

A Performance-Based Approach to Cooling Water Chemistry Control

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ABSTRACT

Cooling water treatment programs traditionally rely on the application of chemical products to design-based residuals, with the use of external – typically reactive – analysis and monitoring techniques to maintain system performance. Such programs can be inherently inefficient, using too much or too little chemical at the wrong times. Decision-making is often based on how the system was behaving in the past, not how it is performing currently, or how it may perform in days or weeks to come.

The Otahuhu B Power Station is a modern 380 MW single-shaft combined cycle facility, incorporating a low-cycle, estuarine water, evaporative hybrid cooling tower. A comprehensive control and instrumentation project is underway to modernise the cooling water treatment program. The ultimate goal of this project is to move from a passive control system with very little monitoring to one based around real-time, on-line, semi-predictive performance monitoring techniques that proactively manage the application of varying residuals according to actual system requirements. Control programs are being designed to assess the known system parameters and the plant performance, and to dose chemical on the basis of that performance according to rules-based logic. Work to date has already resulted in a more efficient dosing regime, significantly reducing chemical treatment costs, while simultaneously improving the overall plant monitoring and helping to minimise the environmental impact of discharged effluent.

INTRODUCTION

The Otahuhu B Power Station (*Figure 1*) is a modern, high-efficiency, single-shaft combined cycle facility owned and operated by Contact Energy Limited. It is situated in South Auckland, New Zealand and supplies about 9 % of New Zealand's electricity requirements, making it one of the largest thermal-based electricity generators in the country. The plant was commissioned during 1998 and 1999 by the OEM, Siemens (AG) KWU, and officially handed over to Contact Energy in December 1999.

Cooling Water System

A water pumping station supplies nearly $1\,000\text{ m}^3 \cdot \text{h}^{-1}$ of estuarine makeup cooling water to the open recirculating cooling system. Two 50 % recirculating water pumps furnish water to a 2-pass, titanium-tube condenser at a rate of $5\,000\text{ L} \cdot \text{s}^{-1}$, with a water velocity of $2\text{ m} \cdot \text{s}^{-1}$ through the tubes and a ΔT across the condenser of 9.9 K for the maximum design heat rate of the plant. A tube-ball cleaning system helps maintain condenser cleanliness.

An evaporative, hybrid cooling tower is used for heat rejection. The 8-cell tower is of timber construction, incorporating a high-efficiency, falling-film fill (FC-18). All cells are normally in service. A portion of the hot-return water is fed to the upper area of the tower to re-heat the exhaust air plume and satisfy the requirement for no visible plume from the tower itself.

System losses (evaporative and purge) are monitored, and the makeup water flow maintains a working level in the recirculating water pump pit. Purge water is automatically discharged to maintain the desired 1.25 cycles of concentration; the purge water is held in a $20\,000\text{ m}^3$ holding pond to facilitate temperature and residual oxidant decay in the effluent before it is discharged into the receiving environment once every tide cycle.

The main system pipework is rubber lined, the underground culvert system is concrete, and the return risers are fibreglass. In addition, the condenser tubesheet is epoxy coated. The design therefore effectively eliminates corrosion concerns from the system.



Figure 1: Otahuhu B Power Station (A Station in background).

Cooling Water Chemistry

The conductivity of the estuarine makeup water can vary significantly from season to season due to the influence of rainfall and surface run-off on the river flows into the estuary. From plant operating experience, the known makeup water conductivity is extremely variable, being in the range 1.0 to 50.0 mS · cm⁻¹, with lower values typically noted during winter (high rainfall season) and higher values during summer. The conductivity also varies markedly between low and high tide cycles, by as much as 10 mS · cm⁻¹, independent of any other influence. The incoming water pH is normally in the range 7.7–8.1. The suspended solids loading in the water can vary dramatically, again depending on surface run-off, with turbidity values ranging from 5 NTU to 100 NTU, the latter being the extreme case.

The incoming estuarine makeup water is not filtered and only receives a treatment with industrial-grade bleach (sodium hypochlorite) for biological control. The chemical and service provider for the plant is Nalco New Zealand Ltd; Nalco Stabrex – a stabilised bromine biocide – is dosed into the recirculating water system as the oxidising biocide of choice. Nalco 1383T scale inhibitor – a blend of polyphosphonate and polyacrylate – is also dosed into the recirculating water system. The phosphonate acts as a crystal modifier for scale control, and the acrylate component is a general silt dispersant.

Commissioning experience showed that the use of a biodispersant would result in excessive salt-water spray drift from the cooling tower, breaching the strict resource consent on tower drift. The OEM deemed that the use of sodium hypochlorite in the recirculating water system in the absence of a biodispersant would introduce an unacceptable risk to the medium and long-term plant performance. The stabilised bromine biocide was tested on the recirculating water system during commissioning and found to be an acceptable substitute for the originally proposed hypochlorite/biodispersant regime.

While the makeup water is treated with hypochlorite, the concentration of bromide in the estuarine water results in a partial conversion of chlorine to bromine. Since the bromide concentration varies, so too does the chlorine/bromine ratio in the makeup water and hence the recirculating water (to which the stabilised bromine biocide is dosed). The plant chemistry therefore refers to free and total residual oxidant concentrations, though these concentrations are reported as mg · kg⁻¹ Cl₂ for comparison against published data.

Environmental Aspects

A plethora of environmental and resource consent conditions apply to the use and discharge of water: water velocity in the intake forebay; point discharge temperature; point discharge oxidant concentration; mixing zone temperature; discharge water flow; cycles of concentration; no-plume condition; salt-water drift; etc.

The station has successfully concluded a comprehensive Whole Effluent Toxicity Study, and the company routinely carries out environmental monitoring as part of its requirements and obligations as a conscientious water user.

Cooling Water System Inspections

Use is made of major outages to carry out detailed inspections of the cooling water system. The intake screens (for large debris control) can be lifted and inspected and if possible the recirculating water system is completely drained, allowing access to the condenser, the underground culverts and the tower fill material spaces.

Silt and sludge that enters the system settles in the low-flow areas of the tower cells. The accumulation of solids is disposed of as often as possible, as it is an obvious site for the development and proliferation of macroorganisms, which could possibly be carried over to the bulk water flow, possibly blocking condenser tubes or fill material, or worse, "seeding out" in these areas.

A photographic archive is maintained of such inspections, which aids in the comparison of system cleanliness from year to year.

BACKGROUND

When the plant was handed over to Contact Energy, the cooling water process chemistry was very successful in maintaining clean, efficient plant, but the control of that chemistry was largely manual in nature, with off-line analysis determining the concentration of residual chemical, and subsequent manual adjustment of a dosing pump stroke position, for example.

There was an almost complete deficit of on-line monitoring of chemical residual and system efficiency and performance. Plant fouling risks were not well understood, and while the applied amount of chemical was obviously sufficient to maintain clean plant, there was an impression amongst management that its use could be at the very least optimised if only the fouling processes and risks could be better understood. Indeed, with the cooling water chemical costs accounting for half the production manager's annual budget during 2000 and 2001, there was significant support from the plant management for a re-assessment and re-evaluation of what was known about the cooling water process chemistry.

In August 2001, an international consultancy was commissioned to independently review the process chemistry and comment on any inefficiency in the overall control and management of the process.

The main conclusions arising from that report [1] were:

- The existing chemistry program was successful in maintaining clean plant.

- There was an overall lack of process control that was detrimental to cost efficiency.
- There was considerable cost justification for developing a sophisticated monitoring and control program.
- On-line monitoring of oxidant concentrations and system conductivity was recommended.
- Water treatment considerations did not justify the 1.25 cycles of concentration limit. The limit could be extended upwards with careful planning.

When the author joined Contact Energy as its industrial chemist for the Otahuhu B site in October 2001, a budget had already been approved and assigned to a project that would be charged with taking the consultant's recommendations and making them a reality.

PROGRAM DEVELOPMENT

It was known from system inspections that the critical unit operations of the cooling water system (condenser and fill material) were very clean.

It was also accepted by late 2001 that this was at least in part due to chemical use being conservatively high because the plant fouling risks were not well known.

A reactive approach typical of many facilities had been employed since plant takeover in the analysis and monitoring of the system. This reactive approach was not seen as a defensible mechanism for moving the new process chemistry optimisation program forward. For example, the biological fouling risk was being determined as part of the routine service on the plant in the traditional off-line fashion, with a manual grab sample taken, plated out, and incubated for 48 hours before results were known. By the time any actual risk could be recognised, the system might already be seriously fouled. The fear of unwittingly allowing such fouling to become established fostered an environment of conservatism in the application of chemical, where it was considered better to err on the side of caution rather than take a chance and potentially foul the system. It was acknowledged right at the beginning of the program that a proactive monitoring scheme had to be initiated if ever the desired reduction in chemical use and subsequent cost savings and environmental benefit was to be realised.

Project Goals

While the required approach to fulfil the set goals was not yet established, the goals themselves could readily be catalogued:

- Maintain the existing level of cleanliness and performance at all times.
- Evaluate the fouling risks.
- Optimise the costs of chemical treatment wherever possible.
- Develop a sophisticated and efficient process control for reliable, low-maintenance operation.
- Provide for continuous chemistry and system efficiency monitoring.
- Help reduce the routine involvement of the site chemist and service provider in the day-to-day running of the system chemistry.
- Minimise the environmental impact of the discharged effluent wherever possible.

Proposed Areas of Development

A number of areas of the process chemistry were targeted for control and instrumentation upgrades. The proposed areas of development were:

- Provide for the automated and interlocked control of a continuous hypochlorite dosing system for makeup water dosing.
- Provide for the automated and interlocked control of a continuous flow of makeup cooling water to increase the efficiency of the hypochlorite dosing.
- Provide for the automated and interlocked control of an intermittent stabilised bromine biocide dosing system for the recirculating water dosing.
- Provide for the automated and interlocked control of a variable inhibitor concentration regime.
- Provide for comprehensive on-line condenser efficiency monitoring.
- Develop an overall total water system management package, based on rules-based logic.

THE PERFORMANCE-BASED CONCEPT

Proposals C and D above indicated a move towards the application of chemical according to system demand, rather than by simple application to a fixed residual. The idea was further developed on the premise that if the performance of the system process could be determined on-line and in real time, and if the fouling risks could be evaluated using semi-predictive techniques, then an assessment could be made about how much chemical should be applied now to maintain a given performance level in the future.

This is the performance-based approach in its essence, an approach whereby chemical is used according to system demand in order to provide a known, acceptable level of plant cleanliness and performance at all times.

Figures 2 and 3 give an overview of the concept. The cooling water system and the process chemistry become

highly monitored operations, with data collected from the on-line performance monitors (e.g., chlorine concentration, conductivity, pH, inhibitor residual, biofouling potential, scaling potential, etc.) and the system process variables (ΔT , hot water return temperature, makeup flow, tidal influences, cycles of concentration, etc.).

This data flows back to the DCS where a system-specific rules-based logic package weighs the significance of each parameter and determines a series of outputs, which the control system can then apply. These can include a performance rating (e.g., condenser heat transfer coefficient and/or cooling tower capability and/or overall plant effi-

ciency), an increase/decrease in biofilm control agent, an increase/decrease in scale control agent, a purge water flow rate, etc. The output data can also be matched to action levels or alarm hierarchies to alert operators or the station chemist of immediate or impending process problems, or the data can be used as part of real time DCS trending, or for internal reports.

UNTANGLE THE TRIANGLE

The cooling water treatment triangle (*Figure 4*) shows the four major problem areas [2]. The arms of the triangle encompass the microbiological processes in the centre; the presence or otherwise of microbiological fouling can be central to the initiation, development and overall severity of the plant fouling processes. Biofilm contributes significantly to microbiologically-influenced corrosion (MIC) and under-deposit corrosion. Biofilm also provides possible nucleation sites for mineral scale growth, and this aids the accumulation of general fouling deposits.

Since microbiological fouling is so integral to the issues faced in cooling water treatment, this topic is discussed in detail below. The other fouling processes are also discussed in some detail.

Understanding each of the fouling processes individually helps gain some appreciation for how they interrelate in a typical cooling water system.

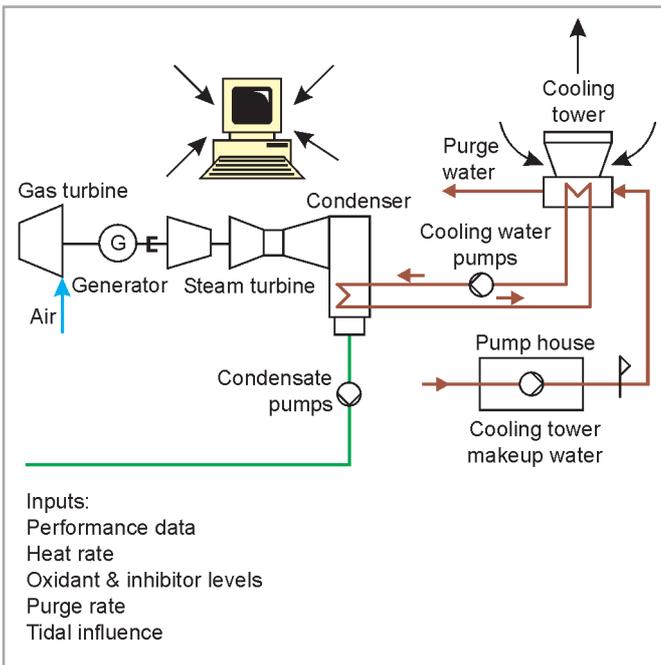


Figure 2: Performance-based inputs.

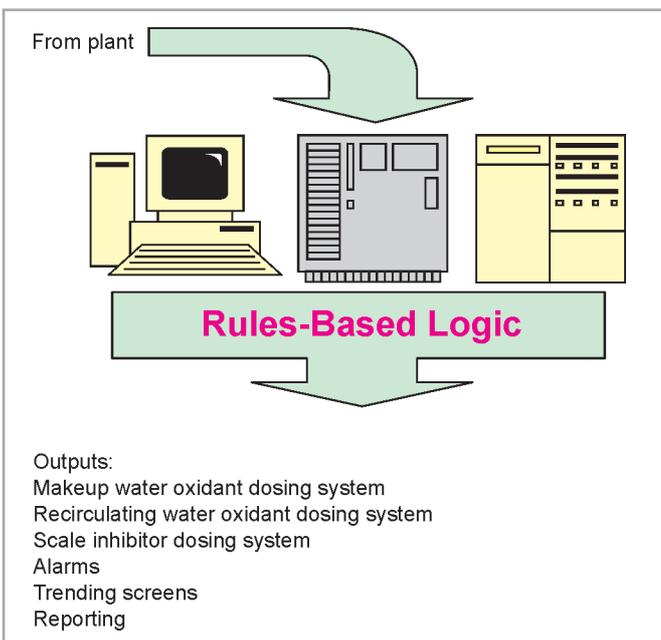


Figure 3: Performance-based outputs.

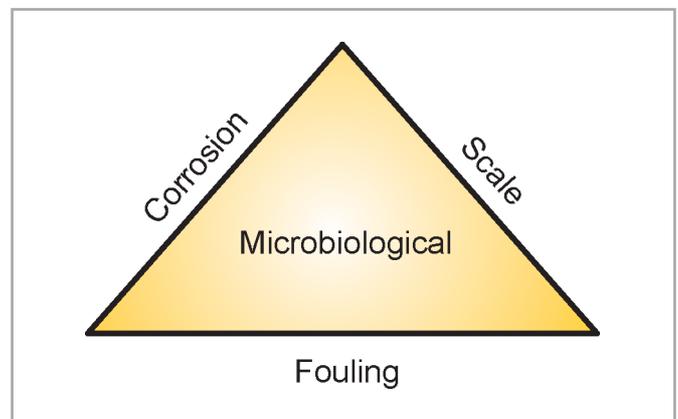


Figure 4: The fouling triangle.

Biofouling

If allowed to develop in an uncontrolled manner in cooling water systems, microbial populations can result in the proliferation of biofilm on system surfaces [3]. A biofilm is an aggregation of microbial cells and their associated extracellular polymeric substances (EPS, also termed exopolysaccharides) on a system surface. It is interesting to note that more than 99 % of viable microorganisms in a system reside within surface biofilms.

Biofilm initially forms when particles within the bulk water phase (fats, proteins, etc.) adhere to the system surface

and form a conditioning film, which aids bacterial attachment by modifying surface properties such as free energy and surface tension [4]. This early attachment phase is generally reversible, with cells moving freely to, from and around the surface. This infant biofilm can be readily removed from the surface and the cells involved can still be termed *planktonic*.

If the surface density of cells increases, a stage of irreversible attachment is reached where there is a permanent bonding between the bacteria and the substratum, mediated by the production of EPS. This EPS produced by the bacteria is a sticky, "slimy" substance, which holds the entire community together. The adhesion of a critical density of bacteria triggers the expression of a "sigma factor" that derepresses a large number of genes. The next step is important. Gene transfer occurs between bacteria; this evolution in the biofilm cells has produced bacteria that are phenotypically distinct from their planktonic counterparts. The cells are clearly now to be termed *sessile*.

Cellular properties (such as cell-to-cell signalling) enable the biofilm communities to organise themselves structurally in response to both the external conditions and the activity of different biofilm members. The whole colony maximises its available resources, with each bacterium living in a customised "microniche" in a complex microbial community. As the biofilm becomes more established, it acts to trap cells and other particulate matter (nutrients, etc.) flowing past, or deposited on, the surface.

Growth and multiplication of the bacteria results in the formation of "microcolonies" – communities within communities [4]. Once a biofilm reaches a critical thickness, chemical gradients develop within it. For example, the penetration of oxygen into the biofilm is controlled by the rate of oxygen utilisation; regions of the biofilm can become anaerobic, supporting the likes of sulphate reducing bacteria (SRB). Mature biofilms constitute a reservoir of many different bacterial species living together.

Biofilms are dynamic systems, with an equilibrium developing over time between cell loss and cell gain. Cells can be added by replication, and by the attachment of more planktonic bacteria from the bulk water phase. Cells can be lost from the biofilm through the active detachment or budding of mature or daughter cells back into the bulk water phase [4]. This is a worrisome level of development in the life of a biofilm, for such detachment can seed the formation of biofilm elsewhere in the system. Cells can also be lost by erosion and "sloughing", brought about by turbulence or a general change in the external environment, including the introduction of a stress (e.g., toxic stress), which might penetrate the biofilm and profoundly disrupt the community's equilibrium.

The presence of biofilm can result in several process problems:

- 1) Microbiologically-influenced corrosion:
Biofilms cause variations in oxygen and pH between

the upper layer of biofilm and the layer attached to the metal surface. These chemical gradients affect surface properties, producing cathodic and anodic areas. Microbial activity can produce metabolic by-products that are corrosive.

Acid-producing bacteria can produce sulphuric acid from the oxidation of sulphides to sulphates, and SRB (existing in anaerobic areas beneath deposits) can reduce sulphate to corrosive hydrogen sulphide.

- 2) Reduction in heat transfer:
The thermal conductivity of a biofilm ($0.6 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$) is comparable to that of water, which is not so surprising given that a biofilm is 95 % water. Note that the thermal conductivity of copper is in the order of $380 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ at 20 °C. Biofilm is even more insulating than calcium carbonate scale, which has a thermal conductivity in the range $0.8\text{--}2.0 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ [5].
- 3) Increased chemical costs:
Bacteria within biofilms have an increased resistance to anti-microbial agents. Bacteria in biofilm can be 150 to 3,000 times more resistant to HOCl and up to 100 times more resistant to NH_2Cl than their planktonic counterparts [4].
The presence of biofilm can exert a large biocide demand, leaving a much lower residual available to kill the bulk water bacteria, which can then be added to the biofilm.
The EPS layer surrounding bacteria in a biofilm can act as a physical barrier, excluding or limiting the penetration of biocidal agents.
- 4) Act as host for dangerous bacteria:
Established biofilms offer an environment that encourages the establishment of undesirable, possibly dangerous, bacteria, such as coliforms and *Legionella*.

The story is not all doom and gloom, however. While biofilms can tenaciously resist chemicals if they are already highly developed, they have little resistance while in the infant stages of development. Penetration into the biofilm is the key to disrupting the delicate balance of the synergistic microbial communities. If a toxic shock can penetrate deep into a biofilm, the biofilm becomes profoundly stressed, and if the shock is sufficient it will cause sections of the biofilm to slough off into the bulk water, where a residual concentration of the toxicant should be maintained. The resistance of the sloughed off bacteria to chemical will be markedly reduced while they are part of the bulk water phase – this is the time to deactivate and destroy the organisms. If sufficient toxicity remains in the water to penetrate further into the newly exposed surface biofilm, then more biofilm can be removed.

Even if bacteria exist in the bulk water phase, it does not automatically imply that biofilm will result, as long as a program is in place to routinely and proactively vary the stresses in the system, such that no bacterial community can reach an equilibrium with its external environment, which would otherwise facilitate its plating out on system surfaces.

Risk Analysis For the Otahuhu B facility, the fouling risk due to microbiological activity was considered moderate-to-high, due to the influence of the river water in the estuary, and the plentiful nutrient sources.

Scale

The tendency to form inorganic deposits on heat transfer equipment is a function of the concentration of hardness salts in the makeup water, cycles of concentration, and water temperature [6].

Scale forms when inorganic water constituents are concentrated to the extent whereby supersaturated solutions are formed. The hardness salts (calcium and magnesium) in the makeup water will be in solution. However, when the water is further concentrated in a recirculating water system, the water can become saturated, whereby the maximum solubility of hardness salts has been reached. Concentrating the water any more than this will result in a supersaturated solution, which leads to precipitation of a dense, adherent scale.

The more hardness per unit volume that exists in the incoming water, the less that water can be concentrated before supersaturation occurs.

In addition, since hardness salts exhibit a phenomenon known as "retrograde solubility", the more the water is heated as it goes around the recirculation loop, the less hardness that can be accommodated in the water, and the scaling risk increases accordingly.

Calcium carbonate scale is the most common scale encountered, as the calcium concentration in the water is often quite significant, and calcium scale is generally less soluble than most other scales (e.g., magnesium or silica scales) so it tends to form most readily.

Predicting when scale might form in a system is not a straightforward task. Scaling indices such as the Langelier Saturation Index (LSI) and the Ryzner Stability Index (RSI) have proved useful for many users. Software packages are now also available, which are significantly more powerful than the abovementioned indices in that they help determine the relative saturation of all common cooling water deposits, not just calcium carbonate, which the LSI and RSI limit their evaluations to.

No matter what the technique used, the user must understand that predicting the simple saturation of calcium carbonate (or any other water constituent) is not the same as predicting when deposits will form. All prediction tools only determine the conditions of the bulk water. A high heat flux and the presence of biofilm or corrosion cells on an exchange surface can potentially create deposits where otherwise they might not have been expected [6].

Scale acts as a thermal insulator. If scale deposits out on heat exchange surfaces, it causes a serious reduction in

available heat transfer. Calcium carbonate-based scale has a typical thermal conductivity in the range 0.8 to $2.0 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$.

Scaling also increases surface roughness, thereby increasing turbulence and pressure drop, and reducing water velocity. This has a direct impact on pumping costs and on process heat transfer efficiency.

Scale can promote surface adhesion of nutrients, bacteria, or even simple deposits, promoting biofilm development and under-deposit corrosion.

Scaling potential is mitigated by the use of phosphonates and polymers. Phosphonates act as crystal modifiers rather than as true scale inhibitors, changing the morphology of any scale crystals that form such that they cannot bind together as readily to each other or to a system surface as they otherwise would. Since phosphonates only interfere with but don't react with scale, they can be used in relatively low concentrations.

Polymers also act as crystal modifiers and as general dispersants, helping to keep contaminants suspended in the bulk phase. This dispersing quality is important in systems with a lot of silt or other deposits, as it helps prevent plugging of cooling tower fill, or sedimentation in any area of a condenser. Common and popular forms of polymers are the single compound polyacrylates and polymaleates. Copolymers – polymerised monomers – are also used [6].

Risk Analysis For the Otahuhu B facility, the fouling risk due to scale deposition was considered moderate, due to the low, fixed cycles of concentration.

Corrosion

Corrosion in cooling water systems is primarily related to the formation of deposits and the activity of sessile microorganisms. The two effects are interrelated, with deposits providing useful sites for bacteria to develop, and the sticky biofilm produced by proliferating bacterial populations promoting the deposition of inorganic contaminants from the bulk water phase.

MIC is both the biggest concern and the biggest problem for most utilities, as MIC can produce localised corrosion as a result of localised, non-uniform effects, resulting in severe pitting of system materials (low-alloy steels, copper alloys, and stainless steel). The corrosion rates associated with MIC can be orders of magnitude higher than typical general corrosion rates [7].

If the three facets of cooling water control – dispersion control, biological control, and scale control – are not well maintained at all times, then deposits can form on system surfaces and bacteria can collect beneath these deposits. The biofilm that develops in and around such deposits can consist of a whole host of different bacteria all living in harmony with each other, maximising resource utilisation

and resisting the influence of applied chemicals. The presence of the biofilm community causes anodic and cathodic areas to form on a surface due to the chemical gradients within the biofilm affecting surface properties. Corrosion cells are thus initiated. Microbial activity also produces metabolic by-products that can be corrosive. Acid-producing bacteria can produce sulphuric acid, and if sulphate reducing bacteria exist in anaerobic pockets within either a biofilm or a deposit, corrosive hydrogen sulphide can be produced. Differential oxygen corrosion cells can also be a problem initiated by the presence of biofilms.

System corrosion can be countered by having good deposit control, and applying a corrosion inhibitor if required. Maintaining good biological control is also very important. Corrosion monitoring equipment is becoming more and more advanced, with on-line systems being developed to track corrosion rates in real time. Corrosion coupons are used widely in many facilities, though it is important to realise that corrosion processes can cause significant damage in short periods of time, and any corrosion noted on a coupon could have been caused by one, or a few, major system upsets, rather than being indicative of low-level corrosion over the entire exposure period (usually 30, 60, or 90 days).

Risk Analysis For the Otahuhu B facility, the fouling risk due to corrosion processes was considered low despite the presence of the estuarine water, due to the design of the system: titanium-tube condenser; rubber-lined pipework; concrete, fibreglass, and timber materials of construction. Corrosion monitoring and control is not a part of this project; the site routinely exposes and tests corrosion coupons, but as expected, corrosion rates are low.

Fouling

Fouling can be considered as the deposition of hardness scale and of inorganic particulate matter [3]. Since hardness issues have already been discussed, the topic is limited in this case to deposition fouling.

Deposition fouling is encouraged when the loading of particulate matter is excessive, when dispersion control is not adequate, and when fluidised particulate matter enters low flow areas, where a reduction in water velocity results in settling.

In most well-controlled systems, deposition is limited to the settling of particulate matter in the low-flow areas, such as the cooling tower cells. This usually has a low impact on the plant, as long as the sludge is not allowed to accumulate to the extent that it acts as a breeding ground for macroorganisms or for *Legionella*.

Where surface properties become modified by other scaling or microbiological fouling processes, however, deposits can settle out on process surfaces, such as in condenser tubes, on pipework, or in cooling tower fill material. Such deposits can further exacerbate anodic/cathodic

corrosion cells, promoting pitting corrosion. Deposits can harbour biofilm, with the subsequent MIC-related issues discussed earlier. Deposits can lead to severe plugging of fill material, significantly impacting on the cooling tower capability.

Deposition fouling can be countered by filtering of makeup water, addition of a dispersant, and good control of the scaling and biofilm fouling processes that might otherwise encourage particulate matter to deposit out on surfaces.

Risk Analysis For the Otahuhu B facility, the fouling risk due to fouling processes was considered moderate, due to the use of a falling-film fill in the tower and a significant loading of particulate matter in the unfiltered makeup water.

PROJECT INITIATION: EQUIPMENT SELECTION

The performance-based approach revolves around the core principles of equipment, data management, and control. If chemicals are to be applied according to the requirements placed on them by system demand and performance, then all chemical residuals must be reliably trended and the fouling processes they help control predictively monitored. On-line methods are the most suitable fit to such a performance-based control philosophy. On-line monitoring allows for real-time assessment of performance, system demand, and fouling risks.

New sampling and monitoring racks were installed (*Figure 5*) in a staged approach, following some extensive trialling of available technology. The core technologies are detailed as follows:

- A Colourimetric free and total oxidant analysers
Several trials with amperometric-based technology had failed, and while it was possible that the water hardness levels might react with the DPD¹ liquid reagents and lead to analytical interferences, direct experience with the Hach CL17 colourimetric residual oxidant monitors was extremely successful. The plant had used the DPD method for off-line oxidant monitoring both before and after plant takeover, so using the same principle for the on-line analysis simplified the transition for the operating staff and ensured that there was an exactly equivalent method for cross-reference and calibration of the on-line meters. A total residual oxidant (TRO) analyser was installed as part of the recirculating water analyser rack. TRO is the appropriate parameter to monitor in this case due to the presence of bromine in the recirculating water. A free oxidant analyser was installed on the makeup water system analyser rack (not shown).

¹ Diethyl-p-phenylenediamine

B Conductivity analysers

Monitoring for conductivity gives a general indication of makeup water quality and tidal influence, and is also central to the control of cycles in the system.

Due to the estuarine nature of the water and the known level of silt and other deposits in the water, toroidal-type conductivity probes were selected. These Endress + Hauser probes are based on the principle of induction. Consequently, it is not necessary for the probe to be completely clean at all times to get accurate results. The probe and transmitter combination has proved extremely reliable and virtually maintenance free.

One unit was installed on the recirculating water analyser rack, and one on the makeup water analyser rack.

C Deposit accumulating testing system

A DATS™ analyser was installed on a self-contained rack to facilitate its relocation around different test points (condenser inlet and outlet sampling points). The scaling monitor was procured as an integral part of the scale inhibitor optimisation program, allowing the plant to safely move towards a demand-based dosing program by helping to track the scaling potential of the water with a lead factor.

The DATS™ technology is discussed in more detail in a later section of this paper.

D BIOGEORGE™ electrochemical biofilm monitoring system

A BIOGEORGE™ system, consisting of a probe, cable and controller, was procured for the purpose of monitoring biofilm formation in the system. Like the scaling monitoring technology, the biofouling monitor can be set up to provide a "lead factor", whereby microbiological fouling of the probe surfaces will take place before any fouling occurs on the process surfaces. This effectively acts as an early warning system, prompting the user to apply more chemical, or otherwise interfere in the process chemistry to assure performance. The biofouling monitor is by its construction a compact, rugged, and mobile technology. This permitted the trialling of the technology in a number of different plant areas (untreated estuary water; makeup water; recirculating water).

The BIOGEORGE™ system is discussed in detail below.

E TRASAR® 350 Fluorescence Sensor/Controller

The Nalco TRASAR® 350 unit is based on their fluorescence technology, where control of scale inhibitor is regulated via trace monitoring.

This unit was already installed when the plant was first taken over by Contact Energy Limited. However, it was used solely to trend the residual of inhibitor in the system and did not have any controlling function; any adjustments to the inhibitor dosing pump were performed manually.

The performance-based approach dictated that the unit be interlocked into the main inhibitor dosing system so scale-control chemical could be applied efficiently to an exact concentration.

The fluorescence sensor unit would be used in alliance with the scaling monitor analyser and efficiency monitoring data to provide for a demand-based dosing program for scale control.

A PERFORMANCE-BASED APPROACH TO BIOFILM CONTROL

Overview

While it is certainly useful to test bulk water samples for ATP² levels and total viable counts (TVCs), it is essential for the user to realise that more than 99 % of viable microbial organisms in a system reside inside surface biofilms. It is these sessile communities that cause the deposit fouling, corrosion, and efficiency-loss problems that can plague a utility. Given that there is no correlation between planktonic and sessile population counts, plant performance cannot be accurately gauged using only planktonic-based data.

Similarly, on-line monitoring and control of oxidant levels to a target residual only tells part of the story. While such a system provides demand-based control of planktonic bacteria, maintaining a healthy bulk water oxidant concentration is no guarantee that sessile communities are similarly controlled.

² Adenosine 5'-triphosphate



Figure 5: Equipment installations.

Appreciating the need for performance monitoring of the activity of sessile communities, the plant sought out available technology for on-line monitoring of biofilm and was indicated to the BloGEORGE™ system. This became a key element in the performance-based biofilm control program. If biofilm formation could be reliably tracked, then chemical could be applied to counter the threat. Since cleanliness of system surfaces is the real goal of water treatment, and not sterility of the bulk water, oxidant concentrations as measured by side-stream samples become secondary performance indicators. Why apply expensive chemical to a system that does not require it?

The likeliest source of viable organisms into the recirculating water system was from the makeup water. A program strategy was considered whereby this primary loading would be countered by the controlled application of the relatively inexpensive bleach. To ensure there were no "dosing holidays" in the makeup water treatment, the makeup water flow – which up to that point was intermittent – was made continuous. This had the effect of keeping the interlocked hypochlorite system in service at all times, ensuring continuous steady dosing of chemical for better control. The previous operating history of the hypochlorite dosing system was that when the makeup water system started, it would take a minute or two for the hypochlorite dosing to fully run-in. The result of this was that a significant amount of biological and nutrient-rich untreated water was added to the recirculating water system each time the intermittent makeup water flow was initiated. Not only would this untreated water increase the chemical demand in the recirculating water system, it would also increase the viable microbial counts in the system, increasing the risk of biofilm development.

With the primary demand met in the makeup water, the liquid stabilised bromine biocide chemical could be applied to the recirculating water almost exclusively as a biofilm control agent. With the biofouling monitoring system tracking the biological fouling potential in real time, the stabilised bromine biocide could be applied intelligently as a form of intermittent secondary treatment according to system demand and performance.

Use of a Stabilised Bromine Biocide in the Management and Control of Biofilm

Stabrex is a biomimetic stabilised liquid bromine biocide that mimics the stabilised bromine produced naturally in the human immune system [8].

Compared to traditional halogen-based biocides, the stabilised bromine biocide is less reactive, less toxic, less volatile, more compatible with other treatment chemicals (e.g., phosphonates), and is purported to be better at biofilm control [8].

How could something that is less toxic and less reactive be better at controlling complex communities of sessile microorganisms? The bromine molecule is uncharged, and

the stabilisation of the molecule makes it less reactive. Both these attributes allow the molecule to penetrate deep into biofilms, which have areas of positive and negative charge that can repel traditional non-stabilised halogen molecules [8].

The increased penetration introduces the uncharged bromine molecule into the heart of the biofilm. Subsequent release of HOBr from the stabilised molecule has two effects: firstly, the biofilm community is profoundly stressed and the equilibrium disrupted, with the result that part of the biofilm is sloughed off into the bulk water; secondly, the HOBr is toxic to bacteria, thus deactivating and destroying them.

For all its purported plus points, the stabilised bromine biocide also has one significant minus: it is considerably more expensive than traditional halogens, especially when compared to sodium hypochlorite. The cost of the product necessitates its efficient use. If the primary planktonic load in the water can be met with a cheaper product (sodium hypochlorite), then use can be made of the stabilised bromine's superior biofilm stripping potential (compared to traditional non-stabilised halogens) to control the activity and development of sessile bacterial populations.

The use of the liquid stabilised bromine biocide in a performance-based system is therefore quite clear. First, ensure that the planktonic load in the makeup water is met. Then monitor the tendency to form biofilm in the recirculating water in real time (preferably with a lead factor) and apply the stabilised bromine biocide to maintain the desired level of performance.

Since it is known that biofilm cannot in general tolerate an environment where the stress in the system is constantly varying, the stabilised bromine biocide can be incorporated into an overall program of proactive stress management, where positive system upsets are applied intermittently according to a rules-based logic control program in order to subvert any tendency towards biofilm formation.

Monitoring Microbial Diversity and Biofilm Formation – The Biofouling Monitoring Technology

The BloGEORGE™ electrochemical biofilm monitoring system (*Figure 6*) consists of a 2-electrode probe, a cable, and a controller [7]. Each electrode is comprised of a series of titanium or stainless steel disks. The probe is subjected to an intermittent polarisation to a preset potential and biofilm activity is detected from an increase in the *applied current* required to achieve that potential.

If biofilm does exist on the probe, then it can itself generate current during times when the applied potential is off. Measuring this *generated current* provides a second means of tracking biofilm formation.

The controller automatically applies the user-set potential for the desired time (normally recommended to be 1 hour

per day), and automatically logs data and registers alarms according to the user-set limits. A data management software package is also available whereby the data is automatically downloaded at routine intervals and a series of trend charts and operation summaries are made available to the user.

The biofouling monitoring technology has been designed to provide on-line and real-time indications of biofilm activity. Current trend deviations (applied and/or generated current) from a flat baseline alert the user to the formation of biofilm on the sensor. Because the sensor actively encourages biofilm formation on its surfaces, biofilm plates out on the sensor surfaces before it does so on the general non-polarised surfaces of the main system. Not only does this provide an indication of the activity of sessile bacterial communities, but it also provides the user with a lead factor, whereby future plant performance can be assessed and changes to dosing programs made before biological control is lost.

In general, if the control system can keep the biofilm sensor clean, then it can be assumed that the non-polarised main system surfaces are similarly free of biofilm. This promotes a performance-based approach, where chemical is applied to counter a known, monitored plant fouling risk.

Validating the Performance-Based Concept

While the biofouling monitoring system had been employed on other sites with good success [7, 9], it was certainly not in the best interests of the plant or the cooling water system to place new technology on-line, turn off the chemical dosing, and wait for the current trends to indicate biofilm activity. As the technology is still relatively new

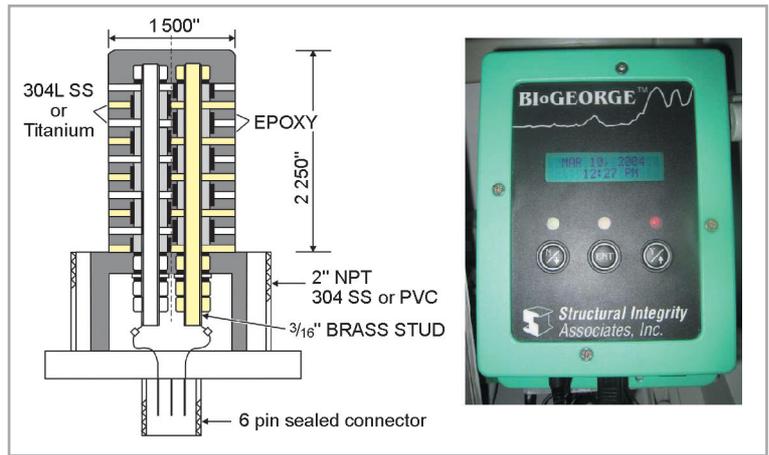


Figure 6: The BioGEORGE™ probe and controller.

and not as yet in widespread use, especially in estuarine-cooled facilities, the biofouling monitoring system had to be first comprehensively validated before its inclusion into any performance-based control could be considered.

Testing of the biofouling monitoring system allowed for simultaneous validation of the entire performance-based concept. The biofouling monitor sensor was set up in a tapping point where a side-stream sample of process water was manipulated such that a low-velocity water flow continuously passed the sensor. The biofouling monitor controller was set up to apply 200 mV to the 2-electrode probe for one hour per day. Initial exposure of the sensor to these conditions resulted in some variation in the current trends, but the residual of oxidant in the water would always retrieve the situation, such that current trends again followed the flat baseline.

To prove the technology more rigorously (Figure 7), the sensor was exposed to a dead leg of process water for about two weeks and the applied potential set to 400 mV

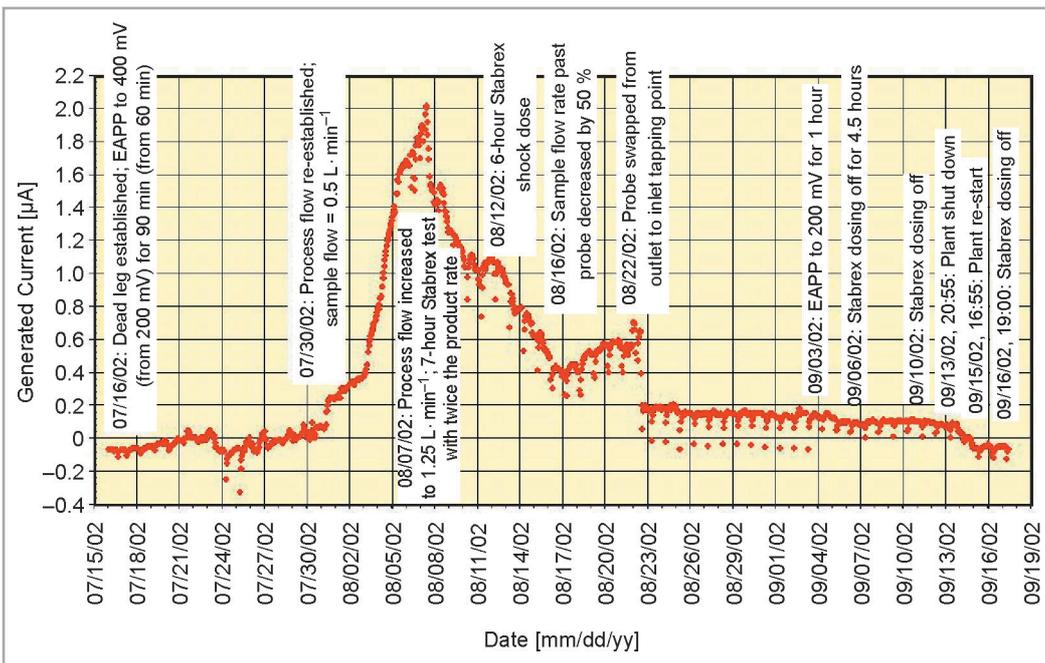


Figure 7: Early experience with bio-film tracking. EAPP applied potential of the BioGEORGE™

to promote any viable organisms in the dead leg to plate out and flourish on the sensor.

As shown in Figure 7, when the dead leg was removed (July 30th 2002) and process water was again allowed to pass the sensor, the current trends began to increase dramatically. Figure 7 shows the generated current trend only, but the applied current trend is basically identical in form. It is interesting to note that even though the process water contacting the probe at this time had a generous residual oxidant concentration ($0.20 \text{ mg} \cdot \text{L}^{-1}$ as Cl_2), the biofilm on the probe was able to flourish, as indicated by the sharp increase in the reported current. The reason for this may be that the "lean" biofilm that formed during the dead-leg exposure was suddenly exposed to nutrient-rich process water, and the stress imposed on the community by the oxidant was not sufficient to counter the biofilm's utilisation of this nutrient load. The peak of the curve occurs around August 7th, one week after process water flow was first established.

Following a 7-hour shock dose of the liquid stabilised bromine biocide, where the biocide dose rate into the system was doubled, the current trend quickly decreased dur-

ing and after the event. A further 6-hour shock dose of stabilised bromine biocide (dosing rate doubled) on August 12th (when the trend indicated the biofilm may be recovering from the first shock) caused a further significant fall off in the current flow.

From August 17th the current was again trending upwards, indicating biofilm recovery after the second shock dose. On August 22nd, the probe was swapped over to a high velocity process water flow, containing a significant residual oxidant concentration. It is obvious from the way that the current trend collapses and stays consistently flat thereafter that the biofilm on the probe was profoundly stressed by the new environment.

Differential microbial analysis (DMA) of this probe, and a second biofouling monitor probe set up under almost identical test conditions, and a non-polarised surface representative of the general main system surfaces, indicates the following (*Table 1*):

- Bacterial counts on the probes are higher than on non-polarised surfaces, supporting the view that the biofouling monitor sensor actively promotes biofilm formation on its surfaces.

17 September 2002	On-Line Biofouling Monitor	Test Biofouling Monitor	Slide BioBox	Corrosion Coupon
Microscopic examination (1 000 x magnification)				
Sludge	+	+	++++	++
Siliceous material	–	–	+	+
Protozoa	–	–	–	–
Nematodes	–	–	–	–
Diatoms	+	+	++++	++
Unicellular algae	+	+	++	++
Filamentous algae	–	–	–	–
Unicellular bacteria				
Filamentous bacteria				
Amphipods (larvae, nymphs, etc.)				
Yeast (filamentous fungi)				
Culturing (CFU ³ per mL)				
Yeasts	ND	ND	ND	ND
Moulds	100	100	500	ND
TVC at 25 °C	14 000	13 000	7 000	1 100
Anaerobic SRB	ND	ND	ND	200
Total anaerobic bacteria				
Pseudomonas	ND	2 000	100	ND
Clostridium	ND	ND	ND	ND
Heterotrophic iron ppt. bacteria	100	ND	100	ND
Nitrifying bacteria	ND		ND	ND
Denitrifying bacteria	ND		ND	ND

³ Colony-forming units

Table 1: Differential microbial analysis (DMA) for two probes (swabs).

- Given that a biofouling monitor sensor could encourage biofilm development in a system that was oxidised, it is reasonable to assume the sensor would be a valid indicator of biofilm activity during periods where oxidant dosing was insufficient.
- The results between the two separately exposed biofouling monitor probes on the same process water, using the same settings for each probe, are very similar, showing good repeatability and consistency of the method.

The second DMA (*Table 2*) indicates that for swabs taken of the probe electrodes and the probe epoxy material, which separates the electrode disks, there are significantly more (order of magnitude more) bacterial counts on the former, as expected. This clearly indicates that the probe itself is not just accidentally or arbitrarily being coated with biofilm; the probe electrodes themselves are promoting biofilm growth on those same electrodes, and biofilm growth develops there because it is a beneficial environment for bacteria. As can be seen from the DMA, the counts on the epoxy are similar to the counts for the representative non-polarised system surface (the corrosion coupon). Note that the "BioBox" is a sludge and sediment

collecting device, and so is only included in the DMA to indicate what bacterial populations lie beneath heavy silt or sludge deposits, such as might exist in plugged cooling tower fill.

The conclusions that can be drawn from this extended trial are:

- The biofouling monitoring system is sensitive to the activity of sessile bacteria.
- The biofouling monitoring system actively encourages biofilm to form on the probe; biofilm establishes itself there before it does so on general non-polarised system surfaces.
- The Otahuhu B cooling water system is at risk of biological fouling if oxidant dosing control and oxidant penetrating capabilities are not adequate.
- Once established, biofilm can be difficult to remove, to the extent that the original clean condition may not be recovered.
- The liquid stabilised bromine biocide is effective at removing biofilm, especially if intermittently shock dosed.
- Keeping the biofouling monitor probe clean, such that

25 October 2002	On-Line Biofouling Monitor	On-Line Biofouling Monitor	Slide BioBox	Corrosion Coupon
	Titanium	Epoxy		
Microscopic examination (1 000 x magnification)				
Sludge	-	-	-	-
Siliceous material	+	-	-	-
Protozoa	-	-	-	-
Nematodes	-	-	-	-
Diatoms	-	-	-	-
Unicellular algae	-	-	+	-
Filamentous algae	-	-	-	-
Unicellular bacteria	-	-	+	-
Filamentous bacteria	-	-	-	-
Amphipods (larvae, nymphs, etc.)				
Yeast (filamentous fungi)	-	-	-	-
Culturing (CFU per mL)				
Yeasts	ND	ND	ND	ND
Moulds	10	10	ND	ND
TVC at 25 °C	21 000	800	58 000	1 100
Anaerobic SRB	10	ND	600	ND
Total anaerobic bacteria	600	50	230	40
Pseudomonas	13 000	700	2 100	800
Clostridium	50	ND	90	ND
Heterotrophic iron ppt. bacteria	200	20	30	ND
Nitrifying bacteria	ND	ND	ND	ND
Denitrifying bacteria	ND	ND	ND	ND

Table 2: DMA of probe electrodes and epoxy materials (swabs).

the current trends always follow and return to flat-line conditions, will ensure that the main system surfaces are also kept similarly clean.

Formalising the Performance-Based Approach: Optimisation in the Use of a Stabilised Bromine Biocide

With a high level of confidence in the ability of the biofouling monitoring technology to track and report microbial activity on system surfaces, the plant moved towards the optimisation of the stabilised bromine biocide dosing.

The first step was to monitor the recirculating water system via the biofouling monitoring system while the stabilised bromine biocide was continuously dosed as normal. Once a stable baseline had been set on the unit, the biocide dosing alternated between continuous and intermittent dosing (2 hours on, two hours off), to gauge how the system would react with less biofilm control agent in the water.

The biofouling monitor current trend is shown in *Figure 8* and the subsequent DMA at the end of this dosing trial is shown in *Table 3*.

The current trend indicates that there was low-level biofilm activity in the system on a number of occasions, but that the system itself was able to cope with these minor fouling events. The DMA shows that the biofouling monitor has higher counts than the treated water samples, and that even these counts are not particularly high. The untreated estuary water has higher counts than either the biofouling monitor probe or the treated water. While it is not defensible to try to correlate planktonic and sessile counts, measuring both in this situation indicates that the untreated water has a biological loading that is being met

by the oxidant treatment regime, with the effective control of surface biofilm.

The next step in the optimisation program involved exposing the biofouling monitor probe as before, but further reducing the stabilised bromine biocide dosing to just two 3-hour shock dosing intervals per day. The stabilised bromine biocide would be integral to a stress management system, where repeated, variable stress applied to the system should constantly upset any tendency for sessile bacterial populations to reach equilibrium. Any deterioration in the measured performance would be countered by the application of further shock doses, as required.

Figure 9 illustrates the performance-based approach to biofilm control. When a significant microbiological loading entered the recirculating water system – as indicated by high ATP and total viable counts (TVCs) – the biofouling risk increased. The biofouling monitor probe duly indicated a sudden and significant increase in sessile microbial activity. The control system countered this threat by applying two additional shock doses of stabilised bromine biocide within hours of each other. The chemical successfully subverted the developing biofilm and returned the system to normal. Routine oxidant, ATP and TVC monitoring showed that the peak demand in the system was met and that the bulk water chemistry was returned within its normal limits. The trend on the biofouling monitor duly returned to a flat baseline, supporting the claims that the fouling risk had been controlled.

Subsequent to this event, the cooling water system sat idle for a number of days during a plant shutdown, and on the return-to-service some biofilm activity was again noted on the probe. Another extended shock dose of stabilised bromine biocide effectively managed this event.

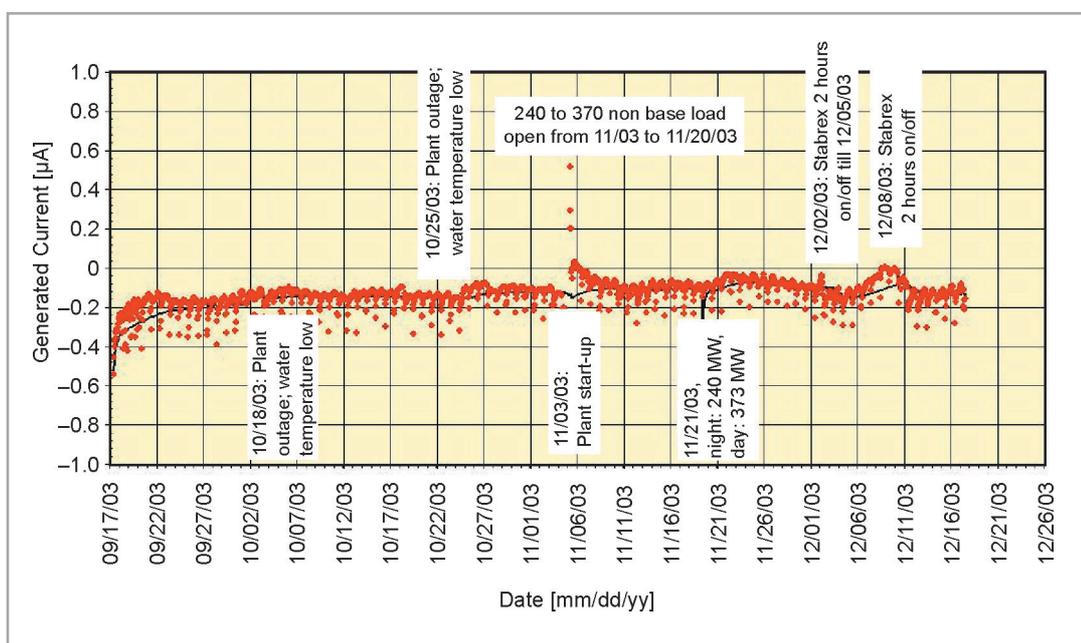


Figure 8: Using less liquid stabilised bromine biocide did not negatively impact on biofilm control.

23 December 2003	Creek Water	MU Water	Recirculating Water	On-Line BG Titanium	BioBox Slide
Microscopic examination (1000 x magnification)					
Sludge	++++	++++	+++++	+	++++
Siliceous material	-	++	-	+++	+++
Protozoa	++++	++	-	+++	++
Nematodes	+	-	-	+	-
Diatoms	++	-	-	-	-
Unicellular algae	++++	+++	++++	+++++	++++
Filamentous algae	+	-	-	-	-
Unicellular bacteria	++++	+++	++++	+++++	++++
Filamentous bacteria	-	-	++	++	++
Amphipods (larvae, nymphs, etc.)	-	-	-	-	-
Yeast (filamentous fungi)	-	-	+	+++	-
Culturing (CFU per mL)					
Yeasts	2	1	< 1	< 10	< 10
Moulds	7	3	< 1	< 10	170
TVC at 25 °C	3 700	170	340	1 200	160 000
Anaerobic SRB	200	< 1	1	< 10	90
Total anaerobic bacteria	780	17	54	300	1 300
Pseudomonas	1 200	< 1	13	< 10	1 500
Clostridium	440	< 1	8	10	210
Heterotrophic iron ppt. bacteria	900	25	27	< 10	1 500
Nitrifying bacteria	< 1	< 1	< 1	< 10	< 10
Denitrifying bacteria	100	100	100	< 10	100

Table 3: The DMA supports the trend indicated by the biofouling monitor sensor.

MU makeup
 BG BioGEORGE™

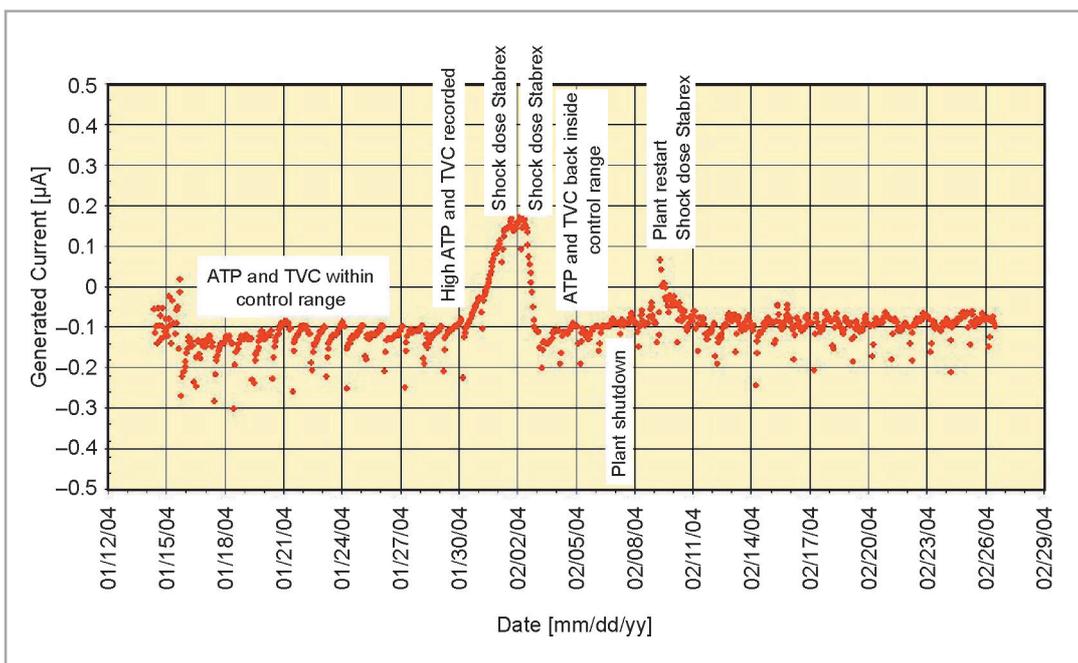


Figure 9: Using the performance-based approach to optimise the addition of a stabilised bromine biocide.

A PERFORMANCE-BASED APPROACH TO SCALE CONTROL

Overview

Though indices exist to help the user predict when saturation of hardness salts might occur, they do not give any idea of when or if scaling might occur. It is the local conditions at the water-to-process surface interface that dictate whether scale forms. The influence of heat flux, deposits, biofilm, etc. can produce conditions locally that are not indicated at all by bulk water monitoring.

Scale formation on a heat exchange surface is best monitored by modelling that surface, using a representative process water sample of the correct water velocity and temperature profile flowing through a test tube of the same dimensions and metallurgy as the process condenser, with the same or higher heat flux being applied to that tube element. An on-line scaling monitoring system provides the required semi-predictive monitoring of scale formation tendency.

As well as monitoring the scaling potential of the process water, this stage of the project was charged with optimising the use of the scale inhibitor.

The original idea was to develop an on-line analysis and monitoring of the available active ingredient in the scale inhibitor, and apply more chemical when the residual of this component was seen to decrease. Due to the presence of natural phosphates in the incoming water stream, however, the concept was considered too complicated for the site to develop.

Another option was to monitor the calcium concentration of the incoming water on-line. Since the calcium-to-magnesium ratio is known, the total hardness of the makeup water could be determined. Using software, the scaling potential of the water could be developed, taking into account other system parameters such as recirculating water pH, heat load, and cycles of concentration. Depending on the scaling potential, an amount of chemical would be dosed to meet the calculated demand. The on-line calcium monitoring was not pursued due to the significant cost of such on-line analysis. However, the future use of such equipment is under review.

The approach finally taken was to monitor the calcium concentration off-line via daily grab sample analysis. Even given the tidal influence, the hardness values do not change markedly from day to day, though they do vary significantly from season to season due to the influence of rainfall and surface run-off on the final composition of the estuarine water. With the hardness concentration known, an algorithm would survey the system conditions and determine the required amount of chemical, which would be allowed to vary within a specified control range. If the algorithm calculated an inhibitor concentration setpoint that was below the range, the logic would simply revise that value upward to the low-limit concentration. This provided

a safety margin, whereby a minimum inventory of inhibitor would be maintained in the bulk water at all times. If the logic calculated a value higher than the upper limit of the control range, the setpoint would hold, but an alarm would alert the operator or chemist to check the system and ensure the calculated dose rate was correct and not simply an error of one of the inputs.

There was a known compromise in the final choice of control for the inhibitor dosing system. Since the fluorescence sensor unit monitors the concentration of a trace element in the chemical and not the active ingredient, there is no indication of chemical demand. However, given the fact that the algorithm was based on the calculated amount of inhibitor required to treat the incoming makeup water flow, and that the half-life of the system is only two hours, it is likely that the monitored inhibitor concentrations provide for sufficient chemical to meet all instantaneous and peak demands.

Developing a Dosing Algorithm for Scale Control

The potential for a water source to form scale deposits on process surfaces depends on water hardness, the pH and alkalinity, the temperature of the water, and how much the water is concentrated in the process loop (cycles of concentration).

Software packages such as French Creek's WaterCycle are designed to measure the relative saturation of all the common cooling water deposits, not just calcium carbonate, across a range of pH, temperature and concentration. Thanks to the consulting services provided to the plant by Nalco, the WaterCycle program was used to develop a basic algorithm that would use calcium concentration, water temperature, and cycles of concentration to determine the best fit for inhibitor dosing at any given moment. The control logic collates the necessary process data, and calculates the inhibitor setpoint via the programmed algorithm. The fluorescence sensor unit measures the actual concentration in the system. If there is a variance between what is measured by the analyser and what is required by control logic, then the rate of inhibitor dosing is automatically adjusted.

Monitoring Water Scaling Tendency – The Scaling Monitor Technology

The DATS™ (*Figure 10*) is a sophisticated heat transfer resistance monitor that can be used to simulate the process condenser and monitor even minor indications of scale formation.

A side-stream of process fluid is fed through the tube section at a controlled rate. A heater that simulates the actual heat load surrounds the tube. Calibrated temperature probes measure both the fluid and heater temperatures; these data, the flow rate, and the heat flux are used to automatically calculate the heat transfer resistance (HTR).



Figure 10: Deposit accumulating testing system.

Since scale acts as a thermal insulator, the presence of scaling on the tube element will cause an increase in the HTR.

The scaling monitor allows for a wide range of water velocity and heat flux setpoints to be applied to the test element. This allows the tube to be tested under conditions that might be more severe than those experienced in the process equipment. For example, if a lower water velocity and higher heat flux is applied to the tube relative to the process heat exchanger, scaling can be promoted in the test tube first, providing a useful indication of what the general scaling potential of the water is.

The user should use a tube element of the same metallurgy and internal and external diameters as the tubes in the process heat exchanger. The HTR should be zeroed

when the tube is first put into service. Changes in the HTR above this zero baseline will indicate fouling of the tube.

The HTR can also increase if biofilm is present on the tube surface. If scaling processes are to be looked at in isolation, then it is advisable to have the sample water well treated with oxidant to ensure that any increase in HTR can be tracked back to scaling events rather than biofouling events.

Optimising Scale Inhibitor Control

A typical data trend from the scaling monitoring system is shown in Figure 11.

During the variable inhibitor dosing trial, the HTR trend was noted to be very steady despite applying between two and four times the process heat flux across the test element. The water velocity through the test tube was set to $2.02 \text{ m} \cdot \text{s}^{-1}$, the same as the process exchanger. This flow was regulated automatically by the scaling monitor unit.

At the conclusion of a nearly 2-year exposure of the same tube element to a range of scaling trials, the tube was removed and the heating area examined for scaling deposits. A deposit weight density test indicated that there was no pitting or other corrosion of the surface, and that a deposit weight density of $1.08 \text{ mg} \cdot \text{cm}^{-2}$ ($1.0 \text{ g} \cdot \text{ft}^{-2}$) was recorded. In addition, an X-ray analysis of the inorganic content of the collected deposit showed that it consisted of 60 % calcium and 15 % silica.

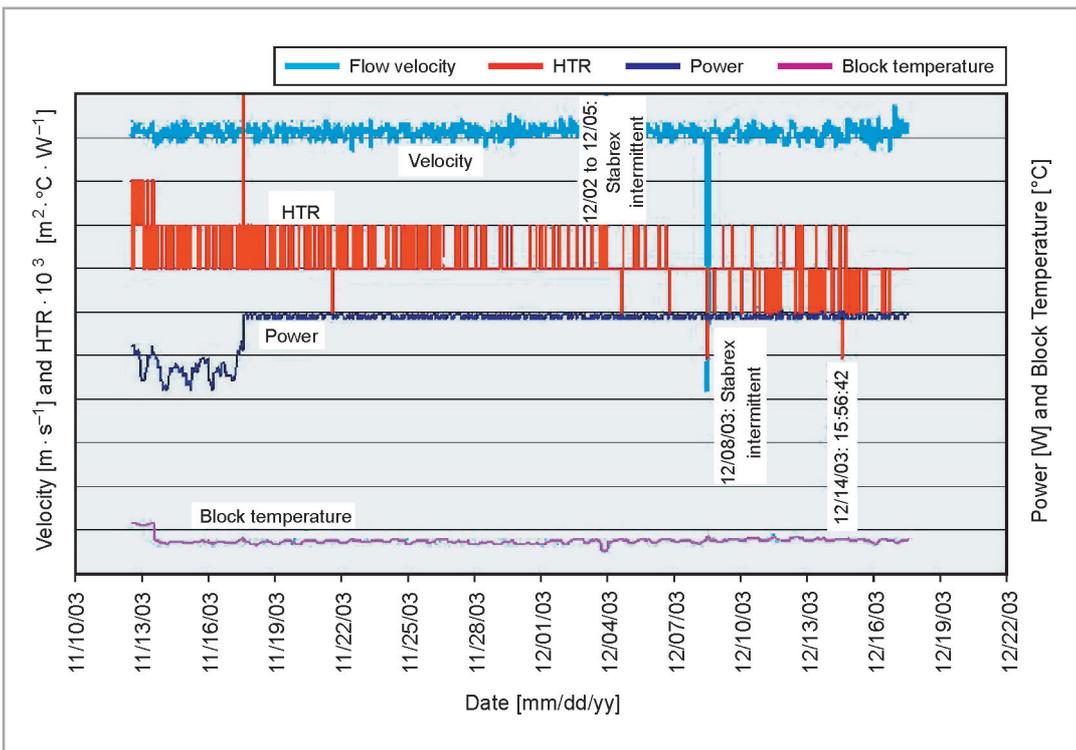


Figure 11: Scaling monitor trend during inhibitor optimisation program.

A PERFORMANCE-BASED APPROACH TO DEPOSITION FOULING CONTROL

Overview

Because the Nalco scale inhibitor used on site is a blend of crystal modifier and dispersant, any reduction in the dose rate of the former (as a result of a performance-based scale control program) impacts proportionately on the concentration of dispersant in the water.

The scaling and deposition potentials of the system do not always coincide, meaning that high hardness/low inorganic particulate water might enter the plant or vice versa. As such, the application of the Nalco 1383T inhibitor is a compromise between the need to have the polyphosphate component present for scale control and the polyacrylate component present for dispersion control. Running an aggressive scale control program could be to the detriment of deposition control in the cooling water system.

As such it is necessary to have some means for monitoring the deposition potential in the system, especially in the cooling tower where the narrow spaces of the falling-film fill could become blocked by deposited particulate material.

It is proposed to install weight sensing load cells in the cooling tower, such that an increase in the monitored weight of a test block of fill material would indicate a general risk of deposition fouling in the process fill material.

This part of the program is being considered for future work in alliance with a program to increase the cycles of concentration value upwards.

Load Cells as Deposition Monitors

The concept being developed involves the installation of blocks of fill material on supporting framework, with the entire construction being connected to strain gauges that monitor the weight of the test blocks. The measured weight will be continuously recorded and the data collected and trended. Any increase in weight above a baseline will indicate some fouling in the fill material of the test blocks. A decision can then be made by the control (or the system operator) to increase the amount of dispersant in the system. Note that biocide or biofilm control agent may also be required, as it may be the formation of biofilm in the test blocks that has promoted the deposition of inorganic solids.

Locating the test blocks in the lower level of the tower, beneath the existing fill material, would probably act as the worst-case scenario for monitoring, and this could provide an effective lead time, whereby deposition fouling should occur in the test blocks first before it occurs in the process fill.

Load cells (strain gauges) are widely available. Depending on the eventual design of the test blocks and supporting framework, different types of load cells might be consid-

ered, e.g., compression, compression/tension, S-beam, bending beam, etc.

EFFICIENCY MONITORING

Condenser

By collecting on-line data for condenser vacuum, condensate return temperature, cooling water inlet and outlet temperatures, and steam and cooling water mass flows, the heat rates on the water and steam sides of the condenser can be determined. From this data, the heat transfer coefficient can be calculated:

$$U = \frac{Q}{A \cdot \Delta T_{LM}} \quad (1)$$

where

U is the overall heat transfer coefficient, $W \cdot m^{-2} \cdot K^{-1}$

Q is the heat rate, W

A is the surface area of the condenser tubes, m^2

ΔT_{LM} is the log mean temperature difference, K

The log mean temperature difference can be readily calculated, and fudge-factors can be applied to account for different configurations of heat exchange equipment.

Once the U-value is determined it can be compared against the design coefficient for the process and a percentage cleanliness factor (CF) can be calculated as follows:

$$CF = \frac{U'_w \cdot 100}{U_w} \quad (2)$$

where the subscript refers to the water side and U'_w is denoted as being the calculated U-value. Given that the CF is in the range 0–100 %, this is a user-friendly way to report the condenser efficiency.

The condenser approach temperature, or terminal temperature difference (TTD), is the simple difference between the condensate return temperature and the cooling water hot return temperature. The TTD is a sensitive measurement of condenser performance and responds to even minor fouling events on either the steam or water sides.

A condenser can be simulated using heat transfer monitors such as the DATS™, where a tube element identical to those in the heat exchanger is subjected to the process-representative flow velocity and heat flux. Any fouling that occurs on the test element will negatively impact on the available heat transfer, causing a change in the displayed trend. It would then be assumed that the process exchanger is subject to a similar fouling risk.

Other mathematical methods for modelling condenser performance can be employed, for example the NTU Effectiveness Method.

Figure 12 shows some of the trends resulting from data collection and analysis at the Otahuhu B station.

Cooling Tower

Monitoring of the cooling tower capability is being considered, requiring the following parameters to be monitored:

- Wet bulb temperature profile around the tower basin (achieved by remote monitoring linked to a central data collector).

- Return and supply water temperatures and ΔT across the tower (for each cell, preferably).
- Liquid flow over the tower (for each cell, preferably). This requires the installation of flow monitors.
- Air flow (fan output; for each cell, preferably). This requires fan kW monitoring and accurate fan curves.

For the Otahuhu B facility, correction would have to be made for the additional heat load on the tower because of the internal exchangers used to reduce plume visibility. This could complicate any working model.

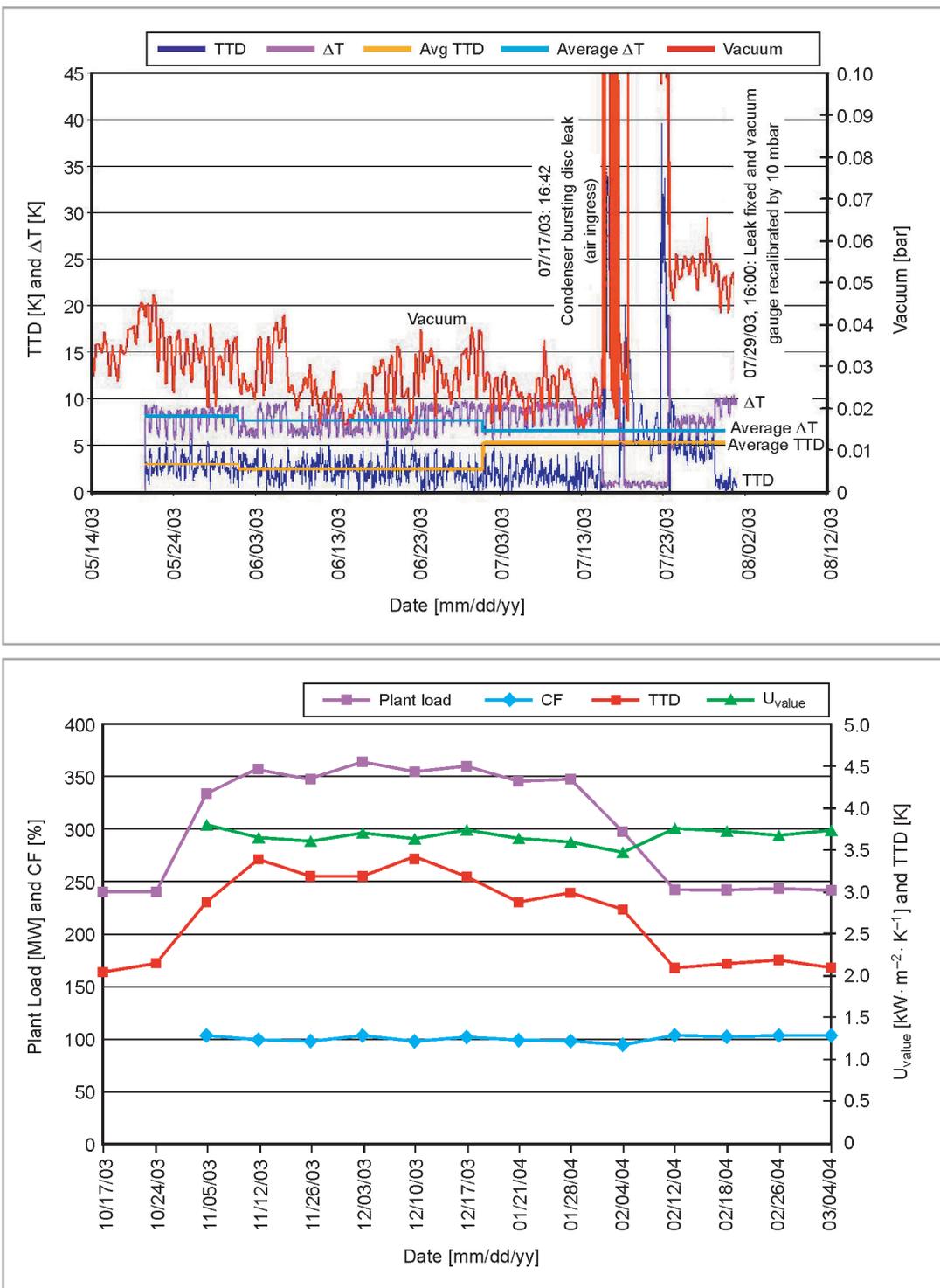


Figure 12: Condenser monitoring and efficiency data.

THE ROLE OF CONTROL

One ambitious aim of this project is to provide a total water system management package that can assess a number of data streams and weigh their relative importance before assigning proactive commands to the chemical dosing systems in order to protect plant from fouling risks at all times.

An attempt is being made to develop the necessary rules-based logic in-house, though it is also possible that a proprietary "fuzzy-logic" control package will be used to sort and filter the data into levels of control hierarchy. Given the complexities and interrelationship of the fouling processes, the development of any such control system is likely to take some time.

At this point it is worth noting that integrated, stand-alone monitoring and control packages are now being developed by water treatment providers based on the concept of applying chemical according to system demand and performance. This can only be welcomed.

COUNTING THE COSTS OF A PERFORMANCE-BASED APPROACH

Since the cooling water chemistry control and instrumentation upgrade project was first initiated in 2001, great strides have been taken in the development of a performance-based approach. The fouling processes are better understood and better monitored. On-line data collection allows for real-time condenser cleanliness and efficiency monitoring. A control system is being developed that in its finished form will proactively manage the water chemistry.

All these improvements have allowed for significant chemical cost savings (*Figure 13*), to the extent that the cost of the project has already been recouped.

CONCLUSIONS

Some general conclusions can be drawn from the results to date of the Otahuhu B cooling water process chemistry control and instrumentation upgrade:

- For reasons of cost and regulatory compliance, the use of treatment chemicals needs to be as efficient as possible.
- To achieve efficiency of application, chemicals should be dosed according to system demand and performance.
- Fouling processes are complex and interrelated. To minimise risk to plant, these processes should be monitored on-line and in real time wherever possible.
- Once the fouling risks are monitored, a performance-based approach to cooling water chemistry control becomes achievable.
- The optimisation of dosing control has resulted in significant cost savings for the Otahuhu B station.
- As continuous data trending and analysis show, these cost savings have not come at the expense of plant efficiency or cleanliness, both of which remain very satisfactory.
- Due to the control improvements made and the increased involvement of operations staff in the routine management of the cooling water chemistry, the site chemist and the service provider can now limit their own involvements to more specialist tasks.

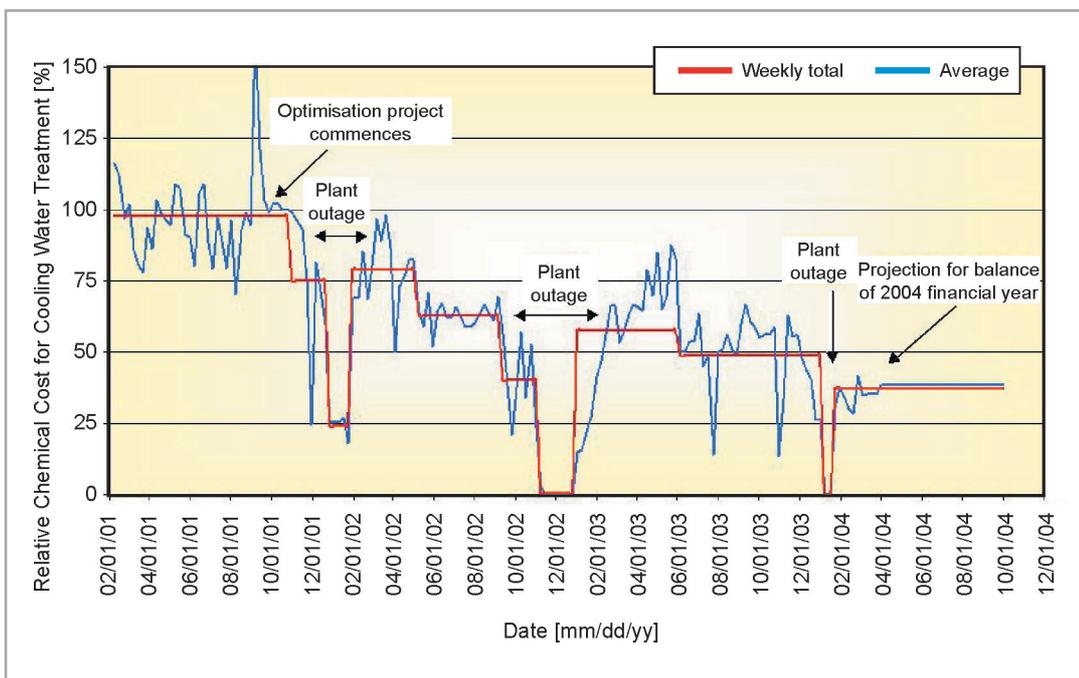


Figure 13: Cost savings arising out of the performance-based approach to cooling water chemistry control.

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