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Silica Deposition Experiments:Past Work and Future Research Directions

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ABSTRACT

After 40 years of investigations silica scaling is qualitatively well understood, but reliable predictions of scaling under typical power station operating conditions are still not possible.

In this paper we review a few selected field silica scaling experiments undertaken primarily in New Zealand, which have involved measuring scaling rates. The aim is to provide insights into what can be learnt from such studies and to show that there is much more to understand about the scaling process.

Aging of water to allow silica polymerization has been shown to reduce scaling potential. Icelandic researchers have demonstrated that rapid cooling and dilution are very effective at suppressing deposition. We describe work underway at Wairakei to determine the effectiveness of this technique for New Zealand waters.

1. INTRODUCTION

Understanding the chemistry and behaviour of silica in geothermal environments is the key to solving the major and expensive problem of disposing of water saturated with silica and of scaling in surface and subsurface piping. More than 50 years of world-wide geothermal laboratory and field research has not provided a universally applicable and, most importantly, an economically viable solution to this intractable problem. Acid dosing to suppress silica scaling is very effective but control of acid addition is difficult (Mroczek et al., 2010).

The chemistry of silica has been extensively studied because of its industrial importance but it is still difficult to predict the scaling tendency of any given water. This is because colloidal silica can exist in numerous physical forms, the behaviour of which is highly dependent on their mode of formation, process conditions and water chemistry. Rates of colloid particle growth and aggregation at elevated temperature cannot be easily predicted, and the effect of trace impurities such as Fe, Al, and Ca is still poorly understood. Water discharging from adjacent wells with different subsurface mineralogies may result in different scaling rates. This makes it virtually impossible to adequately simulate geothermal water and scaling in the laboratory. Solving scaling problems usually means that comprehensive site-specific field tests need to be undertaken before designing any silica disposal or treatment process.

The literature of geothermal silica scaling and how to deal with the problem is extensive and wide-ranging. In this paper we review a few selected field silica scaling experiments undertaken over the last 40 years, primarily in New Zealand but also elsewhere, which have involved measuring scaling rates. The aim is to provide insights into what can be learnt from such studies and to show that there is much more to understand about the scaling process. Our interest is in data showing the beneficial effect of polymerization and aging on reducing scaling and we discuss the recent trials utilizing aged water undertaken at Wairakei which have also given promising results.

2. FIELD TRIALS

2.1 Japan

Yangase et al. (1970) showed at Otake that aging the fluid (~1hr) was successful in decreasing the amount of scale deposited in pipes downstream of a hold-up tank by up to 90%. In similar experiments at Hachobaru, Yokoyama et al. (1987) concluded that the concentration of monosilicic acid ("monomer") is a major factor controlling the rate of silica deposition. Interestingly they also found that dissolved Al also appeared to play a role in the deposition. It was inferred that ponding reduces silica scaling as it allows the dissolved silica to be converted to colloidal silica which prevented cementation of the weakly adhering deposits and their conversion to solid scale.

2.2 Philippines

Candelariaet al. (1996) reported a successful trial of cold water injection at the Mindanao Geothermal Project. The water was cooled in baffled ponds to increase residence time allowing the silica to polymerize from an initial 3x oversaturation. Only a fraction of the silica was deposited as scale and after three years there was no serious decline in injectivity although scraper runs showed that "fluffy" gelatinous silica was deposited in the well. They speculated that the polymerized silica was carried out into the formation sufficiently far away from the well bore not to cause any serious injection decline. Currently there is no large scale cold injection of brine as this would add to the thermal degradation of the reservoir (A. Baltazar, Pers. Comm, 13/5/11).

In contrast Candelariaet al. (1996) reported that cold water injection at Botong was not successful and the gelatinous precipitate flowing with the silica eventually blocked the reinjection well. They speculated that the large particle size (30μm) and smaller fractures contributed to the fast decline.However it appears the failure of this trial was due to a problem with the design of the baffled pond and also not being able to achieve the required flowrate. Acold water injection scheme with scale inhibitor was implemented (A. Baltazar, Pers. Comm, 13/5/11) and blocking of the well and formation could be avoided as long as flushing to remove the gelatinous silica took place immediately after plant shut down. Nevertheless acidizing is done every 2 to 3 years to improve well injection capacityis still required (A. Baltazar, Pers. Comm, 13/5/11).

Panopioand Solis (2010) reported that the present low temperature water injection at Botongusing a silica inhibitor is being replaced by hot water injection with silica inhibitor which appears to be more efficient at suppressing deposition at the higher temperature.

2.3New Zealand

Similar experiments to Yangase et al. (1970) at Wairakei (Mahon et al. 1975) were not as successful. Ponding for 1hr at ~ 90^{o}C reduced the scaling by 30 to 50%. Polymerization of silica in the Wairakei waters is slow compared to Otake which Mahon et al. (1975) suggested was the probable explanation for the higher scaling results. However 1:1 dilution with cold low mineralized water and ponding at 62^{o}C for 1hr reduced the scaling by 93% and the scales were friable and easy to remove.

Subsequent experiments at Wairakei and Broadlands (Ohaaki) were undertaken by Rothbaum et al. (1979) utilizing fluid at temperatures 75-95^{o}C and aging in tanks.Contrary to the earlier work they found that the quantity of scale formed wasnot greatly affected by the polymerization of silica. However the character of the scale was found to be highly dependent on the time of ponding. Thus, in well BR11, where the fluid ishigh pH and low in silica (slow polymerization), there was no effect on scale characteristics. However well BR22, where the silica polymerizes quickly, at short hold-up times the scale consisted of hard spikes oriented in the direction of flow while at longer hold-up times the scale was fine-grained, soft and easily removed. They also found that aeration of the fresh discharges had the biggest effect on the quantity of scale formed. They postulated that this was the result of oxidation of ferrous iron to ferric iron which nucleated the silica deposition. In addition to iron Cawas also thought to be involved as nuclei for scale formation. They found high Al in the scales at Broadlands and Wairakei but considered that Al was not involved in nucleation. They concluded that ponding or aging of geothermal waters was not an effective treatment option because the slow rates of polymerization did not change the character of colloidal silica sufficiently to reduce adhesion.

Rothbaum et al.(1979) work was further expanded by Brown and McDowell (1982) at Broadlands. They found that aeration had no effect on the scaling rate. In their experiments fluid at 115^{o}C was passed through insulated pipes. They postulated that the lack of effect was because silica was only just beginning to polymerize while in the previous experiments the longer hold-up times enabled colloidal silica to form which was then flocculated by the nuclei formed by oxidation with air.

In the second set of experiments Brown and McDowell (1983) investigated the effect of aging (tanks) and aeration. The experiments were more comparable to the previous work of Rothbaum et al. (1979) except that after aging the fluid was passed through insulated steam pipe, not over tiles in an open channel. Again, as in their initial experiments, there was no increase in scaling due to aeration at normal pH.After aging at pH 5 there was a slight increase in scaling due to aeration but the scale at this pH also contained substantial amounts (10-18%) of amorphous arsenic and antimony sulphides which may have been responsible for the increased silica deposition. Maximum scaling was at pH 7 where silica polymerization was fastest. Significantly they found that aging was almost as effective (and even more so with a small pH reduction) as acidification in reducing scaling. The scaling characteristics, hard and vitreous, were also different from that found in previous work by Mahon and Rothbaum. Brown and McDowell (1983) ascribed this to low turbulence in their pipes which limited the rate at which colloidal particles could adhereto the pipe walls.

Rothbaum et al. (1979) concluded ponding is of little benefit and aeration greatly increased scaling whereas Brown and McDowell (1982,1983) reached the opposite conclusion that ponding was almost at effective as acidification. Both studies utilized fluid from the same well (BR22) at Broadlands. This illustrates the care with which field experiments must be designed and undertaken, always keeping in mind the application of the end results. Small differences to the experimental methodology can cause significant changes for reasons which in these experiments werepoorly understood.

Mroczek and McDowell (1990) reported scaling results from Rotokawa geothermal field well RK4, which had substantially different chemistry from Broadlands well BR22. The deposition of silica was studied as a function of flow rate in 150 mm diameter by 3.3 m long packed gravel beds, and in 25 mm diameter by 45 m long pipe units. The deposition rate in the pipes normalized to geometric pipe surface area is shown in Figure 1. Where the monomer concentration remained constant, indicating that polymerization was not occurring then scaling was uniform along the length of pipe (for example at 180^{o}C ~ 50-60 mg cm^{-2} year^{-1}) and appeared uniform acrossthe bed. The gravel chips in the bed were strongly cemented together from beginning to end. Where substantial polymerization had occurred, the deposition rate dropped exponentially along the length of the pipe; for example at 120°C the deposition rate decreased from 153 to 12 mg cm^{-2}year^{-1} which was 92% lower than at the inlet. At the outlet the monomeric (dissolved) silica was at amorphous silica saturation concentration and although over 50% of the silica was present as colloidal particles there was no tendency for these to deposit. The fluid in the pipes was calculated not to be in a turbulent regime.

Turbulence effects would be expected to occur in the gravel bed. At 30 L/min and 140°C, where the silica was rapidly polymerizing the silica deposited as a soft low density deposit at the inlet of the bed where the fluid impacted on the bed material at high velocity. Thereafter the gravel chips were cemented together. At 3 L/min under the same conditions there was very little silica deposited anywhere in the gravel bed. At 120°C the behaviour was similar to that observed at the lower flow rate at 140°C, that is - a soft deposit at the inlet with no obvious silica deposited elsewhere in the bed. At 120°C and 3 L/min there was no silica deposited at the inlet oranywhere in the bed. These results suggest that Rothbaum et al. (1979) conclusion that aging has no effect on scaling rate may only be correct for turbulent flow.

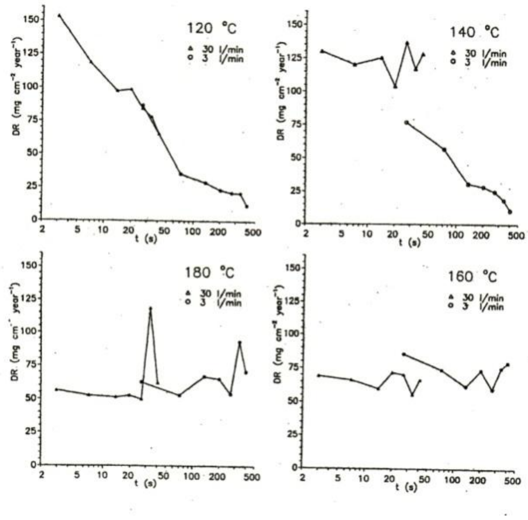

Figure 1: Scaling in pipes at well RK4 (Rotokawa).

The Rotokawa pipe results are qualitatively comparable to Brown and McDowell (1983) results. In their study at pH 7 where the silica polymerization was most rapid the deposition rate decayed from 197 to 52 mg cm^{-2} year^{-1}. However after a suitable hold-up time, which allowed the polymerization to complete, the deposition rate was found to be much lower and fairly uniform along the pipe; decreasing from 22 to 15 mg cm^{-2} year^{-1}. In their earlier study on the effects of aeration (Brown and McDowell, 1982) found the silica deposition rate at 115-112°C was more/less constant along the pipe and measured the annual rate of growth of silica of 0.42 mm year^{-1}. They calculated the molecular deposition rate (i.e. direct chemical bonding of dissolved silica on to a solid surface of silica) at 100°C, using equations presented by Weres et al., (1982) to be 0.015 mm year^{-1}. They concluded that the scaling rate was accelerated over thedirect monomeric deposition of silica. However repeating the calculation at the conditions of the experiment at 115°C,the rate is calculated to be 0.8 mm year^{-1} (Mroczek, 1994), double that experimentally observedby Brown and McDowell (1982).

Following Weres et al. (1982) they concluded that deposition of colloidal silica (mechanism discussed below) must be operating to account for the majority of the scale deposited. They presented electron microscope micrographs showing assemblages of spherical particles supporting this conclusion. However earlier work by Bohlmann et al. (1981) showed that such assemblages of spheroids can be formed in place rather than depositing from solution, so it is not certain how much colloidal silica deposition was contributing to the “increased” scaling rate. Bohlmann et al. (1980) found erratic scaling rates until the surfaces were fully coated with silica. The scale in Brown and McDowell (1982) experimental pipes was uneven and consisted of 20-50% corrosion product. It is also possible that the direct deposition of silica as well as colloidal silica directly onto the pipe walls was accelerated by the corrosion product. However similar experiments at Rotokawa observed no such acceleration in rate (Mroczek and McDowell, 1990).

Weres and Tsao (1981) conducted deposition experiments using synthetic water at 95°C which was pumped at 46 ml/hr through 3 mm quartz tubes. The scaling rates in the tubes dropped off rapidly with time and distance exactly as observedin the field experiments of Brown and McDowell (1983) and Mroczek and McDowell (1990). They noted that the decrease in scaling rate was roughly in parallel to the decrease in monomer concentration. As only a small fraction of the colloidal silica deposited as scale, they concluded that the decrease in scaling rate could not have been caused by the decrease in colloidal silica concentration. They therefore concluded that the rate of molecular deposition must be controlling the overall scaling rate under their conditions. Quoting from their paper “*almost certainly, the first step of scale deposition involves the attachment of colloidal silica particles and 'clumps' formed in the liquid phase to the tube wall by electrostatic forces identical to those that cause flocculation in the liquid phase. The particles are then permanently attached and the deposit made solid by molecular deposition of dissolved silica between the particles. This model was originally proposed by Iler”*.

Bohlmann et al. (1981) suggest however thatthe increase of low molecular deposition rates by one to more than two orders of magnitude can be simply explained by changes in surface area rather than deposition of colloidal silica aggregates. Furthermore they reported that there was no tendency for colloidal silica to deposit from simulated waters containing both colloidal and monomeric silica. Essentially the same conclusion was recently reached by Angcoy and Arnórsson (2010).

The importance of colloidal silica for increasing the apparent scaling rate above the low molecular rate of monomeric deposition is not settled. The field work discussed above shows that with increasing polymerization the scaling rate in pipes and under specific conditions in a packed bed, dramatically decreases.

One of the difficulties in undertaking silica scaling field experiments in pipes and packed beds is the long duration of the experiments (4 to 8 weeks) required to allow sufficient scale to accumulate. In addition any change in process conditions requires the experiment to be repeated. In a study to verify that field precipitation rates can be reliably predicted from laboratory derived measurements a fluidized sand bed was used at Wairakei to measure removal rates of dissolved silica (Carroll et al. 1998). In these experiments silica removal rates approached steady state as soon as thermal equilibrium was reached and temperature and flow control was precise and accurate over the short run times. The large surface area presented by the sand leads to measurable differences between inlet and effluent silica concentrations (unlike pipes where there was no discernable difference in total silica). Any change in experimental conditions results in an immediate shift in the silica removal rate to a new steady state value. The silica “deposition” rate is calculated from the difference in concentrations and not from the measured accumulation of scale. In these experiments the fluid was separated at 180°C and cooled before being introduced into the packed and fluidized beds. The rapid transit time through the bed precluded any colloidal growth.

The experiments were subsequently repeated and compared in stainless steel pipes packed with 2 mm diameter zirconia ceramic beads (Mroczek, et al. 2000).

The amorphous silica depositing on the sand grains was of hemispheroidal morphology (Carroll et al. 1998). The silica removal rates are shown in Figure 2 with good agreement with the packed bed method. High turbulence in the fluidized bedcould have enhanced mass transfer rates but this does not seem to have been an important factor.The changes in deposition rate with decreasing oversaturation are shown in Figure 3.

However there is one very important difference. The fluidized bed rates tend to zero as the silica saturation solubility is approached while in packed bed, scaling is observed at 129°C where none is expected as the solution is “theoretically” undersaturated with respect to amorphous silica. At the highest temperature ~129°C,three experiments were each conducted one month apart. The rates agree well with each other so it is difficult to discount the results as an experimental artifact.

It appears then that the scaling rates observed can depend on the technique used to measure them. The reason for this unusual result is not known but one explanation may be the faster deposition kinetics due to Al impurity, which is known to decrease silica solubility (Carroll et al. 1998). Al has also been observed in geothermal scales (Rothbaum et al., 1979; Gallup, 1998). The Al concentration in amorphous silica deposited on the sand was ~ 2wt% (Carroll et al., 1998). Unfortunately the Al in scale deposited on the ceramic beads was only analyzed in two pipes, one of which was at 96°C (Al 5.5 wt %) and the other at 129°C (7.5 wt %). At 100°C the scaling rate in the packed bed was about 1.5-2x that in the fluidized bed but at lower temperatures the rates were comparable (see Figure 2). Fast removal of silica reduces the dissolved Al concentration available for deposition. At very slow silica disposition rates such as occurs in the packed bed due to low surface area, there is always at higher ratio of Al to the quantity of silica depositing.

Although the silica scaling rates of the Wairakei water measured in these trials are very low, the 15MWe Wairakei Binary Power Station which utilizes flashed geothermal fluid at 130°C and cools it to 90°C, still requires 4-6 monthly cleaning of the tubes. The absolute amount of scale removed is very low given the large tube surface area (about 2x20litre buckets of sandy debris each water-blasting). However the rough morphology of the scale (“sharkskin”) creates an unacceptable flow resistance which reduces the performance of the plant. The plant has a maximum acceptable pressure drop and, as it scales up, the control circuitry reduces the flow to stay within the pressure limit.

It is not known whether the higher turbulence is a factor or where the majority of the scale is deposited. Nevertheless it illustrates that any work must be carefully designed to match operating conditions otherwise unexpected results are likely to occur. Conversely the plant could have been designed to be less sensitive to such a problem.

The Wairakei Binary Station has operated for 6 years. At the outlet temperature the silica saturation index is ~ 1.8 and there are no reports of declining injectivity in the reinjection wells.

2.4 Comparison of Rotokawa and Wairakei scaling with results predicted,using kinetic models of Bohlmann et al. (1980) and Weres et al. (1981,1982).

Bohlmann et al. (1980) presented an empirical rate equation which described the rate of linear growth r (cm min^{1}) of an amorphous silica surface in 1 m NaCl in the pH range 5-8 and temperatures from 60 to 120°C by

$$r = 3.1(C - C_e)^2 \left[OH^-\right]^{0.7} \quad (1)$$

Where ($C-C_e$) is the silica oversaturation (mol kg^{-1}) and OH^- is the hydroxide concentration. The rates derived from the Bohlmann et al. (1980) model, which are independent of temperature, are only valid at salinities of 1 mol kg-1 NaCl and so are not strictly comparable to the field results. Decreasing the salt concentration to 0.086 mol kg^{-1} (only slightly higher than the Wairakei fluid ionic strength) reduced the rate by a factor of 2.Bohlmann et al. (1980) considered that their equation could possibly model real systems when homogeneous nucleation was not a competing process or if the model included the kinetics of nucleation. However they noted that heterogeneous nucleation behaviour, the effect of partially covered substrates, the effect of hydrodynamics, the change of specific area of the coated deposit with deposition and the relationship between the surface area of the substrate are all unknown.

Weres et al. (1981) studied both homogeneous nucleation and molecular deposition. In the latter experiments the growth kinetics of monomeric silica onto Ludox colloidal silica particles of known surface was determined between 50° and 100°C and as a function of pH and salinity. They defined molecular deposition as the formation of compact, non-porous amorphous silica deposits by chemical bonding of dissolved monomeric silica directly onto colloidal silica particles. This is also the mechanism by which colloidal particles grow once nucleated.

Weres et al. (1982) summarized their previous findings and gave examples on how the results may be applied to the utilization of geothermal fluids.

The rate of molecular deposition r (g cm^{-2} min^{-1}) was given by

$$r = F(pH, pH_{nom})\, K_T\, ff(S_a)\,(1 - S)^{-1} \qquad (2)$$

where $F(pH,pH_{nom})$ accounts for the effect of pH and salinity on the rate of molecular deposition, K_T is the rate constant dependent only on temperature, $ff(S_a)$ is proportional to the rate of the deposition reaction while $(1-S^{-1})$ corrects for the effect of simultaneous dissolution. S_a is the saturation ratio (corrected for ionization) while S is the actual saturation ratio with all effects of salinity taken into account.

Klein (1995) rightly cautions not to over interpret the results of laboratory derived scaling rates under conditions which are not strictly comparable to field experiments.

Nevertheless Figure 2 shows that using "geometric surface" area and, assuming a vitreous high density scale of $2.25 g/cm^3$, the predicted scaling rates for Wairakei are only slightly overestimated using the Bohlmann et al. (1980) equation; recalling that the calculated rate is for water at much higher ionic strength. Weres et al. (1982) rate data is 5x lower than measured but tends towards measured rates at low silica oversaturation.

The Rotokawa fluid chemistry and composition is quite different from Wairakei and in particular the silica concentration is double at ~ 1000-1200 mg/L. At 180°C and 160°C all the silica was essentially present as monomer while at 120°C approximately 80% and 50% of the total silica was present as monomer at the inlet and outlet of the pipes.

Table 1 gives the calculated and observed rates.

At 120°C the predications using Weres et al. (1982) equation are accurate and at this temperature up to 50% of the total silica is colloidal. At higher temperatures, well outside the applicable range, the theoretical rates are overestimated with better agreement with Bohlmann et al. (1980) predictions which are 1.5 – 2 times higher than observed.

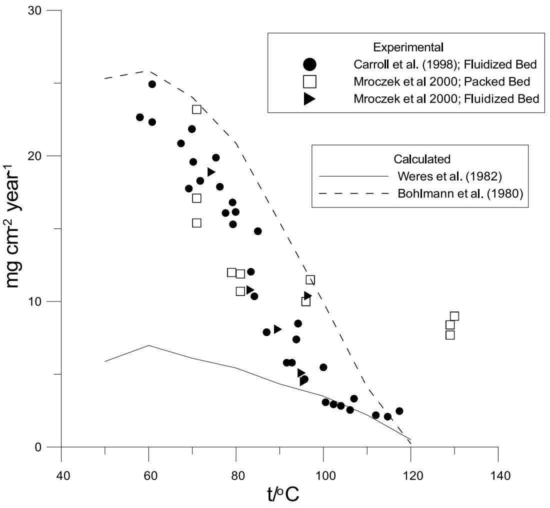

Figure 2: Comparison of Wairakei experimental fluidized bed and packed bed silica deposition rates with calculated rates. Rates are normalized with respect to geometric surface area.

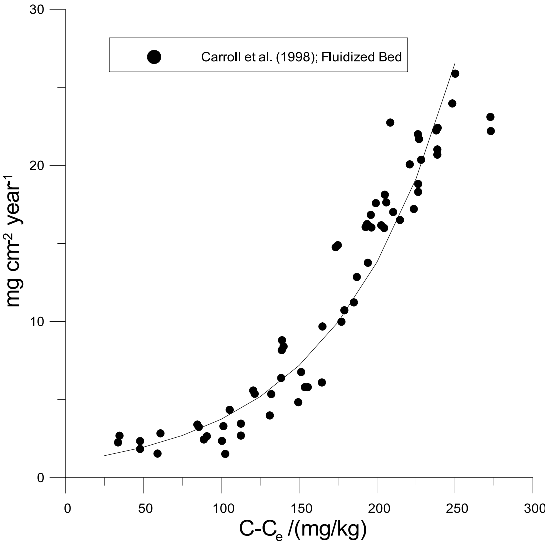

Figure 3: Silica deposition rate in a fluidized sand bed at Wairakei as a function of amorphous silica over-saturation. Rates are normalized with respect to geometric surface area.

Table 1: Rotokawa scaling rates compared to calculated values.

		Bohlmann et al. (1980)	Weres et al. (1982)	Observed
		Deposition rate		
T°C		(mg cm^{-2} year^{-1})		
160		154	287	73
180		93	264	62
120	inlet	206	134	153
120	outlet	18	14	12

2.5 Summary

The results of two studies from New Zealand fields produce too small a sample to allow total confidence in the accuracy of the empirical rate equations, especially athigher salinities and under different experimental regimes. However it isstill very useful to be able to estimate a ballpark figure, atleast for New Zealand type waters, where the depositing scale is of high density and low surface area, thepredictions at worst are only 2-5x higher than actual measured rates.

Klein (1995) states that where particle deposition is dominant, scaling rates are highly variable yet in the Rotokawa work over half the silica was polymerized. Possibly poor experimental design and poor control of the experimental parameters led to inconsistent results found in these trials. At Rotokawa scaling reduced in the pipes with polymerization. However in the packed bed a soft loosely adhering silica deposited where the fluid impacted the gravel chips at the inlet and thereafter no silica deposited. The question of the effect of turbulence is far from settled but controlled experiments are difficult to undertake (Dunstall and Brown, 2000).

Whether colloidal silica accelerates the apparent molecular deposition rate or whether this can be explained by surface area changes needs to be investigated further.

There is still no clear understanding of the effect of chemical impurities, especially the effect of Fe, Ca and Al. Do these nucleate silica deposition and is the effect of Al simply to reduce the solubility of amorphous silica without affecting the deposition kinetics?The effect of impurities may change depending on chemistry (e.g. pH) and temperature. The field experimental rates are lower than the empirical laboratory derived rates using synthetic but “clean” solutions. Does this imply that impurities have no influence or is this an artifact of laboratory measured rates incorrectly applied in the field? This will require both carefully controlled laboratory as well as field experiments to resolve.

For accurate results it is best to measure deposition rates through silica removed in solution rather than by the weight of solid scale.Techniques such as the fluidized bed or packed bed, which have high surface area substrates, are most applicable. The fluid composition, chemistry and physical parameters are easily changed and controlled where necessary. The challenge then is to correlate rate data from different reactor types and ultimately to determine whether the results can be meaningfully applied to scaling in a power station or reinjection aquifer.

3. RAPID COOLING

The discussion of the previous scaling results suggests that aging and polymerization, over relatively short periods of time, can reduce scaling. However aging is insufficient to completely eliminate scaling in the surface infrastructure and can also pose a risk through clogging of the injection wellbore. It was however observed at Wairakei that rapid cooling, over a few minutes to less than 50°C,was much more effective at suppressing silica scaling than slow cooling (e.g. in large tank) over a period of hours (Carey at al. 1996). It could be that rapid cooling to low temperatures nucleates more particles that do not grow as big and are less prone to aggregation.

Arnórsson (2000) reported that rapid cooling was highly effective atsuppressing amorphous silica deposition at Svartsengi and even better in the lower salinity fields of Námafjall and Nesjavellir. In subsequent work Gunnarssonand Arnórsson (2005) showed that scaling was effectively avoided from Nesjavellir power station fluids by rapid cooling in “capillary heat exchangers”, aging for 1-2 hours followed by dilution with steam condensate. Gunnarsson et al. (2010) reported that after 4 years of operation the “retention tank” at Nesjavellir had <1 to 3 mm of scale and that the fluid was being successfully reinjected.

Given the success of rapid cooling for suppressing silica scaling in Iceland we have embarked on an experimental programme to demonstrate the effectiveness of this technique at Wairakei. The aim is to produce silica colloids of small size that do not aggregate and can be safely injected.

In recent larger scale field experimentsat Wairakei we have shown that rapidcooling, keeping colloidal silica particle size low, and *static*aging for a sufficiently long period (i.e. much longer than the few hours previously accepted as being sufficient to minimize monomer concentrations)produces a stable colloidal suspension which did not aggregateor deposit.

The result of a typical experiment is shown in Figure 4 where rapid cooling and prolonged aging was highly effective in suppressing silica scaling. However the scaling rate appears to be dependent on both particle size and concentration.

The size of the silica colloids in B was 17 nm (s.d. 7 nm). In C the total silica was 541 mg/L and monomeric silica 518 mg/L.

In one trial water at 47°C was used, with a silica colloid size of 64 nm and silica concentration of 947 mg/L. Over 33 days, 270,000 litres of water and 266 kilograms of silica was passed through the column. Silica deposition was assessed by taking 5 grams of ceramic beads from each end of the column for silica dissolution in hydrofluoric acid. The results showed that minimal deposition had occurred, with 2.65 and 0.31 mgsilica per g ceramic beads at the column inlet and outlet respectively. The nature of the deposition observed microscopically on the beads suggested that the deposited material was primarily insect parts and pumice dust that had entered the open ageing tank (Figure 5). In particular it is notable that the shine on the beads remained intact.

In another trial using static water aged at a higher temperature of 70°C with a silica colloid size of 91nm and total silica 1140 mg/L (monomer 305 mg/L) 60,000 litreswas passed through the column and 1.8 grams of silicadeposited. This silica was loosely adherent to the ceramic beads and the beads were not cemented together. Over the 12 day trial column pressures increased from day 1 in a linear fashion.

4. CONCLUSIONS AND FUTURE DIRECTIONS

Decades of experimental studies have been partially successful in solving the silica scaling problem. Operational protocols such as adopted in the Philippines make the problem manageable but are still require high maintained and periodic well work-overs.

Aging of water to allow silica polymerization without use of inhibitors has been shown to reduce scaling potential. Icelandic researchers have demonstrated that rapid cooling and dilution are very effective at suppressing deposition. Work is underway at Wairakei to undertake similar experiments to determine the effectiveness of this technique for New Zealand waters.

The adding of scaling inhibitors, pH modification and silica removal are all options for reducing scaling potential. However they are typically complex processes that are expensive, given the large volume of water that must be treated, and are prone to failure. A simple treatment which reduces scaling and enables fluid to be safely injected is the ultimate aim of our present study.

Colloid chemical and surface charge may change long after monomeric silica concentrations appear to have stabilized. This may have a significant effect on colloid aggregation and deposition.The effect of surface charge and zeta potential on colloid stability and silica deposition rates is under investigation.

In future work the first aim is to demonstrate the ageing and cooling process on a larger scale. For exampleby utilizing a three pond system; one filling, one ageing, and one emptying on a rotating basis and possibly with injection into a shallow well. The second aim is to demonstrate that cold and properly aged water injected into a hot aquifer does not induce silica deposition.

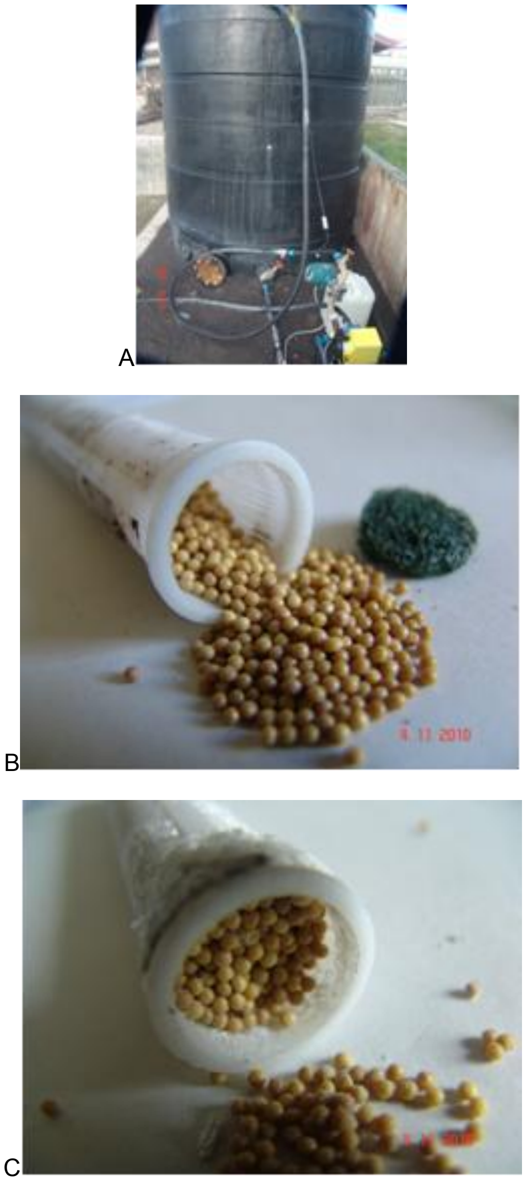

Figure 4: Wairakei prolonged aging; A – aging tank; B – no scaling after 186m^{3}of 50°C aged water passed through a column containing 1mm diameter ceramic beads; C – column blocked after passing 15m^3 of water containing excess monomeric silica

Figure 5: Ceramic bead showing trapped debris

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