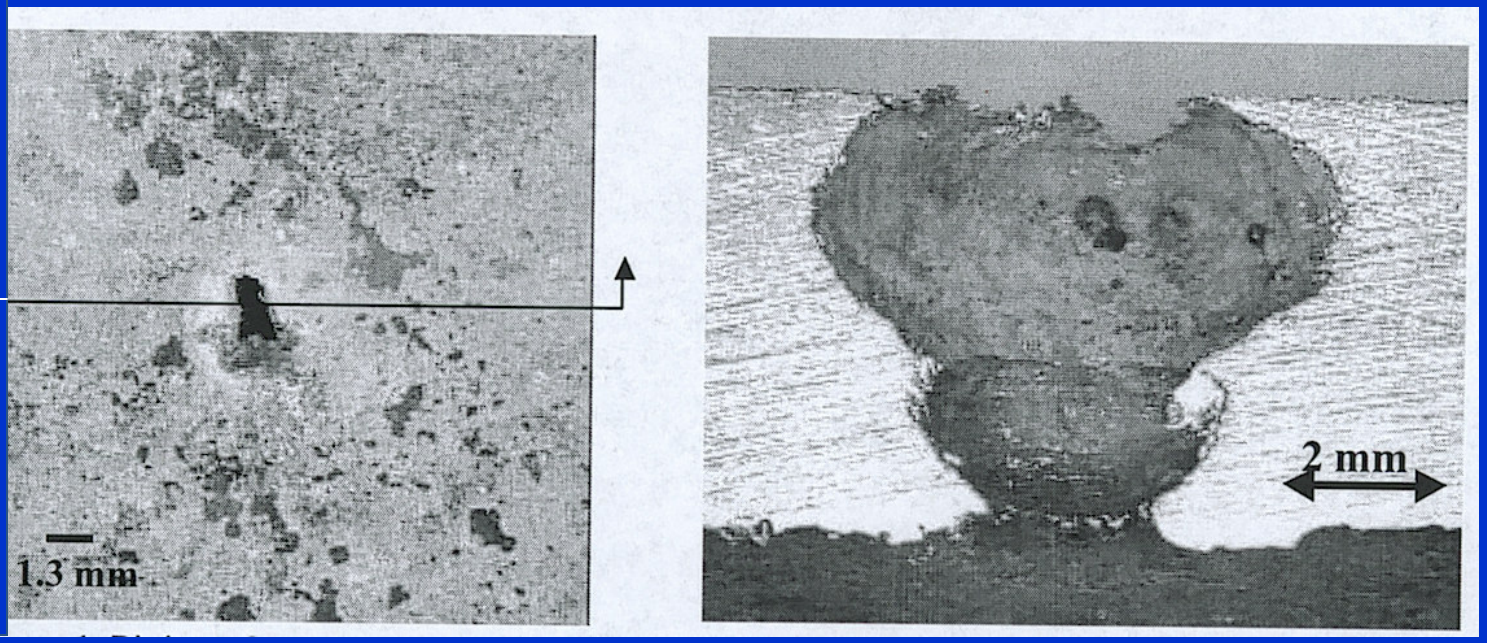
Background: Corrosion Modes

- Uniform Corrosion
  - relatively slow and, in most cases, predictable
- Non-Uniform (Localized) Corrosion
  - high rates of metal penetration, leading to premature failure even though majority of metal surface not affected
  - 90% metal damage in chemical processing industry was caused by localized corrosion (LaQue, F.L., 1974. Localized Corrosion, National Association of Corrosion Engineers)

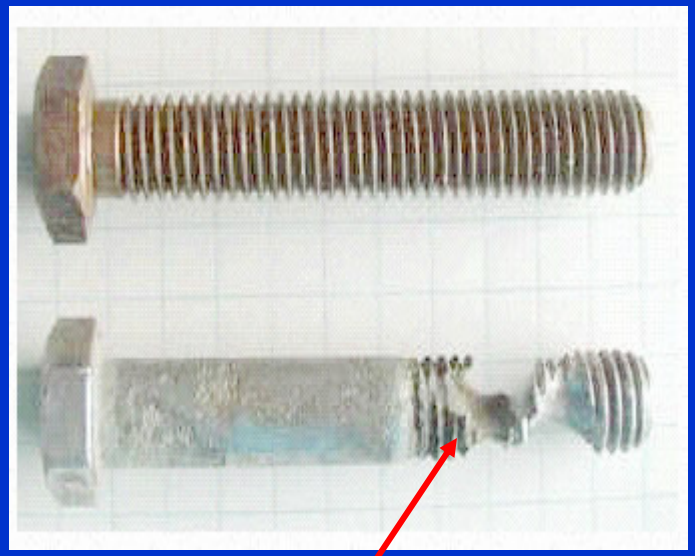
Localized Corrosion: Examples of Pitting Corrosion



Through Hole Pitting of Type 316L Seawater Pipe

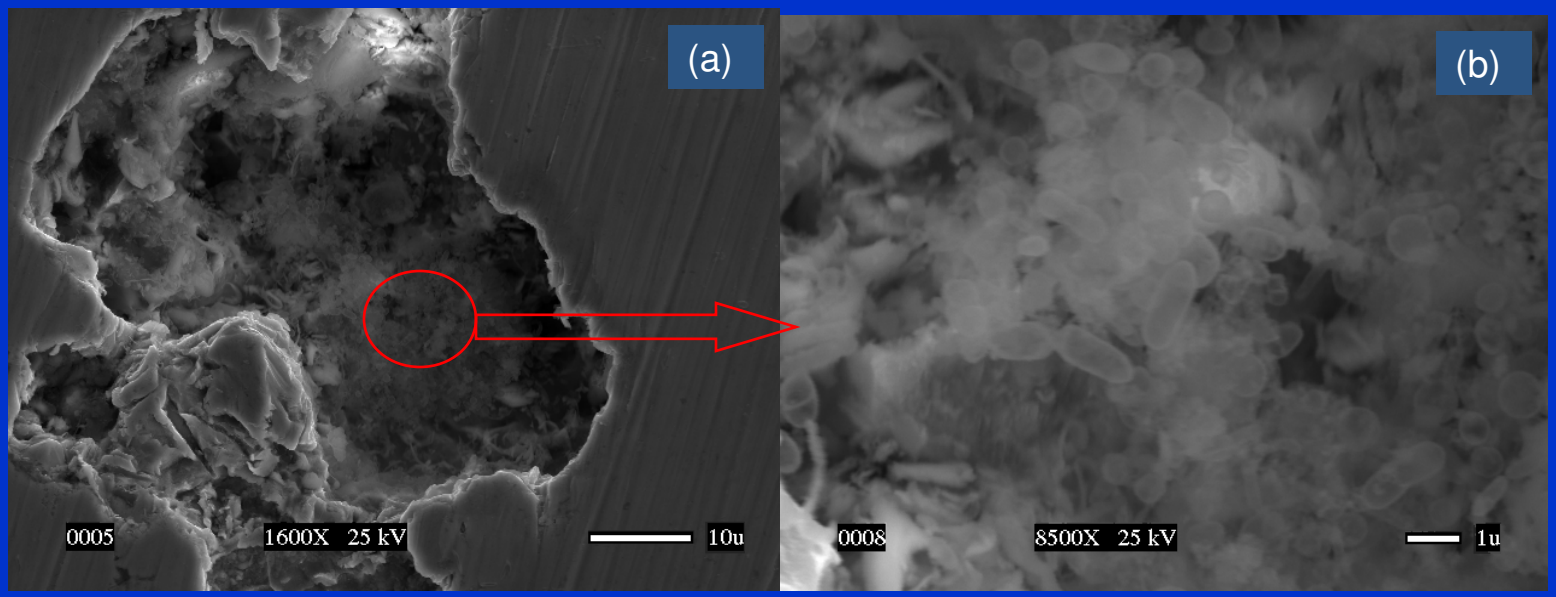
-Courtesy of NACE 2001, Research Topical Symposium, Page 17

Localized Corrosion: Example of Crevice Corrosion



Severe crevice corrosion
under nuts
(Courtesy of Corrosion-Doctor.org
web site)

Localized Corrosion: Example of Microbially Influenced Corrosion

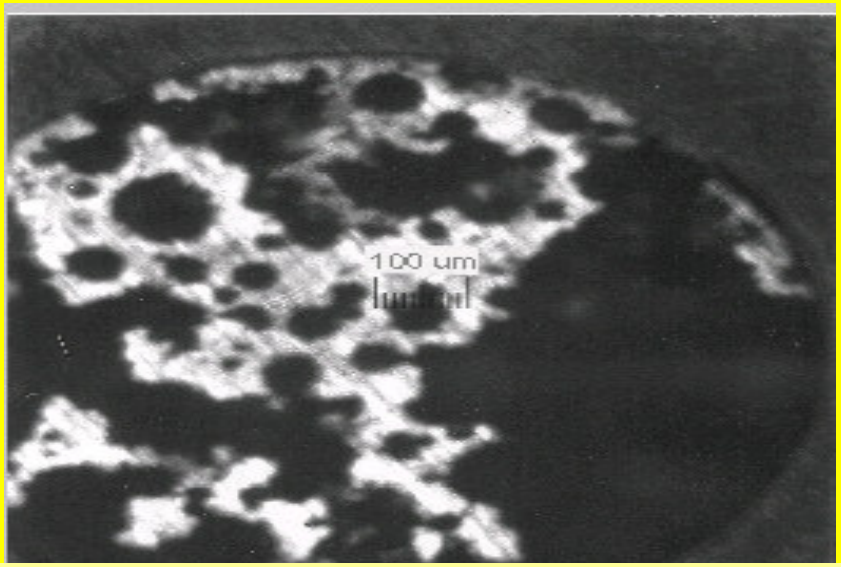


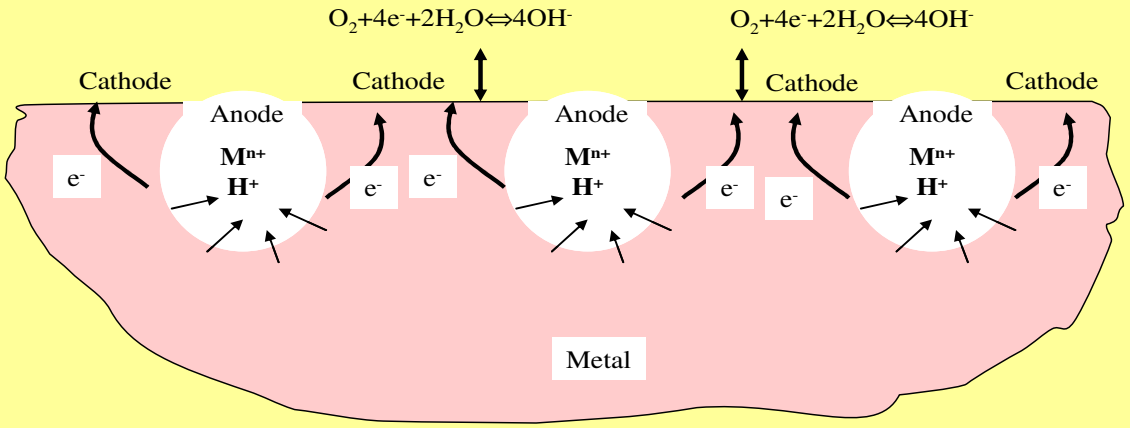
Type 304L SS in SRB Inoculated 0.5-M NaCl Solution

Corrosion Monitoring Methods

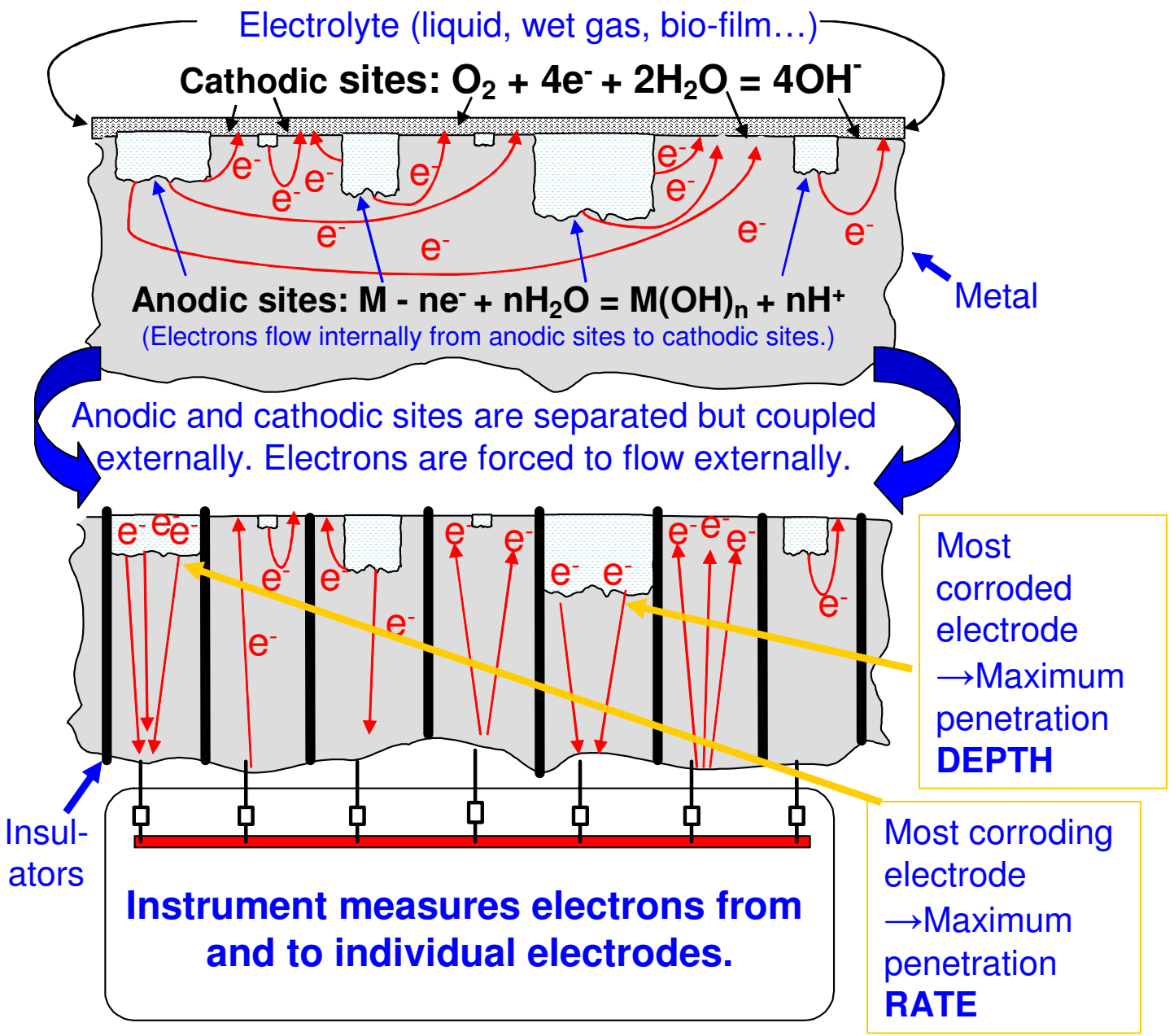
- Uniform Corrosion:
  - Electrical Resistance (ER) Probe
  - Linear Polarization Resistance (LPR) Probe
  - Rotating Disc
  - Hydrogen Probe
  - Electrochemical Impedance
  - Electrochemical Noise Probe
  - Harmonic
- Non-Uniform/Localized Corrosion:
  - ER Field Signature Method (meas. cumulative damage, slow response)
  - Intelligent Ultrasonic Probe (meas. cumulative damage, slow response)
  - Electrochemical Noise Probe (non-quantitative)
  - Coupled Multielectrode Array Sensor
    (high resolution, instant response)

Coupled Multielectrode Sensor Principle -Typical Non-Uniform (Localized) Corrosion

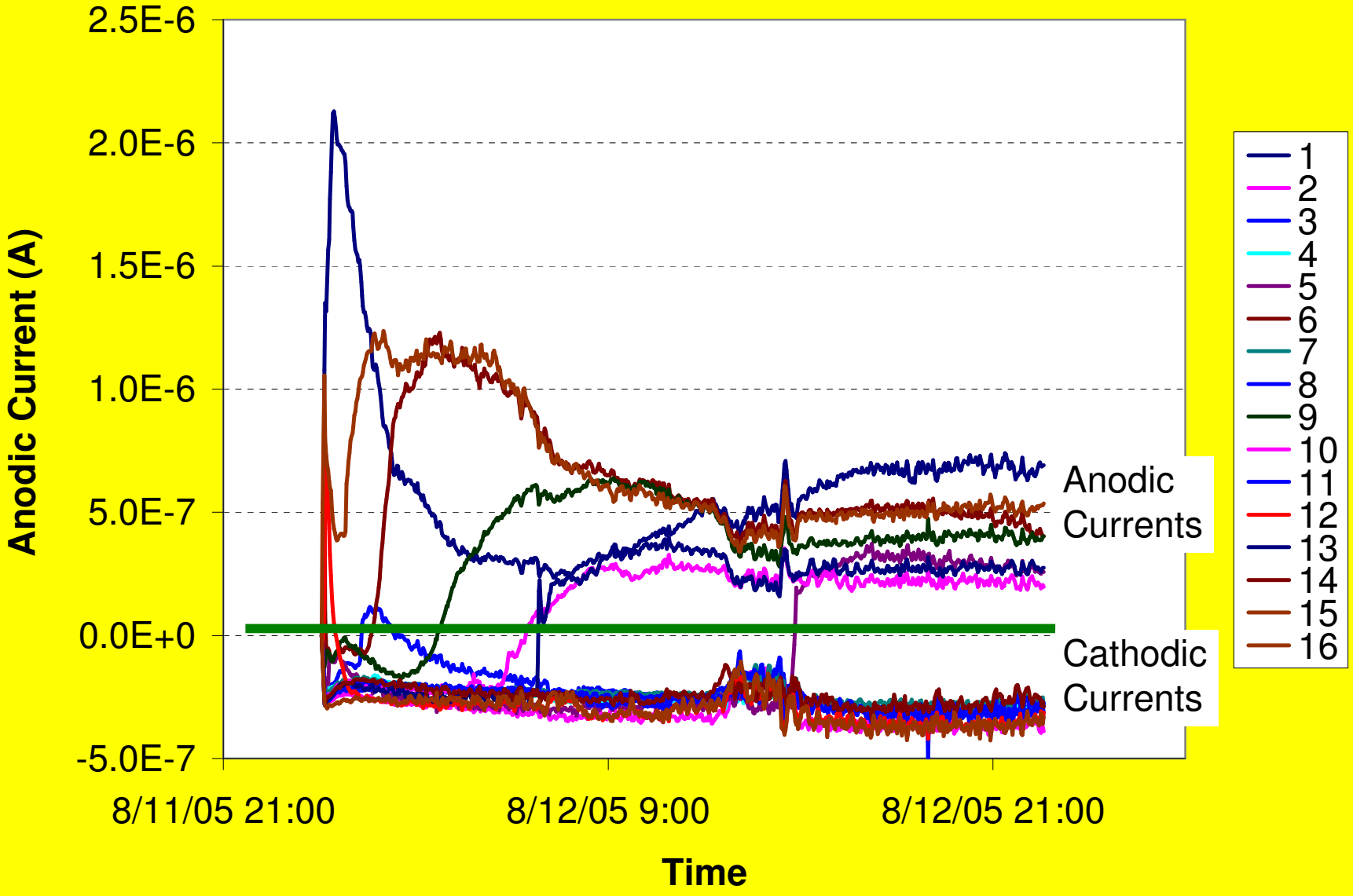




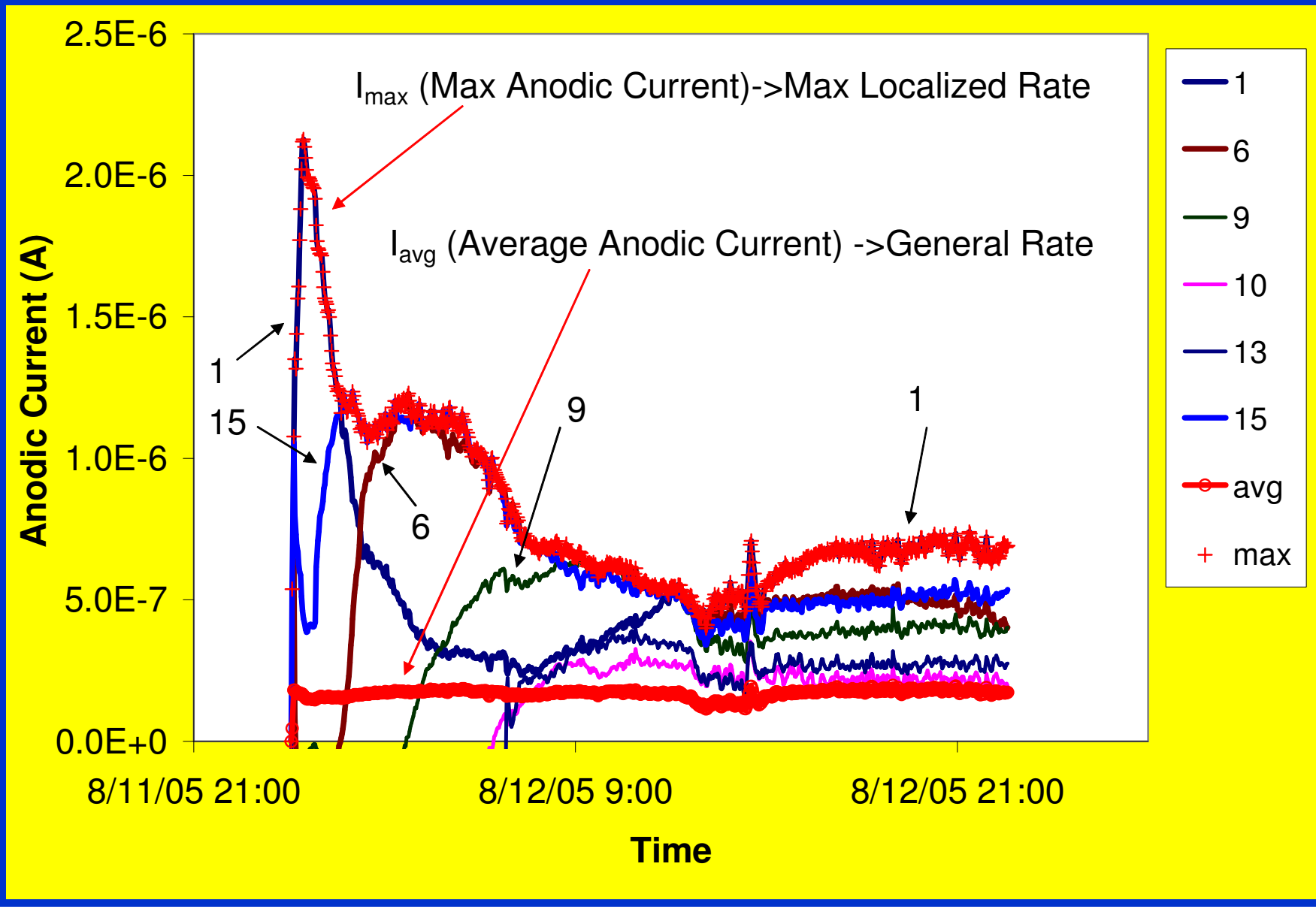
CMAS Probes Measures Directly the Electron Flows



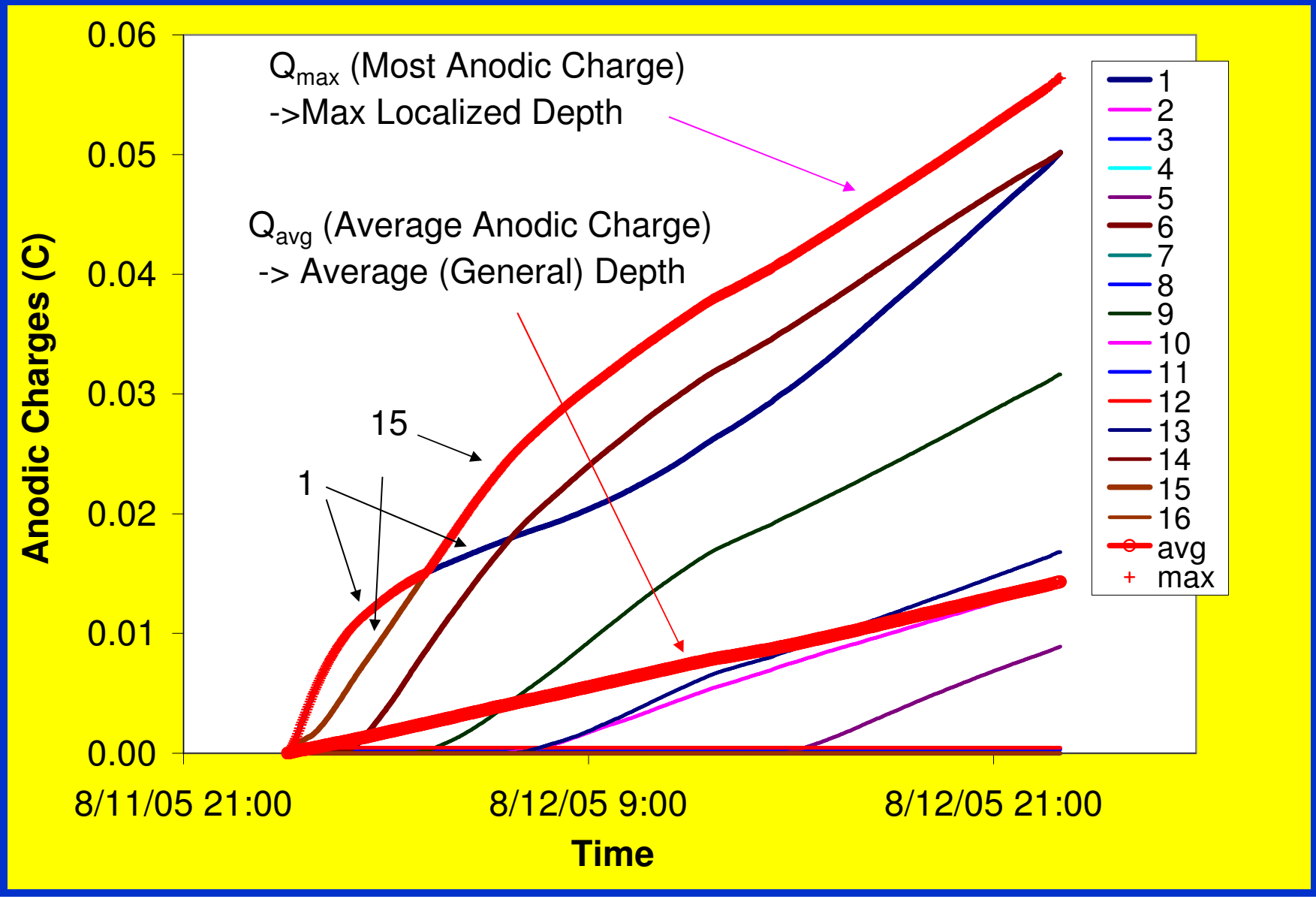
Typical Currents from Coupled Multielectrode Array Sensor (Carbon Steel in Seawater)



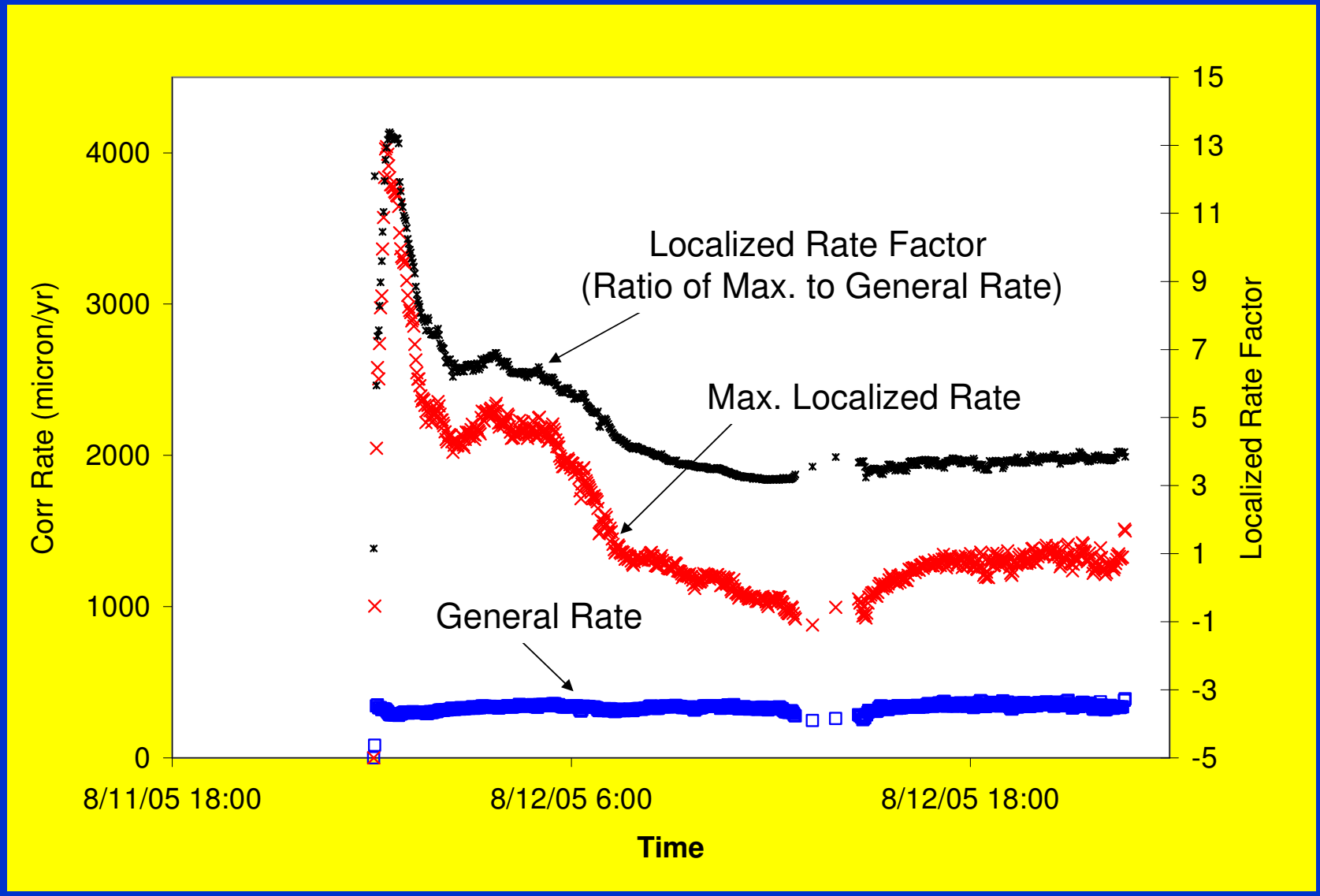
Maximum and Average Anodic Currents, and Localized and General Corrosion Rates



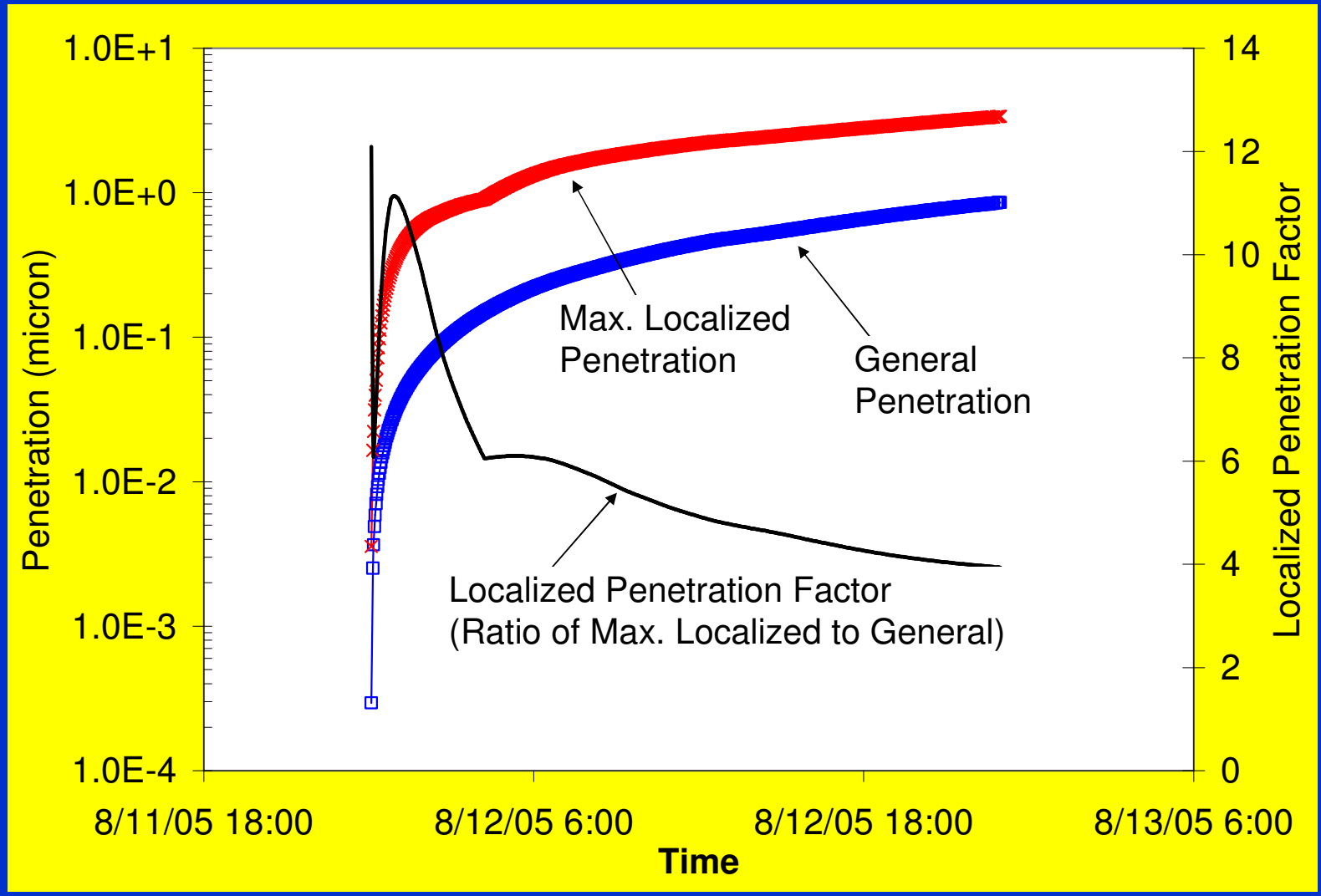
Maximum and Average Anodic Charges, and Localized and General Corrosion Depths



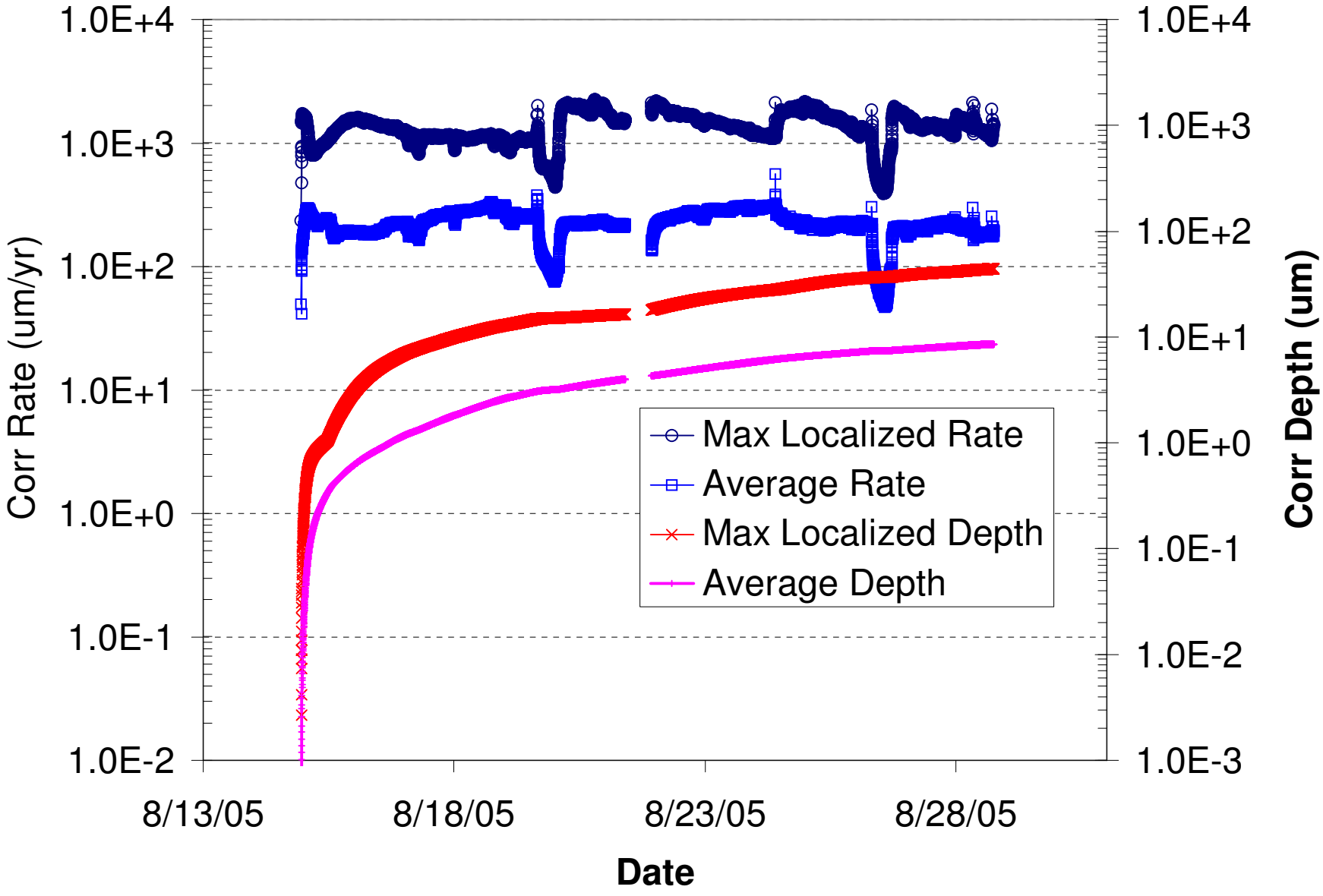
Typical Signals from a Coupled Multielectrode Array Sensor



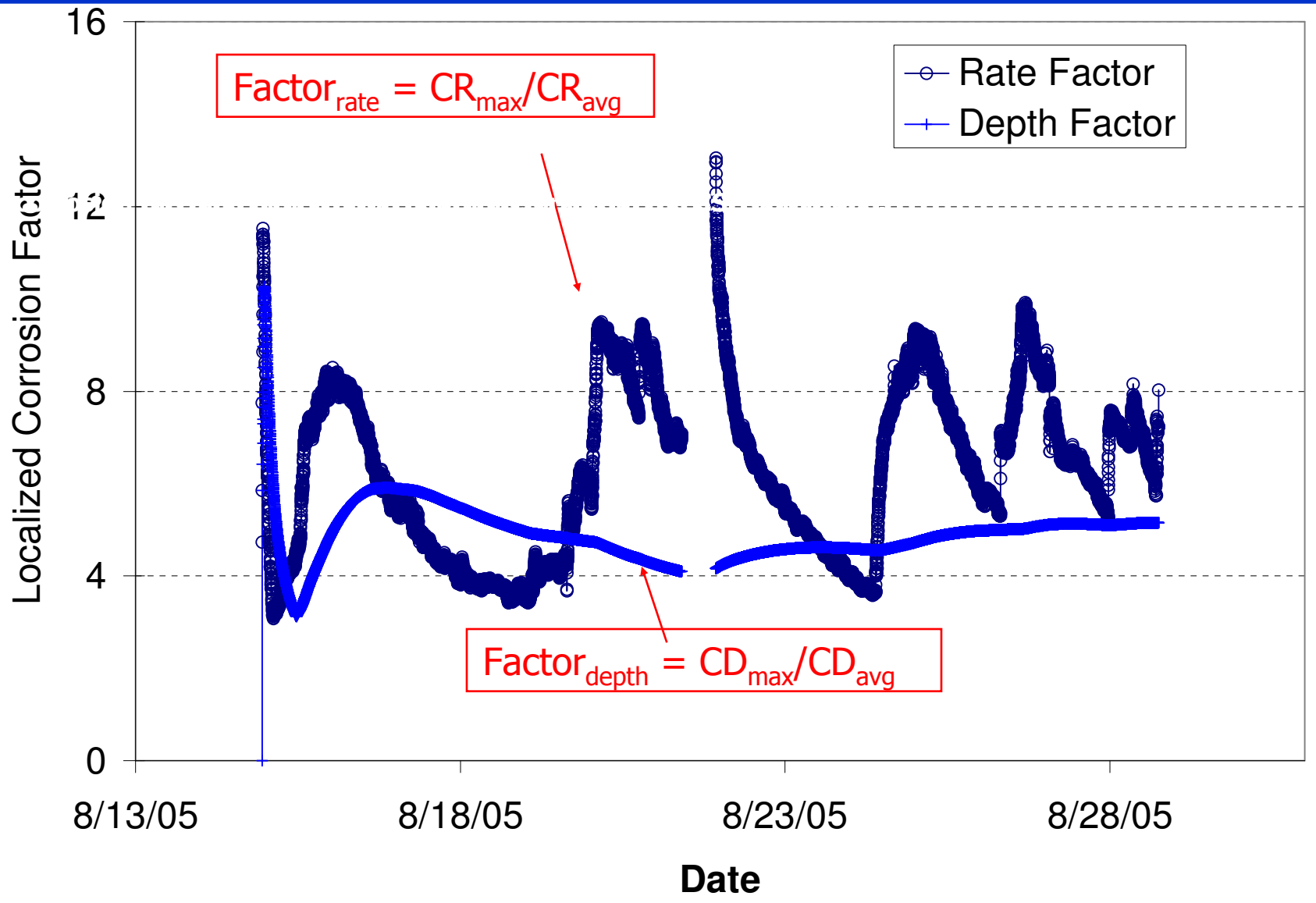
Typical Signals from a Coupled Multielectrode Array Sensor (Carbon Steel in Seawater)



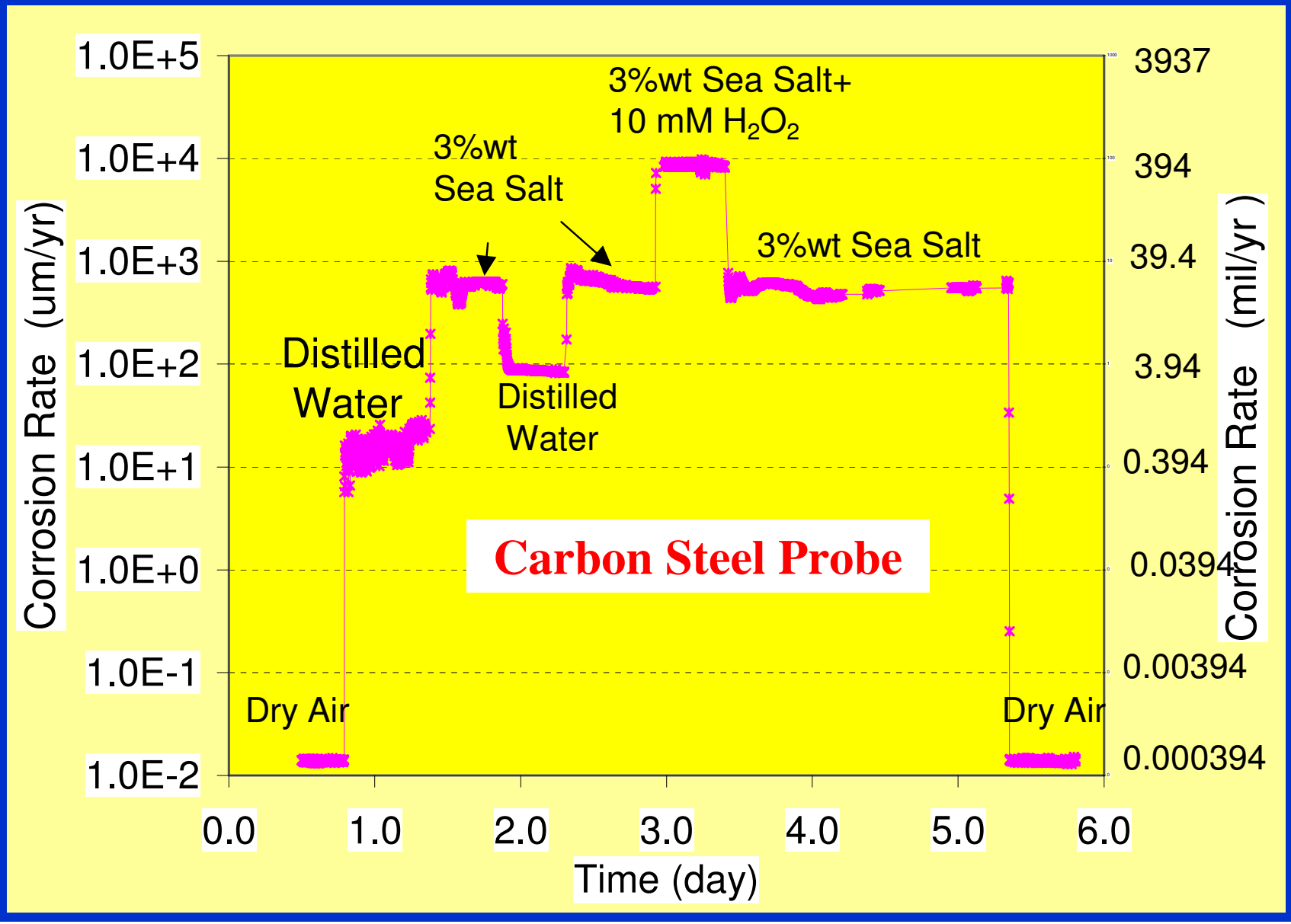
Typical Processed Signals from CorrVisual Software



Typical Processed Signals from CorrVisual Software



Typical Maximum Non-Uniform Corrosion Rates from Coupled Multielectrode Array Sensors (CMAS)



Typical Creviced CMAS Probes

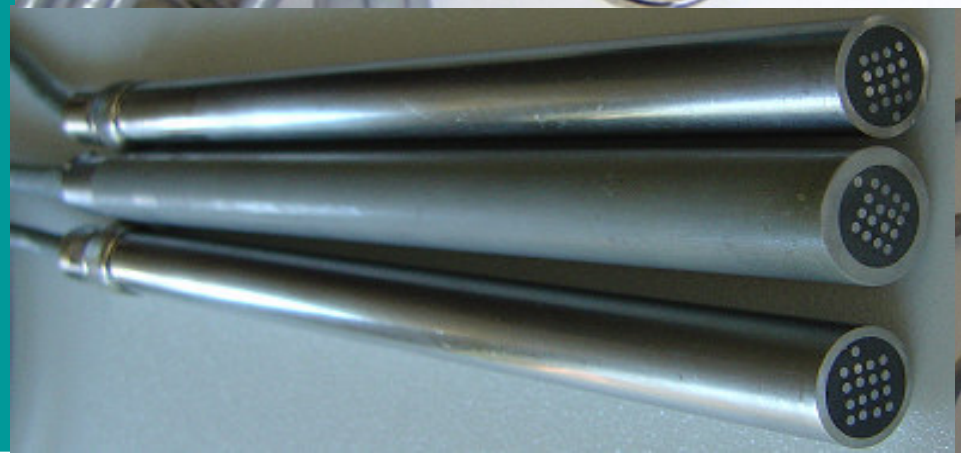
Paper embedded beneath epoxy

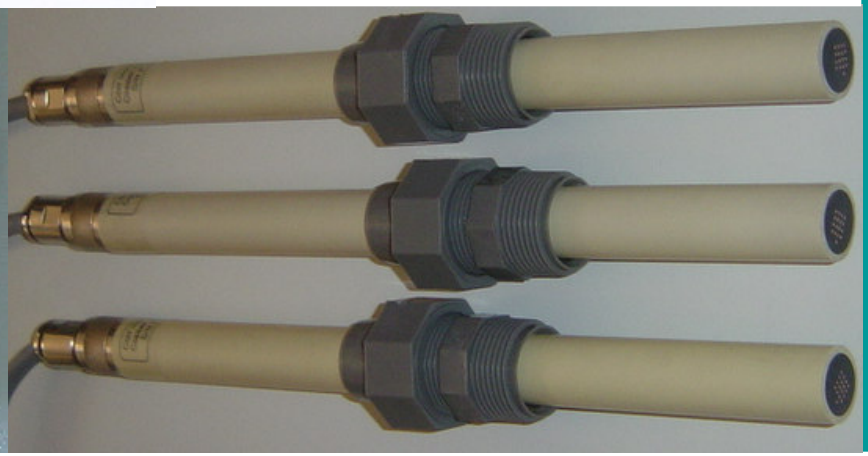
Epoxy

Note: The crevice was formed by imbedding a layer of paper between the sensing surface and epoxy; tightness of crevice is controlled by selecting the thickness of the paper

Coupled Multielectrode Array Sensors (CMAS) Tested for Localized Corrosion Measurements

Courtesy of Materials Performance, 2003 (9), p 48



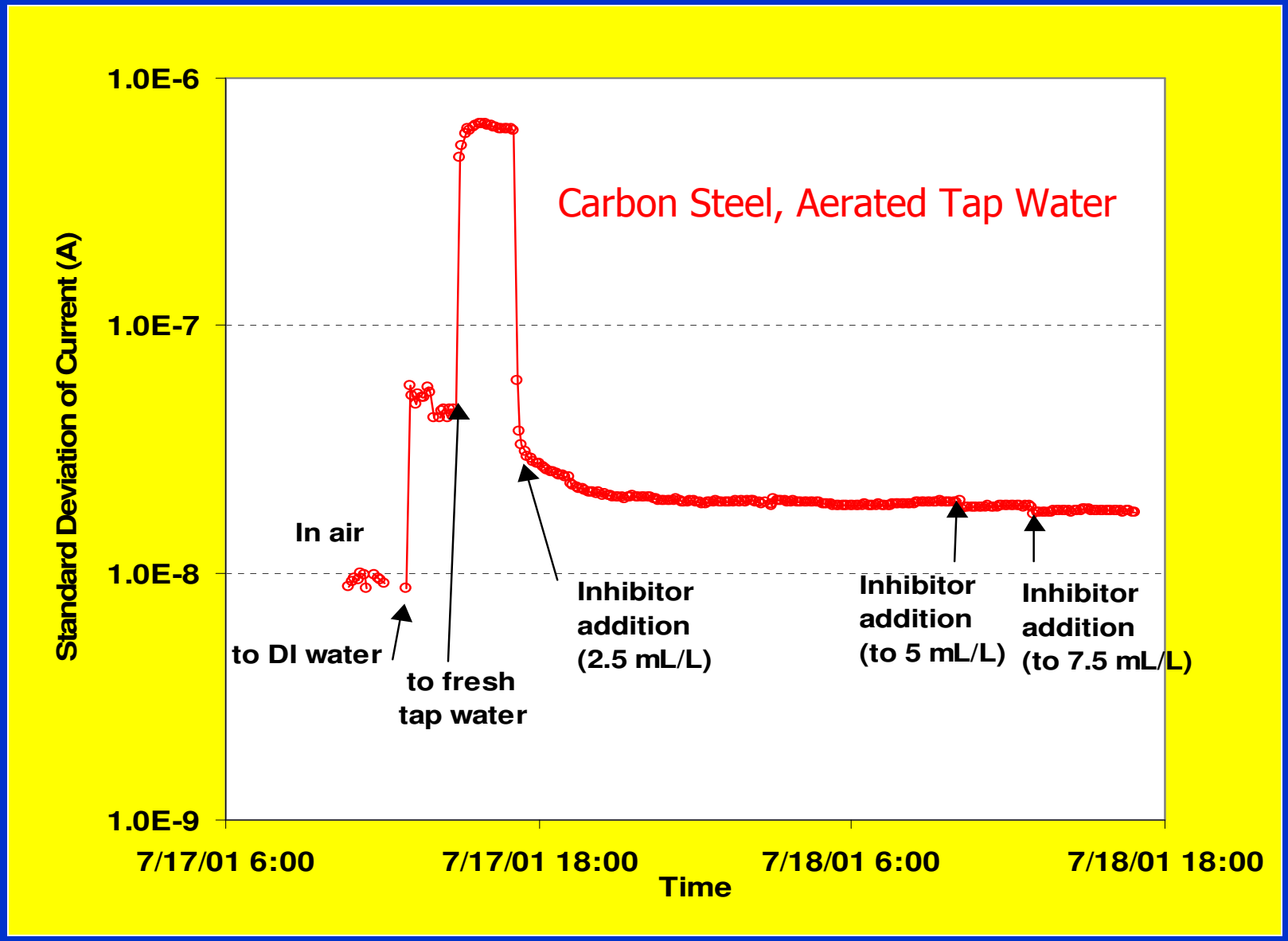


CMAS Probes For High-Temperature and High-Pressure Applications

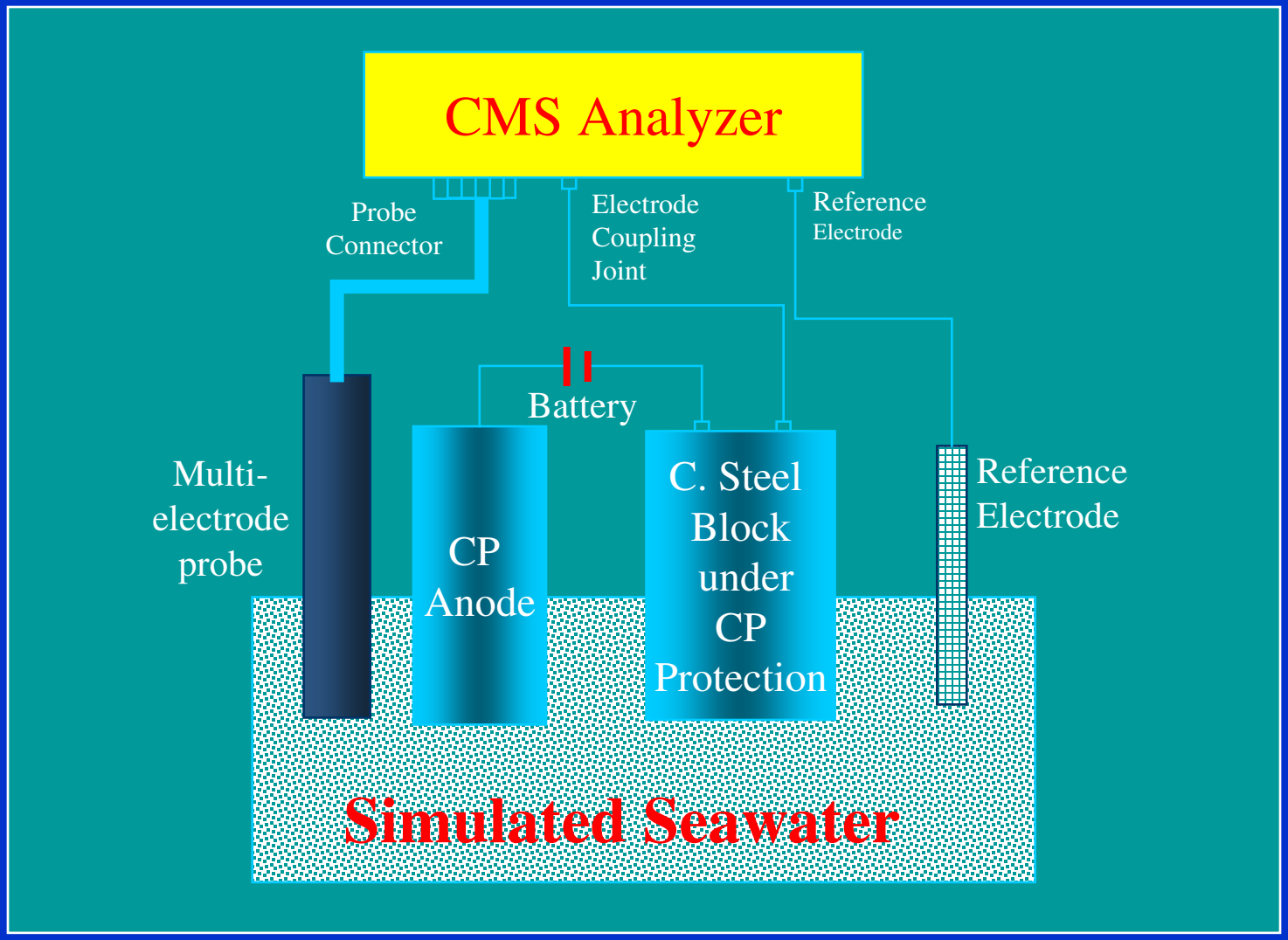
Coupled Multielectrode Probe Case Studies in Laboratories and Industrial Fields (34 publications)

- Aqueous Solutions
  - with inhibitors
  - with cathodic protection (CP)
  - chemical plant process stream
  - chemical plant cooling water
  - low conductivity water (distilled water)
  - sulfide-containing solution
- Gases
  - humidity air
  - simulated high-pressure natural gas pipeline
- Under Biofilm/Coatings
- Oil-Water Mixture
- Soil/Concrete with or without CP
- High-Pressure Liquid Pipeline

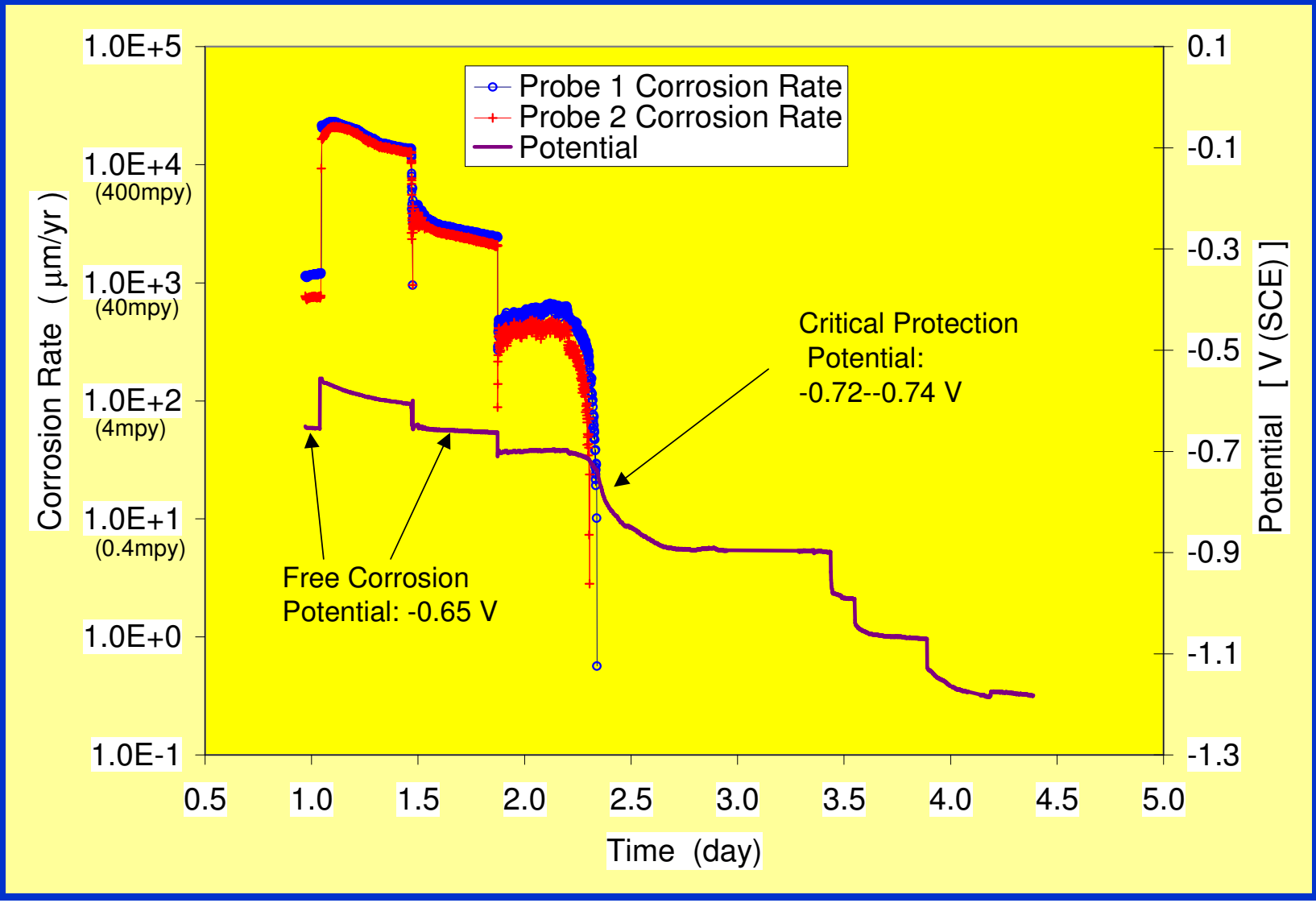
Responses of CMAS Probe to Commercial Inhibitor Dosing



CMAS Probe for Corrosion Monitoring under Cathodic Protection Condition



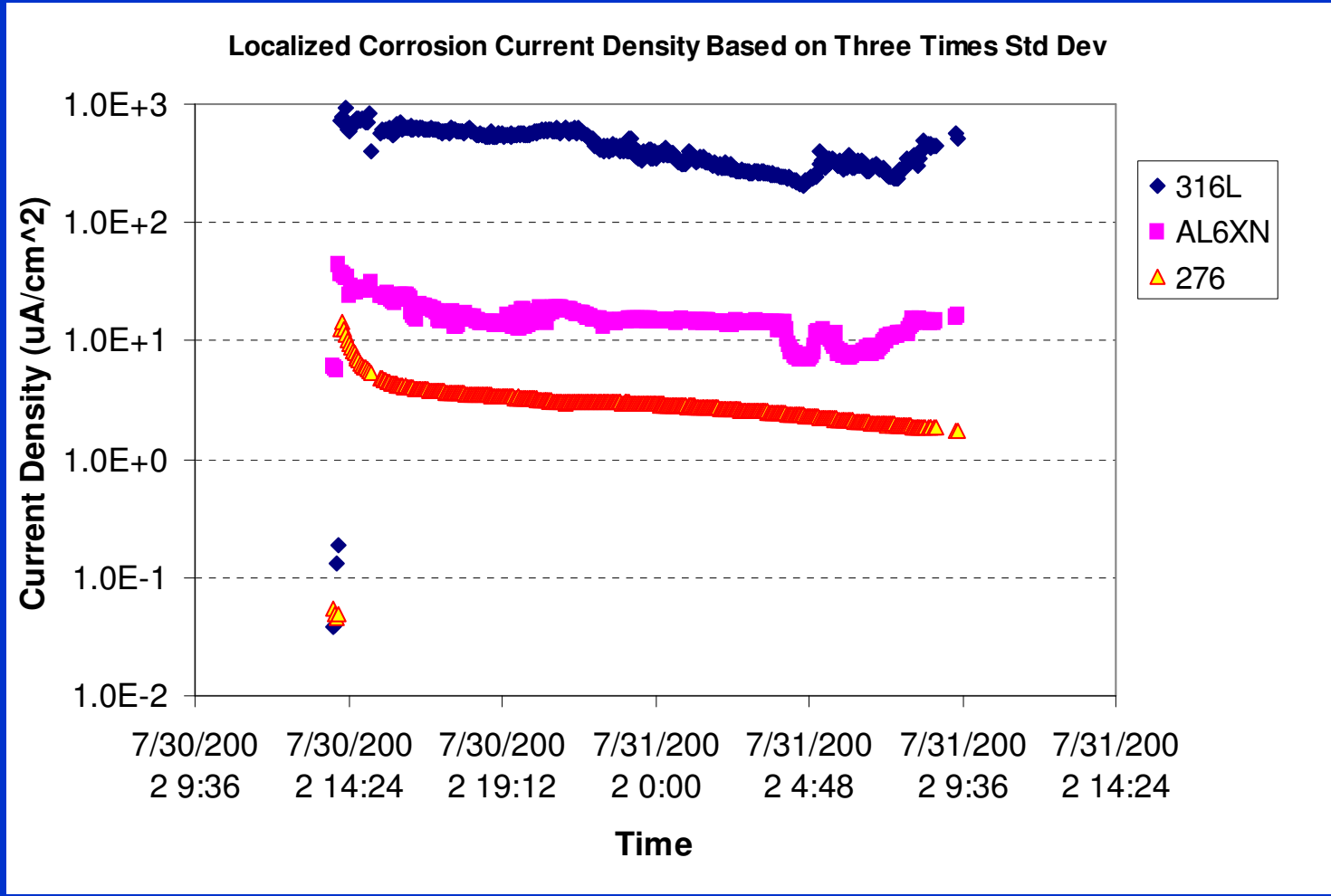
Measurements of Critical Cathodic Protection Potentials for Carbon Steel in Simulated Seawater



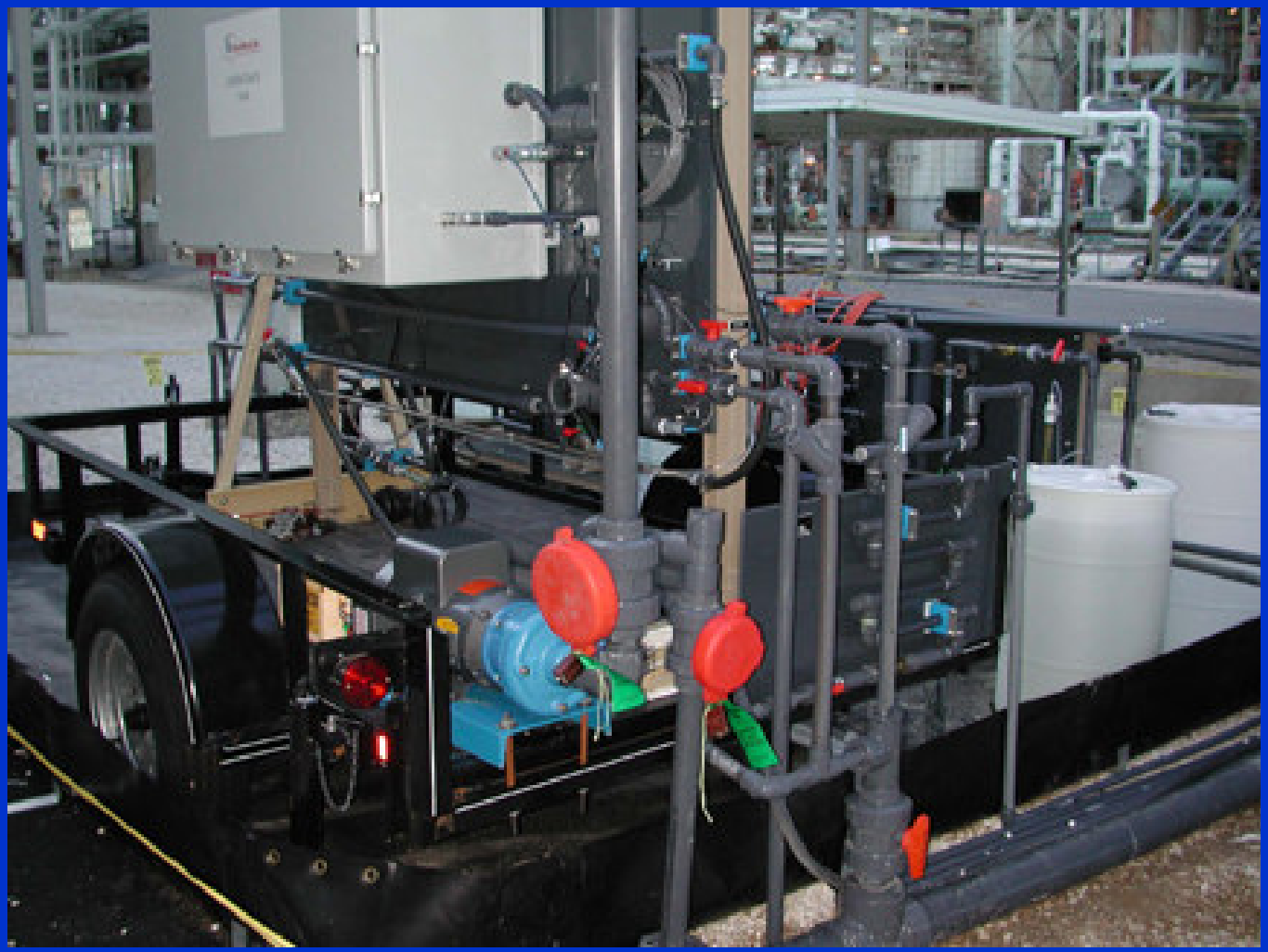
Corrosion Rate Measurements with CMAS in Pressurized Stream of Chemical Plant

NACE paper # 04440, 2004

Sensor Signals in Brine System of Chemical Plan at Elevated Temperature

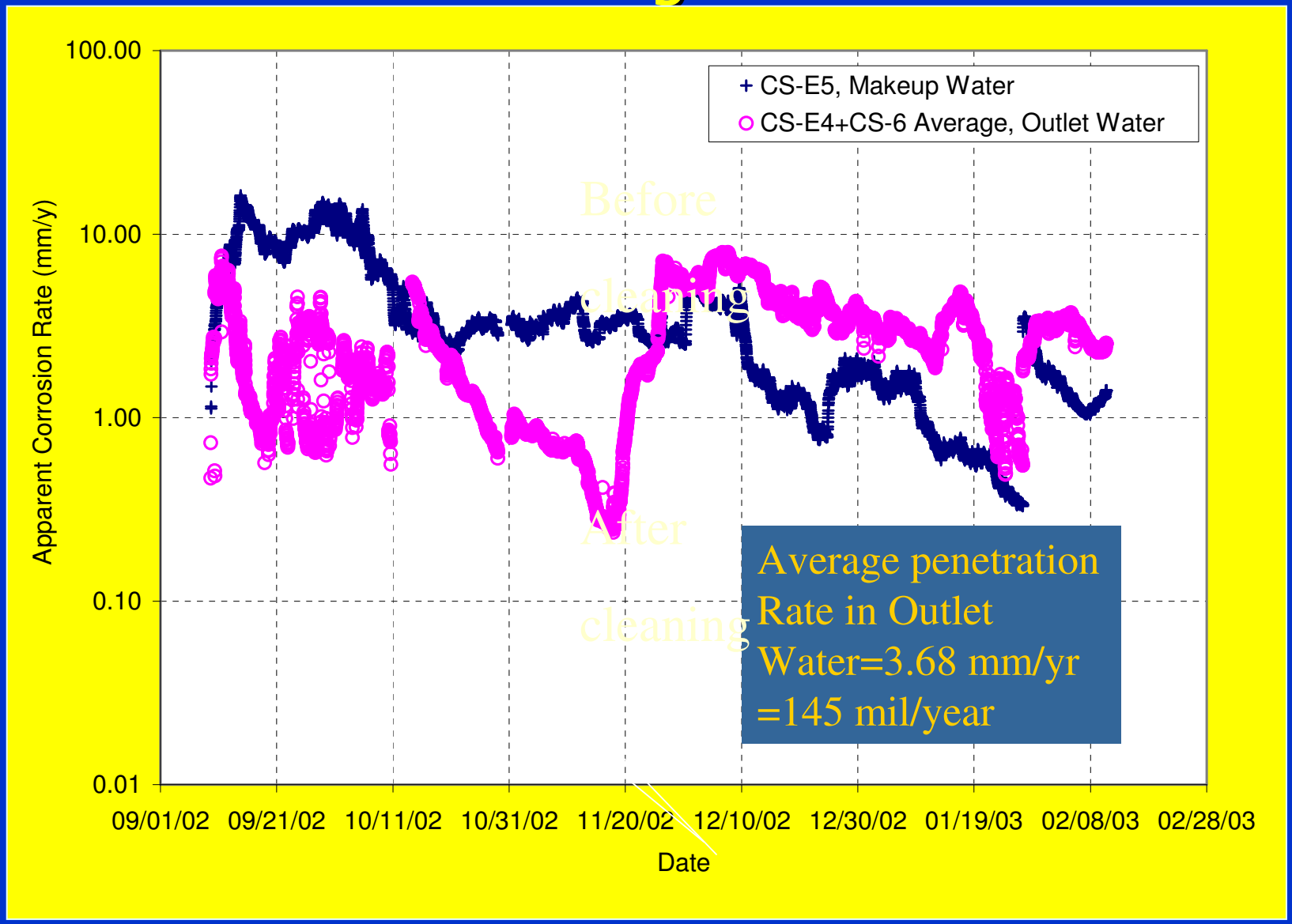


Pitting Corrosion Rate in Cooling Water Monitoring Station at Chemical Plant



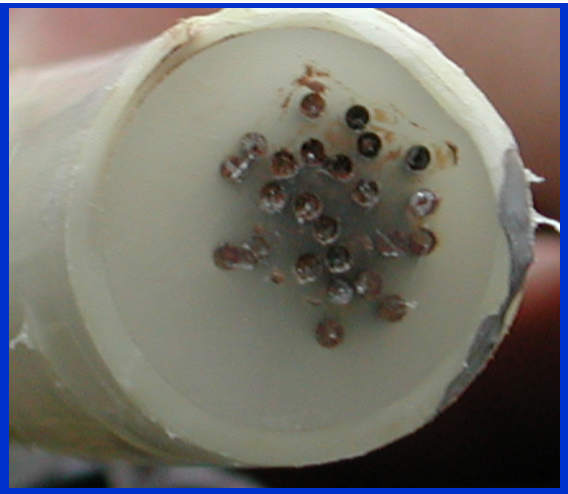
NACE paper # 04077, 2004

Corrosion Rates in Cooling Water System of a Chemical Plant during a 5.5-month Period



Probe Surface after 5.5-month Service and Typical Coupon Appearance after Tests

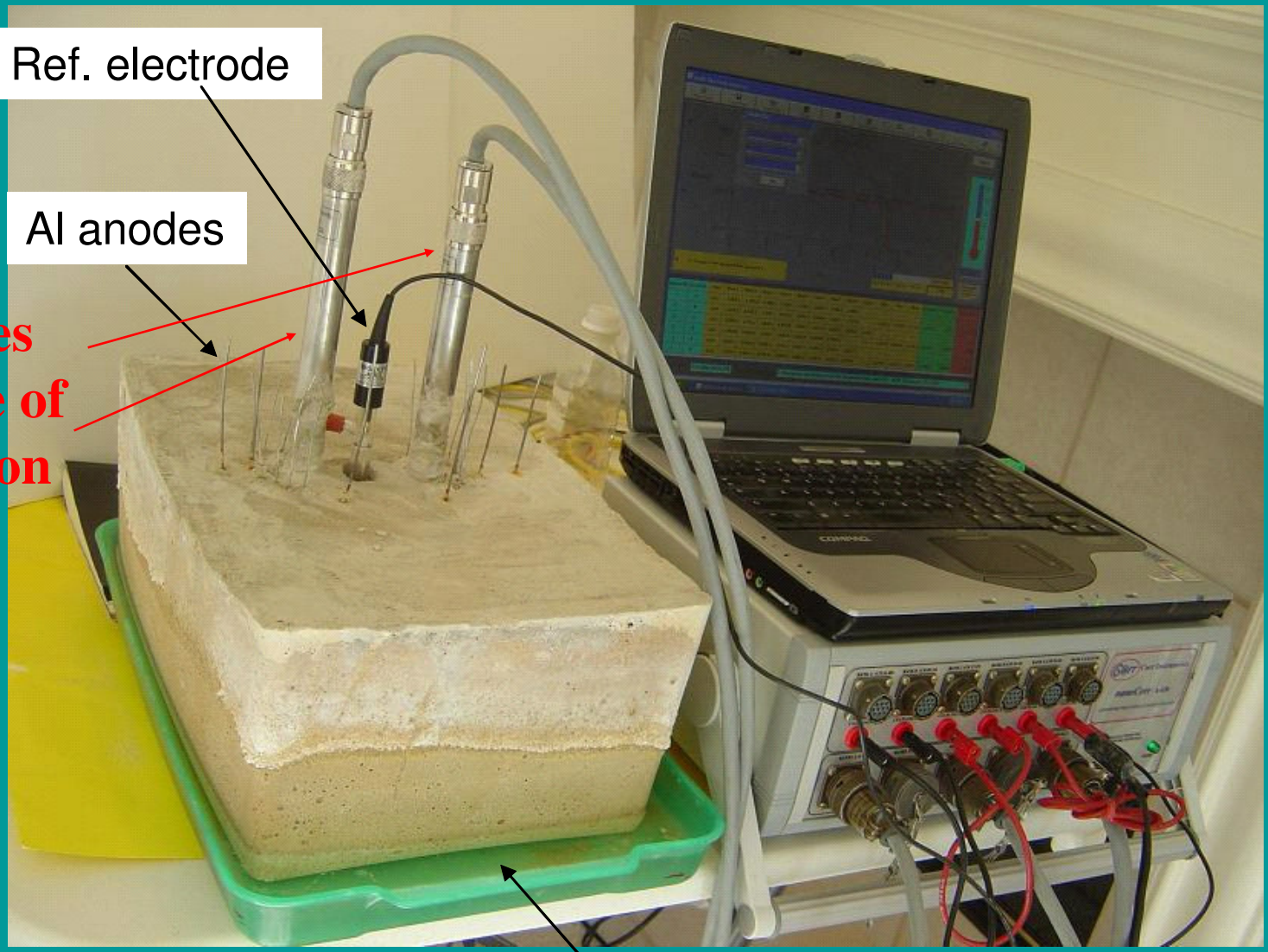
Coupon tests show 100 to 200 mil/year pitting rates



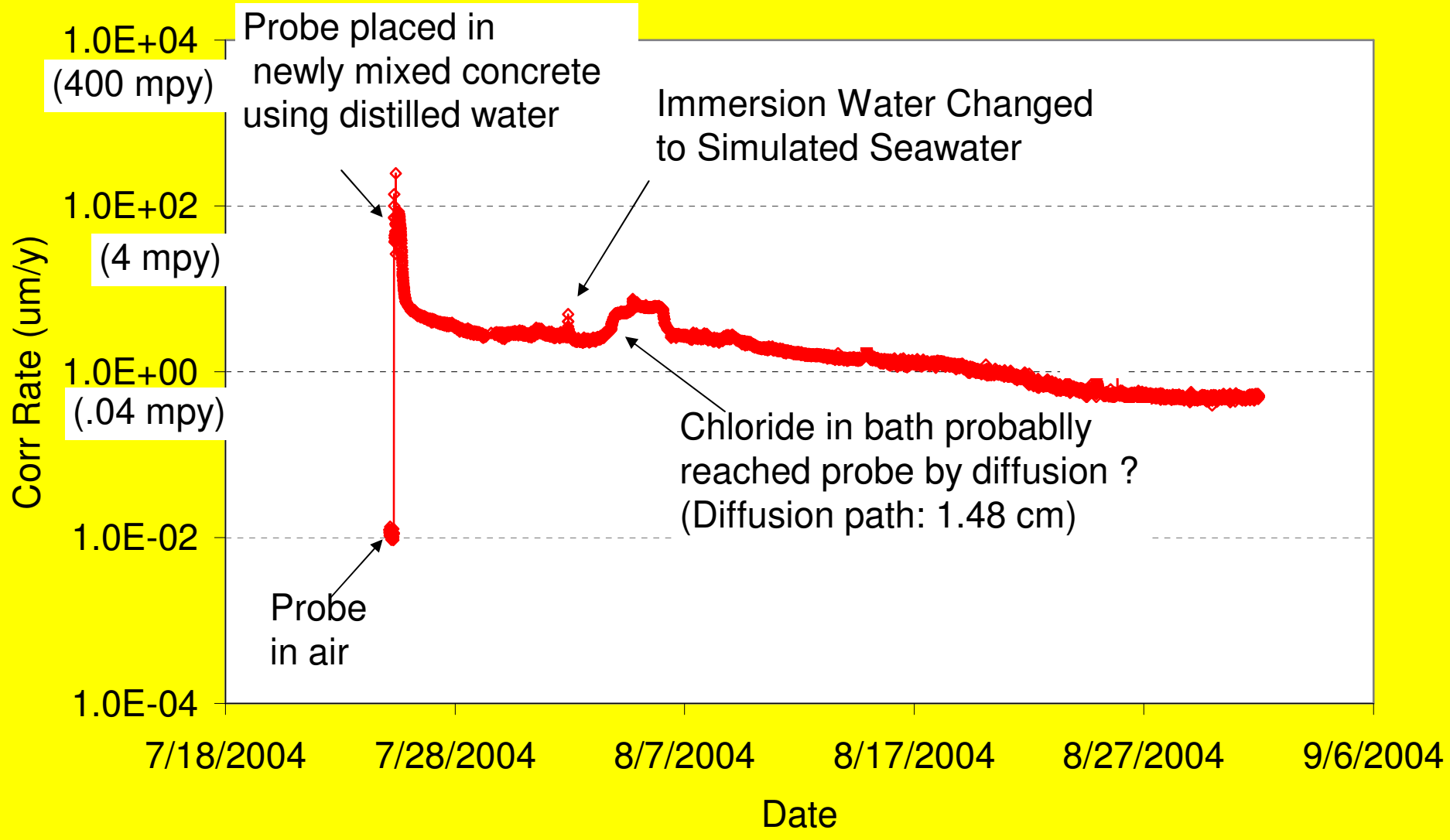
After Cleaning

From maximum penetration rate ~149 mil/year

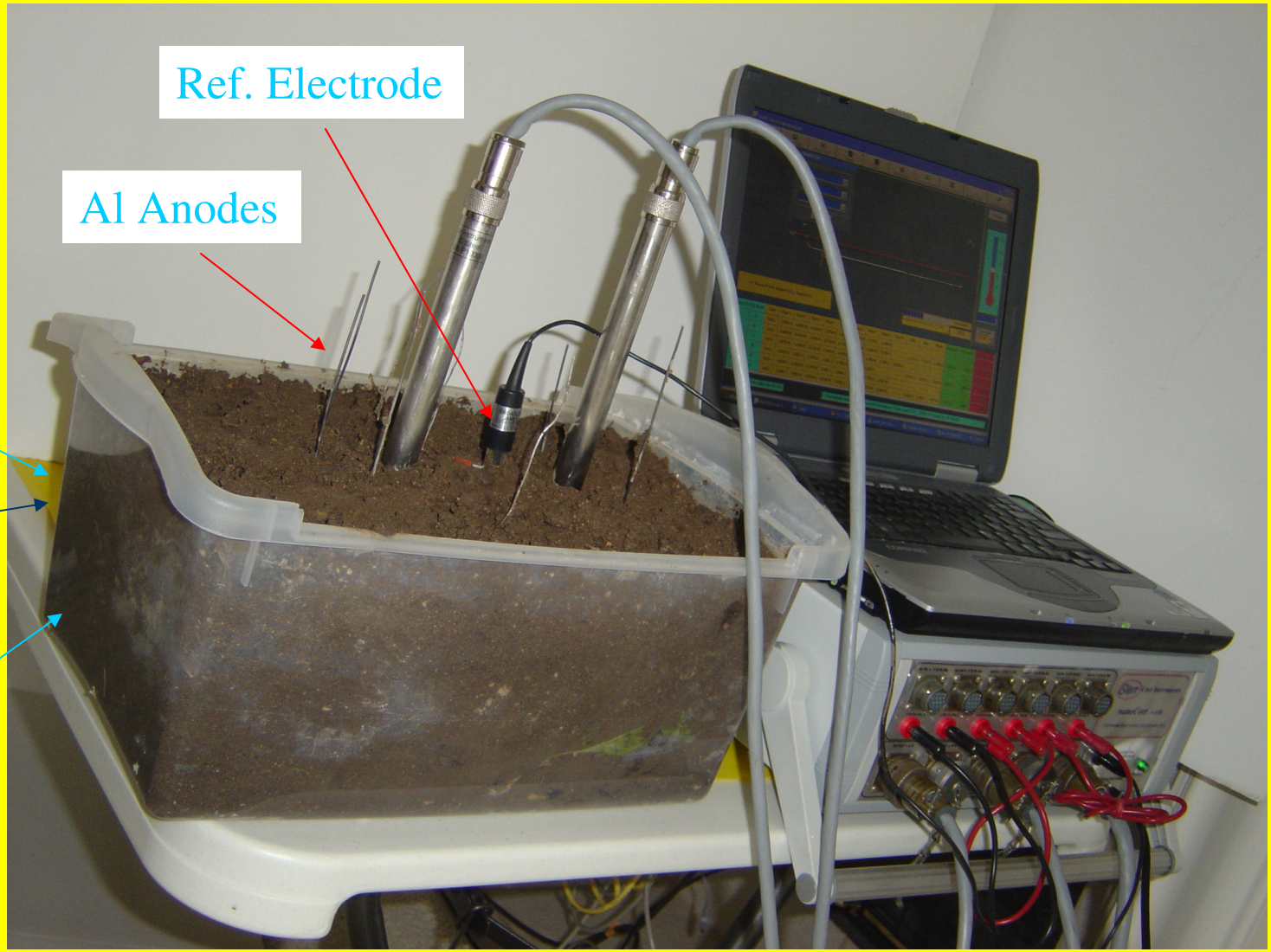
Measurement of Corrosion Rate with CMAS Probes in Concrete



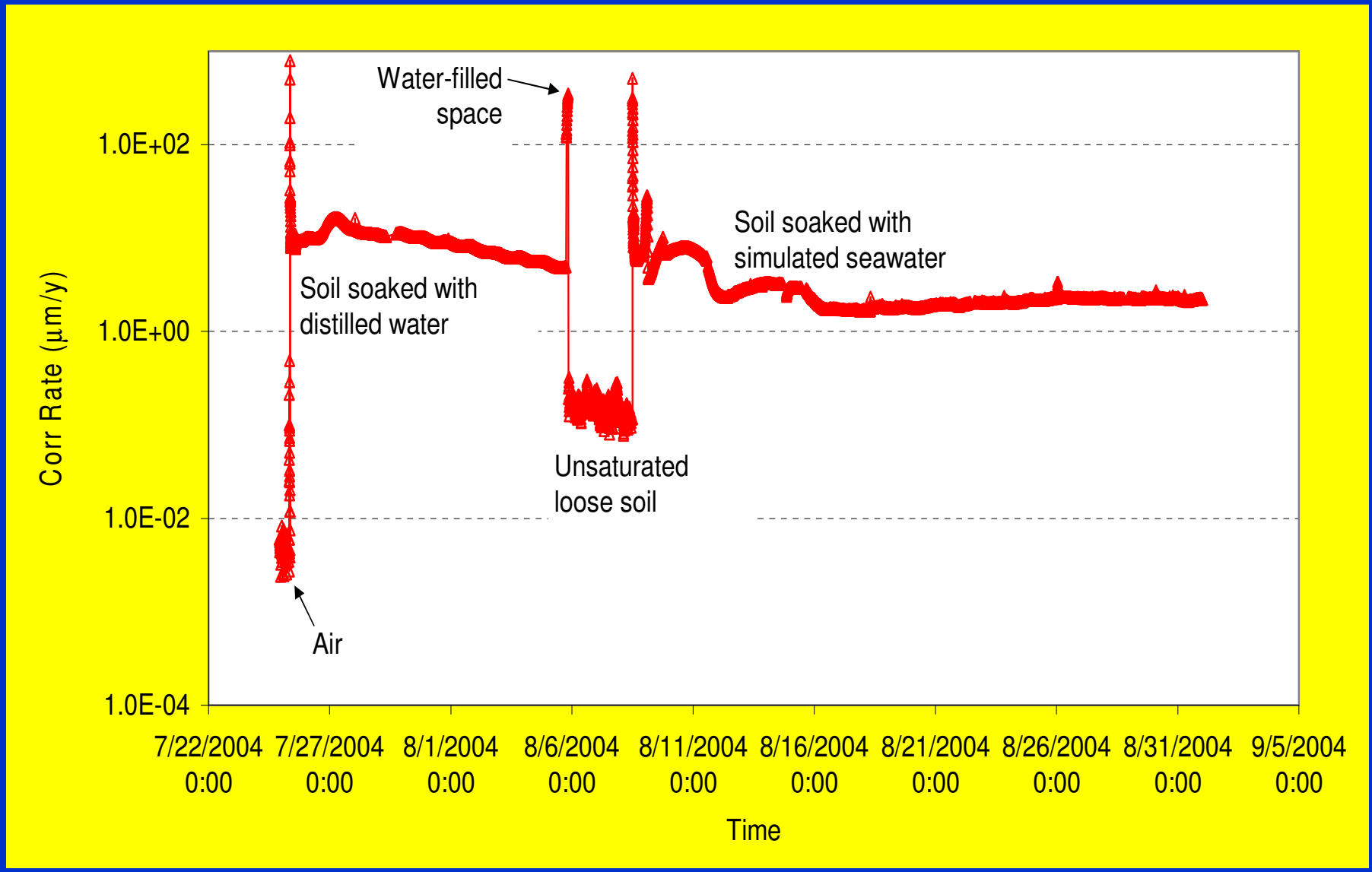
Non-uniform Corrosion Rate for Carbon Steel in Concrete in Simulated Seawater



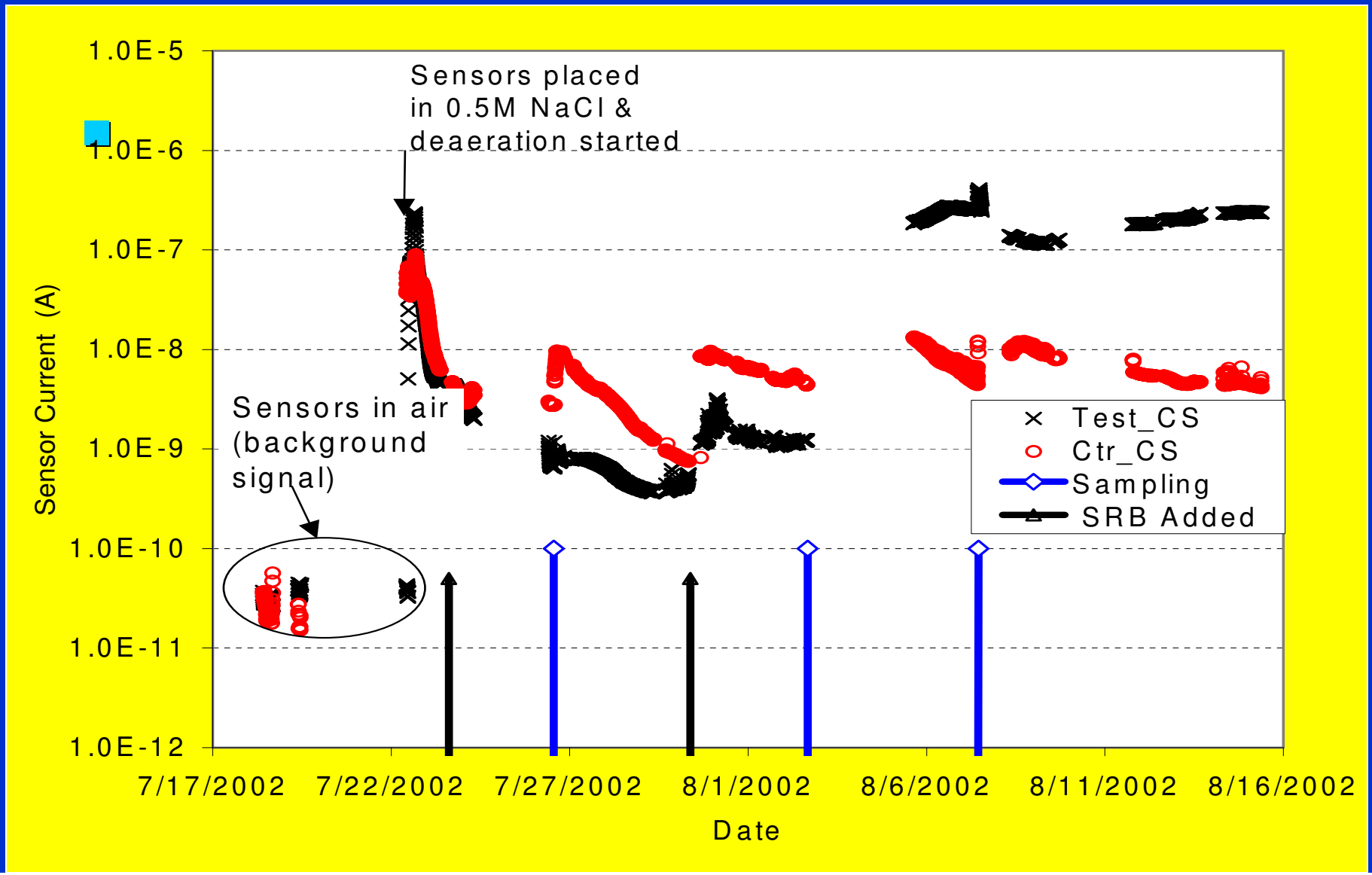
Measurement of Corrosion Rate with CMAS Probes in Soil



Corrosion Rate of Carbon Steel in Different Soil Environments



Carbon Steel Corrosion in Simulated Seawater Containing Sulfate Reducing Bacteria Solution



Posttest Probe Surface Appearance —Electrodes in Biotic Cell Severely Pitted

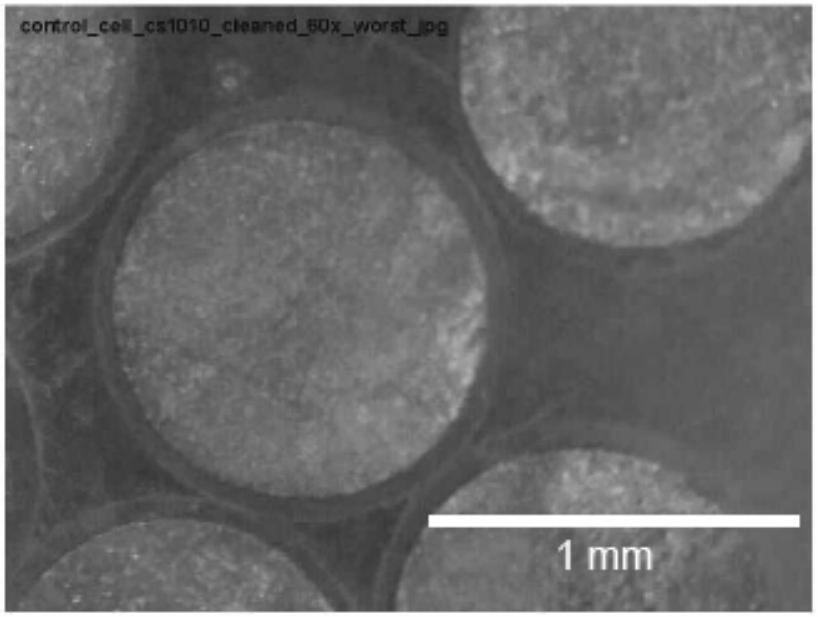


Figure 6: Appearance of carbon steel MASS probe after abiotic test.

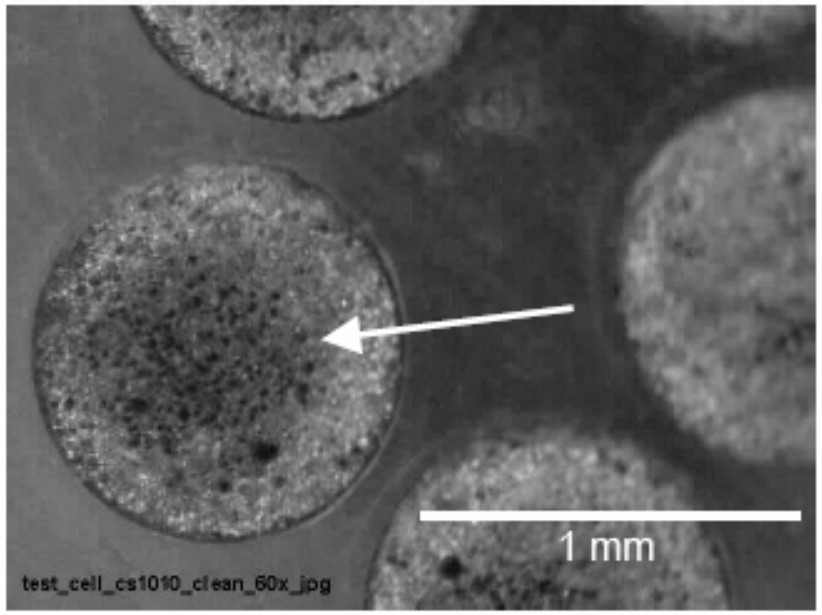
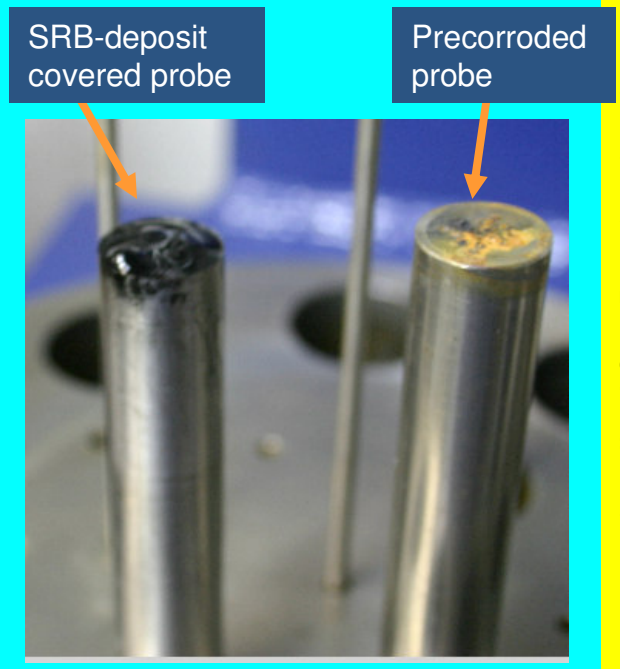
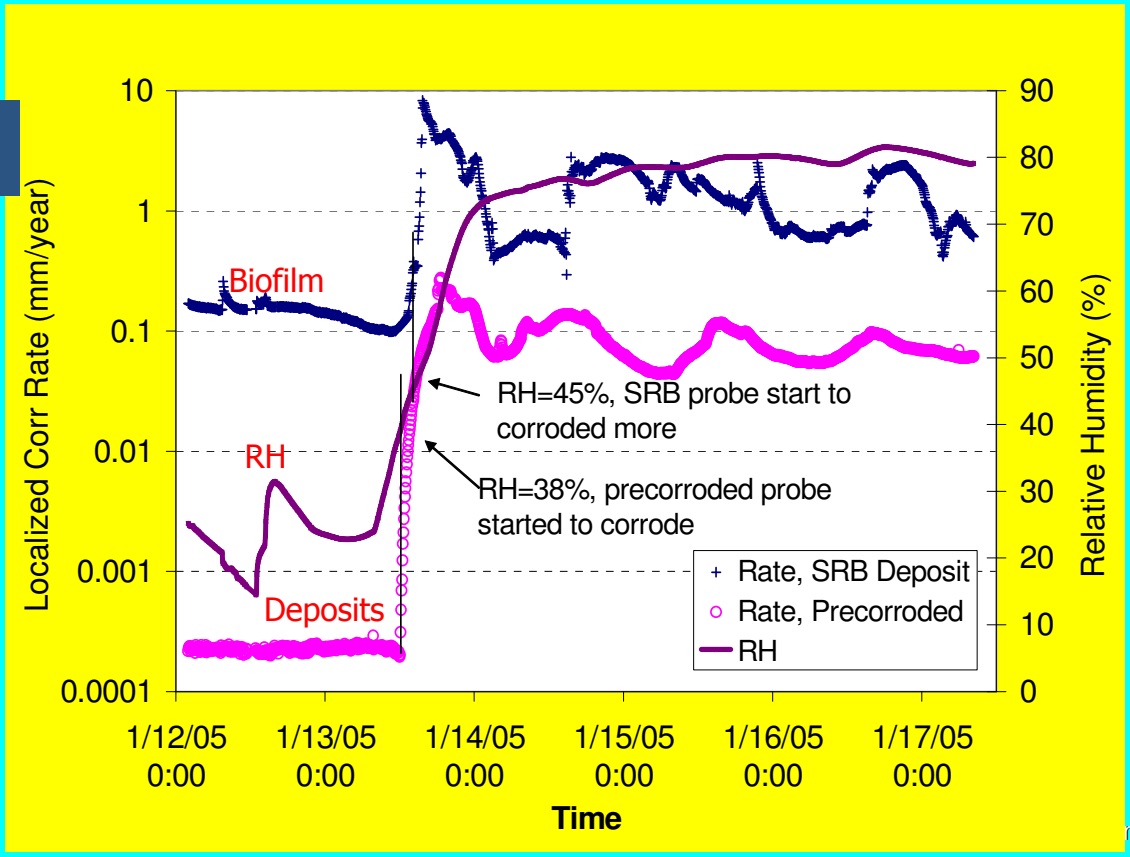


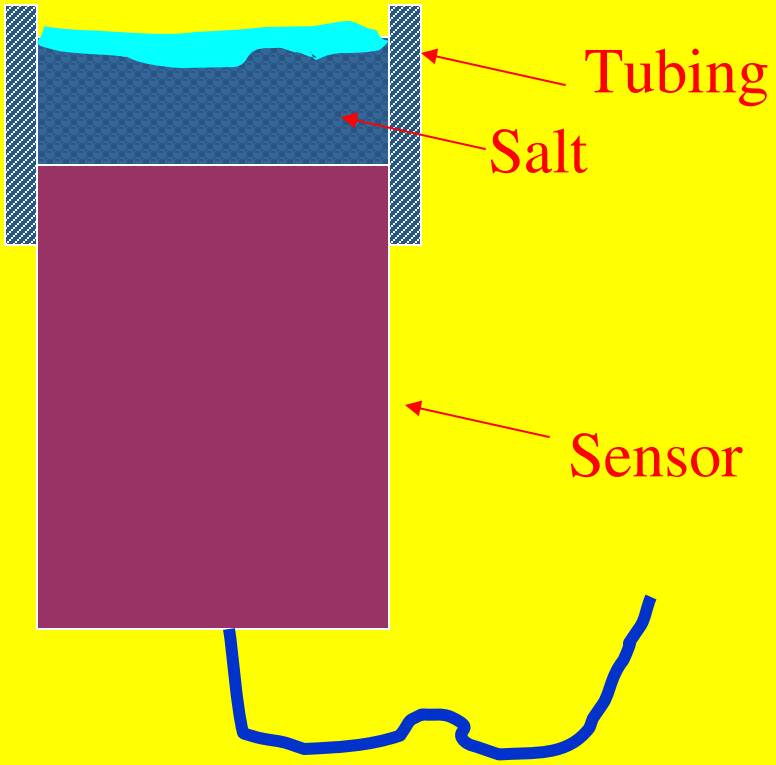
Figure 7: Appearance of carbon steel MASS probe after biotic test. Note small pits on electrode noted by arrow.

Corrosion Monitoring under Biofilm and Corrosion Deposits in Gas System

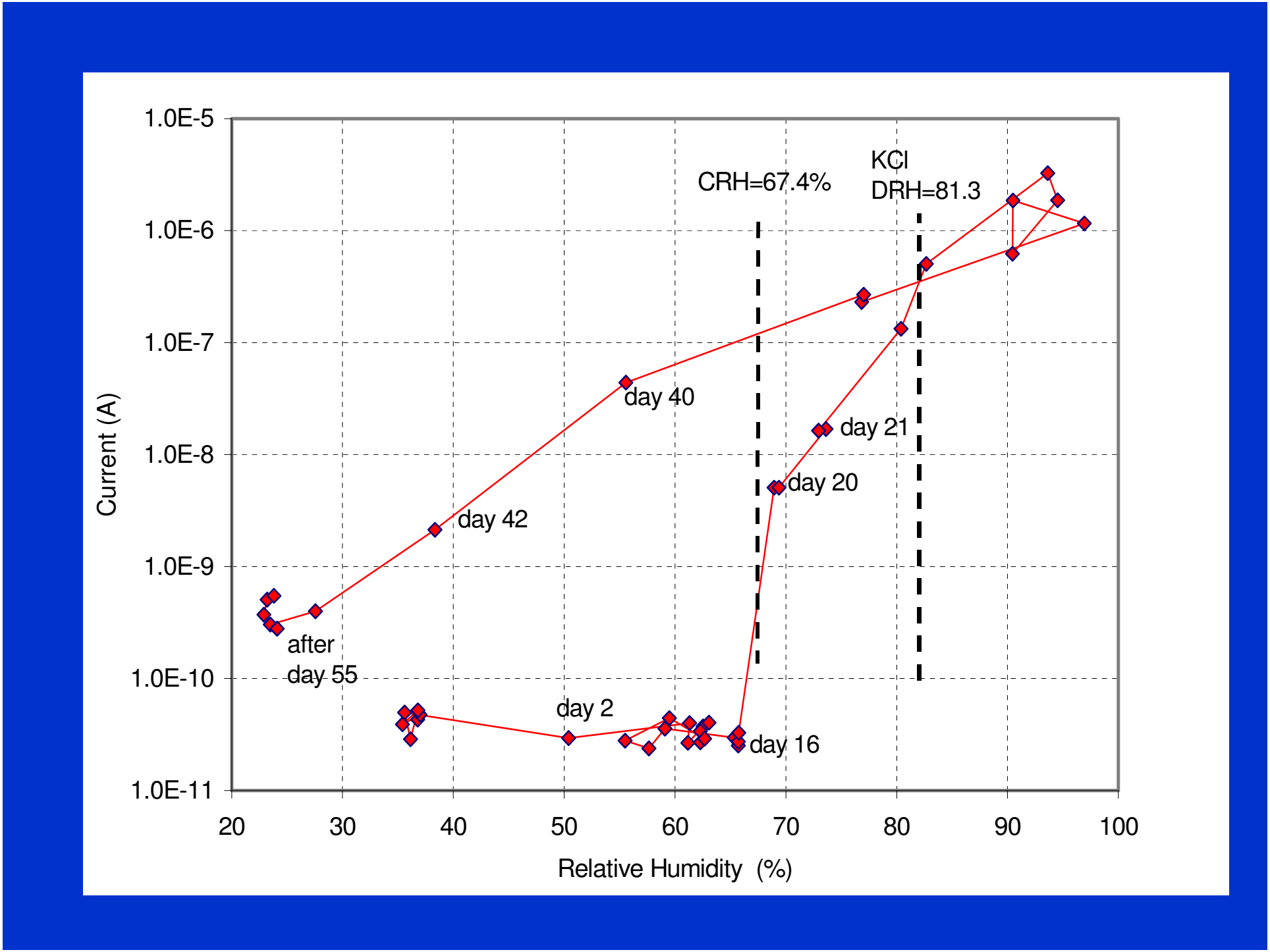




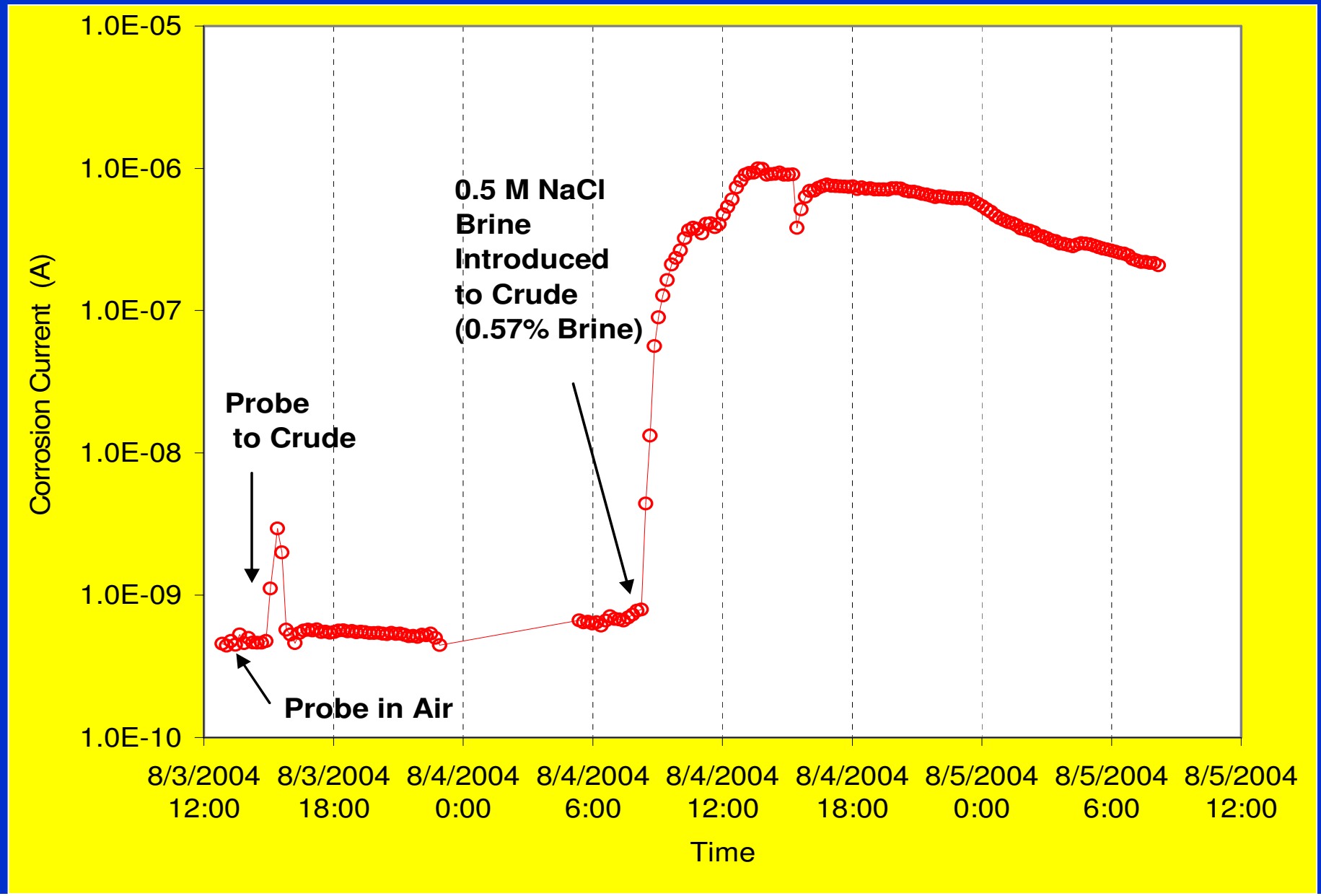
Corrosion Monitoring under Salt Deposits in Air



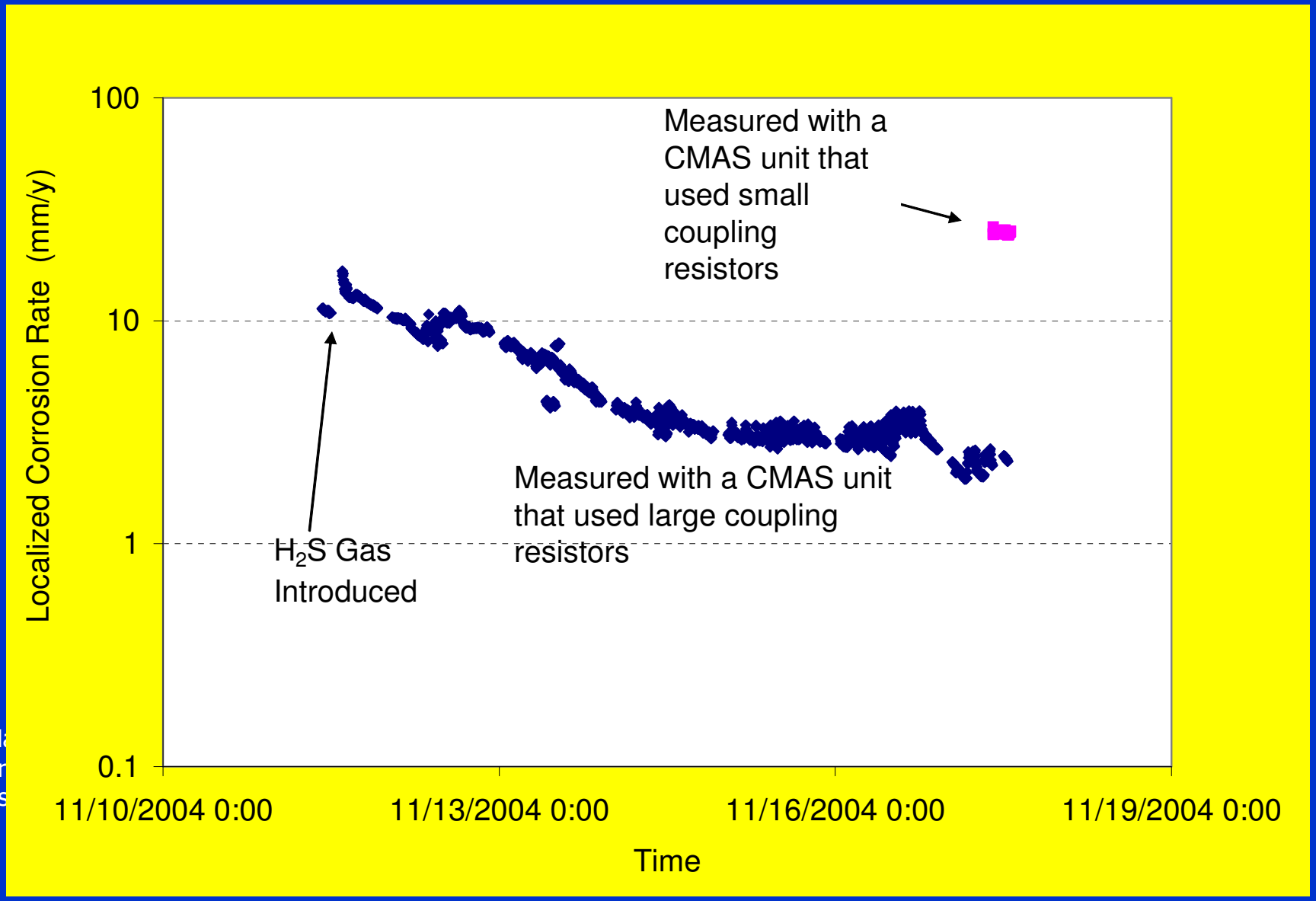
Probes in Humidity Chamber


1.0E-5
1.0E-6
1.0E-7
1.0E-8
1.0E-9
1.0E-10
1.0E-11
Current (A)
CRH=67.4%
KCl
DRH=81.3
day 40
day 21
day 20
day 42
after
day 55
day 2
day 16
20
30
40
50
60
70
80
90
100
Relative Humidity (%)

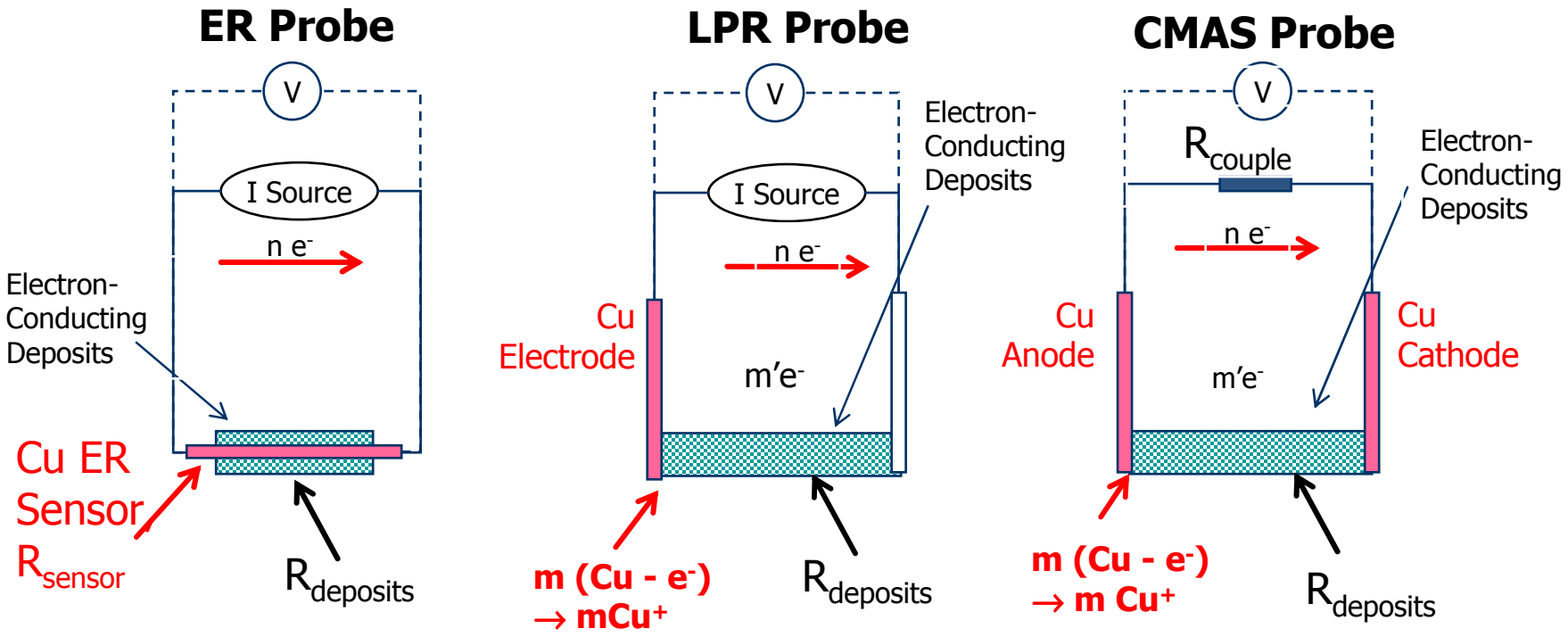
Response of CMAS Probe in Crude Oil to Addition of 0.5 M NaCl Brine



Effect of H2S on CMAS and Minimization of Effect by Using Smaller Coupling Resistors



Effect of H2S on CMAS Probes and Minimization of Effect by Using Smaller Coupling Resistors

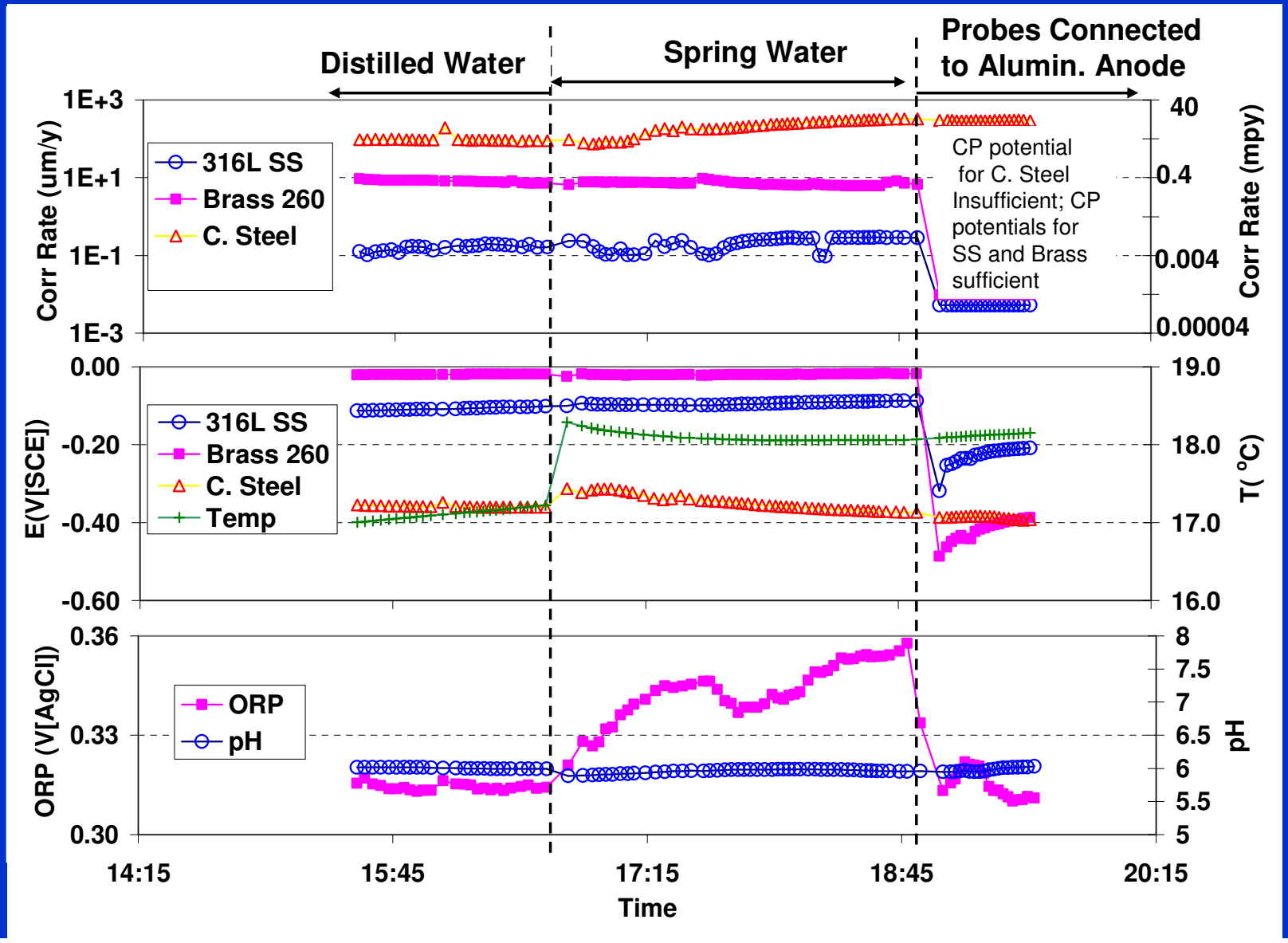


If $R_{deposits}$ low , R(measured) < R(sensor) Bridging Effect

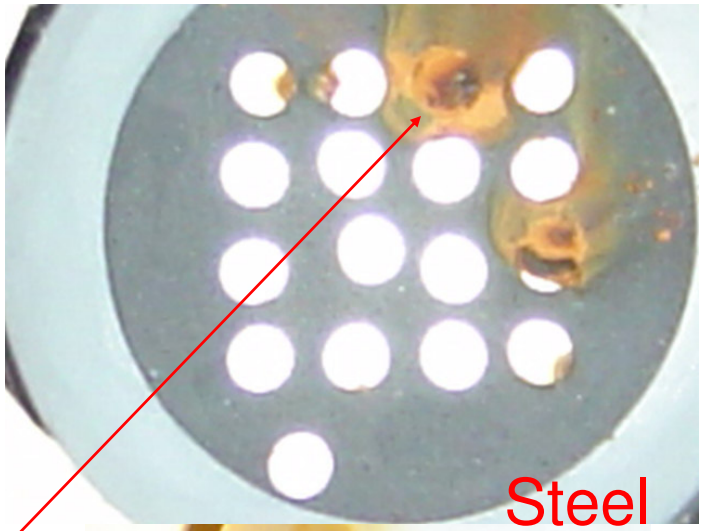
m+m'=n
If $R_{deposits}$ low, n(measured rate) > m(true rate) Bridging Effect

m = n+m'
If R_{couple} << $R_{deposits}$ n(measured rate) → m(true rate) No Bridging Effect

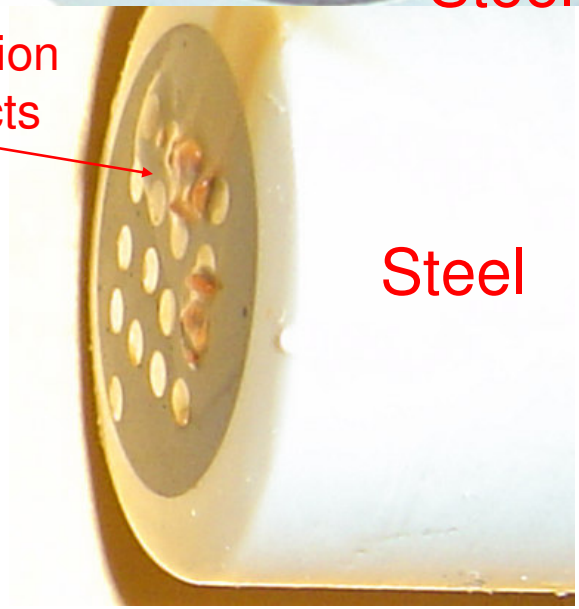
Corrosion Monitoring with CMAS in Low-Conductivity Water

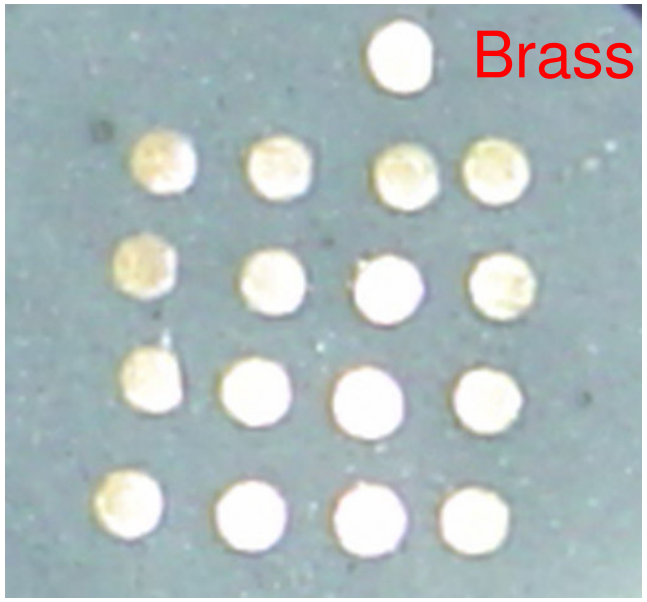


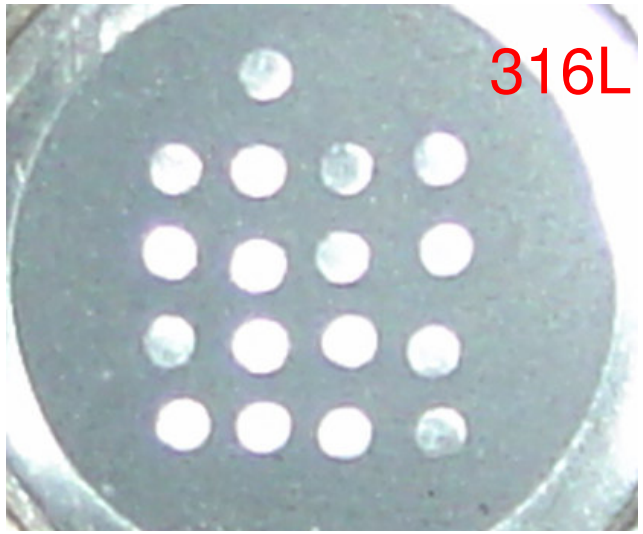
Probe Appearance After 10-day Exposure in Drinking Water



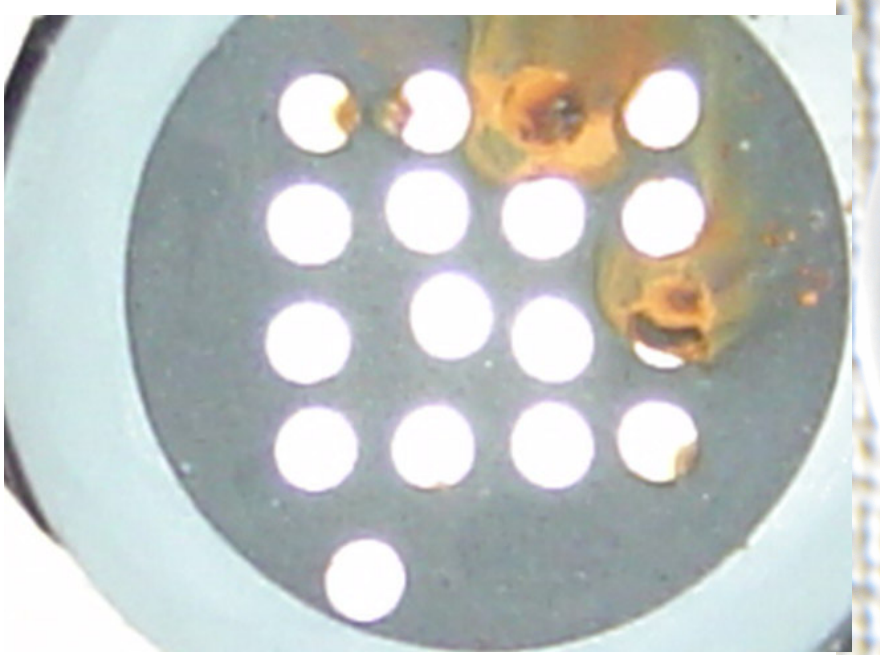
Corrosion Products



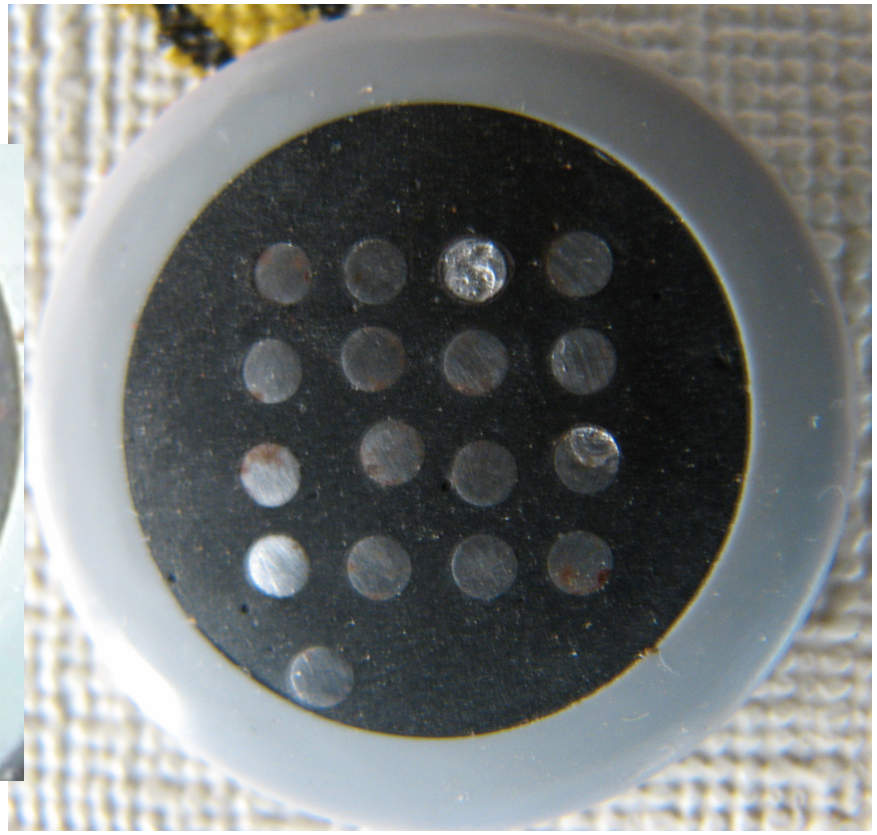




Carbon Steel Probe Appearance After 10-day Exposure in Drinking Water



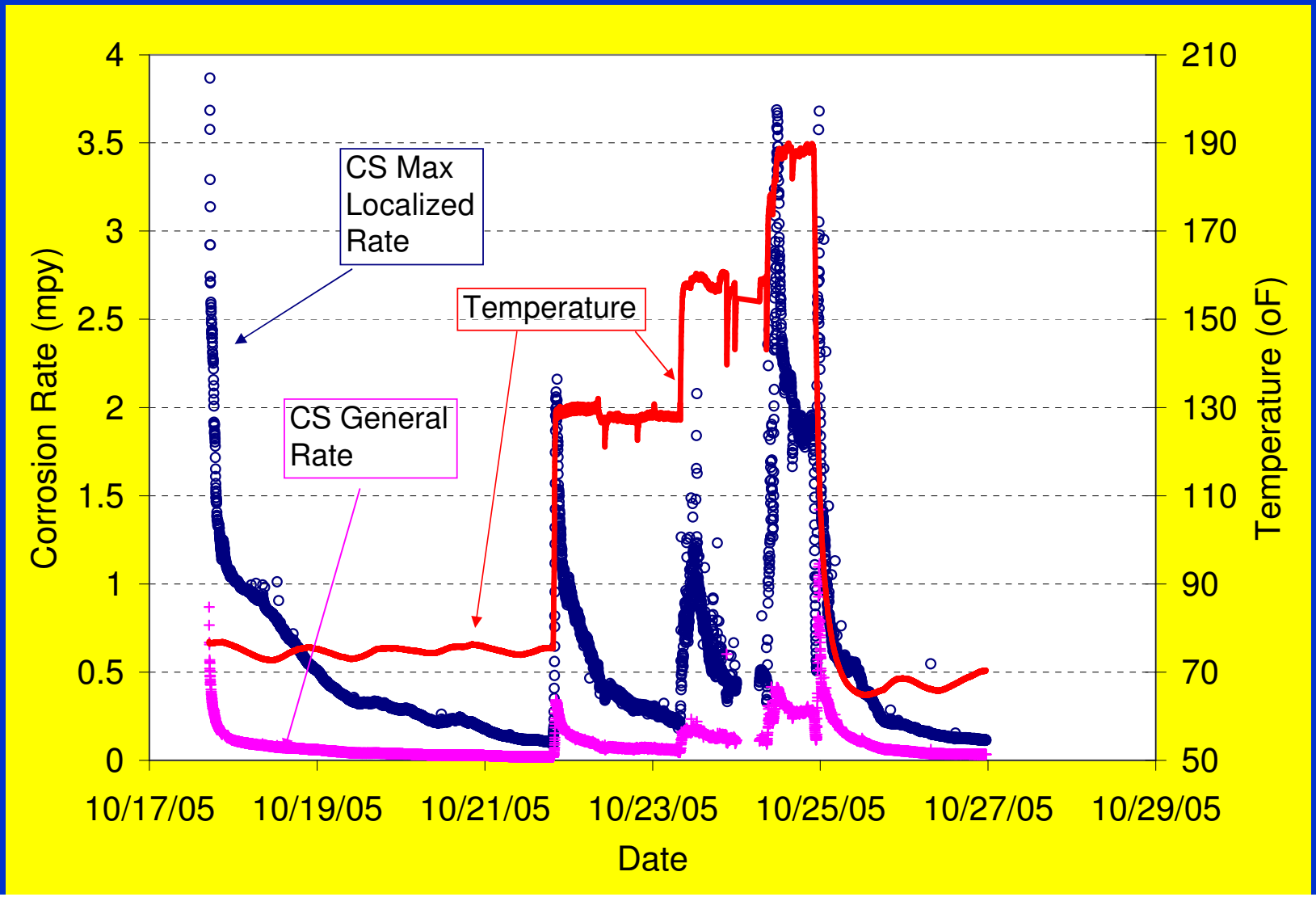
Before Cleaning



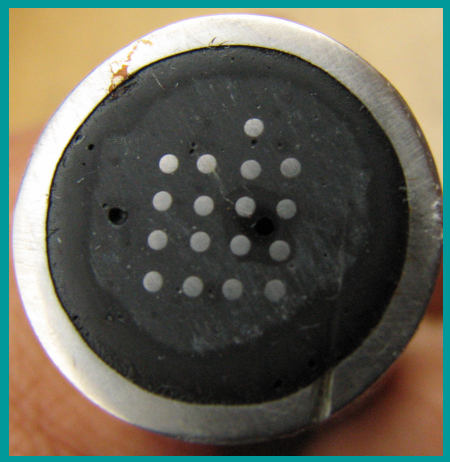
After Cleaning

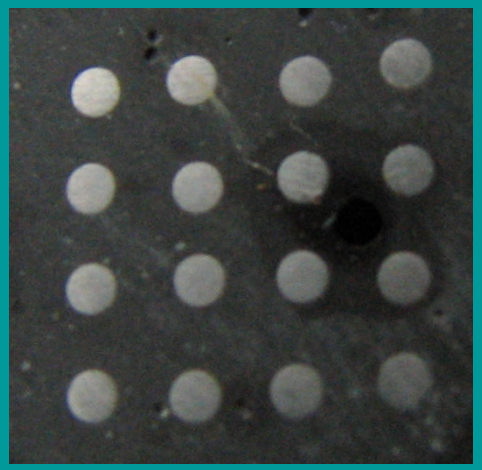
Carbon Steel Corrosion Rates in High-Silica Brine Solution (pH=10)

Courtesy: WCTI, Inc

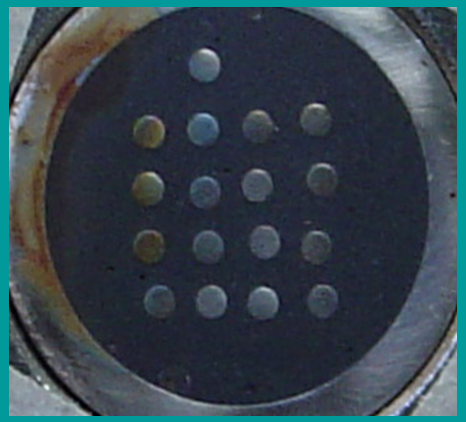


Comparison of Posttest Probe Appearances





Carbon steel, one week in High-Silica Brine Solution (pH=10) at up to 190 °F
Courtesy: WCTI, Inc

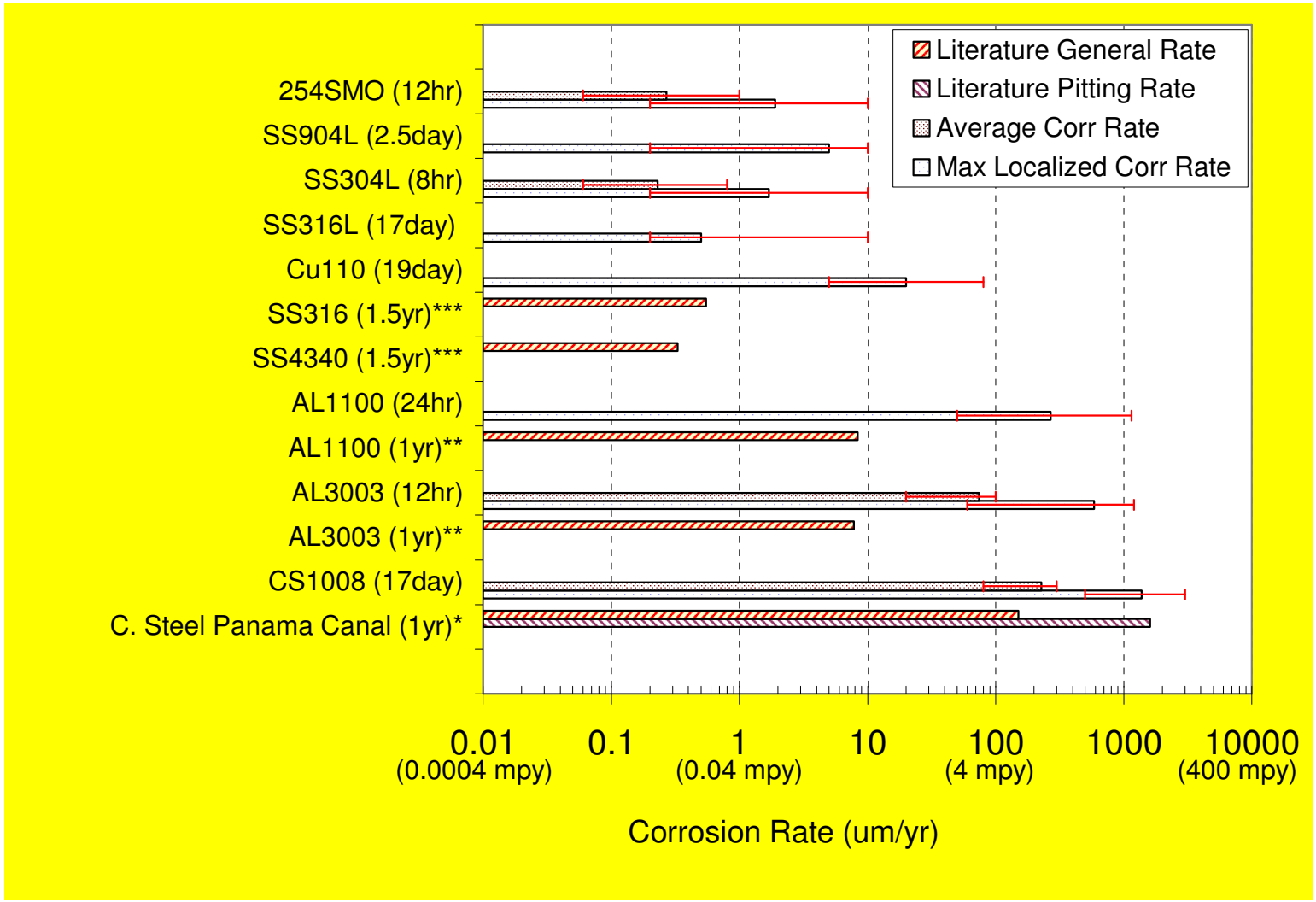


Carbon steel

316L Probe

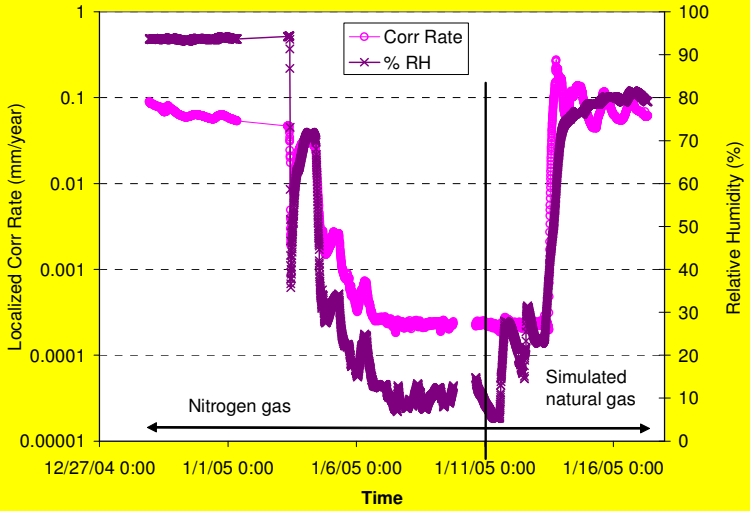
Three week in seawater at room temperature

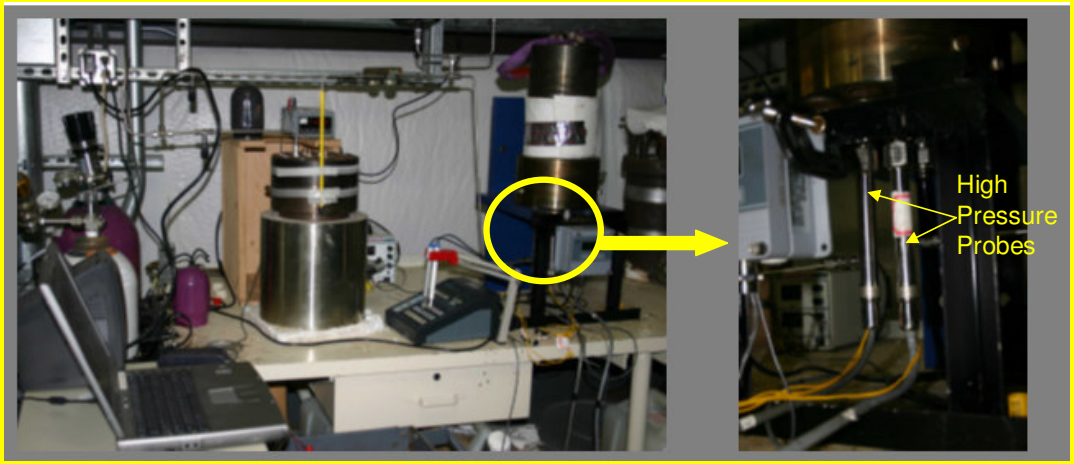
Comparison of Corrosion Rates with Literature Data



*—from Southwell and Alexander, 1970; **—from Hollingsworth and Hunsicker, 1987; ***—from Pelensky, et.al 1976.

Corrosion Monitoring with CMAS in High Pressure Gas Systems





Coupled Multielectrode Sensor Instruments and Software

Summary

- If the electrode size are close to pit size and the number of electrodes is large, Coupled Multielectrode Sensors can be used to measure pitting rate
- Coupled Multielectrode Sensors Have Been Used in:
  - Aqueous Solutions, including extremely low conductivity water, chemical process stream, plant cooling water, sulfide solution.
  - Humid Gases/Engine Exhausts
  - Under Biofilm/Coatings
  - Oil-Water Mixtures
  - Soils/Concrete
  - Gas/Liquid pipeline condition,
- Extensive test results were obtained in laboratories and some industrial fields (We have published >two dozen papers).

Backup Slides

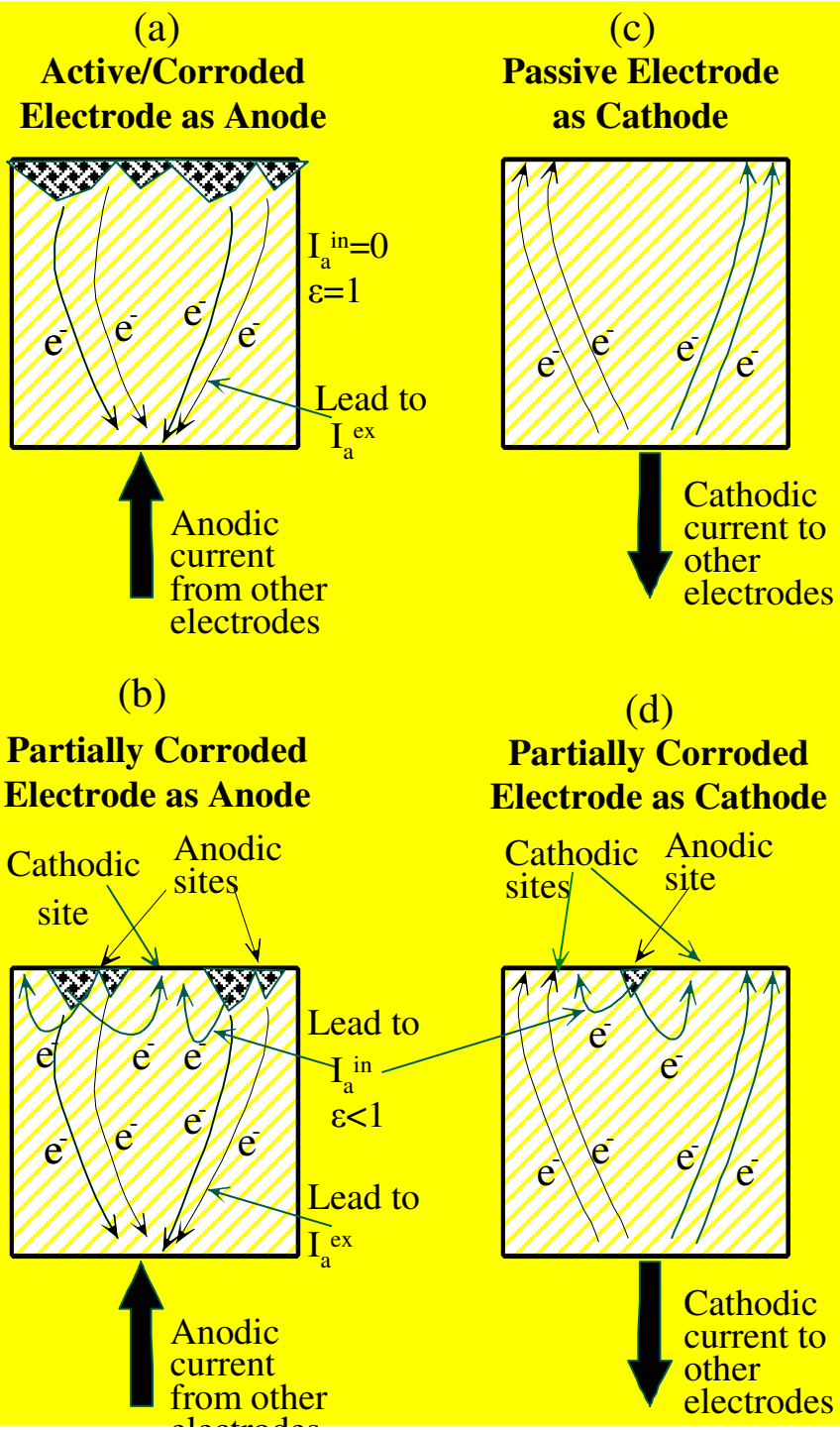
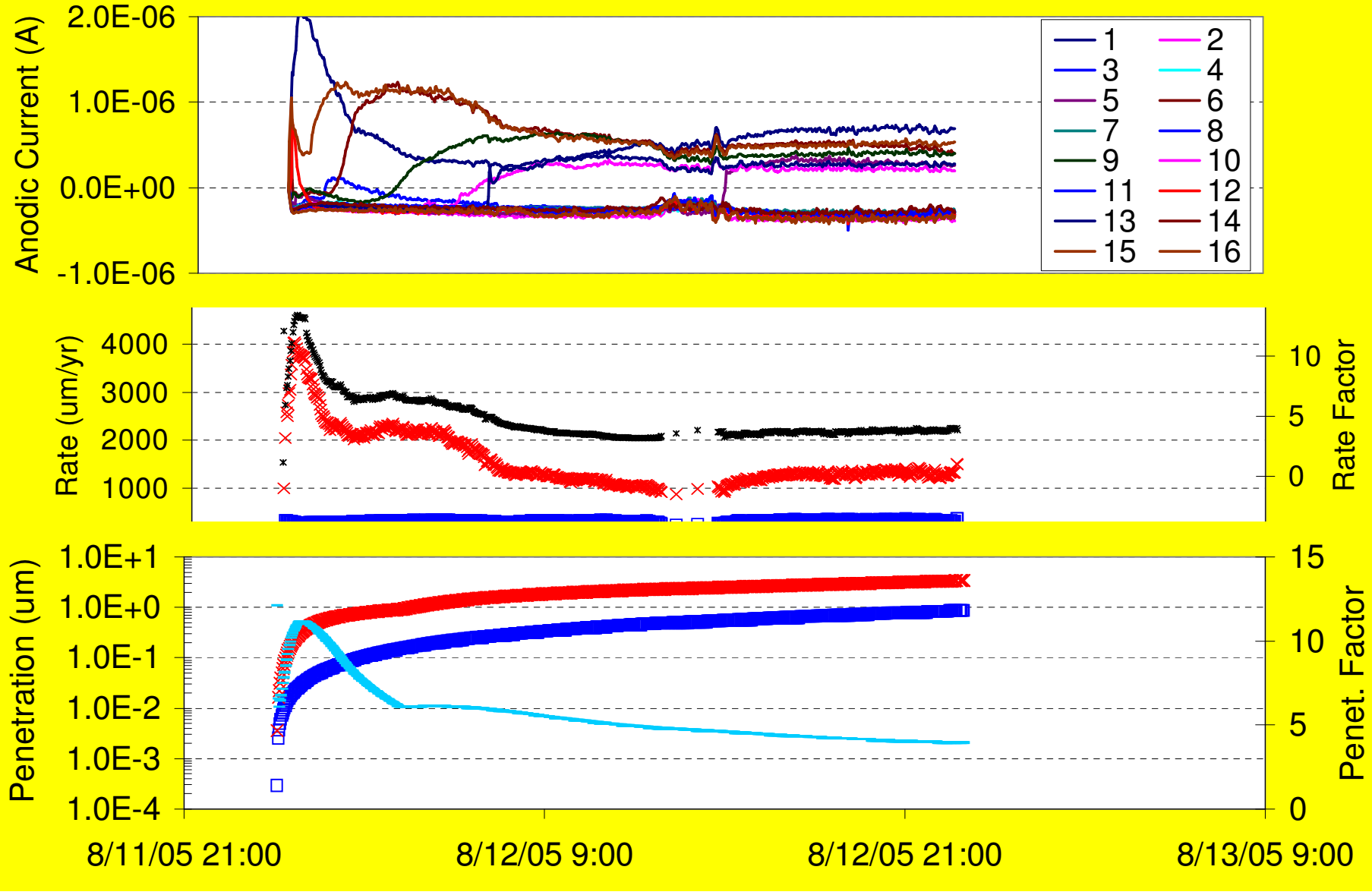
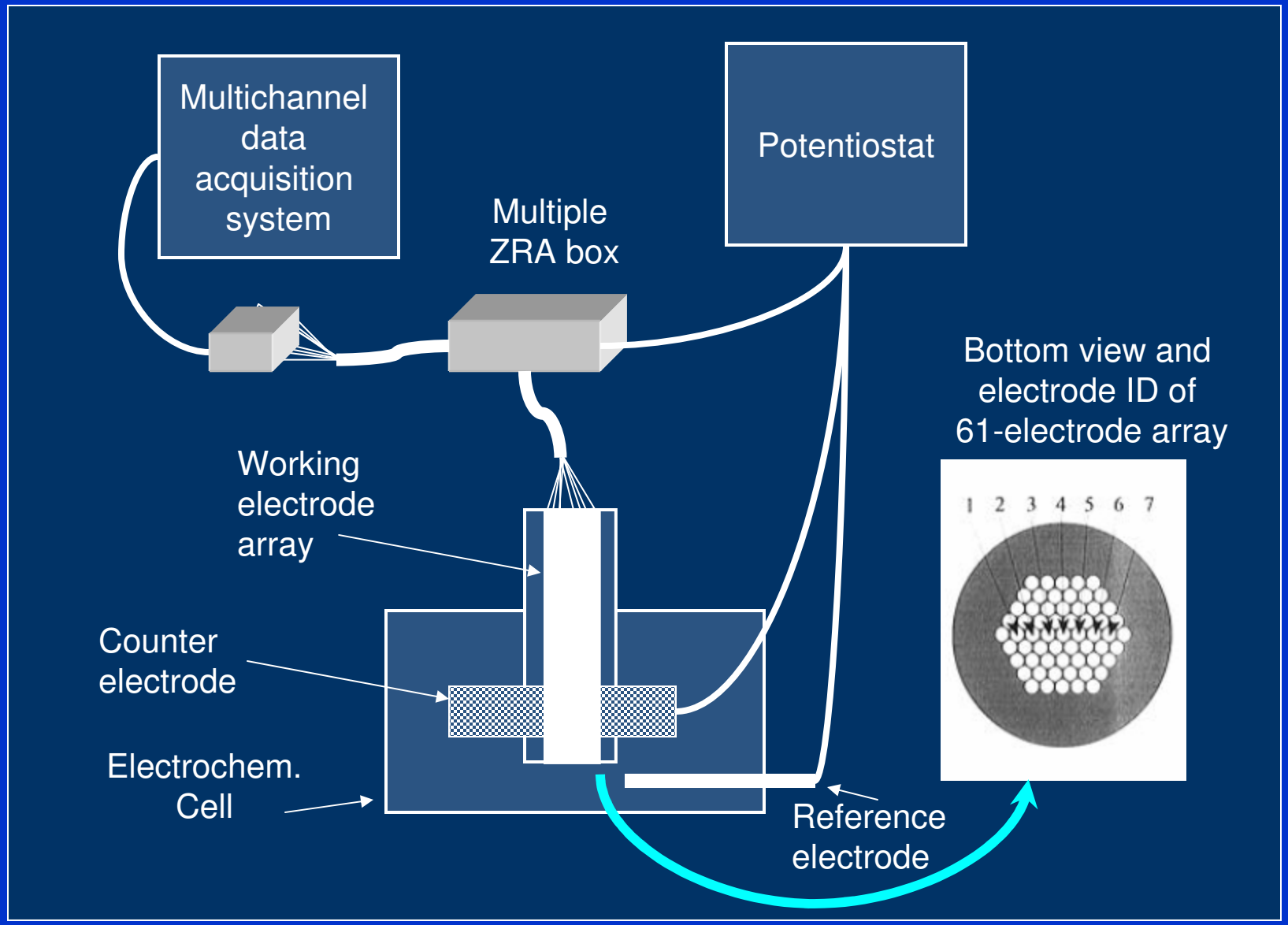


FIGURE 2. Flow of electrons on a totally corroded active electrode as anode (a), a partially corroded electrode as anode (b), a passive electrode as cathode (c), and a partially corroded electrode as cathode (d) in a coupled MAS probe.

Coupled Multielectrode Sensor Instruments and Software

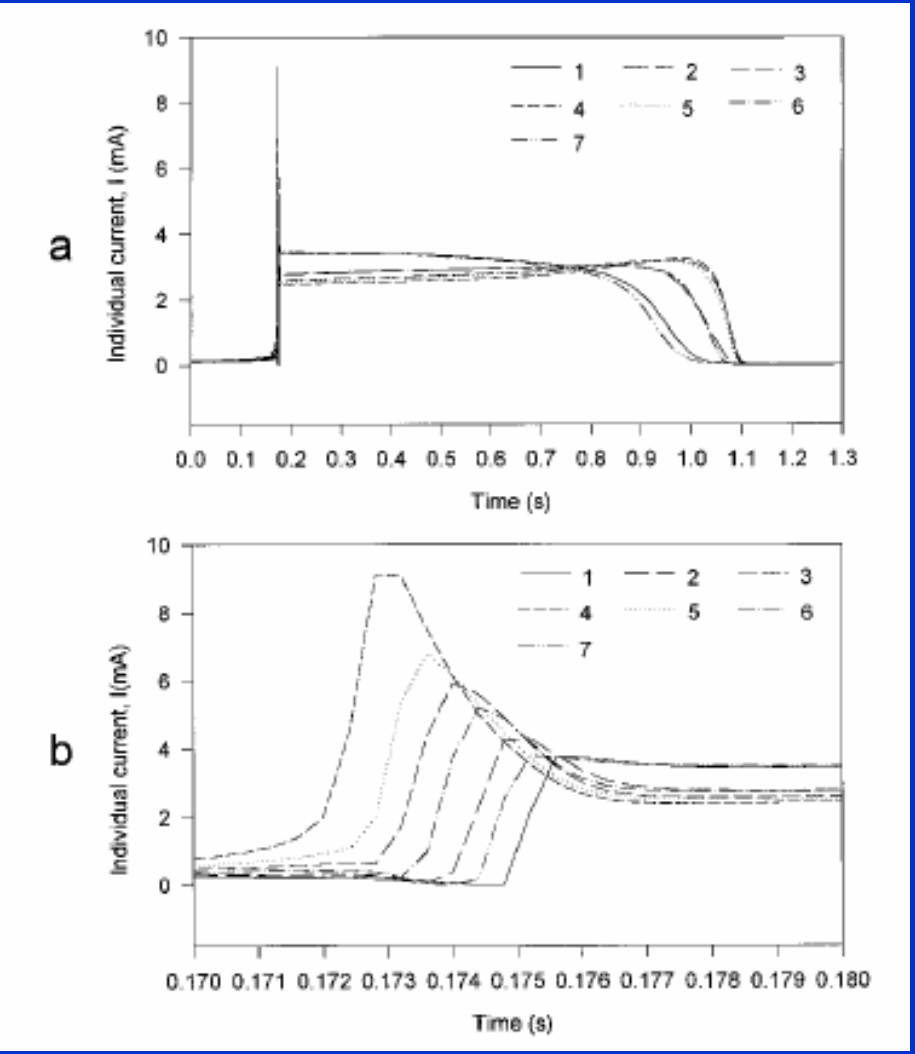


First Coupled Multielectrode Arrays



Fei, R. G. Kelly, and J. L. Hudson, "Spatiotemporal Patterns on Electrode Arrays," J. Phys. Chem., 100, (1996): p. 18986-18991.

Typical Results from First Coupled Multielectrode Arrays



Fei, R. G. Kelly, and J. L. Hudson, "Spatiotemporal Patterns on Electrode Arrays," J. Phys. Chem., 100, (1996): p. 18986-18991.