Improving Condenser Reliability and Availability Through Effective Offline Cleaning and Nondestructive Testing

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ABSTRACT

Losses attributed to condenser tube leaks, fouling and failures continue to climb, costing the power generation industry an estimated half a billion dollars annually in maintenance costs and loss of production. For the period 2008 through 2010, the North American Electric Reliability Corporation (NERC) reported condenser tube related forced outages and derates were responsible for removing over 9.1 million megawatt hours from the grid. To adequately prevent condenser tube failures, effective tube cleaning and nondestructive testing must be performed. Effective tube cleaning should ideally remove all deposits, leaving only the cleanest metal surface. Once tubes are free of fouling deposits, multi-frequency eddy current testing should be used to establish the overall integrity of the condenser tubing.

This paper will examine the implications of condenser tube fouling and failure, and how a "total condenser performance" approach to cleaning and testing can minimize or eliminate risk of tube related forced outages and deratings during the condensers operating cycle.

Cooling Water Basic Chemistry

Makeup water for utility and large industrial cooling towers frequently comes from a surface supply such as a lake or a river. Table 1 outlines a snapshot analysis of the primary cations and anions in the makeup from a cooling lake serving a large Midwestern power plant.

Table 1 – Primary Ions in a Cooling Lake

Cations **(ppm as $CaCO_3$)**	***Anions (silica included)*** **(ppm as $CaCO_3$)**
Calcium – 130	Bicarbonate alkalinity – 115
Magnesium – 8	Chloride –20
Potassium – 5	Sulfate – 50
Sodium – 25	Silica -1

As table 1 indicates, impurities with the highest concentrations include the hardness ions, calcium and magnesium (Ca^{+2} and Mg^{+2}, respectively) and bicarbonate ions (HCO_3^{-2}). All other natural water supplies have these ions in varying concentrations based on local site conditions. Often managers, engineers, and chemists at plants with once-through cooling systems may only give passing thought to scale formation in condensers. This oversight can be costly because the water that comes in from the lake or river and is later discharged is not exactly the same. Unlike familiar compounds such as table salt or sugar, calcium carbonate is less soluble as temperatures increase, so as the cooling water warms in the condenser, scale formation is a distinct possibility as seen in Figure 1. Omaha Public Power District's North Omaha Station (Hansen, J.) and South Texas Project (Moye, W.) were examples of how this scale formation can occur on a river or in a lake, costing the owners in excess of $1.2 million in MW output restrictions and poor heat transfer efficiency.

Figure 1: Scale as removed from condenser tubes

For open recirculating systems, i.e., systems with cooling towers, contaminants cycle up as water evaporates from the cooling tower. Chemical treatment to prevent scale formation is an absolute requirement for these systems, but, even so, some scale formation often occurs. Deposits may include calcium carbonate, calcium phosphate, calcium sulfate and others.

Not to be forgotten, and, an issue that is often more problematic than scale formation, is microbiological fouling of condenser tubes. Cooling systems provide an ideal environment, warm and wet, for microbes. Bacteria will grow in condensers and cooling tower fill, fungi on and in cooling tower wood, and algae on wetted cooling tower components exposed to sunlight. Biocide treatment is absolutely essential to maintain cooling system performance and integrity, but even with good biocide treatment microbes may still attach to condenser tubes, therefore, the tubes must be cleaned.

The Impact of Fouling and Scale on Heat Transfer

An obvious, but very often under-estimated result of fouling or scaling in condenser tubes is the loss of heat transfer. Some of the most common scale-forming compounds, along with their heat transfer coefficients, are shown below, along with the coefficients for several common condenser tube materials.

Table 2 – Common Scale Products and Their Heat Transfer Coefficients As Compared to Common Tube Metals

Compound	***Thermal Conductivity*** **Btu/hr·ft^2·^{o}F/in**
Calcium Carbonate ($CaCO_3$)	6.4
Calcium Phosphate [$Ca_3(PO4)_2$]	25
Calcium Sulfate ($CaSO_4$)	15
304L SS	113
316L SS	113
Admiralty Brass	768
90-10 Copper-Nickel	312

Table 2 shows the insulating properties of the hardness compounds and their effect on thermal conductivity as compared to the common tube metals they may coat. The table also shows why copper alloys were once almost universally selected for condenser tube material; Thick-walled tubes could be utilized for structural integrity, while yielding respectable heat transfer. Silica scales and microbiological foulants can be even more severe on heat transfer. What this means with regard to plant operation is the loss of heat transfer in the condenser requires the boiler to be fired harder, thus increasing fuel consumption to produce the same load. Similar to Buecker, let's examine the situation of a steam turbine with no reheater, and which operates at constant entropy. (Note that turbines are typically 80 to 90 percent efficient, but this is not relevant to the condenser performance issues discussed here) Consider steam entering the turbine at 1000^{o} F and 1000 psia. Per the steam tables, the enthalpy of the inlet steam is 1505.9 Btu/lbm. If the condenser is operating well, the pressure at the turbine exhaust outlet can, especially in winter in northern climates, be reduced to 1 psia (2" Hg) or even lower. The enthalpy of the exhaust steam at these conditions is 923.4 Btu/lbm. Thus, the available energy for the turbine is 1505.9 – 923.4 = 582.5 Btu/lbm.

Now, consider the case where condenser tube fouling, or excess condenser air in-leakage on the steam side, has raised the pressure to 2 psia. The enthalpy of the exhaust steam is 959.8 Btu/lbm, so the available energy for turbine work reduces to 546.1 Btu/lbm, which is very significant.

One can also look at this example from a physical perspective. Consider the comparison of steam exiting the turbine at atmospheric pressure versus 1" psia. Calculations show that the condensation process reduces the fluid volume over 17,000 times. The collapse of the steam generates the very strong vacuum, which acts as a driving force to pull steam through the turbine.

For a large unit, such loss of condenser heat transfer can cost six figures per month in extra fuel costs. And, if deposition in the condenser tubes is very severe, the unit may have to be de-rated. Typically, this occurs in the summertime when the going rate for power may reach $50, $100 or more per megawatt. Emergency power has been known to reach $7,000 per megawatt during July and August heat waves. De-rating at these times can be enormously expensive.

The other major difficulty, and this is particularly true with microbes, is the potential for tube corrosion. Once bacteria settles on condenser tubes, the organisms secrete a polysaccharide layer for protection. This film then will collect silt from the cooling water, thus growing even thicker and further reducing heat transfer. Even though the bacteria at the surface may be aerobic, the secretion layer allows anaerobic bacteria underneath to flourish. These bugs in turn can generate acids and other harmful compounds that directly attack the metal. Microbial deposits also establish concentration cells, where the lack of oxygen underneath the deposit causes the locations to become anodic to other areas of exposed metal. Pitting is often a result, which can cause tube failure well before the expected lifetime of the material.

Deposit Removal

The return on investment (ROI) by having deposits removed before they cause major loss of heat transfer, tube corrosion or ultimately tube failure can be very significant. Not only are there losses in performance to consider, but major equipment repairs often follow tube failures due to cooling water contaminants in the boiler or turbine.

Deposit removal is done either mechanically or chemically. While the latter can be effective, and may be necessary if the deposits are silica-based, chemical cleaning of condensers is maintenance and labor intensive.

Figure 2: Mechanical Tube Cleaner

Mechanical cleaning is usually a very effective alternative. These techniques include high-pressure water washing, or shooting tube cleaners (Figure 2) through the tubes. When one balances the need for clean tubes vs. time required for the cleaning, mechanical tube cleaners are an excellent choice. High-pressure water washing can be very time consuming but using tube cleaner brushes for removing soft deposits or metal tube cleaners for more difficult deposits can be performed in a very short period of time. The common procedure is for contracted cleaning company workers or on-site personnel to insert the tube cleaners in one section of the tube sheet at an inlet waterbox, and then, using pressurized water, shoot the cleaners through to the outlet water box, where those still in good shape are re-used, while old cleaners are discarded. Typically, metal tube cleaners can be used eight to twelve times before they become ineffective. Even with large condensers, cleaning may take only several days and can easily be incorporated into a scheduled outage, or period of reduced load.

Preventing Tube Failures: Evaluating Condenser Tube Conditions and Life Expectancy

Preventing condenser tube failures is vital towards steam generation reliability. Even one condenser tube leak can bring a unit off-line, where the costs for lost generation, labor to repair the leak, and unit startup can easily reach several hundred thousand dollars. Needless to say, repeat tube leaks can be astronomically expensive. Thus, preventive techniques, including tube condition assessment, can be a source of considerable cost savings to generators.

The importance of evaluating the tube conditions has been established, and, after tubes have been properly cleaned, it is possible to evaluate tube wall thicknesses and the risk to unit reliability. This data provides direct information on tube integrity and projected life expectancy. A popular and effective method for these determinations is eddy current testing (ECT). ECT utilizes electromagnetic induction to evaluate tube walls for imperfections and thickness. See Figure 3 showing an ECT probe and the magnetic field created. A uniform wall will give a steady reading, but pitting, corrosion, through wall penetrations, cracks or wall thinning will cause the readings to deviate, which are then recorded by the instrument. Droesch, et al effectively describe the advantages of using multiple frequencies for Eddy Current inspection of condenser tubes.

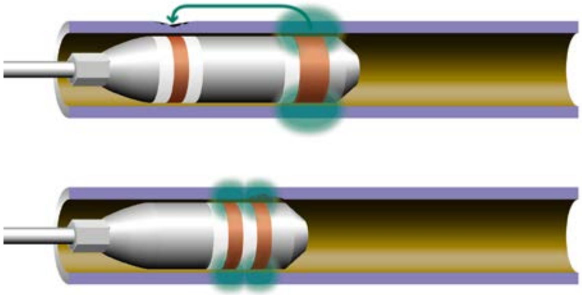

Figure 3: ECT Probe and Magnetic Field

ECT data collection speed is dependent on tube length, material, and type of defects expected. Typically, partial ECT is used to evaluate overall condenser conditions and will be performed say on every tenth tube, or some frequency such as 10%, 20% or 50%. On the other hand, testing at 100% is intended to identify and plug tubes with potential for leaking and causing unit outages. If a particular section of the condenser has suffered from abnormally high tube failures, the ECT testers can focus on that section if necessary. For example, the air removal section of a condenser concentrates oxygen and also ammonia from treatment chemicals. This is a section where a high failure rate of copper alloy tubes may occur. Other locations of common corrosion include tubes directly impinged by steam flow, fretting locations at tube support plates, the area directly below the air removal section, and tubes near entry of process fluids such has feedwater heater drips.

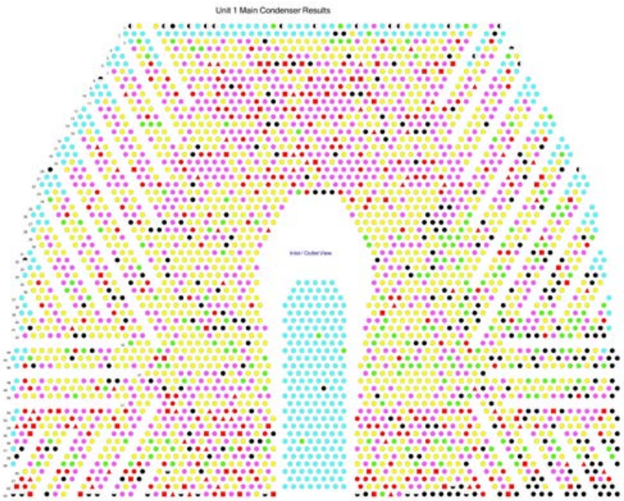

Figure 4: Color-Coded Tubesheet Map

When the analysis of data gathered with ECT is evaluated, tube plugging criteria can be established based on defect parameters. By proactively taking action on questionable tubes, operators can dramatically reduce the likelihood of a tube failure in their next operating cycle. The analysis report generated typically includes a color-coded tubesheet map for easy identification of the problem areas as shown in Figure 4. Selected tubes are then plugged.

For ECT to be successful, effective tube cleaning must first be performed. The ECT probes must be able to obtain a fill factor of greater than 80% and preferably 85% to be accurate. Should tube deposits be left behind, this could cause erroneous readings or mask problem areas. The preventive maintenance costs of Eddy Current testing may easily outweigh the costs related to a single tube failure.

Condenser Tube Plugging

In the event ECT results indicate, or a condenser tube leak or failure occurs, the tube must be plugged. It is imperative to have the right tube plugs on hand. It is recommended to have a ready supply of correctly sized tube plugs for the condenser and various heat exchangers in stock and ready for use. A good rule of thumb is to maintain enough plugs equal to 2% of your tube quantity. A 10,000 tube condenser is recommended to have 200 plugs on hand. Additional to plugging new leaks, inspecting and replacing existing plugs should be performed regularly. Both ends of the tube should be properly cleaned and dried, and the plug fit into each end of the tube in accordance with the manufacturer's recommended instruction. Otherwise, the plug itself may fail, generating similar risk to reliability and availability as an original tube leak.

If there is a tube leak or a failure, the tube will have to be located and plugged quickly so as to avoid costly downtime and lost generation revenue. Having the plugs on hand expedites the process. When selecting plugs, it is necessary to know the size of the tube to be plugged, the tube material and whether or not the tube should be plugged permanently or if there will be an examination or assessment later. Both ends of the tube must be plugged. Figure 5 shows a cross-section of a highly reliable tube plug. Tube plug evaluations have been published, such as presented by Hovland and Saxon, where information regarding metrics such as vibration and pressure limits are reported.

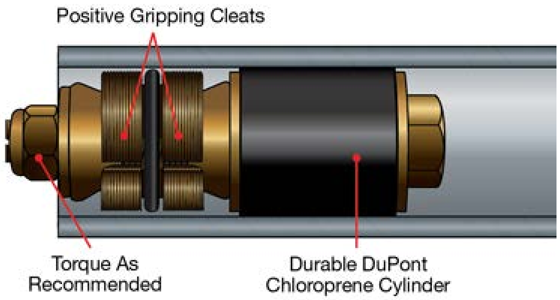

Figure 5: Cross Section of Tube Plug

Recording plugged tubes on a tubesheet map similar to that provided as a result of an eddy current test or as provided by the manufacturer is recommended. Any details regarding the failure should also be recorded so as to better understand the failure mechanism and prevent such failures from reoccurring.

Case Histories

The following case histories demonstrate the effective use of the techniques described for preventive and corrective actions to minimize condenser tube failures and improve plant reliability and availability. The cases are from two coal-fired power stations. They emphasize the importance of the above discussion.

Case History No. 1

In the fall of 2007, a 758 MW Midwest coal-fired plant began experiencing weeping tube leaks in one of their three condensers. The condenser contained 27,716 copper-beryllium alloy tubes and had never been replaced. The last leak test performed was in the early 1980's and over the following several years, over 2,000 tubes had been plugged as leaks developed. The plant had no capital expenditures in the immediate future calling for the replacement of the condenser tubes.

Plant personnel sought an experienced nondestructive testing (NDT) company to provide them with an ECT survey of approximately 10% of the 27,716 tubes. The intent of the work was to get a snapshot of the overall tube integrity and make further decisions based on the results.

As the NDT firm completed the 10% ECT survey, numerous tube defects were observed and plant managers requested to expand the testing to 20% to get more detailed feedback on tube condition.

Before the contractor finished the 20% testing, it was apparent that many of the tubes tested would need plugging due to critical wall thinning or defects, and plant managers opted at that time to fully test the entire condenser. The NDT contractor utilized multi-frequency digital acquisition equipment to generate a comprehensive report and full color tube sheet map of the condenser. After four weeks, the entire unit had been thoroughly tested and tube condition was far worse than the plant had anticipated.

Using an 88% or more thru-wall condition as a guide, the plant proceeded to plug 348 tubes. This brought the total number of plugged tubes in the condenser to 2,540, which at 9.16%, was below the plant's 10% flow restriction guideline for the condenser. A die test was performed and results showed that all the leaks had been sealed. It was estimated that many of the 348 tubes plugged would have failed in the next operating cycle had they not been discovered with the eddy current testing.

Case History No. 2

In March 2009, an 1800+ MW base loaded coal-fired power plant located in the Northeastern US contracted for the cleaning and testing of their Unit 1 main condenser. The two stage condenser had 42,848 7/8" x 22 BWG type 304 stainless steel tubes which are original to the condenser installed in 1967. The unit has been cleaned prior to 1999 with plastic pigs. After noticing a buildup of manganese, the plant chose a tube cleaning company with expertise in spring-loaded metal tube cleaners and utilized this manner of cleaning on a 3-4 year cycle to present.

Upon cleaning of the entire 42,848 tubes, nondestructive examination using ECT began on approximately 50% of the unit's condenser tubes as directed by the plant. The testing company utilized multi-frequency digital acquisition ECT systems capable of ultra-high and ultra-low frequency ranges. Technicians tested every other row of the condenser's two stages and auxiliary condenser totaling approximately 21,400 tubes evaluated.

Data gathered showed significant through-wall loss had occurred over time on the condenser tubing with the largest percentage of tubes affected falling in the 80-100% through-wall loss category shown in Table 3. Because of the large volume of tubes at this data point, plant engineers opted to hydrostatically test, sealing leaking tubes as well as plug tubes that fell within a measurement of >94% wall loss. This particular case is an excellent example of how ECT not only prevented a possible forced shutdown due to a tube(s) failure, but also provides plant managers a comprehensive condition report for retubing consideration.

Table 3 – Unit 1 Main Condenser Eddy Current Results (not including auxiliary)

Unit Description	***Tube Qty***	***Wall Loss***
1A 1st Stage Upper	20	20-39%
	6	40-59%
	3	60-79%
	20	80-100%
1A 1st Stage Lower	3	20-39%
	3	40-59%
	13	60-79%
	60	80-100%
1B 1st Stage Upper	17	20-39%
	25	40-59%
	94	60-79%
	460	80-100%
1B 1st Stage Lower	5	20-39%
	14	40-59%
	27	60-79%
	200	80-100%

Unit Description	***Tube Qty***	***Wall Loss***
1A 2nd Stage Upper	0	20-39%
	2	40-59%
	14	60-79%
	47	80-100%
1A 2nd Stage Lower	2	20-39%
	9	40-59%
	37	60-79%
	178	80-100%
1B 2nd Stage Upper	8	20-39%
	14	40-59%
	68	60-79%
	323	80-100%
1B 2nd Stage Lower	8	20-39%
	10	40-59%
	58	60-79%
	442	80-100%

Conclusion

With the large number of outages and costs associated with condenser tube failures, it is important to incorporate programs that help to minimize the risk to availability and reliability associated with them. Tube deposits and scaling not only can cause tube corrosion and contribute to potential failures, but also rob the condenser of its efficiency. Specific programs that focus on effective deposit removal and ECT can dramatically reduce the likelihood of unplanned outages related to tube failure. In addition to reducing events related to tube failures, such programs can also dramatically improve condenser efficiency to a point where increased megawatt output, reduced fuel consumption and lower emissions can offset the costs of the program altogether.

The cases presented demonstrate the usefulness of ECT technology to assist in the prevention and correction of condenser tube failures. Once tubes are free of fouling deposits, testing the overall integrity of condenser tubes can easily be established with multi-frequency eddy current testing. Plugging is recommended for the tubes with poor integrity that put condenser reliability at risk.

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