

## THE USE OF COMPARATIVE MODELLING OF HEAT EXCHANGERS IN COOLING WATER TO AVOID UNSCHEDULED PRODUCTION DOWNTIME

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### ABSTRACT

The global economy has forced a shift in the emphasis from preventative maintenance to risk based maintenance with expectations of extending the time between scheduled outages such as turnarounds, while also moving towards longer duration between unscheduled downtime in an effort to increase profitability. Cooling system design compared to actual operational conditions may not approach best practice; hence predictions using modeling to identify potential areas susceptible to failure and then monitoring techniques to predict the health and performance of said cooling system unit operations are outlined to assist in defining the risks and rewards. The modeling allows one to make fundamental changes in either heat exchanger operational conditions or cooling water chemistry or both where needed. This approach was applied to a chemical processing plant's cooling system resulting in an extension of "time to tube leaks" and heat exchanger bundle life, while avoiding unscheduled, forced outages for repairs. Tube leak rates of 7 per year were reduced to 1 per 36 months and bundle life from 6 months to a year were extended to a prorated 13.5 years based upon the actual type and rate of corrosion compared to an ideal target of 17 years.

### INTRODUCTION

The design, metallurgy and associated operation of heat exchangers within open recirculatory cooling water systems has not changed significantly over the years, however the conditions influencing their actual operation may have. Where-in loss of system hydraulic balance, pumping discharge pressures, capacity and or internal mechanical maintenance reductions may have allowed the flow velocities to degrade and allow heat exchange surface temperatures to slowly creep up, thus enhances the conditions associated with fouling. Added to these issues are the increasing shortage of fresh water and continued environmental regulation tightening. Where-in the later are driving out the usage of metals, nitrogen and phosphorous based organic and inorganic compounds used for corrosion and deposit control in cooling waters. Hence the quality of the water used for cooling water is decreasing and the chemical composition of cooling water additives may be of lower performance, both increasing the corrosion and fouling potential within cooling water systems. Make-up

waters to cooling systems, depending on their source, may possess impurities that generate higher corrosion and or fouling potential in the cooling water circuit. For example; evaporated or reverse osmosis water are corrosive, cold lime clarified water can have high localized corrosion potential, reclaimed and recycled water from cascading within the site processes may increase corrosive anions that are not balanced effectively with alkalinity (i.e. Larson Skold Index) and hardness or contain process or biological nutrients contamination chemistry that leads to fouling (i.e. inorganic, organic, or biofouling) and localized corrosion. And of course the evaporative cooling process concentrates these corrosion and fouling constituents within the cooling system.

Foulants will slow down the process side once the heat transfer resistance exceeds the heat exchanger design fouling allowance. However, the foulants can always be cleaned at a scheduled time to restore performance. Unfortunately, all forms of fouling, except inorganic insitu crystallization, lead to localized corrosion. Unfortunately the forms of localized corrosion will develop when the heat transfer reduction rates are still below the heat exchanger design fouling allowance. Localized corrosion leads to rapid depreciation and through wall perforations that can halt production or lead to unscheduled downtime to repair. Profits are then diminished from corrosion occurrence and capital expenditures' also increase. Approximately 10% of the corrosion related failures, are related to the process side compared to 60% on the waterside. Of these waterside corrosion issues, only 20% are due to general corrosion compared to 70% being associated with localized corrosion. A simplistic solution would be to "alloy - up" and apply protective non-fouling coatings in order negate the fouling and corrosion within a cooling system. Quite effective in the power industry where surface condenser cooling operates at high velocities (> 6 feet/second), low surface temperatures (< 120 degree Fahrenheit) and zero process contamination potential. In other cooling applications, the performance is not so assured due to the operating complexity and associated variabilities.

The reduction in the quality and quantity of water used in cooling systems coupled with reduced maintenance increases the need more than ever to perform predictive modeling of cooling systems equipment such as pumping and hydraulic balances, cooling tower heat rejection and

heat exchanger thermal efficiencies<sup>1,2,3,4</sup>. This needs to be coupled with predictive modeling of the cooling water chemistry and the effects of corrosion and fouling performance enhancing chemicals<sup>5</sup>. Coupling them both allows one to identify which KOI (Key Operating Indicator) variables that need to be adjusted and what can be attained from said adjustments. The adjustments may be identified as changes in pH, chemical/concentration, cycles of concentration, make-up source and or quantity/quality in a blend of multiple sources, exchanger velocity, residence time, surface temperature, number of passes, number of tubes, tube diameter, while keeping the heat duty (i.e. overall heat transfer coefficient) fixed. Therefore a chemical, operational or mechanical design solution can be found to resolve the poor performance issue. The use of on-line monitoring equipment on the cooling water may be needed to validate the cause and corrective action of the poor performance as the models are built on data, trends and analyses obtained from said monitoring equipment.

**MODELING**

Improving cooling water system reliability and availability can be achieved by identifying conditions which are not in concert with “best practices”. The best practices were based upon models developed to predict performance associated with fouling due to “actual equipment operational conditions vs design” as well as fouling and corrosion associated with both cooling water chemistry and chemical additives in use. These models were originally used to develop and test the performance expectations of corrosion and fouling control under exact cooling water operational conditions (i.e. “alpha” as a laboratory pilot cooling system and “beta” as an infield side stream site cooling system monitoring). The models have also been used to identify what changes to either chemistry or operational conditions of a site poorly performing heat exchanger can be made to resolve the fouling and corrosion performance issues as well as validate the improvements. The data generation for product and process development, monitoring, problem solving and validation is obtained with monitoring equipment bundled to be compliant 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

Further information, laboratory and field applications can be found in references 6 through 19.

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 that is then used to define the impurity saturation index value associated with the operational chemistry, surface temperature and shear stress of which 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 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>20</sup>, an empirical model from the data was developed to characterize the fouling tendencies, namely the Hydrothermal Stress Coefficient (HTSC)<sup>1,2,3,4</sup>. The input/output and interpretation of the program simulation are provided in Table 1. Prediction of the type of fouling and severity is noted.

Table 1  
Shell and Tube Heat Exchanger Fouling Potential Model

<u>Input Data</u> Tube Diameter (id)(inches) Tube Length (feet) Number of Tubes per Pass Number of Passes		Inlet Water Temperature (°F) Outlet Water Temperature (°F) Water Flow Rate	
<u>Output Data</u> 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			
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 precoolers, process by-pass, re-circulation loops, etc. that increase velocity (shear stress), lower skin temperature and lower residence time can be explored with the simulation program. While holding the overall design 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 affects on HTSC values, residence time, velocity, outlet skin temperature and heat transfer rates<sup>2</sup>.

#### FIELD APPLICATION

One of a number of cooling systems in a chemical processing complex had been experiencing reliability and availability problems for a few years. The heat exchangers would develop tube leaks from localized through wall corrosion fouled by process leakage into the cooling system and require repair and cleaning seven times per year and the bundle life was as low as 6 to 12 months. The cooling system contained 24 carbon steel heat exchangers with 7 of them paired in series. The make – up water was a blend from multiple sources including process condensate. The system's health comparison when undergoing a light hydrocarbon process leak, plus the use of process condensate as make-up, which had variability in it's contaminants, is provided in Table 2. The plant had reliability and availability issues with the cooling water heat exchangers prior to 2006. It was unknown if the system and heat exchangers were effectively pre-cleaned (degreased) and pre-passivated, if at all. Historically, tuberculated carbon steel exchanger tubes existed. When tube leaks occurred, off-line tube plugging and hydro-jet cleaning would be done, only to have another leak months later. In an effort to reduce the heat exchanger bundle leakage occurrences or replacements, both old and new bundle cleaning and passivation procedures were put in place. Hydro-jetting tuberculated tube surfaces leads to incomplete dissolution of corrosion products within the pit base and only increases the corrosion activity and overall penetration

rates. Old bundles were then chemically cleaned and re-passivated after hydro jetting with a blend of citric acid (i.e., removal of rust and tubercular corrosion products) and passivating chemistry containing zinc, orthophosphate and polyphosphate. New bundles were degreased with alkaline phosphate-silicate surfactant chemistry and then chemically cleaned and passivated as done for the old bundles. Old bundle leakage frequency was decreased from 7 per 12 months of system run time to 9 per 24 months, a 36% improvement; however, still not acceptable (incident 1). Hence, further investigative reviews were performed and will be discussed herein.

Table 2  
Cooling Water System Health Comparisons

Test	No Process Leak	Light Hydrocarb on Process Leak	Process Leak Plus Process Condensate
Carbon Steel Corrosion Rate, mpy	0.3 - 0.4	0.5 - 0.75	1.50
Iron as Fe, mg/L	2.5	3.4	5.5
Chemical Oxygen Demand, mg/L	180 - 230	350 - 500	900
Oxidation Reduction Potential, mV	550	500	>450
ΔORP (Supply - Returns)	15 - 20	40 - 45	
<u>Note:</u>			
1) The process condensate concentrations vary for iron, phosphate, organics, pH, hydrogen sulfide and oxidation reduction potential (+25 to -100mV).			
2) If the return ORP value cannot be maintained at 450 mV with continuous hypochlorite feed, then chlorine dioxide is pulse fed to achieve >450 mV.			

Chemistry, chemical additives, and heat exchanger operational conditions were reviewed and the results were compared to the models previously noted in order to determine which changes would be required to improve the reliability and availability of the cooling system. The intent was to achieve increased mean time to failure of the tube bundles, which increases the time between turnaround outages, increased tube bundle life, which decreases asset depreciation costs and avoiding a forced outage by staying on a scheduled maintenance plan. Initially the chemistry and chemical additives interdependency were looked at in an effort to lower the potential corrosion influencers. The general corrosion rates were very low at 0.3 to 0.4 mpy and localized corrosion was present in the form of tuberculated pitting. As seen in Table 3, the Larson Skold value was 12.

Table 3  
Cooling Water System Chemistry

Test	Composite Make Up Water	Cooling Water Control Levels
Calcium as CaCO <sub>3</sub>	12.0 mg/L	120 - 140 mg/L
Zinc as Zn	0.15 mg/L	1 - 2 mg/L
Silicate as SiO <sub>2</sub>	0.5 mg/L	20 - 25 mg/L
Ortho Phosphate as PO <sub>4</sub>	1.1 mg/L	8 - 12 mg/L
Polyphosphate as PO <sub>4</sub>	0.25 mg/L	2 - 4 mg/L
Delta Phosphate as PO <sub>4</sub>	0.5 mg/L	≤1.3 mg/L
Chloride as Cl	57 mg/L	<1,000 mg/L
Chemical Oxygen Demand	23 mg/L	<250 mg/L
Turbidity	16 NTU	<30 NTU
Conductivity	400 uS/cm	<5,000 uS/cm
pH	6.7	7.2 - 7.6
Free Residual Chlorine	None	0.3 - 0.5 mg/L
Oxidation Reduction Potential (Supply)	NA	550 mV
Cycles of Concentration	NA	5 - 6
System Apparent Retention Time	NA	13 - 16 days
Larson Skold	NA	12

The zinc, ortho and poly phosphate corrosion inhibitor concentrations, even for the low calcium hardness water, should have prevented pit initiation. Tuberculated tubes were sampled and the deposit analyzed and the average results of 12 samples are reported in Table 4. It can be seen that, the deposit is insitu corrosion products and the corrosion process was still active based upon the the acidic pH of a 1% deposit suspension and the pit bases were orange/red in color.

Table 4  
Heat Exchanger Tubercle Deposit Composition

Constituent	Percent
Calcium as CaCO <sub>3</sub>	0.2
Magnesium as MgCO <sub>3</sub>	0.1
Iron as Fe <sub>2</sub> O <sub>3</sub>	63.1
Phosphate as PO <sub>4</sub>	20.1
Sulfate as SO <sub>4</sub>	0.8
Sulfide as S <sup>2-</sup>	Nil
Acid Insoluble's	3.6
Loss On Ignition at 800 °C	10.1
pH of 1% Suspension	4.7
Sulfate Reducing Bacteria as CFU/gm	Nil
The above results are from an average of 12 deposit analysis	

The ion paring modeling indicated there were no calcium or iron phosphate depositions potential. However, a mass balance was performed and percentage recovery of phosphate species, iron, zinc and suspended solids

calculated in excess of 120 to almost 300 percent. The delta phosphate (i.e. Unfiltered – Filtered ortho phosphate) was 1.9 with only 65 % recovery and both the filtered and unfiltered phosphates were 140 and 120 percent recovery respectively (incident 2). This was indicative of localized active low pH corrosion occurrence as the bulk water pH was 7.3 and displacement of zinc, phosphate and iron from the active surfaces was leading to exsitu production of suspended solids. The overall result was fouling due to the presence of lower concentration of polymeric dispersant to compensate for the higher iron and phosphate surface displacement. A process leak developed from poor quality process condensate used for make-up, which partially masked the leak. The following was noted and corrected;

- The stored process condensate that was used as make-up was inconsistent in contaminates. Oxidation of the stream prior to reuse to an ORP value of 450 mV was instituted to control the microorganisms present, oxidize the soluble iron and kill the hydrogen sulfide present. The cooling water dispersant dosage was upgraded to include the iron contribution of the process condensate.
- Process leak history revealed that some had lasted 13-14 months and most recently 18 months without a leak. On-line monitoring of ORP on the cooling water return was instituted to decrease the time to leak detection. Contingency processes and chemical adjustments were put in place for prolonged process inleakage run times. The maintenance of greater than 450 mV ORP in the cooling water returns at all times and a positive residual on the outlet of the offensive heat exchanger were also included.
- Shell-side heat exchangers were to be back flushed while nitrogen rumbling when the pressure drop increased 2 to 4 pounds per square inch above that of operational design under clean conditions.
- Pre and post shut down blow off of cooling system low points and heat exchanger water boxes to be instituted to remove accumulated iron based material and flash rust start-up solids.
- Revised cooling water chemistry control levels provided (see Table 3).

A third incident of fouling was detected about a year later during heat exchange equipment inspections. Reliability records were reviewed and based upon heat exchangers run time records, one leak in 15 months, one clean in 24 months, exchangers running 19, 24 and 36 months without leaks, and a four year run time on a bundle that had a historical run time length of one year were noted. These results indicated that finally the cooling system was back into continuous improvement mode and operations were no longer chasing the tail of the problem. The inspection revealed that post settlement of iron had occurred in the low flow tandem paired, second heat exchanger pass. The iron was not bound (i.e. not from insitu corrosion) and was easily removed. The iron upset was from the process leak that had been ongoing for seven months in which oxidative hydrogen sulfide kill and base metal corrosion

products were produced within the leaking heat exchanger and displaced throughout the cooling water system.

These observations during the inspection led to a review of system hydraulic balance and heat exchanger flows. An overall 94% cooling system flow compared to design was noted; however, the individual heat exchanger actual flow compared to design was a concern. The most problematic heat exchanger was one of the noted low flow tandem ones. In fact, it was exchanger 9B. However, the actual compared to design would not suggest it. The data from this heat exchanger was inputted into the heat exchanger evaluation program<sup>1,2,3,4</sup> and the actual velocity, outlet skin temperature and HTSC did not indicate a concern. Further investigation revealed that a recirculation pump repair had occurred over the past year. This repair resulted in three of the four recirculation pumps in operation as there was never a fifth pump installed for standby use. As a result, there was a reduction in total recirculation flow of 6,600 gpm (13%). Also during the past year, a cooling tower cell from another cooling tower had gone down and required about 13,000 gpm cooling water flow to be extracted/exported from the cooling system under review. This 26% reduction in flow occurred concurrently with the ongoing process leak. Table 5 contains the design heat exchanger flow values and actual values present after the discontinuation of cooling water export.

Table 5  
Cooling System Hydraulic Balance

Heat Exchanger	Cooling Water Flow, gpm		Percent of Design
	Design	Actual	
1	8,124	7,661	94.3
2	8,124	9,290	114.4
3	8,124	5,130	63.1
4	2,950	1,937	65.6
5	1,030	581	56.4
6	2,206	564	25.6
7 A/B	3,448	2,818	81.7
8 A/B	4,451	3,258	73.2
9 A/B	3,681	7,221	196.2
10 A/B	150	387	258.8
11	1,554	2,113	136.0
12	1,404	638	45.4
13 A/B	92	330	358.7
14 A/B	1,801	2,157	119.8
15	1,268	775	61.1
16 A/B	1,567	2,105	134.3
17	123	167	135.7
TOTAL	50,097	47,132	94.1

**Note:** 1) Design/operational flows are from 5 pumps; 4 on, 1 in standby.  
2) Heat exchanger pairs have counter current flows.  
Process flow is from exchanger A to B and cooling water flow is from exchanger B to A.

The effect these reduced flows had on the heat exchangers was randomly explored based upon design data, not actual flow. The heat exchanger evaluation program revealed that 6 out of the 24 heat exchangers were critical based upon the HTSC output. They were overhead (i.e. 50 feet (15.4 meters) from ground level) tandem exchangers 7, 8 and 9 A/B, with the worst being 9A. Most of the exchangers operated with velocities of 3 to 4 ft/sec, residence times below 20 seconds and HTSC values at or below two. Only these tandem exchangers were above a HTSC of two due to residence time; as the second exchanger residence time is that of exchanger B plus A. Skin temperatures of 125°F or less and velocities in the range of 3.4 to 3.5 ft/sec were noted as reasonable. If the design flows were reduced greater than 10%, all heat exchanger HTSC values exceeded two, which is manageable; however, the overhead tandem units were pushed from 2.4 to 3.4 values, indicating compensation in the form of design, operation or chemistry is required. Table 6 contains a summary of heat exchanger 9A and the bracketed values are associated with the inclusion of the forward heat exchanger 9B residence time. The cooling system hydraulics were rebalanced to meet design as close as possible and then slightly trimmed to minimize residence time and maximize velocity attainable using the heat exchanger evaluation program. The critical few exchangers identified by the program are to be monitored for flow reductions or increase in approach temperatures. If flow reductions exceed 10% of design and are not associated with pump maintenance or hydraulic balance issue, or if the approach temperatures increase by 5°F at constant set flow (i.e., no flow reductions), then a scheduled cleaning "on-line" or "off-line" is to be performed.

Table 6  
Heat Exchanger 9A Hydrothermal Stress Coefficient Evaluation

Water Supply	Residence Time (sec) (9A+B)	Tube Velocity (ft/sec)	Surface Temperature °F	HTSC
Design Flow	17.5 (35.0)	3.40	123.4	2.16 (4.32)
90% of Design Flow	19.4 (38.8)	3.06	124.2	2.41 (4.82)
87% of Design Flow	20.1 (40.2)	2.96	124.2	2.49 (4.99)
74% of Design Flow	27.1 (54.2)	2.19	127.2	3.45 (6.89)

The audit finished with a tube removal from heat exchanger 9A bundle for inspection. It had been in service from new for two years and, after the first six months of service, it received direct effluent water from the 9B heat

exchanger that was leaking light, hydrocarbon-containing hydrogen sulfide for four months. Only water jetting of the 9B heat exchanger was performed after the leaking tube was plugged. Heat exchanger 9A operated another four months prior to receiving cooling water in which heat exchanger 8A was undergoing process leakage for another six months prior to the outage. The surface contained very little deposition. Top coating of the deposit was from the corroded iron produced during the six month inleakage of exchanger 8A (Figure 1) and the concurrent reduced cooling water flow discussed previously. Upon mechanically cleaning to the bare surface, pits were noted but inactive as their bases were black and passive. The wall loss associated with the pits ranged from 16 to 21%. This was initiated by exchanger 9B process leak after the first six months of operation of exchanger 9A and occurred over a four month period, resulting in localized wall penetration or corrosion rates of 48-67 mpy (i.e., (inches of penetration x 1,000 x 365 days) / days of penetration duration). The occurrence was prior to leak contingency provided in 2008; however, it re-passivated on-line as can be seen in Figure 2. No sulfur or sulfates were found in the composite surface deposit provided in Table 7.



Fig. 1

Heat Exchanger 9A Tube Sectioned Tube, Cleaned Section, pitted surface. Un-cleaned Section; Note ID tube wall to deposit interface - very little deposition. Wall measurement was 0.10 – 0.106 inches and pit depth varied from 0.016 to 0.022 inches



Fig. 2

Heat Exchanger 9A Tube at 10x Magnification, Mechanically Cleaned to Bare Surface

Table 7  
Heat Exchanger 9A Tube Deposit

Elements	Percent
Iron (as Fe <sub>2</sub> O <sub>3</sub> )	77.4
Phosphorous (as P <sub>2</sub> O <sub>5</sub> )	2.2
Silica (as SiO <sub>2</sub> )	1.3
Carbonate (as CO <sub>2</sub> )	1.2
Loss on Ignition (550°C)	11.7
(1,000°C)	12.9
Probable Combinations	
Hematite	73.5
Ferric Phosphate Hydrate	6.3
Ferric Carbonate	3.2
Silica	1.3
Loss on Ignition (Excess)	9.9
Apparent Total	94.2

What was the life cycle cost of heat exchanger 9A from the localized corrosion? Economic life can be estimated by using Figure 3. The 3/4 inch heat exchanger tube had a wall thickness of 0.106 inches, while an equivalent 3/4 inch schedule 40 carbon steel tube has a wall thickness of 0.1556 inches. Correcting for wall thickness differences and using the localized corrosion rate, the life expectancy would be 3.9 to 4.9 months or 2.5 to 3.0 tube failures per year. Now if we assume re-passivation, as it did; and that a continuous leak is present from another heat exchanger in the system but not in tandem series, then 1.5 mpy or a 17 year life span is then reduced to 13.5 years based on the initial localized wall loss of 0.022 inches. This is illustrated in Table 8. Hence, the longer the leak occurs and is discharged directly into the tandem heat exchanger, localized corrosion will ensue. The in tandem series receiving heat exchanger would be expected to fail in four months. However, if the leak is caught and killed, on the run, with the correct contingency plan, expect 21% depreciation or a reduction in tube life from 17 to 13.5 years. This depreciative loss on exchanger tube life, or let us say all tubes are affected, so exchanger bundle life has to be compared to uninterrupted production throughput profits and the cost of a forced outage with no production or reduced production.

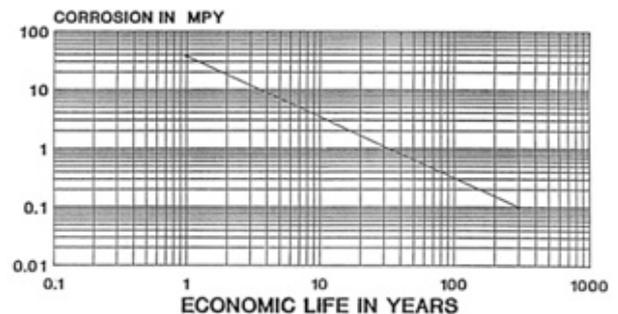


Fig. 3

General Corrosion vs. Equipment Life Schedule 40 Carbon Steel

Table 8 Heat Exchanger Tube Economic Life

Case	Corrosion Rate	Type	Schedule 40 Carbon Steel	Corrected to Tube Wall Thickness
1	1.5 mpy	general	25 years	17 years
2	48 mpy	localized	0.6 years	0.41 years
3	67 mpy	localized	0.475 years	0.33 years
4	1.5 mpy	general	25 years	13.5 years
	plus localized @ 67 mpy			
<b>Note:</b>				
1) ¾" schedule 40 wall thickness = 0.1556 inches.				
2) ¾" carbon steel heat exchanger finned tube wall thickness = 0.106 inches.				
3) Wall loss of 0.022 inches (67 mpy) = 0.084" wall thickness remaining.				
4) Correction factor for case 1 through 3 = $\frac{0.106}{0.1556} = 0.68$				
5) Correction factor for case 4 = $\frac{0.084}{0.1556} = 0.54$				

## DISCUSSION

The field application provided an illustration on how modeling and comparisons to best practices can be used for problem solving and corrective action implementation. A historic improvement in heat exchanger reliability and availability was demonstrated and can be summarized as follows from the noted 3 incident occurrences;

- Incident 1; Baseline investigative work revealed continual and active localized corrosion which was being accelerated by only partial cleaning, allowing for reactivation. Proper, isolated, pre and re cleaning procedures followed by high concentration corrosion inhibitor level passivation were established. This reduced the process leaks and cleans per year from 7 and 7 to 4.5 and 4.5 respectively. A 36% improvement. Operational chemistry and chemical additive in use, where not found to have potential fouling issues and confirmed with the use of the ion pairing program<sup>5</sup>.
- Incident 2; Continued corrosion from process leaks and residual of such leading to corrosion product fouling elsewhere. Updated operational chemistry control limits for the make-up sources and cooling waters under normal and process leakage conditions, chemical dosage changes for the upsets and effective chemistry and chemical contingency plans in place for and during upset conditions. This allowed for run through the upsets/process leakage without taking a forced outage for repair. The follow up results outcome were noticed during incident 3 review. Certain bundle replacements that had required yearly replacement were now lasting 4 years and the run time between leaks was increased to running average values of 19, 24 and 36 months. The leaks and cleans per annum were now down to 0.8 and 0.5 respectively, an 89 % improvement.
- Incident 3; Allowed for an audit and autopsy of a heat exchanger tube. Process leak was able to be run

through twice for 4 and 6 months without a forced outage. The depreciation due to localized corrosion reduced the bundle life from 17 to 13.5 years. The contingency process in place allowed for this to occur and emerge without active localized corrosion as the process had been arrested online after the corrosion inleakage of hydrogen sulfide was killed. Incident 3 uncovered hydraulic issues and corrective actions to avoid future fouling was determined utilizing the modeling program<sup>1,2,3,4</sup>.

A survey of hydrocarbon and chemical processing industry cooling systems was performed on actual heat exchanger operational data and the associated hydrothermal stress co-efficient (HTSC), bundle life, foulant type and status of the outages. The results are summarized in Table 9. It can be seen that:

- Low HTSC heat exchangers do not suffer from forced outages and are rarely microbiologically fouled. Bundle exchanger life is consistent with the norm and other bundles with higher HTSC values that foul due to inorganic scales.
- Inorganically fouled heat exchangers that are highly stressed (i.e., high HTSC values), scale faster and performance degradation is obvious. Unscheduled outage is very rare because they have their own predetermined maintenance outage by virtue of their predictable performance degradation.
- Inorganically fouled heat exchangers that have mid-range HTSC values (i.e., 3 to 5) are not so obvious and as a result, they have no predetermined maintenance schedule. They will be faced with forced outages. For example, time for scheduled maintenance of heat exchangers has been shortened because a few pumps have lost their output capacity and require wear ring replacement and impeller inspection. As a result, not all exchangers will be inspected. The known non-leaker, which historically has not been cleaned or inspection observations do not question the frequency of cleanings is such an example. The pump is tended to and exchanger is not opened. Unfortunately, prior to the next outage, process side throughput has deteriorated due to poor heat transfer in the heat exchanger that was not inspected. The degradation leads to a forced outage prior to the three year run. Sound familiar? Perform a post start-up on-line/in-line chemical clean, or if it is a critical exchanger, practice satellite feed of dispersant to avoid the potential of a forced outage.
- Heat exchangers with high HTSC values and biologically foul are prone to forced outages and that is predictable. These are low temperature-high HTSC affected exchangers that should be addressed. Exchangers with lower HTSC values are typically not prone to forced outages because the degree to which they foul and to what extent is predictable.
- Exchangers that are oversized will foul<sup>12,21</sup> and can operate longer prior to cleaning. However, if the foulant is biological in nature, the longer the fouled run times are, the lower the life expectancy of the heat exchanger due to microbiologically influenced

corrosion (MIC) and under deposit corrosion (UDC). Keep biofilm management under control.

Table 9  
Hydrothermal Stress Co-efficient  
Survey of HPI/CPI Cooling Systems

HTSC	Heat Exchanger Bundle Life (Years)	Foulant Type		Outage Status	
		Biological	Inorganic	Scheduled	Forced
>7	<8.0	Yes	No	No	Yes
>7	12	No	Yes	Yes	No
3 - 5	12	No	Yes	No	Yes
2 - 3	12 - 14 9	No	Yes	Yes	No
		Yes	No	Yes	(Yes)
1 - 2	12	No	Yes	Yes	No
<b>Notes:</b> 1) Carbon steel metallurgy used for heat exchanger tubes. 2) Bundle life target norm - 10 years. 3) Bundle cleaning frequency norm - once every 3 years.					

Combining the field example review work, modeling and the survey outcome, one can better predict which heat exchangers should be inspected, cleaned or replaced and when. Thus avoiding a forced shut down with said predictive risk based maintenance.

**CONCLUSIONS**

Risk based maintenance suggests the decision process is one of risk versus reward. An organization may at some point be confronted with an unscheduled outage in the wake of a decision made well in the past that negatively impacts profitability today or in the future. Clearly, there had been either confusion or a misunderstanding in regard to the complexities associated with both the risks and rewards. Holistic review of the cooling water operation, control and performance at design compared to actual operational conditions, as well as, modeling and predictions with respect to system health have been outlined to assist management and operations in defining the risks versus the rewards. The ability to predict the health of the cooling water system, identification of operational risk areas that require monitoring, proactively addressing and validating such with chemistry changes, correctly selected contingencies and reasonable operational changes will increase availability and reliability of the cooling system. Fast detection of upsets due to added knowledge within the monitoring system provides on-line problem solving to allow for timely corrective actions to control the health of cooling water. This ensures increased run times and forced outages are avoided. With the nature and degree of “off specification” operational condition identified, a scheduled outage and the corrective maintenance requirements can be determined well in advance. As “Best Practices” are not always attainable due to system operational influences and upsets, the use of the common denominator approach as

discussed would allow for the management of assets more effectively as the risks have been clearly defined. The risk may provide short-term rewards prior to asset repair. However, the instantaneous depreciation rate of the upset incident, if handled correctly, may be reward enough if a forced outage is avoided, opportunity costs are not incurred and the operation still remains at an acceptable profitability rate.

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**NOMENCLATURE**

- Corrosion Rate:
  - mils per year, 0.001 inches per year; mpy
  - micrometers per year;  $\mu\text{m/y}$
  - $\mu\text{m/y} \times 25.4 = \text{mpy}$
- Fouling Factor:
  - $(\text{Heat Transfer Coefficient})^{-1}$
  - $\text{hr ft}^2 \text{ }^\circ\text{F} / \text{Btu} \times 5.674 = \text{m}^2\text{K} / \text{W}$
- Flow:
  - gallons per minute; gpm
  - litres per minute; lpm = 0.2642 gpm
  - cubic meters per hour;  $\text{m}^3/\text{hr} = 4.403 \text{ gpm}$
- Velocity:
  - feet per second; ft/sec
  - meters per second; m/sec = 3.25 ft/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:
  - $1^\circ\text{K} = -475.886^\circ\text{F} = -272.15^\circ\text{C}$
- CFU/ml
  - Colony Forming Units per milliliter of water sample
- CFU/gm
  - Colony Forming Units per gram of deposit
- ORP
  - Oxidation Reduction Potential
- Thickness
  - inches = 25.4 mm
- TOC
  - Total Organic Carbon
- Tso
  - Surface temperature of heat exchanger
- Heat Transfer Rate
  - $\text{Btu/hrft}^2 \times 0.1761 = \text{W/m}^2$

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