

CALCIUM PHOSPHATE SCALE FORMATION IN POWER STATION CONDENSERS FED BY COOLING TOWERS: A CASE OF WHEN NOT TO USE SCALING INDICES

D. Hawthorn¹ and D.I. Wilson²

¹ *minDEP Research, 88 Clifton Road, Ruddington, Nottingham NG11 6DE, UK. scaling@hawthorns.name*

² *Department of Chemical Engineering & Biotechnology, University of Cambridge, UK.*

ABSTRACT

Unexpected fouling in condensers on CEGB power stations operating on the river Trent prompted an extensive investigation of the phenomenon. Fouling was caused by deposition of calcium phosphate rich scale on the cooling water side. A fouling test rig was specially constructed to study the performance of different chemical treatments. The rig ran two tubes in parallel, one with dosed water, and the other un-dosed. Over 100 un-dosed data sets were analysed to determine the mechanism and rate of fouling of river water. The trends could not be explained in terms of conventional scaling indices. Insight into the mechanism was provided by separating precipitation (loss from solution) and deposition (adhesion of some of the precipitated mass to the heated surface): scaling was found to be caused by the deposition of particulates in the recirculating cooling water, driven by the change in pH as the water went through the evaporative cooling stage. Quantitative expressions for fouling were generated from tests on short tubes and were found to give a reasonable prediction of the fouling behaviour observed on a full sized (18.3m long) single condenser tube on an operating condenser. The results indicated that recirculating water systems need to be approached very differently from once-through systems, and the use of scaling indices for such systems is not recommended.

INTRODUCTION

Large inland power stations in the UK frequently employ cooling water systems based on evaporative cooling, fed by a river. In the units considered here, calcium carbonate scaling was to be mitigated by installing excess heat transfer area (following the TEMA guidelines for steam condensation) and by operating the cooling water system at a concentration factor (*CF*, being the ratio of salt concentration in the cooling water to that in inlet) of only 1.5 irrespective of summer or winter conditions. It was therefore unexpected when condenser efficiency losses were experienced in the mid-1970s. The scale was found to be calcium phosphate, the phosphate being derived from the influent river water. It was also surprising that adjacent power stations on the same river experienced different condenser fouling rates despite operating under nearly identical thermal and chemical conditions. Furthermore, some steam condensers experienced higher fouling rates than other units on the same power station. Simple considerations of solution chemistry were unable to explain these observations.

This paper summarizes some of the knowledge gained during studies of condenser scaling in stations located along the river Trent during the 1980s by the Midlands region of

the UK's Central Electricity Generating Board (CEGB). The Board decided to install the Taprogge fouling mitigation system in all large power stations along the river Trent, costing around £1 million per condenser (in 1980 prices). Installing these ball cleaning units was expected to take several years so chemists looked for chemical means of control over the short term. A pilot plant was constructed to study chemical methods of inhibiting scale formation.

Detailed analysis of the fouling deposits indicated that these consisted of amorphous calcium phosphate as well as calcium/magnesium sulphate and a small amount of carbonate. The phosphate levels (generally below 10 ppm in the influent river water) were linked to agricultural fertiliser use and treated sewage, and scaling was promoted by the mildly alkaline conditions in the system (pH ~ 8.5) resulting from evaporative cooling towers stripping carbon dioxide from bicarbonates. The small amount of carbonate indicated that both engineers and chemists had been successful in preventing carbonate scaling. Many chemical inhibitor manufacturers offered their products for assessment even though they had not been developed specifically for a phosphate scale. The CEGB Midlands Region's Scientific Services Department designed and built a twin circuit heat transfer rig to compare the efficacy of inhibitor products in dosed river water with un-dosed river water.

Scaling arises from the presence of inverse solubility salts in the water and is often considered to be an example of crystallisation fouling (see Bott, 1988). Early work on the topic often made reference to the Langelier (1936, 1946a,b) and Ryznar (1944) indices as quantitative tools for determining when the water would be saturated in terms of hardness salts, particularly calcium carbonate (see Pritchard, 1988). The fact that these indices had been developed for predicting the tendency of waters to attack iron water pipes and fittings was often ignored. For example, Langelier (working on scaling and corrosion problems in the natural cold water distribution network of California) developed his index based on analyses of water from a variety of wells and lakes. Various other indices have been developed (see Chen et al., 1982) and these have been applied to industrial recirculating waters which have been heated and cooled by evaporation such as in power stations. Müller-Steinhagen and Branch (1988) reported inconsistencies between different indices, demonstrating that they do not provide a definitive insight into scaling propensity.

Corrosion and scaling indices are linked by the thermodynamics of aqueous solution, particularly via pH and carbonate equilibrium contributions when the water chemistry conditions exceed the solubility limit of the respective salt. Scaling can also include the deposition of precipitated material via particulate fouling mechanisms.

The deposit, once, formed, can undergo ageing where crystallisation can occur in interstices. Scaling indices are unable to predict the amount of particulate formation in the bulk liquid as it is determined by nucleation - both heterogeneous and homogeneous.

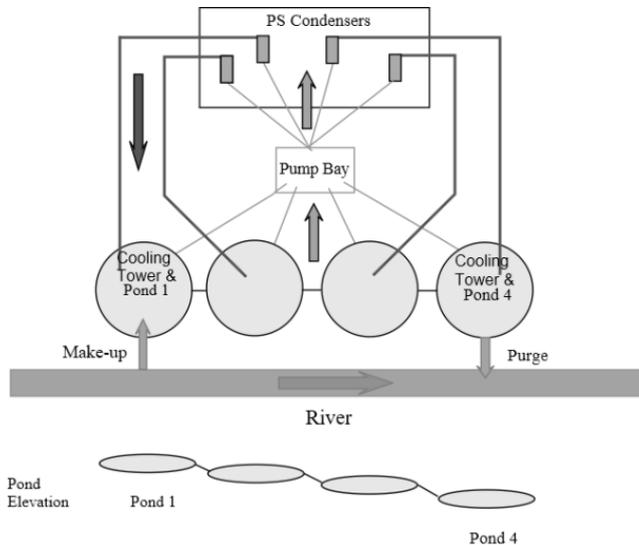


Figure 1. Schematic layout of a power station (PS) cooling water system. Numbers refer to ponds.

The CEGB Trent station condenser fouling proved to be a case of mixed particulate fouling. This arose from the design of the system, which is shown schematically in Fig. 1 with 4 ponds although there would have been eight on a 2000 MW power station. River water is fed to pond 1. Water is taken from the ponds and pumped through a condenser before being fed to the cooling towers. The water flows down over 2 m packing and returns to the ponds before being recirculated. A purge from the final pond (here, 4) is used to limit the build-up of salts. Samples of the circulating water were taken from the nearest pond to the laboratory and the mixing in the common pump bay meant that no difference in solution chemistry would have been observed between ponds. The water experienced an extended residence time in the system as typical ratios of flow rates were: circulation, 80; make-up (input) 3; evaporation, 1; purge, 2 (see Fig. 2). The cooling water can thus be considered to be well mixed and the composition of the purge is the same any sample of the circulated water.

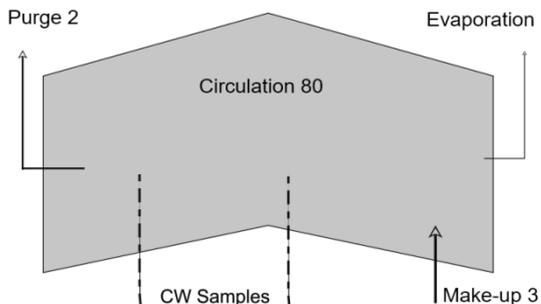


Figure 2. Illustration of flow rates (arrows to scale) in the cooling water recirculation system.

APPARATUS AND METHOD

Fig. 3 is a simplified diagram of the scaling rig. It featured two parallel flow loops, each feeding a single 6 ft long (1.83 m; 25.4 mm o.d., 23.1 mm i.d.) Admiralty brass (composition in wt% Cu, 70-73; Sn, 0.9-1.2; Pb, 0.07; Fe 0.06 max; As, 0.02-0.06, balance Zn) tube from power station stocks mounted in a common steam boiler which operated under vacuum at around 40°C to replicate conditions in the power station condensers. The inlet and outlet water temperatures were monitored. Two other tube diameters were later tested with length set to maintain a similar mean transit time of the water at a flow rate of 6 litre/min: 13.4 mm i.d., 15.9 mm o.d., 7.32 m long and 7.9 mm i.d., 11.1 mm o.d., length 18.3 m. The tube-side Reynolds numbers, Re , all lay in the turbulent regime (see Table 1). The plant operated with an inlet tubeside Reynolds number of 55,000, which was significantly larger than that in the flow loop for the 23.1 mm i.d. tube at the standard flow rate of 6 litre/min used in tests so turbulence promoters and maintainers were installed on this tube.

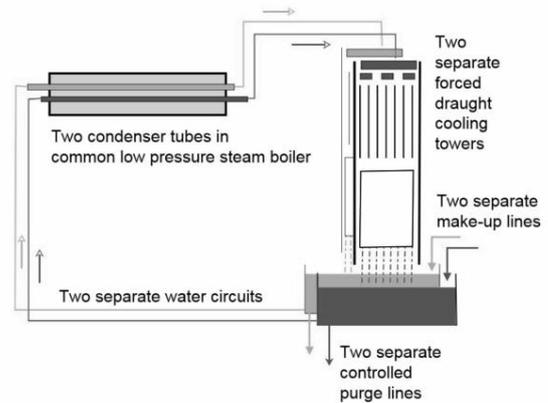


Figure 3. Schematic of the CEGB scaling rig

Each loop had a dedicated temperature controlled evaporative cooling tower, river water make-up and purge, originally to test scale inhibitors and other additives against untreated river water. The tube length was 1/10th of a plant condenser tube, and the rig pond size was originally 1/10th that associated with one tube. Over the course of the study the pond size was altered, which allowed the role of residence time to be investigated. This fortuitously enabled examination of the role of residence time in the final analysis. The range of operating parameters is summarised in Table 1.

Table 1. Summary of scaling rig test parameters

Parameter	Value
Water flow rate	6-11 litre/min
System volume	135-375 litre
Water transit time in tube	5.4-8.6 s
Half-life of water in system	5-72 hr
Inlet temperature	5-27 °C
Tube inner diameter	23.1, 13.4, 7.9 mm
Temperature gain along tube	3.0-13.0 K

Concentration factor	1.15-2.50
Estimated wall shear stress	0.22-14 Pa
Reynolds Number	7,500 – 24,000

The residence time of water in system, t_{res} , was calculated from

$$t_{res} = 3t_{1/2} = 3 \frac{\text{volume}}{\text{purge rate}} \ln(2) \quad (1)$$

The wall shear stress, τ , was estimated using (Perry and Chilton, 1973)

$$\tau = 0.046 \text{Re}^{-0.2} \frac{\rho u_m^2}{2} \quad (2)$$

Experiments started with concentrating the initial charge of river water to the conditions to be tested. The heat transfer tube was then changed to a clean one and the experiment continued under steady conditions. Following a test the tubes were cleaned with acid and the wash solutions analysed for calcium/magnesium and phosphate by inductively coupled plasma atomic emission spectroscopy. Circulating water samples could be withdrawn during the test for chemical analysis; they and the feed water were analysed on site for phosphate by atomic absorption and for calcium and magnesium by EDTA titration.

The concentration factor was calculated from sodium responsive electrode measurements via

$$CF = \frac{[Na]_{circuit}}{[Na]_{inlet}} \quad (3)$$

CF was controlled by adjustment of the purge rate, itself maintained by a timer regulating a lock-hopper design pump. The concentration of precipitated phosphate was estimated from the difference between the phosphate present in the inlet river water and that leaving in the purge:

$$[PO_4]_{precipitated} = [PO_4]_{inlet} - ([PO_4]_{purge} / CF) \quad (4)$$

Experiments generally ran for 72 hr and control of the forced draft cooling towers maintained temperatures constant, day and night. pH was maintained at a set level by injection of very dilute sulphuric acid solution. The pH would have been naturally higher than that seen on power stations with splash packing, as was common at the time of construction.

Chlorination of the system was by intermittent injection of (acidic) chlorine water adjacent to the pH electrode. Alkaline sodium hypochlorite was not used as this would have initiated precipitation. To enhance phosphate levels during high phosphate trials, a dilute solution of phosphoric acid was added to the influent water. Inspection of plant and pilot scale tubes indicated that scale was not deposited evenly along the tube (see Fig. 4) so scaling was quantified in terms of mass of deposit per tube.

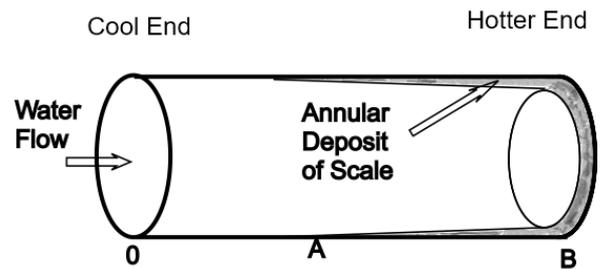


Figure 4. Tapered scale deposited with a heated tube.

The amount of scale formation was measured by acid cleaning (1wt% HCl) of the tube at the end of a test when it had been removed from the apparatus. Separate calculations (see Fig. 5) showed that a significant amount of scale would have to be deposited before it gave rise to a noticeable change in the overall heat transfer coefficient. This insensitivity could be wrongly interpreted in terms of an induction period for fouling of 70 days.

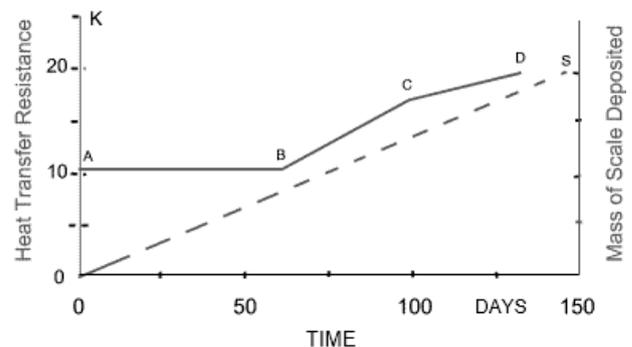


Figure 5. Effect of steady deposition (dashed line) on tube overall heat transfer resistance (solid line) evaluated at points A-D.

The rig's use of a vacuum boiler for heating avoided the use of hot liquids or electrical heating, which would have promoted deposit spalling (seen on other test units) during testing or at the end of a test.

As scaling was known to be a summer phenomenon, the rig was designed to be able to concentrate 'winter' water to 'summer' conditions by control of the forced draft cooling towers. This meant that the rig could operate all year round. Over one hundred experiments were performed and the data sets from the un-dosed circuit, originally collected as experimental controls for testing additive packages, were analysed to try to develop a phosphate scaling index similar to the classic indexes for calcium carbonate. The data set featured separated parameters which are normally confounded in plant studies. The versatility of the rig lay in its ability to investigate variables that are normally confounded on the plant, so that it was possible to study high temperatures and pH with winter-type water concentrations; lower pHs and phosphates during periods of high temperatures; and low or high concentration factors, independent of the weather and river conditions.

RESULTS AND DISCUSSION

Fig. 6 plots the observed rig deposition rate (calculated as mass of deposit ÷ operating time) versus the KRW phosphate scaling index (1981). The KRW index was based on work by Green and Holmes (1941) and relied on knowledge of the form of calcium phosphate being deposited. Since the deposited scale was amorphous, speciation – whether it consisted of tricalcium phosphate, fluorapatite or hydroxyapatite – was not possible and the index was not useful as a predictive tool (chemical analysis showed the presence of fluoride as this was also present in the feed water). It can be seen that there is no causal link shown between scaling and the index.

The rig design was initially blamed for not being able to confirm a link between scaling and the concentration of scalant in the circulating water. Furthermore, it was suggested that the section of the river Trent involved was affected either by fulvic acid (a potential inhibitor) or manganese (an accelerant), since both had been found in analyses. This hypothesis was refuted by using solutions prepared from demineralised water and analytical grade chemicals to match the river water composition. The calcium and magnesium bicarbonates were prepared by bubbling carbon dioxide through a suspension of their carbonates. The synthetic waters scaled at the same rate. Later plant monitoring validated the rig construction and its data analysis, confirming that scaling was not linked to conventional indices based on the dissolved species concentrations in the circulating water.

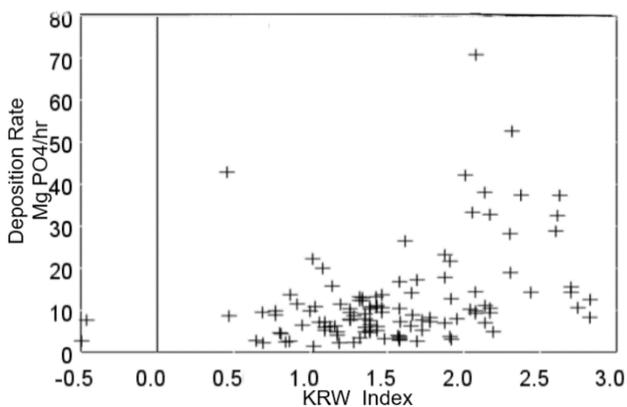


Figure 6. Correlation plot of phosphate deposition rate vs. KRW Index. Data set available in full in Hawthorn (1994).

The tests on the un-dosed river water circuit indicated that this case of phosphate scaling was a two-stage process comprising precipitation (loss from solution) and deposition (adhesion of part of the precipitated material to the heated surface of the heat exchanger). Fig. 7 shows that the deposition rate was directly related to the mass flow rate of phosphate in the feed water (both dissolved and particulate): the chemical composition, temperatures and heat duty (temperature gain) were notionally identical. The non-zero intercept was attributed to the solution concentration at which precipitated particles appear (*i.e.* the saturation limit).

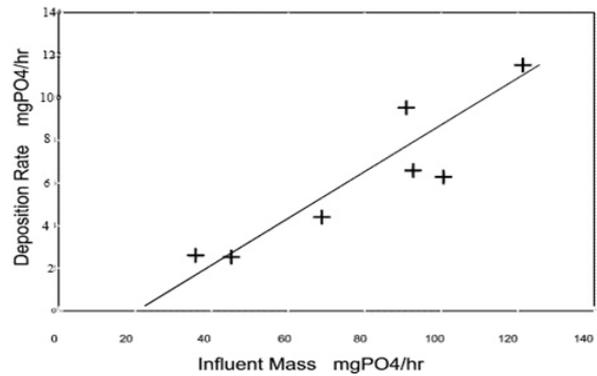


Figure 7. Rig observations: deposition vs influent mass of phosphate for similar experimental conditions. Operating conditions summarised in Table 2.

This hypothesis was confirmed by analysis of scale from the plant, which was composed of finely divided particles of both silt and phosphate. Particle size analysis gave a mean phosphate size of $3.5 \mu\text{m}$ with 50% between 2 and $6 \mu\text{m}$. The entrapped silt was of similar size and was not dissimilar to the solids suspended in the circulating water (mean $1.8 \mu\text{m}$, 50% between 0.06 and $6 \mu\text{m}$) except that the very fine silt material was not present in the deposit. The amount of scale on plant and test rig tubes increased along its length, but it was not possible to determine the local distribution of deposit. Since silt does not grow *in situ*, these observations suggest that this form of scaling could be due to particle capture at the heated surface. A second hypothesis is that both types of particle were trapped in a growing calcium phosphate matrix. It was not possible to differentiate these mechanisms on the basis of these tests but the amorphous nature of the deposit suggested that the former was more likely.

Table 2. Operating parameters for tests in Fig. 7

Parameter	Value
T_{in}	$23.1 \pm 0.2 \text{ } ^\circ\text{C}$
T_{out}	$32.3 \pm 0.3 \text{ } ^\circ\text{C}$
pH	8.38 ± 0.03
[PO ₄] in cooling water	$6.6 \pm 0.3 \text{ mg/L}$
[Ca] in cooling water	$158 \pm 6 \text{ mg/L}$
Mass flow rate of PO ₄ in feed	36-122 mg/hr
Estimated wall shear stress	0.22-14 Pa

Subsequent analysis of the fouling rate showed that the influent mass flow rate of phosphate, M , was a determining parameter. At one time scaling showed positive correlation with around ten of the monitored parameters. It was not until the scaling process was seen as a two stage process that understandable quantitative equations were developed. Scaling was divided into precipitation (loss of scalant from solution) and deposition (adhesion of part of the precipitated material onto the heated condenser tubes). Not all of the precipitated scalant was deposited on the heat transfer tubes; some was deposited in the ponds (a little on the cooling tower packing) and some left the system in the purge.

The data were modelled as a two-stage process:

Inlet water → precipitated material → deposit

Sequential multiple linear regression analysis gave the mass flow rate of precipitated material in the cooling water as

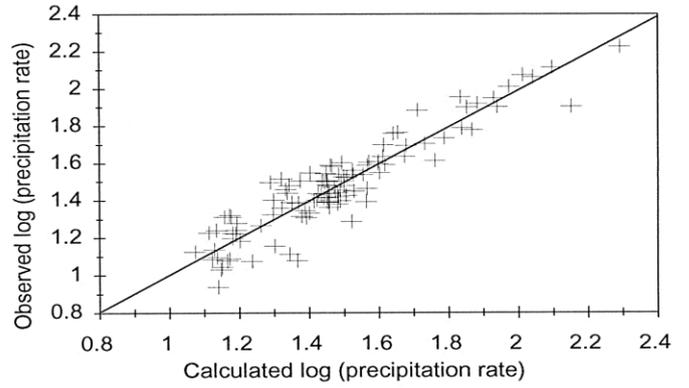
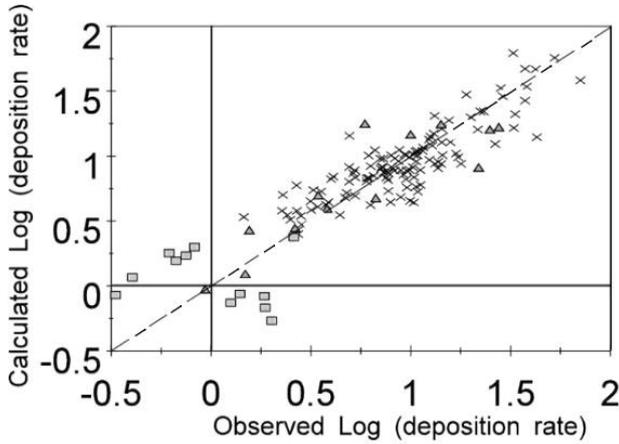


Figure 8. Agreement between measured precipitation mass rate (mg PO₄/hr) and fitted result (Equation (5)). Solid locus shows line of equality. Correlation coefficient $R^2 = 0.87$.

Figure 9. Agreement between estimated deposition rate (mg PO₄/hr) (Equation (6)) and that based on measured adherent scale. $R^2 = 0.80$. Dashed solid locus shows line of equality. Symbols indicate tube i.d: crosses - 23.1 mm; triangle - 15.9 mm; square - 7.9 mm.

Equation (6) can be compared with the behaviour expected for particulate fouling, where the rate of deposition would be expected to take the form

$$D = ASk_m[PO_4]_{ppt} \quad (7)$$

Here A is the heat transfer surface area, S is a sticking factor and k_m is a mass transfer coefficient for particulates: S is expected to decrease with flow velocity, u_m , whereas k_m will increase. Inspection of the u_m contributions in Eqn. (6) gives

$$\begin{aligned} D &\propto M \times \text{Re}^{1.5} \times \tau^{-1} \\ &\approx (u_m \times [PO_4]_{ppt}) \times \text{Re}^{1.5} \times \tau^{-1} \\ &\propto u_m \times u_m^{1.5} \times (u_m^2 \times u_m^{-0.2})^{-1} = u_m^{0.7} \end{aligned} \quad (8)$$

This dependency on flow velocity is close to that expected for a convective mass transfer coefficient in the turbulent flow regime, suggesting that the sticking factor is close to unity or has a small velocity dependence. Fig. 7 indicates about 10% of the particles entering the tube end up in the deposit, which is a large fraction and is consistent with the sticking probability being large.

PLANT MONITORING

Scaling of the flow loop results was investigated by measuring the amount of deposit generated in a single tube on the full size condenser (20,000 tubes, 18.3 m long). The test configuration is shown in Fig. 10. Under normal operation (the fouling phase), water was withdrawn from the cooling water header via valve A and passed along the tube and discharged to waste at valve D. At the end of the test, valves A and D were closed to isolate the tube and 1 wt% hydrochloric acid solution was recirculated through it reservoir via valves C and B. The acid composition was analysed and the mass of scalant deposited calculated knowing the volume of acid in the reservoir.

$$\begin{aligned} \log M &= 1.22 \log(Q \times ([PO_4]_{in} - [PO_4]_{sat} / CF)) + 0.23 \text{pH} \\ &+ 1.101 \log[Ca]_{CW} + 1887 \left\{ \frac{1}{273} - \frac{1}{273 + T_{out}} \right\} \\ &+ 0.165 \log t_{1/2} - 5.896 \end{aligned} \quad (5)$$

where Q is the make-up rate, temperatures are in Celsius and $[Ca]_{CW}$ is the concentration of calcium in the circulating water. The factor $[PO_4]_{sat}/CF$ allows for dissolution of pre-deposited scale when the concentration of scalant in solution is less than saturation $[PO_4]_{sat}$, around 2 ppm, which could arise in winter.

This relationship is specific to the waters studied. It contains expected trends, such as increasing precipitation with bulk temperature, calcium concentration and residence time in the ponds. The agreement with test data is shown in Fig. 8.

Applying a similar approach to the deposition rate, D , gave

$$\begin{aligned} \log D &= \log M + 0.5 \text{pH} + 0.025 \cdot (T_{out} - T_{in}) \\ &+ 0.15 \log t_{1/2} + 1.5 \log \text{Re} - \log \tau - \beta \end{aligned} \quad (6)$$

where β is a factor which varies between the 20,000 tubes in the 4 condensers on the plant. Fig. 9 shows a reasonable fit to the experimental data.

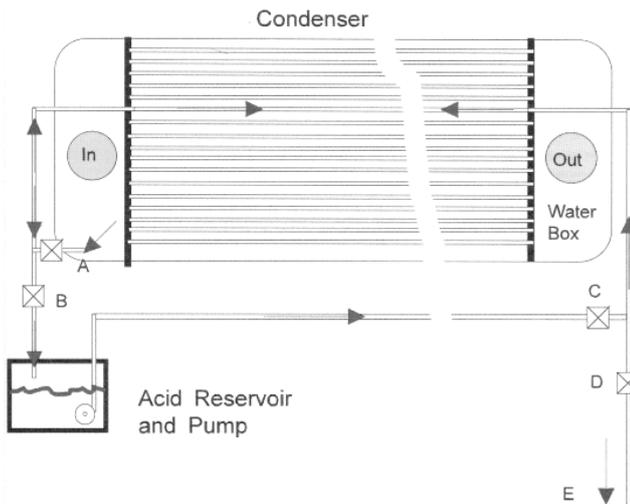


Figure 10. Schematic diagram of plant monitoring rig.

The plant-derived data from 22 tests are compared with those obtained from the pilot rig in Fig. 11. The chemistry model (Equation (6)) shows excellent agreement with the results for the full-scale system. The deposition rate (Figure 9(b)) is predicted reasonably well, particularly given the difference in tube length between the two systems.

The scaling rate often varied between condenser units and this could be linked to designs where the cooling water was fed primarily from one pond. The amount of fresh precipitate would be greatest in pond 1, where the incoming river water contacted the different (higher) pH conditions in the recycled cooling circuit, promoting precipitation.

The two-stage model was also able to explain the differences in fouling observed between two adjacent power stations. Although of similar design, the operating volume of the ponds in one (49, 000 m³) was a third of its neighbour (147, 000 m³) owing to accumulated silt and gravel from upstream operations. The free water depth was 30 cm in places. This station did not report any heat transfer or scaling problems in its condensers, unlike its neighbour. The units operated with similar purge rates (3,400 m³/hr) so t_{res} differed by a factor of 3. This parameter affects both $[PO_4]$ (Equation (5)) and D (Equation (6)), giving a difference of 9:1 in predicted scaling rates. Had this knowledge been considered at the time, the installation of the Taproge systems could have been delayed until the effect of pond dredging had been evaluated.

A further observation was that the KRW index for the cooling water in the two stations differed noticeably. A higher value was found for the plant with the smaller pond volume, as more hardness salts remained in solution because they were not subject to a long residence time which favoured particulate formation.

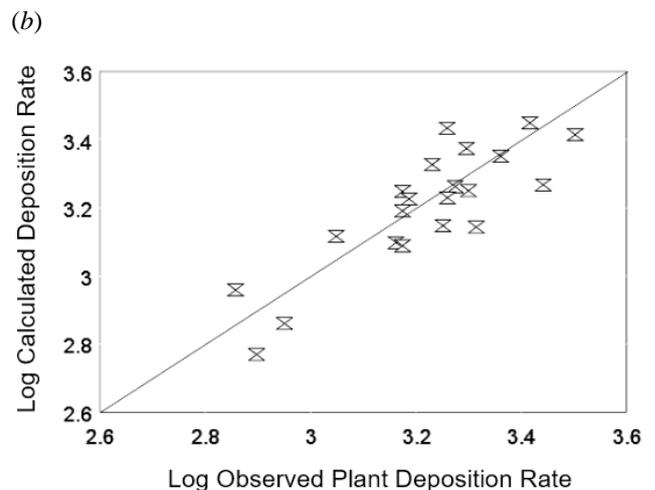
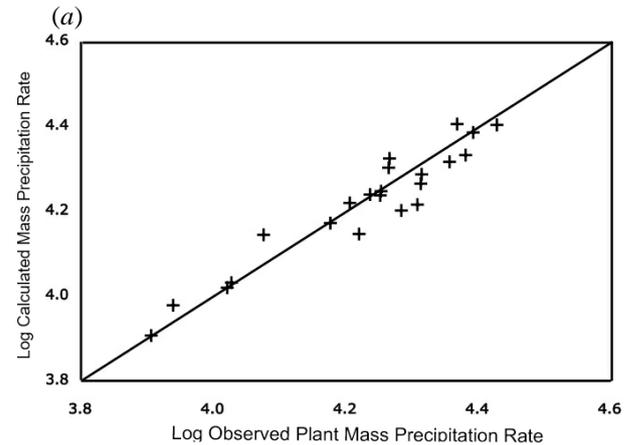


Figure 11. Prediction of plant fouling performance.

Comparison of (a) observed precipitation rate and pilot plant prediction (mg PO₄/hr), Equation (6); (b) measured plant deposition rate (mg PO₄/hr) and pilot plant prediction, Equation (7). Solid loci show lines of equality.

DISCUSSION

Scaling indices proved to be unable to explain the observed occurrence of calcium phosphate deposition in this instance. The experimental programme described above demonstrated that this was primarily a case of particulate fouling, where the particles were very small so that they were not visible to the naked eye. A filtration-based mitigation strategy would have required microfiltration with regular washing or cleaning. Measurement of particulates should have been performed more regularly in this instance: modern instrumentation makes these on-line measurements considerably more affordable and accurate.

An important factor is that the cooling water system was not considered as a process in its own right: the ponds effectively acted as a well-mixed tank, with relatively small flows of river water feed and purge output. The composition of the purge stream was effectively that of the cooling water, so that a mass balance such as Equation (4) could have been evaluated to determine the amount of insoluble material in the water.

A second processing aspect that was not understood properly (and has yet to be quantified) was the impact of the cooling tower operation on the pH of the water. Cooling is achieved by evaporation, and this simultaneously strips dissolved carbon dioxide from the water, increasing the pH and promoting precipitation of all common hardness salts (carbonates, sulphates and phosphates). This is demonstrated in Fig. 12, which shows the concentration of calcium in solution at room temperature when an initially saturated solution of calcium hydrogen carbonate is subjected to continuous nitrogen bubbling (replicating the stripping which occurs in cooling tower packing).

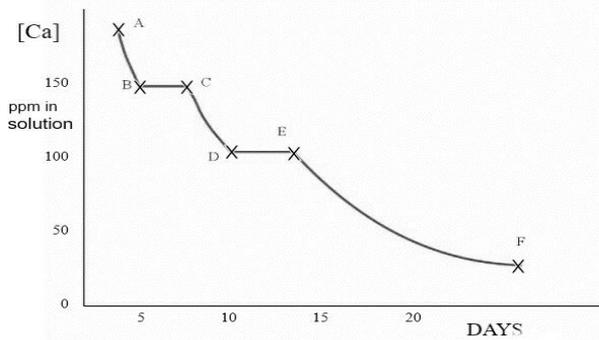


Figure 12. Effect of nitrogen sparging on an aqueous solution of calcium bicarbonate. Gas sparging was stopped over weekends at BC and DE.

The reduction in calcium in solution was accompanied by the visible precipitation of calcium carbonate. On the power station, the towers thus promote particulate formation. Furthermore, Fig. 12 shows no change in calcium concentration in the absence of stripping, indicating that at these conditions – which are not far removed from cooling tower operation - spontaneous nucleation was not occurring in the bulk solution and also that there was negligible growth of the existing crystals.

The role of cooling tower packing and stripping needs careful consideration as the pH switch induced by evaporation effectively determines the amount and size of precipitated particles. Tests on recirculating waters should ideally feature different packing heights in order to quantify this effect.

One of the reasons why scaling indices can lead to erroneous results is that the measurements of concentrations of the species involved can be subject to artefacts. Associated with this point is the lesson from trials on calcium carbonate fouling that the best methods for preparing a test solution is by sparging CO_2 through a suspension of calcium carbonate rather than by mixing calcium chloride with a bicarbonate, unless steps are taken to equilibrate the latter solution with the CO_2 level in the air.

Seasonal effects are also important. Weather (rain runoff) and temperature variations cause the inlet concentration of scalant to vary over the year as shown in Fig. 13. In practice the observed concentration differs: in the warmer months this is caused by precipitation (as described in the experimental study) but in the colder months dissolution of material present in the ponds will increase the amount present in solution and reduce the rate of deposition.

Operating at a CF of 1.5 is costly and is not required in the winter: a higher concentration factor could be used over the winter period, with appropriate monitoring and data interpretation to detect when the level of precipitation had started to become significant. Moreover, the high concentration compared to the river in the winter months would be interpreted by a scaling index as promoting deposition, whereas it arises from an effect that mitigates fouling.

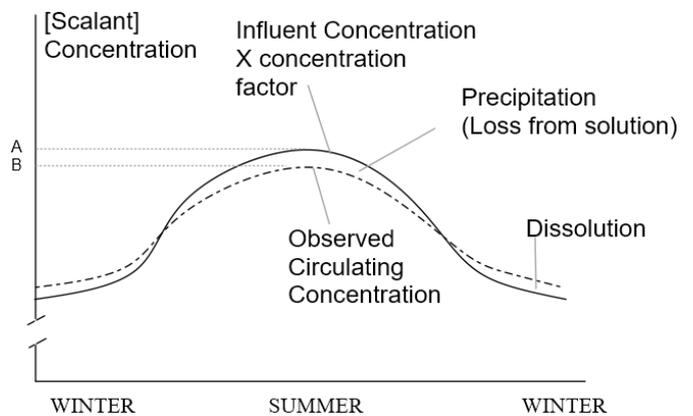


Figure 13 Expected variation of scalant concentration over time. Solid line – expected from inlet conditions and ambient conditions; dashed locus – measured values.

USE OF SCALING INDEXES

The studies by Langelier and by Ryznar related to water that was not being recycled or evaporatively concentrated; it was not being stripped of carbon dioxide as happens when warmed water passes down the packing of a cooling tower. In their studies the water passed through heat exchangers and was purged. This has not been the practice in power stations since the 1950s. The reasons why scaling indexes proved ineffective in this case, and should be challenged if their use is proposed for other applications, include:

(i) Scaling indexes were developed originally for corrosion. Their application to polymorphic systems such as calcium phosphate has not reached the open literature.

(ii) Scaling indices are useful for once-through systems, where the composition is directly related to the feed water composition. In this case the composition of interest was that of the purge, and the difference between the inlet and

the purge. Recirculating systems and those subject to evaporation require more careful assessment.

(iii) Scaling indices focus on dissolved amounts of fouling species as they are aimed to establish whether a solution is close to saturation, and are not suitable for assessing suspensions. In the case of a solution in equilibrium with suspended crystals, a scaling index would predict no fouling but this would refer to *crystallisation* fouling alone.

CONCLUSIONS

An experimental test rig originally constructed to compare the effectiveness of commercial products for a chemical dosing fouling mitigation strategy for power station cooling water systems was fortunately constructed with two heat transfer loops, with one operating as a control. The data collected on the control loop have been evaluated and demonstrate that the hypothesis that scaling was caused by crystallization fouling was incorrect, and that fouling was caused by the deposition of calcium phosphate precipitated in the cooling water. Regression analysis of the data set allowed a working model to be constructed which gave reasonable agreement with separate measurements of scale formation in tubes on an operating condenser unit.

The results highlight the need to diagnose the cause of fouling properly. Scaling indices, which are often used to assess propensity for crystallization fouling, were not able to explain the observed trends in test rig and condenser behaviour, and the differences between power stations. This should have provoked a review of the hypothesized mechanism, which could have led to cheaper mitigation measures.

Some of the shortfalls associated with the interpretation of scaling indices have been presented. A rig similar to the one described here is seen as a suitable vehicle for quantifying calcium carbonate scaling.

NOMENCLATURE

Roman

A	area for heat transfer	m^2
CF	concentration factor	-
D	scale deposition rate	kg/s
k_m	mass transfer coefficient	m/s
M	mass flow rate of phosphate into tube	kg/s
Q	make up rate	m^3/s
Re	Reynolds number	-
S	sticking probability	-
T	temperature	$^{\circ}C$
t_{res}	cooling water residence time	hr
u_m	mean velocity	m/s
[X]	concentration of species X	kg/m^3

Greek

β	deposition rate factor	-
ρ	density	kg/m^3
τ	wall shear stress	Pa

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