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Corrosion and Fouling Monitoring of Water Systems

By Bennett P. Boffardi, Ph.D., Bennett P. Boffardi and Associates, Inc.

Corrosion monitoring is an integral part of any water treatment program. It is used to determine treatment effectiveness and to establish the optimum level of chemical treatment that is most cost effective, not necessarily the least expensive per pound.

The purpose of corrosion monitoring is to assess or predict corrosion behavior of the system. Basically, there are two objectives to monitoring: (1) to obtain information on the condition of the operational equipment, and (2) to relate this information to the operating variables (i.e., pH, temperature, water quality, chemical treatment, etc.). Meeting these objectives will provide the following results:

1. Increased life of the plant
2. Improved quality of the plant's product
3. Prediction of maintenance needs at the plant
4. Reduction in the plant's operating costs

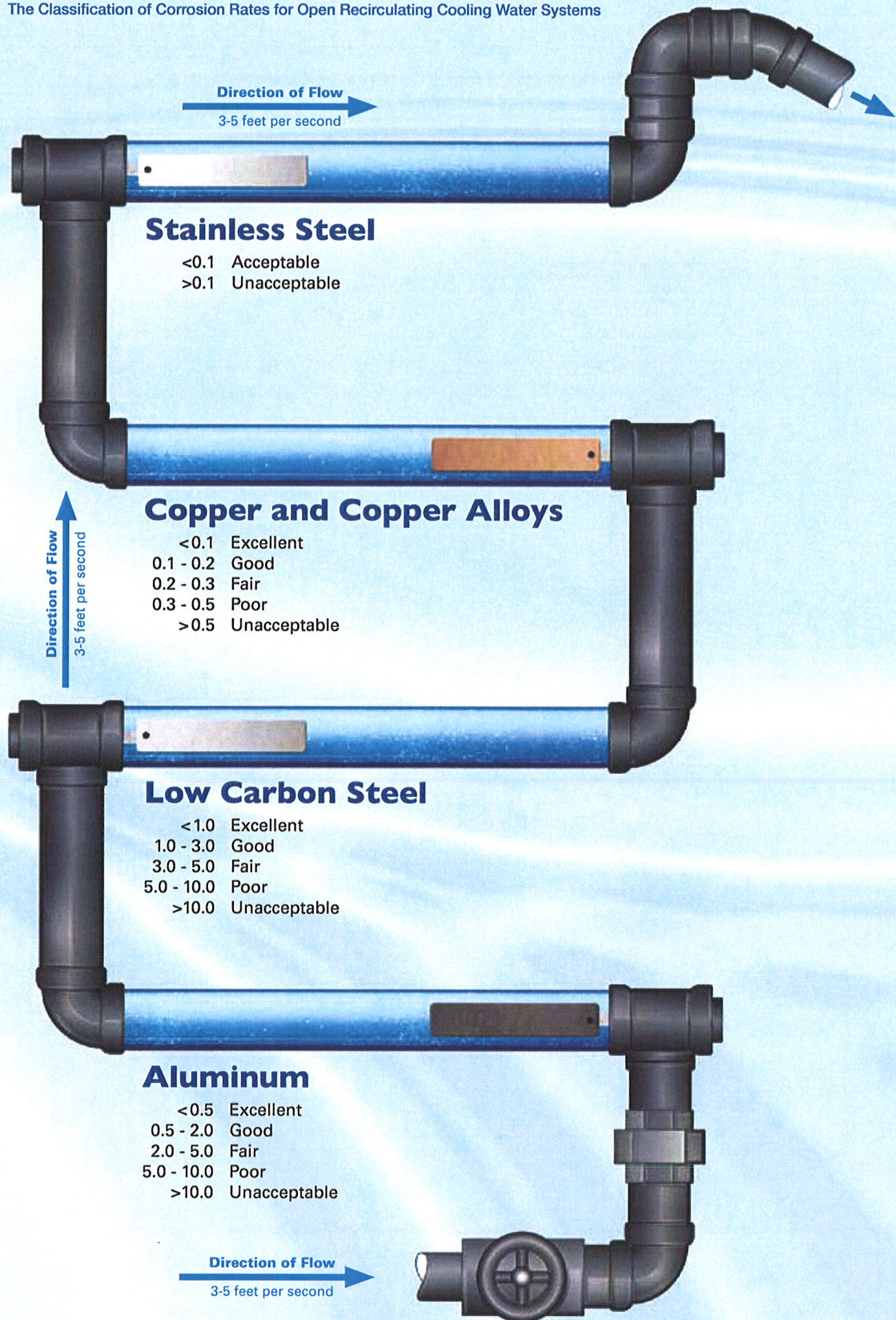
Corrosion monitoring is standard practice in the water treatment industry. The plant engineer can use this information to predict equipment life. Monitoring helps the engineer identify significant factors responsible for corrosion problems and assures implementation of solutions.

Corrosion monitoring is a diagnostic tool. It provides information for the solution of corrosion problems. Knowledge of corrosion trends can be very valuable. Frequently, several variables might appear to be significant, and the ability to correlate corrosion rates with a single variable under specific conditions can be vital. As a logical extension of its diagnostic capabilities, corrosion monitoring is used to assess the effectiveness of a solution to a specific water treatment problem.

Corrosion monitoring can be used to provide operational information. If corrosion can be controlled by maintaining a single variable (e.g., temperature, pH, chemical treatment, etc.) within limits previously determined, then that variable can be used to predict changes in corrosion patterns as the limits are exceeded in both a positive and negative direction. An extension of this technique is to use a monitored variable to control chemical addition directly through automatic feed systems.

The particular corrosion monitoring techniques selected depend upon their applicability to the system and the information being sought. Some techniques provide information that is effectively instantaneous. Other techniques provide a measure of corrosion rate. Others measure total corrosion or the remaining metal thickness, while others provide information on the overall system.

The Classification of Corrosion Rates for Open Recirculating Cooling Water Systems



Most corrosion monitoring techniques are best suited to situations where corrosion is of a general nature, but some techniques provide at least some information on localized attack, such as pitting.

No one monitoring technique will provide all the necessary data to properly evaluate the efficacy of the treatment program. More than one technique may be necessary to monitor a particular system.

An overview of the various corrosion monitoring techniques used in cooling water systems is shown in Tables 1–3, on the following page. The essential information is listed in Table 1, whereas Table 2 lists some of the characteristics of the monitoring techniques. Table 3 is a summary chart of the various monitoring techniques overall.

Corrosion Coupons

The most obvious method of assessing the corrosivity of a cooling water system to a specific material is to expose a specimen or coupon made of that material for a given time in the flowing water. Coupons are made from specific alloys, which have been cleaned and pre-weighed with a known surface area. Coupons vary widely in size and shape. Some commonly used coupons are 1/2 inch (12.5 mm) wide, 3 inch (75 mm) in length, and 1/16 inch (1.6 mm) thick, having an approximately 3.4 in² (2194 mm²) surface area. At selected time intervals, the coupons are removed, cleaned, and reweighed to determine the metal loss.

The weight loss is converted to overall thickness loss or average corrosion rate expressed in mpy, as follows:

$$\text{mpy} = 22.25 \times \Delta W / (A \times d \times D)$$

where

ΔW = weight change (mg), A = coupon surface area (in²),
 d = metal density (g/cm³), and D = exposure time (days).

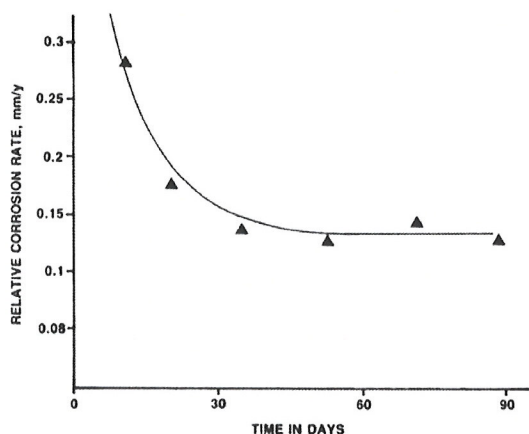
Conversion to metric units, millimeter per year (mm/y), requires the above equation to be multiplied by 0.0254.

$$\text{mm/y} = 0.0254 \times \text{mpy}$$

Corrosion coupons are highly susceptible to initial corrosion because the metal surface is in an “active” state due to surface preparation. Coupons should not be

touched during monitoring and installation processes. Use of plastic gloves when handling the coupons is highly recommended. Normally, 30 days is a typical test period for low-corrosivity water under 10 mpy (0.25 mm/y). Low-corrosivity water usually contains chemical treatments to stifle corrosion attack. Exposure periods less than 30 days can yield misleading results. Frequently, long-term tests are required for up to 90 days’ exposure. During this time frame, three sets of coupons are normally placed in a test rack and changed in a sequence of 30-, 60-, and 90-day intervals. Normally, the longer the exposure period, the lower the measured average corrosion rate and the more closely the coupons will approximate conditions in the system. Figure 1 graphically shows the decrease in corrosion rate with exposure time. Steady state is normally achieved in the 60- to 90-day time frame.

Figure 1: Corrosion Rate Time Curve



Screws and nuts made of nylon or plastic should be used to hold the coupons to the coupon holder. Mixed metallurgy should be avoided. Copper-base screws and nuts should not be used to hold carbon steel or stainless steel coupons. Galvanized screws and nuts should never be used.

Coupons having large amounts of deposits or tuberculation may indicate insufficient chemical treatment, unstable water characteristics, or highly corrosive conditions. Alternatively, deposits may have been transported from elsewhere in the system. Heavy, uniform deposits will reduce corrosion rates, since they can act as a protective barrier.

General guidelines for acceptable uniform corrosion depend upon the coupon metallurgy. General classification of corrosion rates are shown in Tables 4 and 5.

Table 1: Corrosion Monitoring

Method	Measures	Applications
Coupon Testing	<ul style="list-style-type: none"> • Average corrosion rate expressed as uniform corrosion in mpy. • Weight change over 30 to 90 days duration. 	<ul style="list-style-type: none"> • Most suitable for uniform corrosion under steady state conditions. • Can indicate localized attack, i.e., pitting, underdeposit, galvanic, etc. • Coupons made from most engineering alloys.
Linear Polarization Resistance, LPR (Corrater®)	<ul style="list-style-type: none"> • Instantaneous corrosion rate is measured by electrochemical polarization of ± 10 mv between two electrodes. • Pitting tendency can be measured. 	<ul style="list-style-type: none"> • Suitable for most engineering alloys. • Probe must be placed in fluid of sufficient conductivity to provide accurate rate. • Alloy multiplier required for materials other than low carbon steel.
Electrical Resistance, ER Corrosometer®	<ul style="list-style-type: none"> • Metal loss is determined from resistance change of a corroding metal element. • Uniform corrosion rates are calculated from resistance reading. • Does not measure localized corrosion. 	<ul style="list-style-type: none"> • Suitable for measurements in low conductivity environments, either liquids or vapor. • Element design is a function of probe life and sensitivity.
Analytical	<ul style="list-style-type: none"> • Concentration of dissolved or suspended species in fluid systems including pH and conductivity. • Does not measure localized corrosion. 	<ul style="list-style-type: none"> • Determine water quality, level of chemical treatment, inhibitory and antagonistic species, dissolved and suspended corrosion products.
Heat Transfer Unit	<ul style="list-style-type: none"> • Visual observation of attack on heat transfer surfaces. • Unit can determine corrosion rate from weight loss of heated surface. 	<ul style="list-style-type: none"> • Most suitable in simulating conditions in heat exchanger for corrosive attack. • Heat transfer tube can be made from most engineering alloys.

Table 2: Monitoring Technique Characteristics

Method	Time Interval for Measurement	Type of Information	Response to Changing Conditions	Plant Environment	Type of Corrosion	Ease of Interpretation
Coupon Testing	Long-term duration, 30 to 90 days	Average uniform corrosion rate	Poor	Any	Uniform and localized attack	Simple
LPR	Instantaneous	Corrosion rate, pitting index	Fast	Conductive	Uniform	Simple
ER	Short duration	Integrated corrosion rate	Moderate	Any	Uniform	Simple
Analytical	Fast	Species influencing corrosive attack	Fast	Any	Not applicable	Moderate
Heat Transfer Unit	Long-term duration, 30 to 90 days	Corrosion rate, scale and fouling	Moderate	Any	Uniform and localized attack besides deposition	Difficult

Table 3: Monitoring Devices

System	Coupon	LPR	ER	Analytical	Test Heat Exchanger
Once-Through Cooling	X	X	X	X	
Closed System Cooling	X	X		X	
Open Recirculating Cooling	X	X		X	X

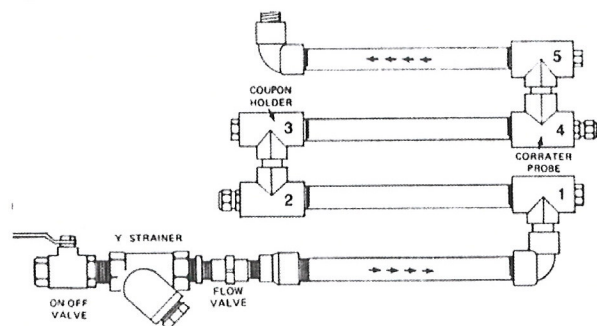
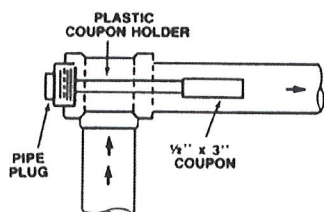
Table 4: Qualitative Classification of Corrosion Rates in Recirculating Cooling Water—mpy

Metal/Classification	Low Carbon Steel	Copper Alloys	Galvanized Steel	Aluminum	Stainless Steel
Excellent	<0.1	<0.1	< 2.0	<0.5	<0.1
Good	1.0-3.0	0.0-0.2	2.0-4.0	0.5-2.0	
Fair	3.0-5.0	0.2-0.3	4.0-8.0	2.0-5.0	
Poor	5.0-10.0	0.3-0.5	8.0-10.0	5.0-10.0	
Unacceptable	>10.0	>0.5	>10.0	> 10.0	>0.14

Table 5: Qualitative Classification of Corrosion Rates in Closed Cooling Water—mpy

Metal/Classification	Low Carbon Steel	Copper Alloys	Stainless Steel
Excellent	< 0.2	<0.1	<0.1
Good	0.2-0.5	0.1-0.3	
Fair	0.5-1.0	0.3-0.5	
Poor	> 1.0	>0.5	>0.1

Coupon installation should be placed in a coupon test rack shown in Figure 2. Note that in Figure 3 the broad face of the coupon is vertical to prevent deposits from settling during periods of low flow. It is important that the flow rate through the rack corresponds to the heat exchanger flow rate.

Figure 2: Corrosion Test Rack**Figure 3: Coupon Orientation**

Too high a flow rate will keep debris off of the coupons and may initiate erosion attack on copper-base alloys. Low flow rates may result in excessive corrosion and

fouling. Normally, flow rates of 3 to 5 ft/s (1 to 2 m/s) are adequate. The coupon rack should be connected to the return riser to the tower or at the exit of the hottest part of the system using plastic piping or any other material that will not influence coupon corrosion rates. For example, do not use galvanized

pipe, copper pipe, or brass valves to connect the test loop to the riser. Note in Figure 2 the use of an optional strainer. The strainer should be used in water systems known to have high-suspended solids or assorted foreign matter, or both.

Flow through the coupon rack can be controlled using an orifice control valve, but this valve is subject to plugging. A plugged orifice control valve will have reduced flow or no flow at all, resulting in high coupon corrosion rates. A rotameter valved at the end of the coupon rack will give more flexibility and accuracy in controlling water velocity. A strainer in the system will prevent plugging of the fluid control valve. Cooling water discharge from the rack should go to a sump (drain, tower basin, etc.) and not be plumbed back into the cooling system. The outflow of the rack must be open to the atmosphere.

In a high-rise building the cooling tower is normally placed on the roof and the corrosion rack is in the mechanical room, which is frequently in the basement. In this situation, the corrosion rack is plumbed between the down comer and the riser. Materials of construction for the corrosion rack should be made of stainless steel to provide rigidity and have minimal influence on the coupons. Use of carbon steel or galvanized steel is not recommended as construction materials. Coupon placement in the rack follows the galvanic series, starting from the active end. That is, aluminum, low carbon steel, stainless steel, and then copper-base alloys.

Coupon corrosion studies are simple to perform. This is the most direct method, aside from inspection of the actual plant equipment, to determine the efficacy of a treatment. Coupon evaluation allows simple comparison between different alloys, which provides visual examination for localized attack, such as pitting, crevice attack, dealloying, or any other form of non-uniform attack. However, there are limitations to coupon evaluation. Coupons provide weight loss determination of corrosion rates. This consists of accumulated loss of material over

the period of exposure. Therefore, coupons cannot determine the time or magnitude of corrosion upsets within the exposed time frame. Finally, 30 to 90 days are needed to allow sufficient weight change to be meaningful. This 30- to 90-day exposure can sometimes indicate differences between short-term and long-term corrosion rates.

Linear Polarization Resistance Meter (LPR)

The linear polarization resistance (LPR) technique is the only corrosion monitoring method that allows corrosion rates to be measured in real time. Although limited to electrolytically conducting liquids, the response time and data quality of this technique make it superior, where applicable, to all other forms of corrosion monitoring.

LPR is particularly useful as a method to rapidly identify corrosion upsets and, thus, evaluate remedial action—reducing and minimizing unscheduled downtime, thereby prolonging plant life.

The most common LPR device is a two-electrode probe. The basic operation of the LPR instrument uses two electrodes made of the material of interest, i.e., low carbon steel, Admiralty, 90:10 copper nickel, etc. One of the electrodes acts as an anode, the other as a cathode. During the operation of the instrument, a very small voltage of 20 mV is applied across the electrodes. In this region, the polarization curves approach linearity, hence the term LPR. The applied potential divided by the measured current i_{meas} is a resistance term called Polarization Resistance, or R_p . The resistance to current flow between the two electrodes of the LPR probe is the sum of polarization resistance values at each electrode and the resistance of the solution between the electrodes (R_s).

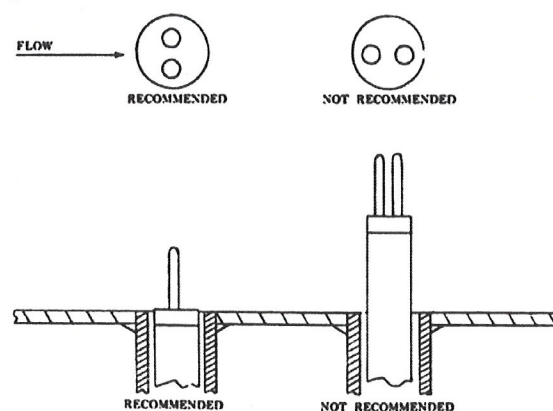
$$\Delta E = i_{\text{meas}} (2R_p + R_s)$$

In addition to general or uniform corrosion, localized corrosion (pitting) may occur in a system. A Pitting Index or Imbalance measurement can be obtained from some LPR meters. The electrochemical current generated is a qualitative measurement or index. If there is a low imbalance reading compared to a general corrosion rate, then pitting is probably minimal. A high imbalance reading compared to a general corrosion rate can indicate that pitting or crevice corrosion will be the main form of

attack. When a general corrosion rate reading is about the same as the imbalance index, then some pitting is indicated, but the pits will probably be broad and shallow.

The LPR probe should be installed perpendicular to the water flow in a representative water stream, which is part of the piping system or at the end of the coupon test rack. The probe must be installed such that water flows between the two electrodes in order to avoid fouling of the electrodes. The two electrodes should project into the flowing water, with the probe lead flush with the pipe wall, as shown in Figure 4.

Figure 4: LPR Probe



Serious errors in corrosion rate measurements may occur in low-conductivity water due to solution resistivity effects. This situation tends to occur at moderate to high corrosion rates and is manifested by indicating lower corrosion rates than actual. The operating range for various LPR instruments can be obtained from the manufacturer. Table 6 lists the commercial LPR Cor-rater® electrode multiplier.

Table 6: Corrater® Electrode Multiplier

Metal	Multiplier
Low carbon steel	1.00
Type 304 stainless steel	0.92
Type 316 stainless steel	0.94
Copper	2.00
Admiralty	1.81
Aluminum Brass	1.90
90:10 Copper: nickel	1.88
70:30 Copper: nickel	1.67

The LPR probe alloy multiplier should be used when electrodes are made from materials other than low

carbon steel. The purpose of the multiplier is to convert the built-in constants that are specific for low carbon steel to other alloys. Corrosion rate multipliers account for the specific alloy's anodic reactions, the valency of the anodic reactions, the alloy's equivalent weight, and the alloy density. LPR electrodes should be changed periodically and at least annually.

Corrosion rates obtained with LPR instruments provide rate data directly and within a few minutes. This instrument is well suited to applications where upsets or other accelerated corrosive conditions can be detected quickly, so that remedial action can be taken. The corrosion rates obtained with the meter assume uniform corrosion with a tendency to predict pitting attack. Deposits on the electrodes can bias the pitting index value. If the index value is high, the probe should be removed and the electrode visually examined for debris. Bridging the electrodes with conductive deposits will affect both the general corrosion value and the pitting index.

The LPR reading may not agree with the coupon corrosion rate. The LPR data are real time and measure the corrosion rate at the time of measurement. Coupon rates are an accumulated average mass loss, taking into account all corrosion that has occurred during its exposure period. Coupon mass losses are a direct measure of corrosion rate, whereas LPR data are generated from electrical currents, which are influenced by other factors. The main advantage of LPR devices is the rapid detection of sudden changes in system operating parameters or chemical levels.

Details on how to calculate corrosion rates from electrochemical measurements can be obtained from ASTM G 102, Practice for Calculation of Corrosion Rates and Related Information from Electrochemical Measurements.

Electrical Resistance (ER) Meter

The electrical resistance (ER) technique is an online method of monitoring corrosion rates. It is universally applicable to all types of corrosive environments, i.e., conductive to poorly or nonconductive media (such as deionized or potable waters) and vapor phase systems (such as steam).

There are many manufacturers of ER instruments. ER meters measure the change in resistance of a metal element as it corrodes. The metal element or probe is

usually in the form of a wire, strip, or tube. When it corrodes uniformly, the change in electrical resistance is proportional to corrosion

$$R = K/A$$

where R is the probe resistance, A is the cross sectional area of the metal element, and K is a constant and a function of probe metallurgy, element length, and resistivity. As the probe element corrodes, its cross sectional area is reduced, increasing its electrical resistance. Thus, the measurement of electrical resistance is inversely proportional to the remaining metal in the probe. Therefore, increases in the measured resistance signal increase the metal loss to corrosion. The probe is internally temperature compensated for changes in the probe constant, which is temperature dependent.

The advantage of the ER meters is their ability to measure corrosion in liquids, vapor phases, and in inaccessible locations. The liquid does not have to be conductive or have a minimum conductivity, as with the LPR systems. However, corrosion rates are not instantaneously determined. The time frame required to determine corrosion rates is a function of probe element and metal loss. Also,

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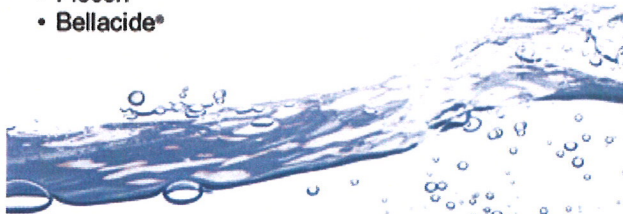
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the ER probes are suitable only for uniform corrosion. There is no pit index built into the instrument. Any pits developed on the element will cause rapid penetration and indicate excessively high corrosion rates.

Typical probe elements are shown in Figure 5. Appropriate response time information for any given probe can be obtained from the manufacturer. The corrosion rate is calculated from the change in dial reading on the instrument.

$$\text{Corrosion rate (mpy)} = \frac{\Delta D \times PF}{T}$$

where ΔD is the change in the dial reading, PF is the probe factor (supplied with each probe), and T is the elapsed time in days. ER probes must be allowed to corrode for a period of time before accurate corrosion rate measurements can be made. The time duration depends upon the corrosion rate. The higher the corrosion rate, the shorter the time period and vice versa. Response times for the various ER probe elements are shown in Figure 6.

Figure 5: Typical ER Probe Element Design

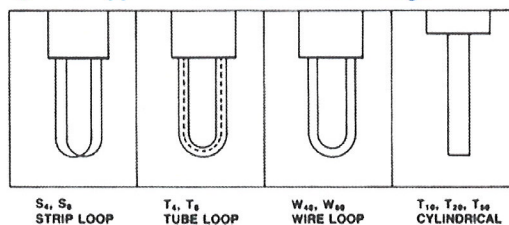
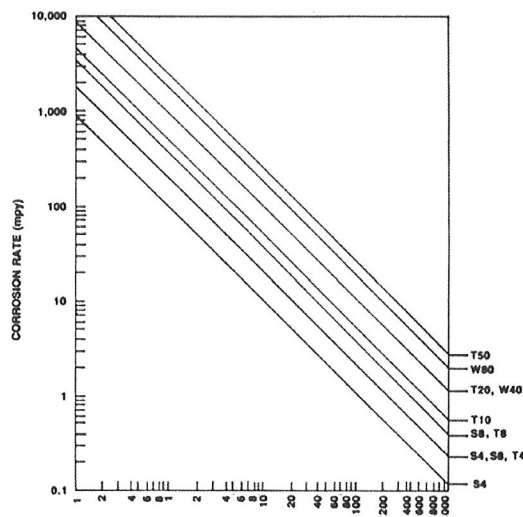


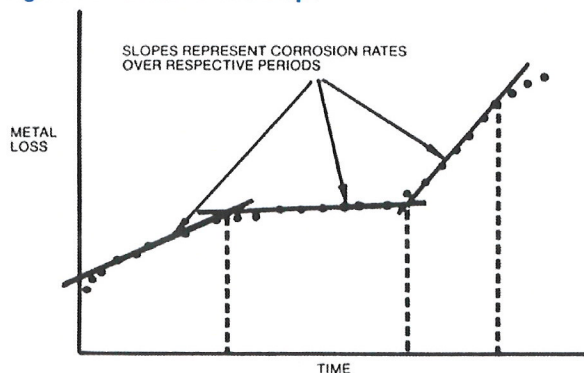
Figure 6: Response Time – Hours (Based On 1 % Probe Life)



Probe placement in the fluid should be similar to LPR electrode placement; that is, the probe element should protrude into the fluid. Flow should pass the element. There is no specific orientation for the probe element.

Figure 7 shows a plot of dial setting or metal loss from the ER meter versus time, which can give an indication of corrosion rates. A large change in slope represents an increase in corrosion, whereas a zero slope indicates no significant increase in corrosion.

Figure 7: Corrosion Rate Slope



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Generally, LPR is the preferred technology for on-line monitoring of corrosion in highly conductive waters such as those in industrial recirculating cooling water systems. The preference is based on two factors: 1) The relative instantaneous nature of the LPR and 2) The distortional effect that even a single pit has on the ER measurement and reducing the usable life of the ER probe.

Chemical Analysis

Water parameters relevant to the corrosion process can be provided through chemical analysis. This monitoring technique does not directly indicate corrosion rate but provides information on factors that can influence the corrosion process. It measures parameters that are known to be associated with acceptable or unacceptable corrosion processes within a system.

A thorough water analysis is not required of every water sample. However, there are core analyses that should be performed to determine the operating state of the system.

It is good practice to periodically obtain complete analyses so that seasonal variations in water composition can be tracked. A “well check” analysis is also advisable. This consists of a thorough analysis when the plant is operating properly and corrosion rates are meeting the objectives. The well check can then be used as base line data when corrosion rates are outside the norm and analyses are being performed to determine the cause.

Parameters to be determined for a thorough analysis and their impact on corrosion/deposit are shown in Table 7.

Test Heat Exchanger

The test heat exchanger is a monitoring tool that evaluates a heat transfer surface for corrosion and deposition. The test heat exchanger is only as good a monitoring or evaluating piece of equipment as its ability to duplicate or represent system conditions. The factors inherent in plant heat exchanger equipment that determine the corrosion and deposition of exchanger surfaces are:

Table 7: Analytical Parameters

pH	Corrosion or scale-forming tendency
P Reading	Monitors buffering capacity, differentiates OH^- , CO_3^{2-} and HCO_3^-
M Reading	Provides data for calculating CaCO_3 potential. Includes all hydrogen titratable species, i.e., PO_4^{3-} , SiO_2 , polymers. If pH/alkalinity relationship is outside of norm, then additional alkalinity value may be due to other titratable species
Conductivity	Estimates total dissolved solids
Suspended Solids	Monitors general water quality or turbidity
Orthophosphate	Monitors inhibitor concentration and/or reversion
Polyphosphate	Monitors inhibitor concentration
Phosphonate	Monitors inhibitor concentration
Total Organic Carbon	Monitors overall water quality
Calcium, Total	Monitors potential hardness scale deposition
Calcium, Dissolved	Monitors hardness scale deposition if value is different from calcium, total
Magnesium, Total	Monitors potential deposition
Magnesium, Dissolved	Monitors potential silicate or hydroxide deposition if value is different from magnesium, total
Iron, Dissolved	Monitors background level and inhibitor concentration need for stabilization
Manganese, Total	Monitors background level
Manganese, Dissolved	Monitors background level and inhibitor concentration need for stabilization
Aluminum, Total	Monitors possible inhibitor adsorption, reducing corrosion protection if concentration is > 0.1 mg/L
Aluminum, Dissolved	Monitors possible inhibitor adsorption, reducing corrosion protection if concentration is > 0.1 mg/L. Loss of 3.5 mg/L of phosphate per 1 mg/L of aluminum
Copper, Total	Monitors potential copper corrosion reducing steel corrosion protection if concentration > 0.1 mg/L
Copper, Dissolved	Monitors potential copper corrosion. Acceptable level < 0.05 mg/L
Zinc, Total	Monitors potential zinc scale deposition and level of chemical treatment needed to inhibit corrosion and/or disperse solids
Zinc, Dissolved	Monitors background levels and active synergist

- Product temperature, which determines metal skin temperature.
- Water flow velocity in the tube, which can influence fouling rate. Low velocities of 0 to <2 ft/s (0–0.6 m/s) can result in more severe fouling. Average velocities of 3 to 5 ft/s (1–2 m/s) would correspond to normal rate of deposition. High velocities of 6 to 12 ft/s (2–4 m/s) will result in less fouling.
- Heat flux, a major influence on scale/deposition rate. Corrosion rates will also be influenced but to a lower degree. Heat flux values of 0 to 2,000 BTU/ft²-h (0–6,300 W/m²) are considered low. Heat flux values of 2,000 to 5,000 BTU/ft²-h (6,300–15,800 W/m²) are average. Heat flux values of 5,000 to 10,000 BTU/ft²-h (15,800–31,500 W/m²) are considered high.
- Cooling water temperature, which accepts heat from the plant exchanger.

In order to obtain reliable results from a test heat exchanger, the above factors must be determined from the plant exchanger in the system that is to be duplicated. Once the plant parameters have been determined, they should be duplicated as nearly as possible in the test unit and held constant.

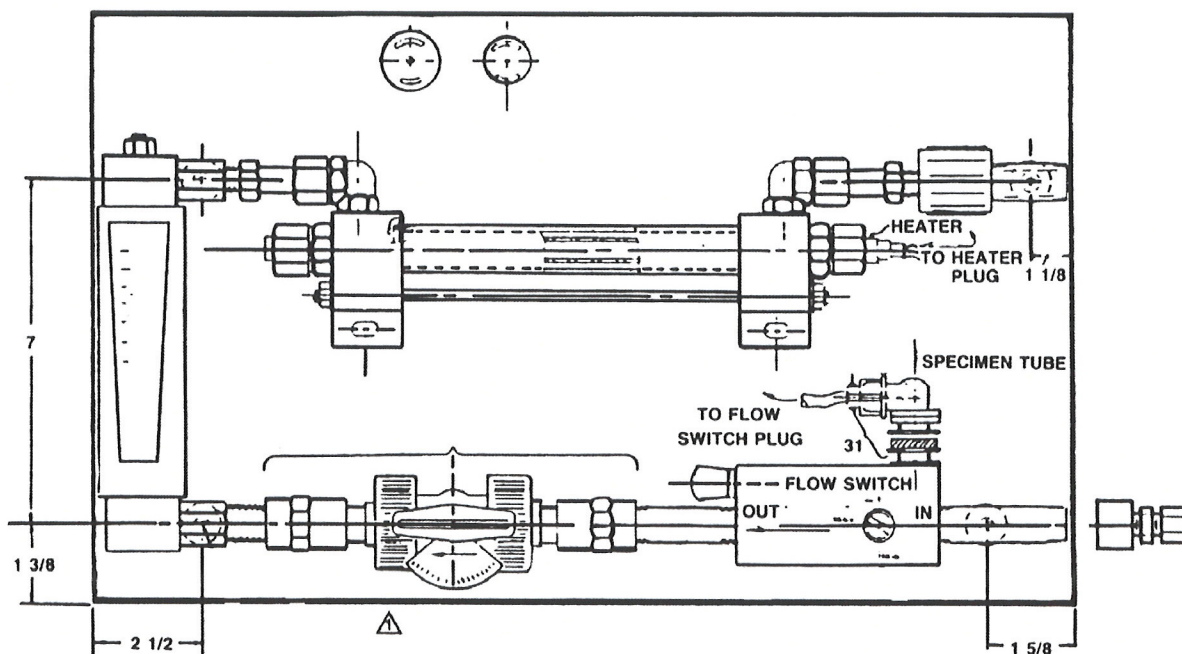
Figure 8 is a schematic of a typical test heat exchanger. An electrical resistance heating element is used to impose a heat load on the tubular metal surface. The metal test specimen is inside the glass jacket in which water flows over the annular space. The glass tube makes it possible to visually examine the metal surface for deposit buildup or corrosive attack.

At the end of the monitoring test period, which is at least 30 days, the heat transfer tubes should be evaluated for scale deposition, fouling, and corrosion. Analysis usually includes:

1. Visually inspecting and photographing the heat transfer.
2. Scraping the deposits from the tube for analysis.
3. Brushing and chemically cleaning the tube to examine tube surface for general and localized corrosion.

These heat exchanger devices require considerable time and expertise to properly operate. They are not commonly used because of manpower commitment and ancillary expenses.

Figure 8: Test Heat Exchanger



Conclusion

A wide range of corrosion monitoring techniques are used in water treatment to systematically measure the corrosion or degradation of equipment and distribution piping. Corrosion monitoring is a viable tool to assess the performance of any chemical treatment program. There

is no one technique that is universally applicable. The wide variety of corrosion monitoring tools can be used in any industry, and, although there are limitations on each technique, they provide a practical means to monitor corrosion behavior. More details on the various monitoring techniques can be found in the technical literature.

Additional Reading Materials

1. Ailor, W. H., *Handbook on Corrosion Testing and Evaluation*, John Wiley & Sons, Inc., NY, 1971.
2. ASTM D 2776, Test Methods for Corrosivity of Water in the Absence of Heat Transfer (Electrical Methods), *Annual Book of ASTM Standards*, ASTM International, West Conshohocken, PA.
3. ASTM G 96, Practice for On-line Monitoring of Corrosion in Plant Equipment (Electrical and Electrochemical Methods), *Annual Book of ASTM Standards*, ASTM International, West Conshohocken, PA.
4. ASTM G 102, Practice for Calculation of Corrosion Rates and Related Information from Electrochemical Measurements, *Annual Book of ASTM Standards*, ASTM International, West Conshohocken, PA.
5. NACE Standard TM0286, Cooling Water Test Units Incorporating Heat Transfer Services, NACE International, Houston, TX.
6. NACE Standard RPO189, Recommended Practice On-line Monitoring of Cooling Waters, NACE International, Houston, TX.

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Corrosion and Fouling Monitoring of Water Systems, by Ben Boffardi

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1. When using carbon steel coupons to measure corrosion rates in closed recirculating cooling water systems, a "good" corrosion rate is:
 - a. Less than or equal to 0.2 mpy
 - b. 0.2 to 0.5 mpy
 - c. 0.5 to 0.8 mpy
 - d. 0.8 to 1.0 mpy
 - e. Greater than or Equal to 1 mpy
2. The usual minimum recommended coupon exposure time is
 - a. 30 days
 - b. 60 days
 - c. 90 days
 - d. 120 days
 - e. 150 days
3. When using copper coupons to measure corrosion rates in open recirculating cooling water systems, a "fair" corrosion rate is:
 - a. Less than 0.1 mpy
 - b. 0.1 to 0.2 mpy
 - c. 0.2 to 0.3 mpy
 - d. 0.3 to 0.5 mpy
 - e. Greater 0.5 mpy
4. The unless trying to match process heat exchanger conditions, the recommended water flow velocity in a corrosion coupon rack is:
 - a. 1 to 2 feet per second
 - b. 2 to 3 feet per second
 - c. 3 to 5 feet per second
 - d. 5 to 7 feet per second
 - e. 7 to 10 feet per second
5. Which of the following corrosion measuring techniques does not allow determining the type (uniform or pitting) of metal loss being experienced?
 - a. Coupon Testing
 - b. Linear Polarization Resistance (LPR)
 - c. Electrical Resistance (ER)
 - d. Analytical
 - e. Heat transfer unit

6. When using a coupon rack to simultaneously measure corrosion rates on several different types of material, which of the following should be installed first (nearest the rack inlet)?
- Zinc
 - Aluminum
 - Low Carbon Steel
 - Copper Alloys
 - Stainless Steel
7. Which of the following measurement techniques give corrosion rates in real time?
- Coupon Testing
 - Linear Polarization Resistance (LPR)
 - Electrical Resistance (ER)
 - Analytical
 - Heat transfer unit
8. When installing carbon steel coupons to their holders, which type of bolt and nut is preferred?
- Carbon steel
 - Stainless Steel
 - Brass
 - Nylon
 - Galvanized Carbon Steel
9. In low pressure cooling water systems, the corrosion coupon rack is typically constructed of PVC pipe. What is the recommended rack material for high pressure systems?
- CPVC Plastic
 - PVDF Plastic
 - Carbon Steel
 - Galvanized Steel
 - Stainless Steel
10. The measurement end of a linear Polarization corrosion probe is designed with the following:
- One cylindrical post
 - Two cylindrical posts
 - A ribbon loop
 - A wire loop
 - A tube loop