# Condensate System Troubleshooting and Optimization

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One of the prime considerations in the operation of a boiler is feedwater quality. The better the feedwater, the less likely that water-related problems will occur. There are many sources of feedwater:

- Raw, untreated water
- Zeolite softened water
- Demineralized water
- Lime-soda softened water

and of course, returned condensate.

Of all these sources, condensate is usually the best economic choice. Condensate, being condensed water vapor (steam) is extremely pure. Since condensate is usually 180°F (*82.2°C*) or greater, less fuel is needed to convert it back to steam because 148 Btu's (*82.2 Kcal*) are in each pound (*kilogram*) of 180°F (*82.2°C*) condensate. And finally, because it is water that the plant has already treated (ion exchange processed, scale/corrosion treated, oxygen removed and evaporated to produce steam), it represents a valuable investment. Therefore, recovering and reusing this water is good management.

Condensate return can help improve the economics of boiler operation through:

***Feedwater temperature increases*** — By increasing feedwater temperature, a plant can reduce the amount of fuel required to produce a pound (*kilogram*) of steam from a pound (*kilogram*) of water. Increasing the amount of returned condensate either increases the feedwater temperature directly, or decreases the amount of steam (deaerator) needed to preheat it.

***Cycles of concentration increase (blowdown decreases)*** — Since condensate is low in dissolved solids, the more returned, the lower the concentration of feedwater solids. Boiler cycles of concentration increase, blowdown decreases, and so does the amount of heat lost in the blowdown.

***Reduced makeup water requirement*** – As more condensate is returned, less makeup is needed for feedwater. Therefore, less money is spent on makeup water treatment (ion exchange regenerant, chemical treatment).

Now that reasons for returning condensate have been established, it is necessary to be aware of problems incurred in the condensate system. Almost all difficulties encountered in condensate systems can be traced to two gases:

- Carbon dioxide
- Oxygen

**Figure 1** — ***Carbonic acid attack on condensate piping***

## CARBON DIOXIDE

In most boiler feedwaters, some carbonate alkalinity is present. Under the pressures and temperatures encountered in the boiler, a portion of the alkalinity breaks down to form carbon dioxide. Carbon dioxide, being a gas, is carried out with the steam. When steam condenses, some of the carbon dioxide dissolves in the condensate and forms carbonic acid. Carbon dioxide is not harmful until it dissolves in condensate.

$$CO_2 + H_2O \rightarrow H_2CO_3 \rightarrow H^+ + HCO_3^-$$

Carbonic acid will cause four characteristic problems:

- The pH of the condensate will drop
- Dissolved iron will increase
- Total dissolved solids will increase
- A trough-like thinning of the bottom of the condensate pipe may occur (Figure 1)

As little as 1 ppm carbon dioxide dissolved in condensate can result in a pH of 5.5 at typical condensate temperatures.

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**Figure 2** — ***Boiler tube with iron deposits***

A pH of 5.5 is 10,000 times more aggressive to mild steel than a pH of 7.5, and 1,000,000 times more aggressive than a pH of 8.5.

What is the impact? Iron is dissolved by low pH condensate and is then returned to the feedwater.

$Fe + 2H^+ + 2HCO_3^- \rightarrow Fe(HCO_3)_2 + H_2$

Simply put, iron is removed from one part of the system (condensate piping) and is deposited in another area of the boiler system (boiler heat transfer surfaces — Figure 2).

The results of carbon dioxide corrosion include:

- Expensive replacement of condensate piping
- Reduced boiler tube life
- In some cases, unexpected boiler shutdowns and production losses

The net result is an outlay for maintenance on the condensate network, chemical cleaning of the boiler, and possible loss of plant production due to an unscheduled outage.

## OXYGEN

Also present in boiler feedwater, this gas may be removed by conventional mechanical and chemical means. Mechanically, oxygen content is reduced by a deaerator, which atomizes the feedwater, and "scrubs" it with steam. The steam increases feedwater temperature, so oxygen becomes less soluble, and is released to the atmosphere at the deaerator vent. Typically, oxygen concentration drops to below 10 ppb.

The rest of the oxygen (even at 10 ppb, still capable of causing severe corrosion) may be scavenged chemically using one or more of the following compounds:

- Sulfite
- Hydrazine
- Other proprietary organic reducing agents

Usually, these two processes, mechanical and chemical feedwater oxygen elimination, are sufficient to prevent oxygen from flashing into the steam. However, in large, extensive condensate systems, air can be drawn in through condensate pumps, improperly operating heat exchangers or tank vents. This air in-leakage brings in both carbon dioxide and oxygen, causing more corrosion problems than either gas individually.

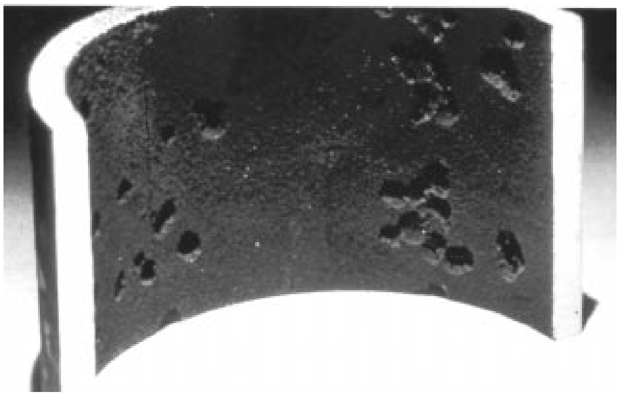

**Figure 3** — ***Pitting of condensate pipe from oxygen attack***

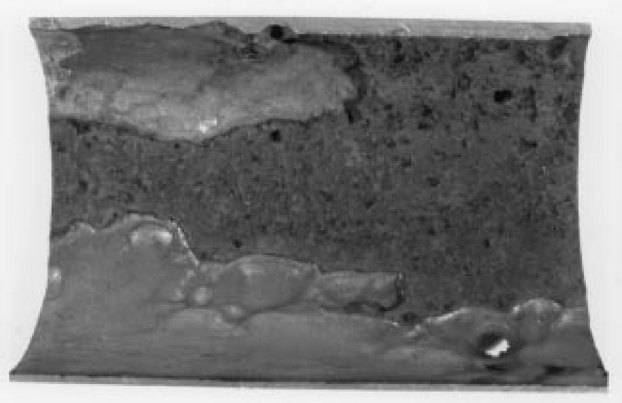

**Figure 4** — ***Carbonic acid and oxygen attack of condensate pipe***

Oxygen attack is characterized by pitting of the condensate pipe (Figure 3).

$4Fe + 3O_2 + 6H_2O \rightarrow 4Fe(OH)_3$

The combined action of carbon dioxide and oxygen can cause accelerated corrosion rates of 10 to 40% more than the sum of the rates of the individual gases (Figure 4).

$2Fe(HCO_3)_2 + 1/2O_2 \rightarrow Fe_2O_3 + 4CO_2 + 2H_2O$

The impact of oxygen attack is the same as that of carbon dioxide – equipment damage, expensive maintenance, unexpected boiler shutdown, and possible costly production losses.

## PROBLEM PREVENTION

The best way of dealing with these two corrosive gases is to prevent their entry into the boiler system. Simple mechanical measures include:

- Good deaeration and properly operating condensate pumps and tank vents can keep oxygen and atmospheric carbon dioxide out of the system.
- Demineralization or dealkalization can greatly reduce the amount of alkalinity in boiler feedwater, and thus the amount of carbon dioxide generated by alkalinity breakdown.
- Condensate polishing, that is, using ion exchange resin to remove and filter hardness and corrosion products, is an effective way to eliminate the results of in-leakage and corrosion, but it does not correct the causes.

Not all problems can be cured mechanically, and due to budget constraints, chemical treatment may be selected. There are chemical answers to carbon dioxide and oxygen corrosion in the condensate.

## NEUTRALIZING AMINES

These products do just what their name indicates: neutralize carbonic acid formed in the condensate. Neutralizing amine programs are generally effective when fed to maintain a minimum pH of 8.5 (suggested range: 8.5 to 9.0). In systems containing no copper alloys, somewhat higher pH values will improve mild steel corrosion control.

Neutralizing amines are added in direct proportion to the amount of carbon dioxide in the steam. In high alkalinity feedwater systems where $CO_2$ generation is appreciable, excessive amounts of neutralizing amines may be required to neutralize the carbonic acid. (Filming amines should be considered in these instances.) Neutralizing amines are characterized by a specific volatility, acid neutralization ability, and basicity.

### VOLATILITY

Every gas in a condensate system has a specific volatility or vapor-to-liquid distribution ratio (V/L). The V/L distribution ratio is defined by:

$$\frac{V}{L} = \frac{\text{(concentration in the vapor or steam phase)}}{\text{(concentration in the liquid or condensate phase)}}$$

The V/L distribution ratio indicates whether the species will condense with the condensate or stay with the steam. For example, a V/L ratio of 4.0 indicates that 4.0 ppm of amine must be present in the steam to get 1.0 ppm in the condensate. The higher the V/L ratio, the more amine will be in the steam. To neutralize carbonic acid, the amine must be in the condensate as the $CO_2$ dissolves.

V/L ratios vary with pressure, pH, temperature, and other operating conditions. Table 1 indicates the V/L ratio of two common neutralizing amines and carbon dioxide.

**Table 1 — *V/L ratios***

| Pressure | | Cyclo-hexylamine | Morpholine | Carbon dioxide |
|---|---|---|---|---|
| psig | barg | | | |
| 0 | 0 | 2.7 | 0.4 | 3.0 |
| 50 | 3.5 | 3.0 | 0.4 | 4.8 |
| 150 | 10.3 | 4.0 | 0.5 | 8.5 |
| 600 | 41.4 | 10.0 | 1.2 | 15.8 |
| 900 | 62.1 | 6.6 | 1.2 | >99.0 |

It is important to realize that V/L ratios are only significant when a phase separation occurs. For example, in a flash tank, condensate enters the vessel while both condensate and steam exit the vessel. Low volatility amines such as morpholine will tend to be present in greater concentration in the condensate exiting the flash tank. High volatility cyclohexylamine will tend to be present at higher concentrations in the steam exiting the flash tank.

V/L ratios are not significant when total condensation occurs. Total condensation occurs when all the carbon dioxide and amines in the steam entering a unit are dissolved into the condensate (no phase separation exists).

### ACID NEUTRALIZING ABILITY

In addition to V/L ratio, which determines the distribution of an amine in a system, another very important aspect of amine choice is its acid neutralizing ability. This is the amount of amine required on a weight basis to neutralize the carbonic acid present. The amine reacts with the carbonic acid in solution to form an amine bicarbonate:

$$RNH_2 + H^+ + HCO_3^- \rightarrow RNH_3^+ + HCO_3^-$$

This characteristic is primarily dependent upon the molecular weight of the amine. On a pound-for-pound basis, lower molecular weight amines will neutralize more carbonic acid than higher molecular weight amines.

### BASICITY

Once all the acid in the condensate system has been neutralized (at a pH of about 8.3), amine basicity becomes important. This is a measure of amine hydrolysis. Any additional amine added to the condensate system will hydrolyze, raising the condensate pH:

$$RNH_2 + H_2O \rightarrow RNH_3^+ + OH^-$$

Basicities of neutralizing amines also vary. For example, cyclohexylamine is a much stronger base than morpholine. Past a certain pH, additional quantities of the weaker neutralizing amines, such as morpholine, will do little to further increase pH.

Figure 5 shows the combined effect of acid neutralizing ability and basicity for three amines.

The V/L ratio, acid neutralizing ability, and the basicity of each amine must be considered when selecting a condensate corrosion inhibitor program. Common neutralizing amines are morpholine, cyclohexylamine, diethylaminoethanol (DEAE), aminomethylpropanol (AMP), dimethylisopropanolamine (DMIPA), and methoxypropylamine (MOPA). As mentioned earlier, neutralizing amines neutralize carbonic acid. Their effect on oxygen is negligible.

## FILMING AMINES

Filming amines are used to protect condensate piping from both oxygen and carbonic acid attack. This is done by laying down a very thin film on the condensate pipe (Figure 6).

In order for the filmer to work, the condensate pH must be high enough for the film to form. Octadecylamine is a commonly used filmer, but the pH must be controlled at a range of 6.5 to 8.0. Outside this range, the film strips off, and can cause deposits in the steam traps and condensate lines (and even the boiler). Also, octadecylamine is difficult to feed.

Another filmer, a proprietary compound is stable over a wider pH range of 6.5 to 9.5, making it much easier to use, and overall, a more flexible program.

In almost all cases, the filmer must be supplemented with a neutralizing amine. Filmers alone do not have enough neutralizing capability to buffer condensate pH into the range where filming can effectively take place. Most filmers are offered as a combination treatment of filming/neutralizing amines to alleviate this problem.

The fact that a filmer/neutralizer program can provide protection at a lower pH than a straight neutralizer may allow a plant to use less neutralizer, and thus reduce treatment costs. It should be noted that the ultimate basis for this decision is the individual plant's treatment performance and operating history.

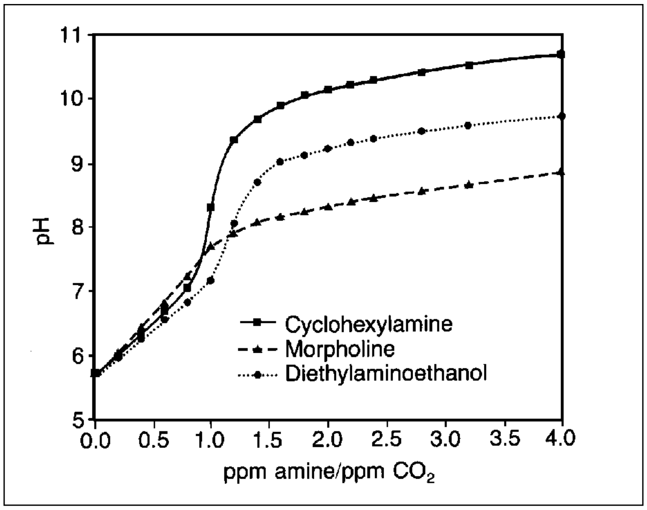

**Figure 5 — *Amine neutralizing ability***

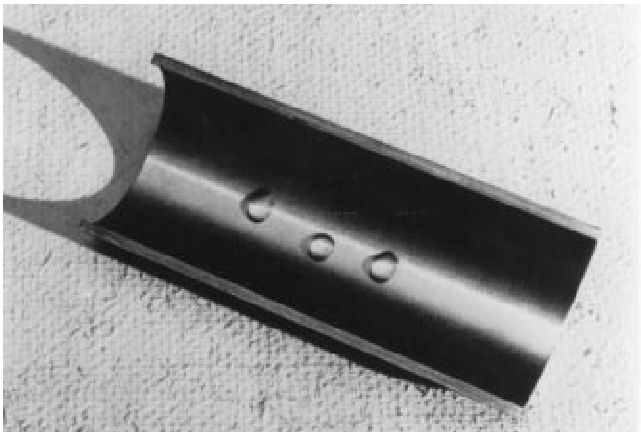

**Figure 6 — *Filming amine providing nonwettable surface***

Another benefit of filming amines noted by some users is an improvement in heat transfer, due to the film promoting nucleate condensation.

## OXYGEN SCAVENGERS/METAL PASSIVATORS

An alternative to filming amines for condensate oxygen corrosion protection is an oxygen scavenger/metal passivator (Figure 7).

These compounds work by the same mechanisms as the feedwater oxygen scavengers mentioned earlier. The oxygen problem is addressed directly by using an oxygen scavenger/metal passivator to treat the steam/condensate system. Some oxygen scavengers enhance metal passivation. At condensate temperatures, metal passivation generally occurs preferentially over oxygen scavenging. However, carbonic acid attacks the passive magnetite film, so passivation improves above pH 8.3, where the acid is not present.

A combination of neutralizing amines and metal passivator can be ideal for many plants. However, if feedwater alkalinities are high, a neutralizer/filmer program may be more economical. The trade-off between ease of control (which favors neutralizer/metal passivator) and economics (which favors neutralizer/filmer) is system dependent.

## CONDENSATE SYSTEM INSPECTION AND TESTING

There are several ways to tell if the condensate system is being treated properly.

*Boiler and condensate line inspections* are the ultimate criteria. Are the condensate pipes clean and well passivated? Are the boiler surfaces free of corrosion product deposits?

**Figure 7** — ***Passivated pipe surface***

*Condensate system monitoring* – A well-administered program of condensate testing can prevent small problems from becoming large ones. Testing and monitoring that will prove useful for system control include:

***pH*** — Checking condensate pH at several places can ensure that the entire condensate network is properly treated for carbonic acid attack. When sampling condensate, technique is extremely important because of the high purity of the sample involved. The sample should be taken through a cooling coil at a temperature of less than 90°F. Higher temperatures will cause flashing of carbon dioxide, oxygen, and amine, and give false results. Also, the sample coil should be throttled at the exit and not the intake, to avoid drawing air into the cooling coil and giving false results. Generally, a pH below 8.3 indicates potential corrosion for a neutralizing amine program.

***Iron measurement*** — Dissolved, insoluble, or total iron measurement can also indicate performance of condensate treatment. Again, due to the nature of the sample, sampling is extremely important. Continuously flowing samples are best, but when not available, flushing sample lines and allowing them to run for a few hours is satisfactory. If iron levels are above 50 ppb, excessive corrosion is taking place. The following are tests that can be run on condensate to determine iron content:

***Millipore® filters*** — This simple test can measure insoluble (particulate) iron by passing a liter of condensate through a membrane filter and comparing the result to a color chart such as the Babcock and Wilcox comparison chart (Figure 8). Although semi-quantitative, this test is also a good tracking method, and can be quite graphic.

***Photometric analysis*** — Laboratory tests to determine iron levels can give very accurate results which are good trend indicators.

***Gas measurement*** — Detecting gases that cause corrosion (oxygen and carbon dioxide) can be the first step in determining if the agents used to combat them are working. There are tests for both carbon dioxide (simple titration) and oxygen (indigo carmine or CHEMets®) which are accurate and reliable. Continuously reading, on-line oxygen meters are also available. Generally, if oxygen level is above 50 ppb, corrosion is taking place.

***Filming amine residual*** — Although a more complex test, the filmer test can indicate if a sufficient amount of filmer is present to assure film formation throughout the system.

***Oxygen scavenger/metal passivator test*** — Usually a simple residual test. Here again, controlling the metal passivator in a given range can ensure optimum results.

***Corrosion coupons (Figure 9)*** — Strips of metal, usually the same metallurgy as the system being monitored, are inserted into condensate flow for a known length of time, normally 30 days. The coupon is removed, and its weight compared with its weight at entry, then a corrosion rate is calculated and expressed in mils per year (mpy). These, like the Millipore filter pads, provide semi-quantitative measurements, but allow good system monitoring.

***Condensate system modeling*** – The previously mentioned tests and analyses have been used for some time.

Nalco is able to offer two additional tools that permit more accurate condensate modeling and evaluation than conventional methods.

The first of these tools is called the *Nalco Mobile Condensate Center (MCC)*. The MCC is a fully automated unit that uses plant-produced steam to determine the combined effects of treatment, dosage and system thermodynamics. Each unit contains a series of coolers and condensing cylinders (Figure 10). Temperature and pressure are controlled by adjusting steam and cooling water flows. The pH of the condensed steam is determined at a series of pressures to profile the steam source and its potential for corrosion.

The purpose of the MCC is simple — tracking amine and carbon dioxide behavior in an entire condensate system from a few sample points. The benefits are many. Potentially overtreated, undertreated or untreated areas can be quickly identified and complete system analysis accomplished without the costs associated with having to shut down a process to install additional sample taps or the costs of large numbers of laboratory analyses. Slight changes in the feedwater, amine feed conditions, or other system changes can be quickly evaluated since the MCC deals with on-line steam samples.

The other tool for condensate analysis is the *Nalco Condensate Computer Model*. The Condensate Computer Model was developed to predict behavior of carbon dioxide and neutralizing amines in condensate systems. All programs either predict pH's at various plant locations, or dosages of amines necessary to attain desired pH levels. The model uses data on carbon dioxide and amine thermodynamic behavior, and plant condensate system configuration to draw its conclusions.

Impact on corrosion rates by filmers is not taken into account, since pH prediction is the main goal of the program. Many of Nalco's filmers are offered in combination with neutralizing amines, so a pH range appropri-

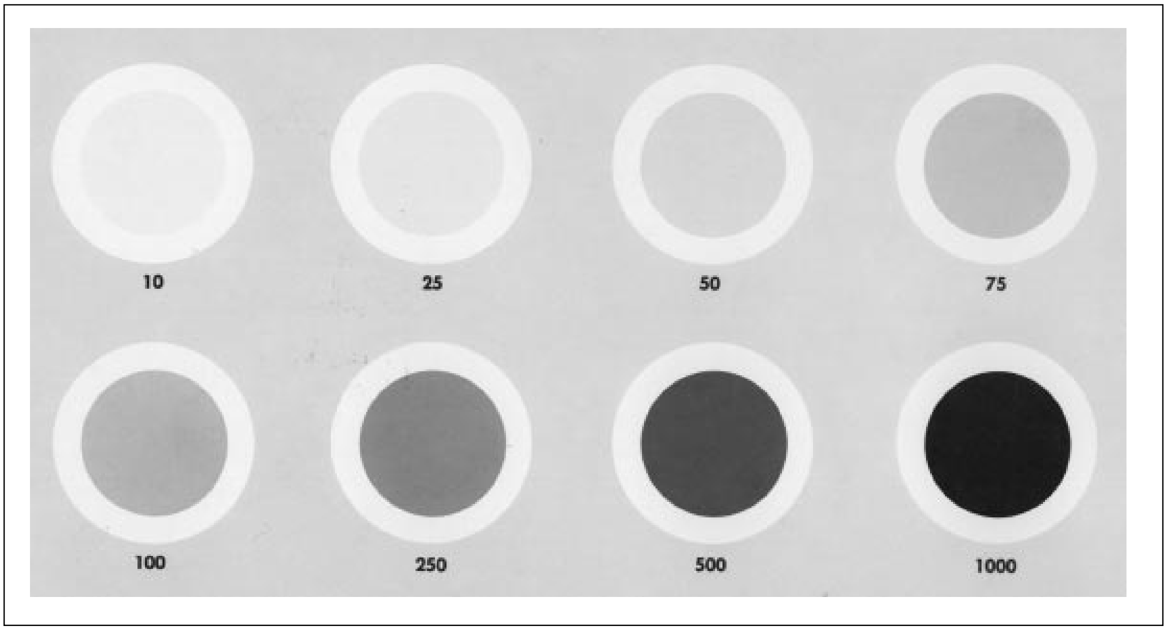

**Figure 8** — ***Babcock & Wilcox membrane charts***

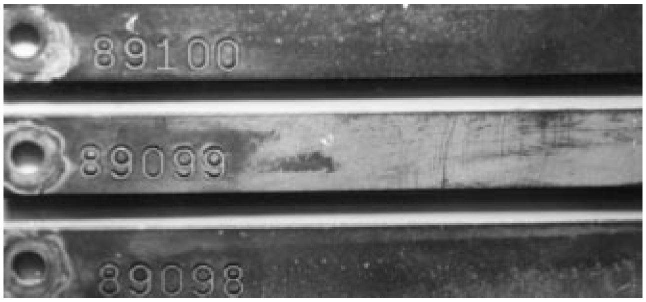

**Figure 9** — ***Corrosion coupons***

ate to a combination treatment can be selected, instead of a pH range appropriate to a neutralization-only treatment. Information on the condensate system and boiler and feedwater chemistry is gathered by the Nalco representative. Condensate pH data, if available, is also recorded, along with dosage information on the current amine treatment.

Using the model, the Nalco representative can:

- Troubleshoot systems and help spot process contamination or air in-leakage by comparing actual vs. predicted pH at key plant locations
- Examine a condensate corrosion inhibitor and its impact on a particular system at different dosages
- Optimize dosage of a particular condensate corrosion inhibitor to attain a desired pH range
- Calculate dosages of inhibitors for satellite feed
- Evaluate amine/carbon dioxide behavior for multiple boilers feeding steam to a common header, as well as for flashed steam (cascading), or thermocompressor systems
- Examine multiple amine feeds

## CASE HISTORIES

### CASE HISTORY 1, EASTERN U.S. REFINERY

A refinery was concerned by the high concentration of iron in their feedwater. Iron concentrations of 200 ppb or more were typically noted for a system for which the suggested ASME feedwater iron limit was ≤25 ppb. This iron was a corrosion product of the condensate system. To expedite the solution, and because numerous sample points were not readily available in the refinery, the Nalco Mobile Condensate Center was brought in to profile the system.

The Mobile Condensate Center was connected to 200 psig (*13.8 barg*) turbine exhaust steam in the main boiler house. Results are shown in Figure 11. The refinery fed a neutralizing/filming amine combination program to protect the condensate system. The recommended pH control range for this program is 6.5 to 9.0, optimally 7.5 to 8.0.

The 200 psig (*13.8 barg*) extraction steam was condensed and subsequently flashed at 175, 80, 40, 20, and 15 psig (*12.0, 5.5, 2.8, 1.4, 1.0 barg, respectively*). Atmospheric-vented receivers were also present in the system. Condensate was produced at each of these pressures and must be adequately treated to prevent corrosion. Results from the Mobile Condensate Center show that except for 7 psig (*0.5 barg*), all pH values were below 7.5. In fact, much of the profile shows a pH of less than 6.5.

The Mobile Condensate Center was also connected to 200 psig (*13.8 barg*) reboiler steam. These boilers were treated by an all-in-one-drum program containing oxygen scavenger, internal treatment, and cyclohexylamine as the condensate corrosion inhibitor.

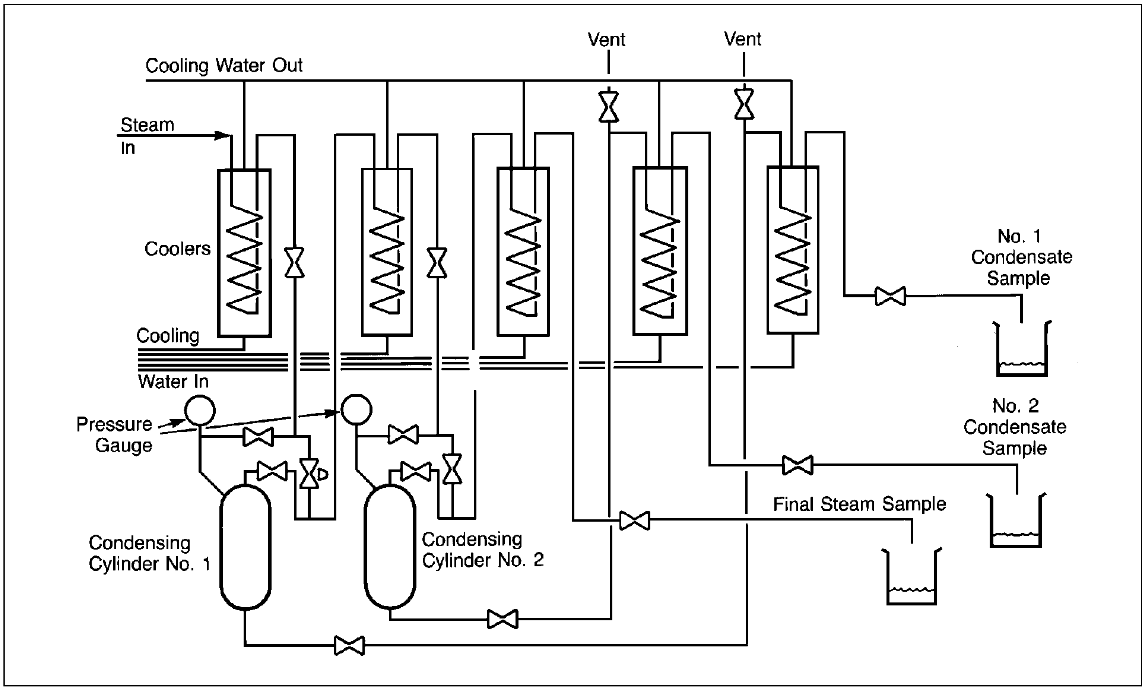

**Figure 10** — ***Schematic of typical condensate monitoring unit***

Results from this sample point are shown in Figure 12. A significantly different profile is seen. The results show that insufficient amine was present at pressures greater than 80 psig (*5.5 barg*) to adequately control the pH. At pressures less than 60 psig (*4.1 barg*), too much amine was present, resulting in this part of the system being overtreated.

The profile shown in Figure 12 is typical of a single amine condensate treatment. Multiple amine combinations provide more effective system protection because each amine can provide a different level of volatility, or tendency to travel with the steam. A blend of several amines will assure that corrosion protection is distributed throughout the entire steam/condensate system.

As a result of the study done by the Mobile Condensate Center, the neutralizing/filming amine treatment dosage was increased to provide a minimum pH of 7.5 at all pressures. This was accomplished without satellite feed. The same program was recommended for treatment of the reboiler steam. Iron concentrations in the feedwater decreased steadily and finally leveled out at approximately 10 to 25 ppb, within the suggested ASME feedwater iron limitations.

## CASE HISTORY 2, MIDWEST U.S. PAPER MILL

A paper mill generating 500 psig (*34.5 barg*) steam was experiencing low pH and high iron levels in certain areas of its condensate system. The mill produces approximately 2.2 million pounds (*1.0 K tonnes*) of steam per day, using hot-lime softened and filtered water and returned condensate for boiler feedwater. Steam is used for process and building heat, and to drive turbines. The plant was using a combination treatment of neutralizing amines, filming amines, and oxygen scavenger. Due to the extent of the system, not all areas of the condensate network could be tested.

The Nalco Condensate Computer Model was used to model the plant's condensate system. Results of the modeling showed areas where condensate pH was too low for film formation. Low pH and lack of film formation were causing high iron levels.

Additional feed of neutralizing amine was initiated to raise condensate pH to a point where the filming amine could work. The iron levels, measured by Millipore filters, dropped from 750 ppb to 100 to 150 ppb. Additional work is continuing to further reduce iron content. Condensate polisher runs were doubled as well. Due to the use of the Condensate Computer Model, corrosion rates decreased dramatically, condensate polisher loading improved, and the amount of iron returned to the boiler decreased significantly.

## CASE HISTORY 3, MIDWEST U.S. FOREST PRODUCTS PLANT

A forest products plant was using 200 psig (*13.8 barg*) steam for its rosin heating and hot press processes. Condensate corrosion from both carbonic acid and oxygen was experienced at the hot press inlet. The plant's boiler system uses sodium zeolite softened water and returned condensate for feedwater. The neutralizing amine program being used was not sufficient to combat carbonic acid, formed by breakdown of alkalinity to carbon dioxide, which left the boiler with the steam. Also, the

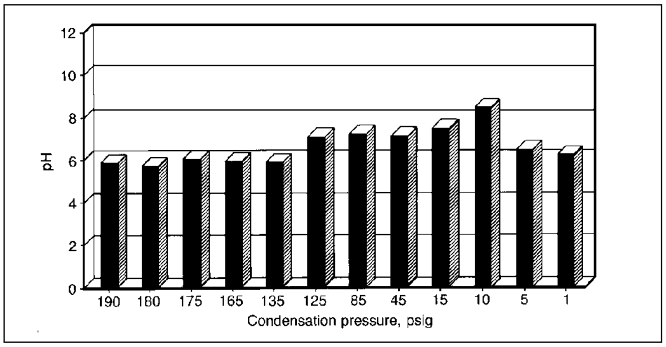

**Figure 11** — ***Eastern refinery 200 psig extraction steam. All values are temperature corrected.***

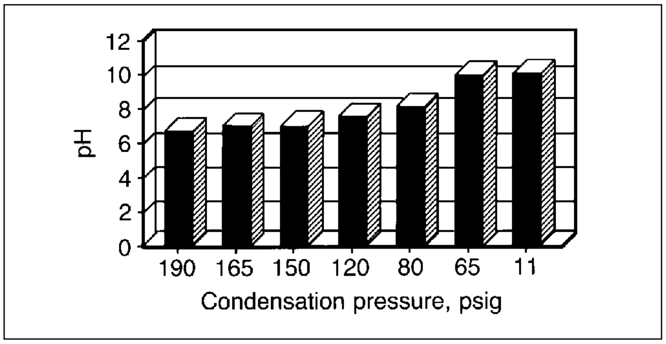

**Figure 12** — ***Eastern refinery 200 psig reboiler steam. All values are temperature corrected.***

neutralizing amine did nothing to address the oxygen problem. Iron levels in the condensate were in excess of 100 ppb.

The Nalco representative used the Nalco Condensate Computer Model to help him analyze and model the system. Good correlation between actual and predicted pH was shown. The model indicated that the plant was feeding excessive amine for a relatively small gain in pH, and that changing programs could give better results at lower cost.

The Nalco representative used his experience and the model to establish a filming amine program for the oxygen problem, and a neutralizing amine program for the carbonic acid attack. Iron levels dropped from over 100 ppb to 4 ppb, a decrease of 96%. Total amine consumption dropped by approximately 75%. The Nalco Condensate Model, combined with the capabilities of the Nalco representative, cured a troublesome corrosion problem for this plant.

## CASE HISTORY 4, WESTERN U.S. REFINERY/ PETROCHEMICAL COMPLEX

A refinery/petrochemical boiler system was experiencing corrosion in the outlying areas of its extensive condensate network. Condensate pH values of less than 6 were common, with Millipore filter tests showing 400 to 500 ppb of iron in the far reaches of the condensate system.

The plant's 800 psig (*55.2 barg*) system generates approximately 18 million pounds (*8.18 K tonnes*) of steam per day, using sodium zeolite, hot-lime softened water and returned condensate for boiler feedwater. The steam is used for process heating, driving turbines, and reboilers. A combination treatment of neutralizing and filming amines with an oxygen scavenger was in use.

The Nalco Condensate Computer Model was used to determine why the complex was having problems. The model showed that a change in feed point or an increase in dosage would produce uniform pH throughout the system. Prior to this, most of the plant pH values were in the range of 7 to 8, except in the extreme ends of the condensate system.

Using the model, the Nalco representative was able to optimize the dosage of amine to adjust pH range and reduce corrosion rates. Iron levels have dropped more than 50%, and pH throughout the plant is more uniform.

## SUMMARY

The rewards for increased condensate return are many. Energy savings and improved steam production reliability are the primary potential benefits. Use of innovative modeling techniques such as the Nalco Condensate Computer Model and the Nalco Mobile Condensate Center, plus a regular in-plant monitoring program, can help ensure optimum results and a well-protected system with minimum energy wastage.

## TRADEMARKS

1. Millipore is a registered trademark of Millipore Corporation.
2. CHEMets is a registered trademark of CHEMetrics, Inc.

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