

## OPERATIONAL AND CHEMISTRY MODELING AND MONITORING OF COOLING WATER HEAT EXCHANGERS FOR THE AVOIDANCE OF WATERSIDE FOULING

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### ABSTRACT

This paper will outline problem solving methods utilized to identify reliability and performance shortcomings associated with an overhead cooling water heat exchanger in the chemical processing environment. Modeling of both the heat exchanger operational conditions compared to design and the cooling water chemistry resulted in small changes in operational conditions, chemistry enhancement and metallurgical upgrading of the heat exchanger tubing. The implementation of the findings resulted in increased life of heat exchanger tubing, removal of the need for annual tube cleaning with a hydro-cutter and improved fouling run rates less than the design fouling allowance of the heat exchanger. The site heat exchanger actual operational conditions were modeled hydrodynamically, then a simulation modeling program was applied to duplicate the operating conditions of the test heat exchanger in the laboratory and side stream in the actual cooling system. The chemistry enhancement was selected based upon the foulant type and hydrodynamic stress found from the model and laboratory trial runs at various operational cooling water stress levels. The operational and chemistry changes were then validated in the actual cooling water system with heat transfer monitoring equipment that duplicate surface temperature and shear stress of the site heat exchanger of concern. This problem solving approach resulted in a 66 % reduction in fouling rates and the monthly mechanical cleaning of the inorganic scales has not been required for the past 10 years.

### INTRODUCTION

There are best practices associated with design, materials of construction and operation of each component utilized in the assembly of a cooling system to ensure reliability and availability. Performance enhancing additives are designed to meet the operational conditions of these components and advanced additives are designed to extend the performance when individual unit process equipment are operated outside of their design specification, otherwise known as stressed conditions. Unfortunately, as the run time increases on the cooling system, hydraulic balances, process controls and potentially water quality, quantity and chemistry drift away from the original design. Therefore,

one should proactively identify the potential poorly performing areas within the cooling system that are operating outside of the best practice or design specification. Using knowledge from modeling and performance stress testing allows one to predict outcomes, to identify the root cause of such stress and to determine which key operating indicators (i.e., KOI variables) need to be adjusted to achieve the key performance indicator (KPI variable), wherein the latter is “Best Practice” or “User Defined”. These predictions enable contingencies to be established such that, if performance deteriorates unscheduled outages can be avoided. The predictions also allow for ranking of risk, determining when maintenance should be scheduled and identifying what maintenance should be performed. The predictions can also be monitored to ensure corrective action has been attained or requires additional improvement to achieve compliance<sup>1</sup>.

### MODELING AND MONITORING

Modeling starts with the design and best practice application of a performance additive or operation of equipment associated within a cooling system. The case of performance additive design is more complex than just equipment operation, as the chemical is designed to allow for equipment operation outside of the original design criteria by compensating for higher fouling and corrosion potentials than allowed. Corrosion and fouling control in a cooling system are further complicated by both the chemistry of the make-up water and the cooling water chemical regime to be maintained. Potential fouling and corrosion problems in cooling systems are listed in Table 1. The type of make-up water to be utilized will determine if any special treatment is required prior to use for cooling. Make-up sources can vary from city water, which is already clarified, filtered and chlorinated, to well water, waste effluent water, cold lime softened, river water, or desalinated water, etc. With these sources of make-up come characteristic ranges of impurities and contaminants. Of most concern are the calcium hardness, magnesium hardness, total alkalinity, silica, iron, manganese, aluminum, organic content, ammonia, nitrate, phosphorous, suspended solids and microbiological activity.

Table 1. Potential Corrosion and Fouling Problems in Cooling Systems

UNIT PROCESS	CORROSION	FOULING	CAUSE
Cooling Tower, Sump (Basin) and Transfer Piping		x	<ul style="list-style-type: none"> <li>• Process inleakage contaminants, microbiological slimes, suspended solids on the distribution deck or in spray nozzle headers and sump or basin</li> <li>• Tower fill same as above plus evaporation to dryness salts</li> </ul>
	x		<ul style="list-style-type: none"> <li>• Microbiological/biofilm corrosion of wood and metal surfaces.</li> <li>• Low pH or oxygen corrosion on metal parts</li> <li>• White rust on galvanized metal</li> <li>• Galvanize loss and underlying corrosion of steel substrate from alkaline or acidic pH</li> <li>• Under deposit corrosion from sludges, sediments</li> <li>• Process inleakage contaminant attack</li> </ul>
Heat Exchanger		x	<ul style="list-style-type: none"> <li>• Microbiological/biofilms</li> <li>• Suspended solids</li> <li>• Inorganic due to heat input/solubility exceedence</li> <li>• Insitu and post fouling of corrosion products</li> <li>• Process inleakage contaminants and reaction products</li> </ul>
	x		<ul style="list-style-type: none"> <li>• General corrosion due to oxygen, dissolved solids (CL, SO<sub>4</sub>) and operational pH</li> <li>• Pitting due to under deposit corrosion - suspended solids and biofouling dependent</li> <li>• Galvanic due to dissimilar metals (tube/tube sheet) or ennobling (i.e. copper plating/deposition on carbon steel etc.)</li> <li>• Process inleakage contaminants</li> <li>• Erosion due to velocity and/or suspended solids</li> <li>• Mechanical fatigue due to vibrations</li> </ul>

Chemical additive designs are tested on a dynamic pilot cooling system set up to operate under the best practice design criteria. The pilot system contains:

- Cooling tower
- Auxiliary heat load/exchanger
- Rack for corrosion coupons
- Three linear polarization modules
- Three heat transfer test sections
- Side-stream counter spray air box containing cooling tower fill
- Conductivity, pH and ORP (Oxidation Reduction Potential) monitoring and control modules
- Apparent retention time of the system can be varied from 3 to 10 days

Up to three metallurgies can be on-line for instantaneous monitoring of fouling and corrosion. The fouling factor or heat transfer resistance values are in units of  $\times 10^{-5}$  hr ft<sup>2</sup> °F/Btu and the corrosion values are in units of

mils per year (mpy). The initial set up is done to comply with real world system operational best practices and only the chemistry/water treatment regime is varied and stressed<sup>2</sup>. One of the heat transfer test sections can also be fitted with an enhanced tube<sup>3,4</sup>. Figure 1 provides an illustration of the pilot cooling tower test rig and Figure 2 reveals the heat transfer test section fitted with an enhanced tube. All evaluations are in compliance with NACE protocols found in:

- Standard Recommended Practice, Pilot Scale Evaluation of Corrosion and Scale Control Additives for Open Recirculating Cooling Water Systems, Item No. 21092
- Standard Recommended Practice, On-line Monitoring of Cooling Waters, RPO – 189, Item No. 21041
- NACE/EFC Joint Publication, Monitoring and Adjustment of Cooling Water Treatment Operating Parameters, Item No. 24238



Fig. 1 Pilot Cooling Tower Test Rig

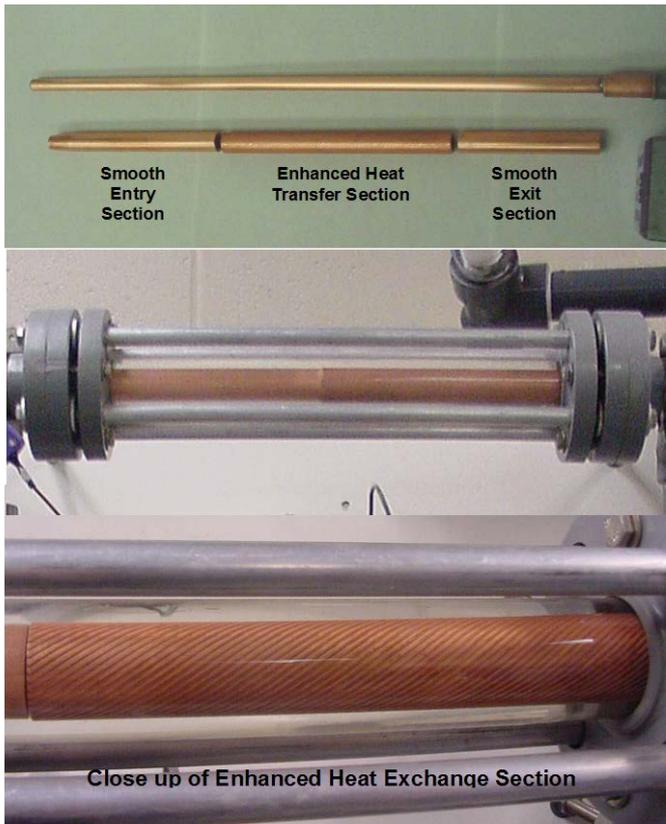


Fig. 2 Heat Transfer Section

Both exsitu crystallization and insitu crystallization inhibitory performance can be attained for optimization of the chemical additives used in the performance blend<sup>1</sup>. This is accomplished by evaluating the deposit weight density (DWD) of a scale coupon and the heat transfer reduction of the heat transfer test section respectively. Additionally, the fouling can be profiled by changing the operating velocity to determine if it is mass transfer or attachment dominant<sup>1</sup>. This is illustrated in Figure 3.

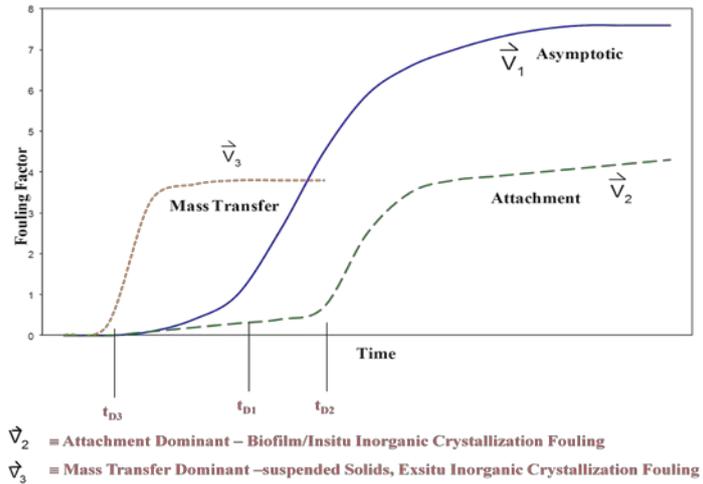


Fig. 3 Attachment vs. Mass Transfer Dominant Fouling

Laboratory conditions can duplicate the site cooling water conditions and heat exchanger operational conditions; where in heat exchanger surface temperature, bulk water temperature., shear stress, system apparent retention time, and cooling water chemistry (i.e. pH, ORP, TOC, conductivity, specific anion and cation impurities) can be simulated while concentrating the impurities up due to evaporative cooling to the point in which fouling and or localized corrosion occurs. At this point the data is inputted into an ion-pairing solubility program<sup>5</sup> that is then used to define the impurity saturation index value associated with the operational chemistry, surface temperature and shear stress in which the fouling control has been lost. This then allows for performance assessment and problem solving in the field of any water, any cooling system duty, any system design, as the chemistry has been distilled down in common denominator terms with a laboratory monitor. The same monitor is portable and can be used in the field at a site cooling system, side stream, again under a common denominator set of reference co-ordinate terms. The field monitor utilizes one heat transfer test unit, two linear polarization corrosion sensors as well as conductivity, ORP and pH monitors. It is illustrated in Figure 4.



Fig. 4 Portable Field Monitor and Controller

The common denominator approach was extended by developing another model associated with the heat exchanger operating conditions. The laboratory and field monitor not only has 45 years of field application utility, but also over 5 million hours of data, corresponding actual site heat exchanger operations data and associated deposit analysis. Considering the thermodynamics associated with the mechanics of heat exchanger operation that also play a role and were well defined by Epstein<sup>6</sup>, an empirical model from the data was developed to characterize the fouling tendency's, namely the Hydrothermal Stress Coefficient (HTSC)<sup>7,8,9,10</sup>. The input/output and interpretation of the program simulation are provided in Table 2. Prediction of the type of fouling and severity is noted.

Table 2. Shell and Tube Heat Exchanger Fouling Potential

<p><b>Input Data</b>                  Tube Diameter (id)(inches)                  Tube Length (feet)                  Number of Tubes per Pass                  Number of Passes</p>	<p>Inlet Water Temperature (°F)                  Outlet Water Temperature (°F)                  Water Flow Rate</p>
<p><b>Output Data</b>                  Heat Transfer Rate (Btu/hr ft<sup>2</sup>)                  Velocity (ft/sec)                  Surface Temperature, T<sub>so</sub> (°F)                  Residence Time (seconds)                  Hydrothermal Stress Co-Efficient (HTSC)                  Severity Without Treatment                  Primary Concern – Fouling Type</p>	

Hydrothermal Stress Co-Efficient (HTSC) Legend			
HTSC	T <sub>so</sub> (°F)	Fouling Type	Severity Without Treatment
<2	40 – 160	Various	Not Significant
>2	32 – 60	Cold Water Scale	Not Common
>2	60 – 110	Biofouling	Variable
>2	110 - 120	Biofouling and Scale	Variable/Slight
>2	120 - 145	Scale	Moderate
>2	145 - 160	Scale	Severe
>2	>160	Scale	Very Severe

From a general and practical applications point of view, HTSC values of 2 to 3 are very easy to work with by adjusting the cooling water chemistry or chemical additive in use. As the HTSC value transitions from 3.0 to 3.5, there is an increasing degree of stress, requiring additional chemical additives of higher design performance. Review of the cooling system and heat exchanger's design and operational conditions should be considered when HTSC values of 3.5 to 4.0 and higher are obtained. Comparing the actual recirculation rate measured to design, pump maintenance issues and/or lack of a standby pump for use during pump maintenance may be revealed. Heat exchanger flow rates may have deteriorated over time. This may be self-fulfilling due to an operational hydraulic imbalance issue compared to design. A branch line servicing many heat exchangers may have adequate flow, but due to poor balancing, a singular heat exchanger take off is receiving less flow or there is insufficient supply pressure to keep an overhead heat exchanger fully flooded when compared to the static gravity head (vacuum) on the outlet return line. These scenarios' require attention and correction. Non-chemical operational improvements, such as the use of booster pumps, fin fan pre-coolers, process by-pass, re-recirculation loops, etc. that increase velocity (shear stress), lower skin temperature and lower residence time can be explored with the simulation program. While holding the design overall heat transfer co-efficient (i.e., U co-efficient) constant, changes in flow rate, number of tubes, diameter of tubes and number of passes can be inputted to see their effects on HTSC values, residence time, velocity, outlet skin temperature and heat transfer rates<sup>8</sup>.

**LABORATORY AND FIELD APPLICATION**

A 12 year old overhead condenser was removed for inspection/replacement. The condenser was fitted with ¾” (0.065 inch wall thickness) arsenical inhibited admiralty brass “U” tubes and design operational conditions of 4 ft/sec velocity, process inlet-outlet temperatures of 300°F to 100°F and cooling water inlet-outlet temperatures of 85°F to 115°F. Approximately 30% of the tubes had already been mechanically sealed with plugs and at times the process inlet temperatures during operation would rise to 400°F. The actual operational conditions were 1.5 ft/sec flow velocity with a calculated surface temperature<sup>10</sup> of 210°F during the 400°F process inlet excursions (HTSC of 11).

None of the tubes were free of hard inorganic scale. The worst were found in the top row of the outlet section and a few were removed for laboratory assessment. The typical deposition is illustrated in Figure 5. It can be seen that it formed a layered, concentric ring-like deposition pattern that contained a majority of zinc and magnesium silicate salts and minor calcium sulfate and phosphate salts. The outcome was quite interesting. The deposit analysis was carried out utilizing atomic adsorption after digestion of the deposit (ASTM D-1971-02) and then the compounds were reported after probable combinations of the elements detected were determined (ASTM D-933-84). Deposit morphology appeared similar to insitu crystallization during nucleic boiling, while the major constituents were not on the radar screen of saturation indices levels<sup>5</sup> reported in Table 3.

Table 3. Stress Cooling Water Analysis Summary

Heat Exchanger Velocity	1.5 ft/sec	
Heat Exchanger Skin Temperature	200 - 210°F	
Cooling Water		
pH	7.3 - 7.8	
Chlorine	0.5 - 1.0 mg/L	
Oxidation Reduction Potential (ORP)	650 - 700 mV	
Conductivity	5,500 - 5,750 (uS/cm)	
Total Alkalinity as CaCO <sub>3</sub>	30 - 80 mg/L	
Calcium as CaCO <sub>3</sub>	825 - 900 mg/L	
Magnesium as CaCO <sub>3</sub>	700 - 775 mg/L	
Silicate as SiO <sub>2</sub>	30 - 35 mg/L	
Chloride as Cl	400 - 450 mg/L	
Sulfate as SO <sub>4</sub>	3,450 - 3,650 mg/L	
Iron as Fe	2.5 - 3.0 mg/L	
Ortho Phosphate as PO <sub>4</sub> Unfiltered	11.8 - 12.5 mg/L	
Ortho Phosphate as PO <sub>4</sub> Filtered	11.2 - 12.2 mg/L	
Delta Ortho Phosphate as PO <sub>4</sub>	0.1 - 0.6 mg/L	
Zinc as Zn	2.0 - 2.4 mg/L	
Corrosion/Deposit Control Additive	175 mg/L	
Radar Screen:	7.3 pH	7.8 pH
Corrosivity Index	54	24
Corrosion Rates --Carbon Steel	1.42 mpy	1.06 mpy
-- Admiralty Brass	0.33 mpy	0.23 mpy
Saturation Levels		
Tricalcium Phosphate	2,438	18,544
Hydroxyapatite	1,279	87,217
Ferric Hydroxide	1,574	12,191
Ferric Phosphate	1,546	963

When the tubes were bead blasted down to bare metal, a water line, gouging and pitting were observed (see Figure 6) and the maximum wall penetration from pitting was 0.020 to 0.030 inches (i.e., 31-46%). Gouged areas had suffered 90-92% wall thickness loss. Some deposits had rifling pattern (see Figure 7) from previous spiral hydro-jetting and gouging was noted in the valley areas of rifle pattern where the tube surface had been exposed. The tube inside diameter, water side surfaces after ASTM E3 preparation, revealed layer type dezincification and

intergranular attack at thickness of 0.005 to 0.012 inches (see Figure 8). In some cases, at the base of pits, the intergranular attack penetrated the entire tube wall. Overall tube losses associated with localized attack was 31 to 46% and 90 to 92% wall losses was associated with gouging. Stress corrosion cracking, fatigue cracking, erosion corrosion or other forms of attack were not observed.

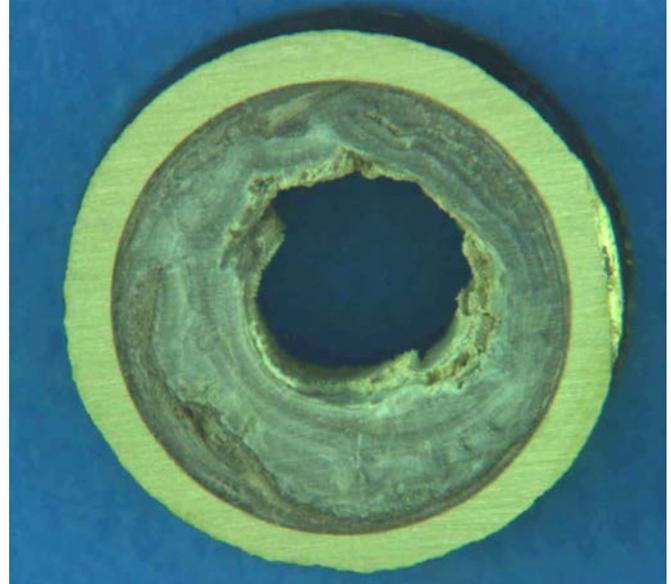


Fig. 5 Overhead Condenser Tube



Fig. 6 Cross Section of Cleaned Tube

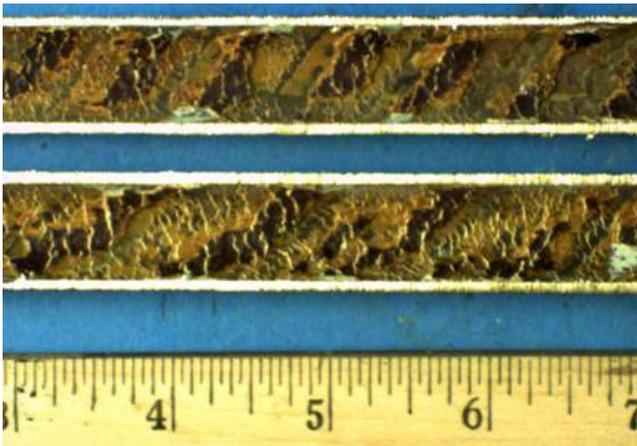


Fig. 7 Rifled Water Side Scale Pattern of Condenser Tube

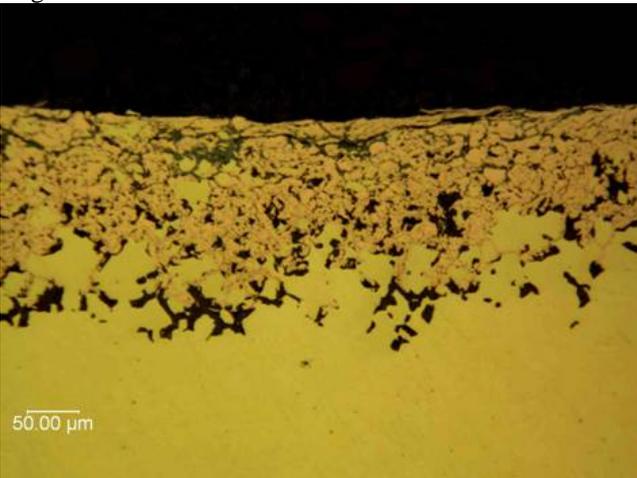


Fig. 8 Intergranular Attack and Dezincification; 160x Magnification

Clearly the operational conditions are well beyond best practices<sup>1</sup>. Laboratory simulation of the overhead condenser operation was duplicated<sup>11</sup> with set up of the pilot cooling system and monitor<sup>12</sup> and field system cooling water was shipped in to do the trial testing. The baseline modelling work with various heat exchange surface metallurgy, at 1.5 ft/sec and 210°F surface temperature with the presence of existing deposit corrosion control additive (zinc, phosphate, phosphonate and polymeric dispersant blend), but, without the high performance dispersant is illustrated in Figure 9. The operational pH (i.e. chemistry) was optimized and then the concentration of supplemental high performance dispersant (i.e. chemical) was optimized as illustrated in Figure 10 and 11 respectively.

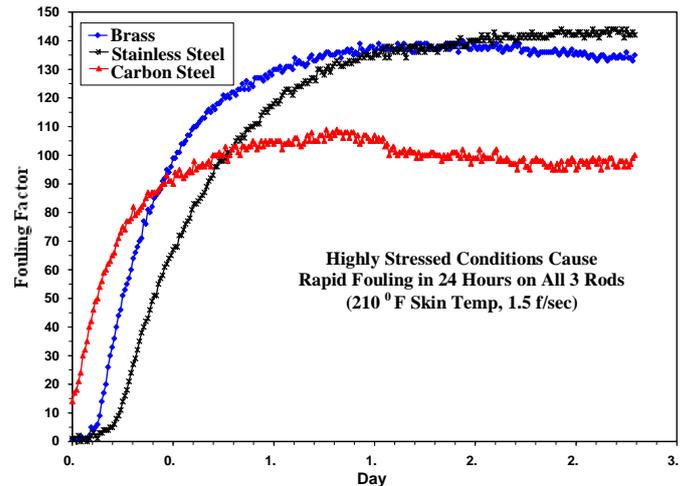


Fig. 9 Fouling Factor vs. Time No Dispersant, pH 7.3

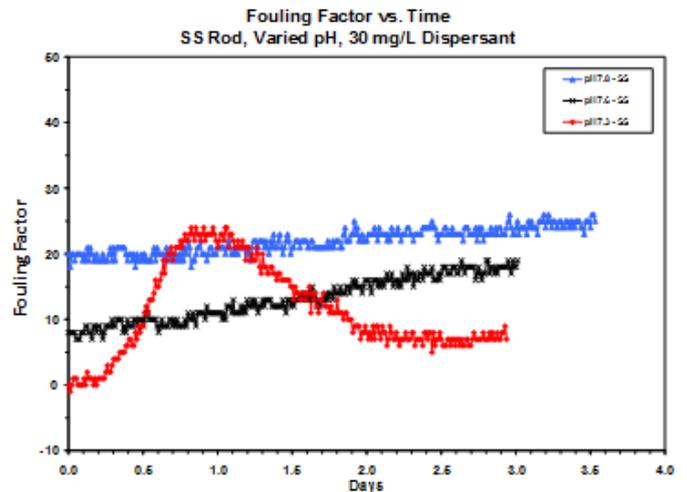


Fig. 10 Fouling Factor vs. Time pH Optimization

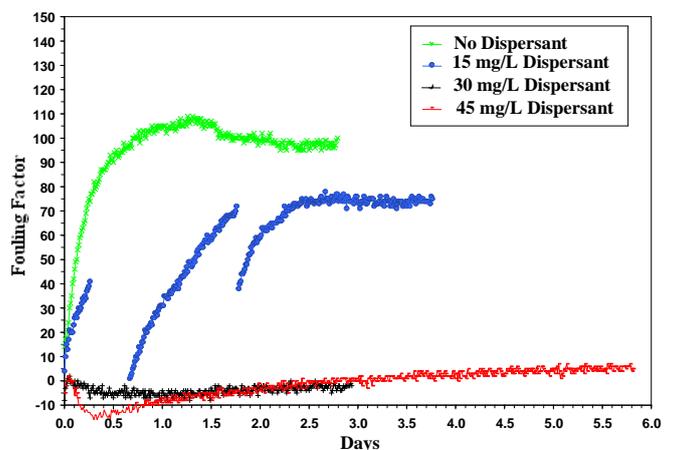


Fig. 11 Fouling Factor vs. Time Dispersant Optimization

## DISCUSSION

The aggressive gouging from intergranular attack was associated with porous, loosely-adhered, deposited areas within the rifling from previous hydro-jetting. The inter-crystalline penetration can occur in the presence of chlorides and sulfates during hot wall effects caused by overheating. While the stressed simulation and dispersant chemical addition revealed dramatic improvements, there is no chemical solution to nucleic boiling under low flow conditions. Ensuring sufficient cooling water flow and supply pressure to keep the tubes completely flooded would be required. The process temperature duty also indicates the temperature should be lowered with, for example, upstream fin fan condensers or the admiralty brass be changed out to monel or titanium.

**Monel was chosen. The system before and after validation of the high performance dispersant application with the field monitor<sup>12</sup> (fitted with a 316 stainless steel heater rod) at the site is illustrated in Figure 12.** It can be seen that the field validation results reveals a 66% reduction in heat transfer loss. The run time to inspections was increased from 2 to 3 years. Service cleanings were reduced from monthly (i.e. linear fouling rate) to none, due to asymptotic fouling rate below the design fouling allowance of 100. Although the run time is slightly over 50 % of the past, there have been no tube failures or reduced process side production from this exchanger in the last 10 years. The dispersant application generated a return on investment of 150% based upon cleaning chemicals and labor alone.

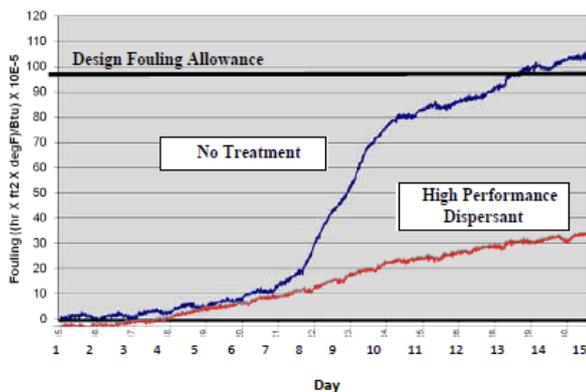


Fig. 12 Overhead Condenser Field Validation Performance Before & After Dispersant Use

## CONCLUSIONS

Improvements in heat exchanger reliability and heat transfer performance can be achieved when applying models which compare best practice design criteria to actual operating conditions associated with chemical additives, chemistry and heat exchangers in cooling water service. This approach was used to determine which operating changes were required, namely, either lower inlet process temperature or change tube metallurgy, ensure the heat exchanger is fully flooded and employ supplemental

dispersant. Field validation revealed the approach provided significant run length increase prior to outage and cleanings were avoided as the fouling rates did not exceed the design fouling allowance. Although no forced outages were incurred, the high hydrothermal stress coefficient (HTSC) value and the fact that the fouling is strictly inorganic scale, means the performance deterioration is predictable and time can be scheduled for outages for mechanical cleans as well as chemical cleans<sup>1</sup>. Chemicals and chemistry were not the leading or sole factors in poor operational performance. The chemistry / chemical model had ruled out such, while the heat exchanger modeling contradicted the chemistry model in a generic sense. In fact, corrosion and inorganic deposition morphology and composition were the indicators for perusal of the corrective actions taken. Without such contradiction and observations, choices to adjust chemistry (i.e. pH range) and add a polymeric dispersant additive would have not resulted in long term correction of the reliability and process side throughput performance issues. The use of “common denominator” models<sup>5,10</sup> associated with the advanced monitor<sup>11,12</sup> allows for corrective action validation assurance.

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## NOMENCLATURE

Corrosion Rate:	- mils per year, 0.001 inches per year; mpy
	- micrometers per year; $\mu\text{m}/\text{y}$
	- $\mu\text{m}/\text{y} \times 25.4 = \text{mpy}$
Fouling Factor:	- (Heat Transfer Coefficient) <sup>-1</sup>
	- $\text{hr ft}^2 \text{ }^\circ\text{F} / \text{Btu} \times 5.674 = \text{m}^2\text{K} / \text{W}$
Flow:	- gallons per minute; gpm
	- litres per minute;
	$\text{lpm} = 0.2642 \text{ gpm}$
	- cubic meters per hour; $\text{m}^3/\text{hr}$
	$= 4.403 \text{ gpm}$
Velocity:	- feet per second; ft/sec
	- meters per second;
	$\text{m}/\text{sec} = 3.25 \text{ ft}/\text{sec}$
Pressure:	- pounds per square inch; PSI
	- atmospheres; bar = 14.7 PSI
Temperature:	- Degree Fahrenheit; $^\circ\text{F}$
	- Degree Celsius;
	$^\circ\text{C} = (^\circ\text{F} - 32) \times 5/9$
	- Degree Kelvin;
	$1^\circ\text{K} = -475.886^\circ\text{F}$
	$= -272.15^\circ\text{C}$
Deposit Weight Density:	- Deposit weight per unit surface area
	$\text{kg}/\text{m}^2 = 0.001 \text{ gm}/\text{cm}^2$
	$= 0.2048 \text{ lbs}/\text{ft}^2$
Deposition Rate:	- Deposit weight per volume per unit time;

$$\begin{aligned} & \text{kg/m}^3/\text{day} \\ & = 0.001 \text{ gm/cm}^2/\text{day} \\ & = 0.0624 \text{ lbs/ft}^3/\text{day} \end{aligned}$$

ORP - Oxidation Reduction Potential

## REFERENCES

- 1) Beardwood, E.S., Treatment and Performance Management for Cooling Waters, NACE International, Corrosion 2011 Symposia, Houston, Texas, USA, Paper 11388.
- 2) Beardwood, E.S., and Gottschalk, K.M., Redefining Cooling Water Treatment, International Water Conference, 2000, Paper No. IWC-00-35, Engineers Society of Western Pennsylvania, Pittsburg, PA, USA.
- 3) Beardwood, E.S., Hays, G.F., and Colby, S.J., Enhanced Tube Fouling Under Cooling Water Conditions, International Water Conference, 2006, Paper No. IWC-06-50, Engineers Society of Western Pennsylvania, Pittsburg, PA, USA.
- 4) Beardwood, E.S., Hays, G.F., Colby, S.J., and Emerich, D.E., Methods for Monitoring Fouling of Aqueous Systems Including Enhanced Heat Exchanger Tubes, U.S. Patent #7,594,430 B2, September 29, 2009.
- 5) French Creek Software Inc, PO Box 68, Valley Forge, PA, USA, 19481-0068, [www.info@frenchcreeksoftware.com](mailto:www.info@frenchcreeksoftware.com)
- 6) Epstein, N., Towards Mitigation of Fouling by Consideration of Fouling Mechanisms, Fouling Mitigation of Industrial Heat Exchange Equipment, Engineering Foundation Conference, San Luis Obispo, California, USA, Pages 13 - 26, © 1997 begellhouse, ISBN 1-56700-056-08.
- 7) Hays, G.F., and Knudsen, J.G., Heat Exchanger Design and Operation to Minimize Efficiency Loss, International Water Conference, 1999, Paper No. IWC-99-11, Engineers Society of Western Pennsylvania, Pittsburg, PA, USA.
- 8) Dewitt-Dick, D.B., and Beardwood, E.S., Prediction and Monitoring of Fouling in Recirculating Cooling Water System Heat Exchangers, International Water Conference 2006, Paper No. IWC-06-09, Engineers Society of Western Pennsylvania, Pittsburg, PA, USA.
- 9) Dewitt-Dick, D.B., Hays, G.F., and Beardwood, E.S., Hydrothermal Stress Coefficient: A Novel Model for Predicting Heat Exchanger Fouling in Cooling Systems, AIChE National Heat Transfer Symposium, Baltimore, 1997, AIChE Symposium Series 314, Volume 93, 1997, Pages 311 - 316, ISBN 0-8169-0739-0.
- 10) HexEval™ is a registered trademark of Solenis LLC
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