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SILICA SCALING FIELD EXPERIMENTS

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ABSTRACT

The deposition of silica from geothermal fluid was investigated as a function of temperature and flow rate in 6" nominal diameter packed gravel beds and 1" pipes. Fluid, at temperatures between 120 and 180°C and silica at supersaturation ratios of 2.7 to 1.4, was passed through the pipes and gravel beds at flow rates of 3 and 30 l/min.

At the higher temperatures of 160 and 180°C, before the onset of rapid nucleation, the deposition rate was uniform across the length of the pipes at about 60 mg cm^{-2} year^{-1}. This corresponds to a linear growth rate of 0.3 mm year^{-1}. At the lower temperatures of 140 and 120°C where the silica was rapidly polymerising the deposition rate was found to decrease from about 150 to 12 mg.cm^{-2} year^{-1} between the pipe inlet and outlet. There appeared to be no substantial enhancement of scaling rate due to the high polymer concentrations at these lower temperatures and little difference between flow rates of 3 and 30 l/min.

In contrast to the behaviour in the pipes deposition in the gravel beds at 140 and 120°C was significantly different at the two flows. At 30 l/min the beds rapidly blocked with a soft porous deposit right at the fluid inlet, while there was very little deposition anywhere in the gravel bed at 3 l/min. At the higher temperatures of 160 and 180°C where the particle concentrations were assumed to be low, and molecular deposition was assumed to be the dominant process, deposition appeared to be uniform across the length of the beds.

INTRODUCTION

Development of a water dominated geothermal resource for power production may be severely constrained unless the problems of silica deposition in plant equipment, transmission pipelines and particularly in injection wells and the rock formation, can be avoided or minimised. After steam is removed for power generation, the dissolved solids become concentrated and the effluent may become supersaturated with respect to amorphous silica. Separation at the saturation temperature will minimise scaling potential but is particularly wasteful in utilising the available energy.

In addition to the silica solubility there are a number of other factors which affect the rate of silica precipitation. The mechanisms of these processes are in general well understood (Her (1979), Weres and Apps (1982), Jamieson (1984) and Kindle et al. (1984)). However lack of experimental data above room temperature and the complexity and interaction of the processes make it difficult to theoretically predict quantitatively the degree of precipitation. Field tests are the only alternative.

EXPERIMENTAL

Reject bore water at the required temperature was fed to a test manifold which distributed the fluid to two 150 mm diameter 3.3 m long gravel (8 mm mesh) packed vessels and two 1" diameter 45 m long steam pipes. The layout is shown in Figure 1.

The flow through each of the test units was controlled by globe valves and the fluid could be individually bypassed to a 350 mm diameter silencer where the flow could be measured accurately by bucket and stopwatch. Each unit and the inlet manifold were lagged with foil covered fibreglass and the lagging joints were sealed by aluminium tape. Thermometer pockets and sampling valves were fitted to the inlet manifold and just prior to the discharge valve on each unit.

Experiments 1, 2, 3 and 4 were nominally at temperatures of 180, 160, 140 and 120°C respectively. Inlet and outlet temperatures, pressures and flow rates were measured each day

1. Separated steam control valve
2. Separated water control valve
3. Manifold master valve
4. Test unit inlet valves
5. Sampling valves and thermometer pockets
6. Test unit discharge control valves
7. Bypass valves to measuring silencer
8. Bypass valves to bore silencer and weirbox

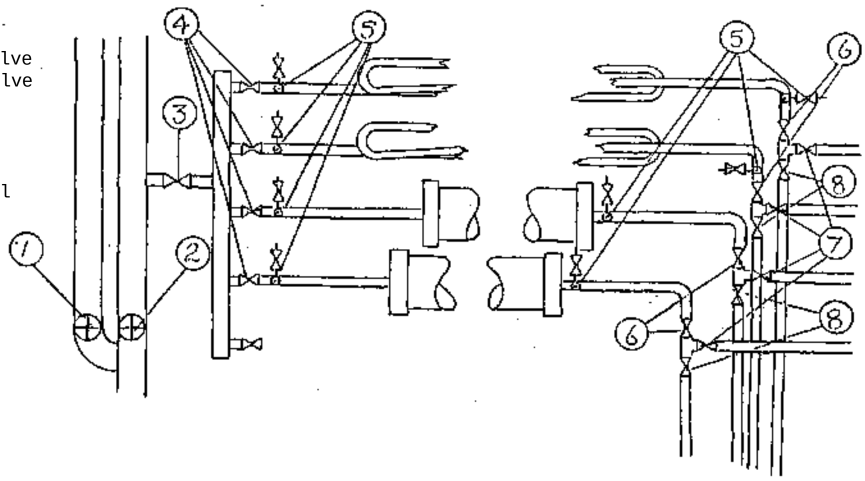

Figure 1: Test Unit Layout. •

during the duration of the experiments. Flows usually had to be adjusted upward due to silica fouling in the outlet control valves. The most severe problem was experienced with the valves controlling the 3 1/min flow since they were only open fractionally. This at times resulted in a reduced flow usually down to 1-2 1/min but in some instances the flow was completely stopped. Inlet temperatures usually varied by 3-4°C from day to day and conductive heat losses at 3 1/min resulted in temperature differences between inlet and outlet of between 5 and 10°C.

Inlet and outlet fluid samples were collected a number of times during each test run and analysed for total silica, monomeric silica and chloride. Silica samples were preserved by 1:10 dilution with an NaOH/EDTA mixture. Initially there were problems in obtaining a reproducible monomeric result. These were solved by collecting, at temperature, a sample in a insulated stainless steel vessel of about 1 ml capacity. The sample was then immediately transferred through a cooling coil into about 50 ml of molybdate reagent.

At the conclusion of each experiment the 1" pipes were dismantled and 10 cm sections were cut at selected positions (seven in total). Each section was scraped and the silica content of the scale was determined by first fusing with sodium bicarbonate, then diluting with an EDTA mixture, followed by analysis by atomic absorption (AA). From this information together with a knowledge of the surface area of the test piece it was possible to calculate the silica deposition rate.

The gravel for the beds was saturated by soaking for 1-2 weeks before filling the vessel. The weight of the vessel and gravel 'full of water^1 and 'drained' was determined before and after each experiment (except for experiment 1). This gave an absolute weight and density of silica deposited.

Tables 1 and 2 give the deposition rates in the pipes and gravel beds, Table 3 shows the changes in silica polymerisation between the inlets and outlets.

The estimated error in the total silica analyses, based on quality control standards and known solutions included with the samples on each analytical run, is 2-5%. The variation in the analysed silica concentration of the weirbox samples (with no sample collection problems) was in many cases greater than 5%. Total chloride analyses were performed with the sole function of checking for changes in fluid chemistry which may account for the silica variations. The chloride analyses were, within each experiment, consistent with each other and show the care required in field silica sampling.

TABLE 1: Silica Deposition Ratet in 1" pipes/(mg cm"^{2} year *)

Expt #			1	2	3	4
Nominal Temperature (°C)			180	160	140	120
Duration (days)			35	29	36	35
Pipe #1 3 1/min						
No.	Distance (m)	Time (s)				
0	2.7	27	62.3	85.5	76.9	86.9
1	7.1	72	52.7	73.9	56.7	35.4
2	13.5	137	66.7	61.7	30.6	28.7
3	20.0	202	65.0	73.6	28.4	23.3
4	26.9	272	53.8	59.7	24.7	21.2
5	33.8	343	92.7	75.2	18.2	20.9 (18.6)*
6	40.2	407	70.2	79.3	10.3	11.8
Pipe #2 30 1/min						
0	2.6	3	56.3	69.1	129.9	153.1
1	7.0	7	52.6	66.2	120.4	118.7
2	13.4	14	51.3	59.8	125.4	97.6
3	19.8	20	52.6	71.9	104.2	98.9
4	26.7	27	49.7	70.3	136.9	84.5
5	33.7	34	118.2 (100)*	55.5	117.2	78.2
6	40.1	41	61.7	66.2	128.3	65.2

* Adjacent test piece
t Experimental Error ±15%

TABLE 2: Silica deposition in 1 m^3 of gravelf/fkg.year"^{1})

Expt #	2	3	4
Nominal temperature (°C)	160	140	120
3 1/min	631	<151tt	183
30 1/min	714	1296*	731**

t porosity 48%
ft below the precision of the weighing method
* based on 24.8 days duration
** based on 16.5 days duration

TABLE 3: Typical Total and Monomeric Silica Concentrations

Temp °C	Saturation Ratio*	% polymerized inlet	outlet	
180	1.4	0-2%	0-2%	all units
160	1.6	0-5%	0-5%	"
140	2.0	30% (11%)T	44-48% 33-38%	3 1/min 30 1/min
120	2.7	29-30%	50-53% 33-41%	3 1/min 30 1/min

* Corrected for ionization, calculated assuming all as monomer
t "normal" level in separator

Sample collection for the monomeric silica determination became easier with decreasing temperature and resulted in better repeatability in the results. Each monomeric result was averaged over 2 or 3 determinations. The error in these was estimated to be 5-10%.

The estimated error of 10-15% in the deposition rate in pipes 1 and 2 is based on the actual recovery of silica in the digestion procedure, final analyses by AA, and incomplete scraping. This latter error was estimated from scraping two adjacent pieces.

Weighing of the gravel beds required a certain amount of art to get reliable results. The precision over the whole range was estimated to be 0.5 kg and the total weight measured (gravel + vessel + water) was of the order of 230 kg. Since the weight of silica deposited ranged from 0.4 to 5 kg there was a large uncertainty on these small quantities which were obtained by difference, about 30-50% except at 140 and 120°C at 3 1/min, where the uncertainty was even greater. However the calculated densities of the deposited silica were all about 2 g/cm^3 which is of the same order as that for vitreous amorphous silica (2.2 g/cm^3). This agreement gave some confidence in the weighing method.

RESULTS

Total and Monomeric Silica Measurements

At all temperatures and flows there was little change in total measured silica concentration between the inlet and outlets. Monomeric silica concentrations at 180 and 160°C were the same at inlet and outlets for all units within experimental error.

At 140°C severe problems were experienced in maintaining a "normal" water level in the separator. About midway through this experiment the adjustment of the water level was abandoned and the separator was run in a "flooded" condition. It appears a combination of physical and chemical factors meant that the difference in residence time between "normal" and "flooded" was of the same order as the induction time before rapid polymerization. At a "normal" water level the inlet monomer and total silica concentrations were within 10% of each other while if the separator was "flooded" the concentration of monomer was lower by about 30%. On adjustment of the water level there was a rapid change (within 1-2 minutes) in fluid turbidity in the weirbox indicating an alteration in the colloid size (tinged blue at a "normal" level and milky in a "flooded" condition). The outlet monomer concentrations at 3 1/min were constant (just above anomalous silica solubility value at 140°C) irrespective of the inlet monomer concentrations. At 30 1/min the inlet and outlet monomer concentrations were the same except in the last few measurements before the gravel bed blocked. In this case the outlet monomer concentrations were near the calculated silica solubility value at 140°C.

Modifications to the separator substantially increased the mass flow and eliminated the problems experienced at 140°C. At 120°C there was little change in inlet monomer concentrations with changes in separator water level and the fluid in the weirbox was clear at all times. The silica was substantially prepolymerised before reaching the inlet manifold and as at 140°C the silica was more polymerised after passing through the pipes and vessels at 3 1/min.

Deposition in Pipes

Initial deposition rates at a residence time of about 3 s, increased with decreasing temperature. At 180 and 160°C the rate is relatively uniform (within the experimental errors) along the length of the pipe and about the same at both flow rates. The sharp increase at section 5 at 180°C at both flows cannot be adequately explained. At 140°C and 30 1/min the deposition rate was about double the rate for the higher temperatures but also uniform along the pipe. However at 3 1/min the deposition rate was significantly lower and decreased as a function of time. At 120°C there was an exponential decrease in deposition rate with overlap between the 3 and 30 1/min flows. There was a reasonable similarity between the deposition curves at 3 1/min at 140 and 120°C (Figure 2).

The nature of the scale deposited changed with temperature. At 180 and 160°C the scale was hard and vitreous and difficult to remove. At lower temperatures the scale, although still dense, was more easily removed particularly at the high residence times i.e. lower flow rate. This may be explained in part by a greater ratio of corrosion products to silica. SEM micrographs showed a change in the 'cemented' spheroid particle size with decreasing temperature and flow rate but only a minor change in porosity. Magnetite (Fe_3O_4) was the only crystalline phase present in all the scale samples.

Deposition in Gravel Beds

At 140 and 120°C the vessels at 30 1/min rapidly blocked with a soft porous amorphous silica deposit at the fluid inlet. At 120°C the gravel chips were not cemented together after this first blocked layer. Very little silica deposited in these two experiments at 3 1/min with no cementation of gravel anywhere in the vessels. A glassy deposit could be observed on the loose chips under an optical microscope. The high rate of deposition at 140°C and 30 1/min was similar to the high rate observed in the steam pipes. At 160°C about the same

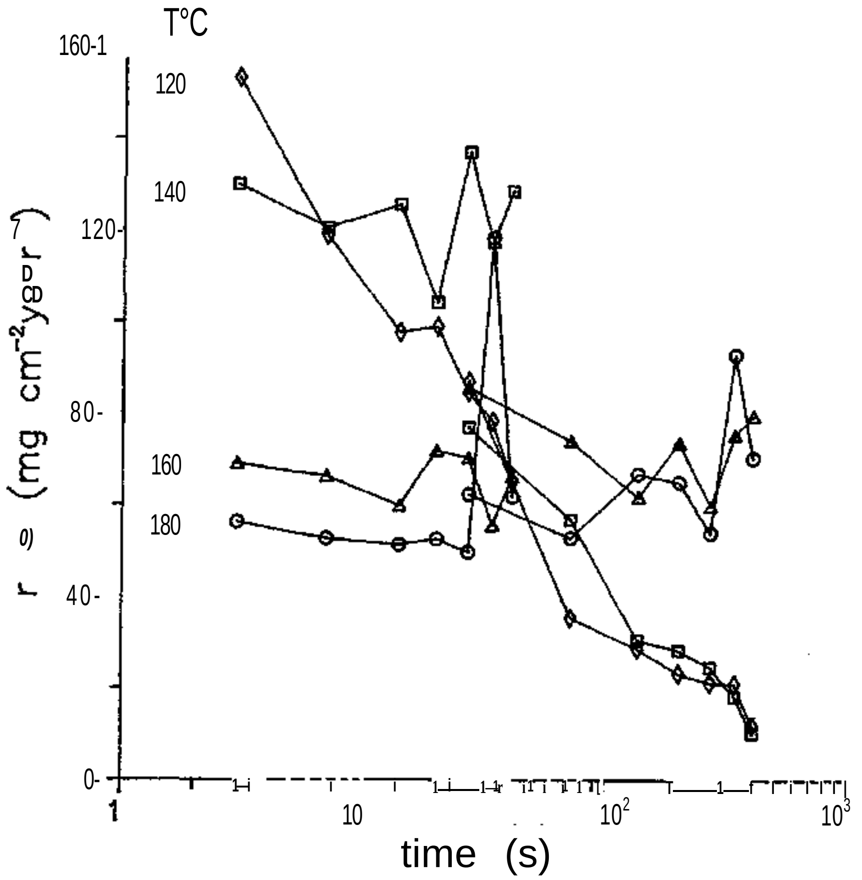

Figure 2: Silica Deposition Rate versus Residence Time.

quantity of silica deposited at both flows and it seems likely that similar behaviour would have been observed at 180°C. At these higher temperatures and at both flows the silica appeared to be uniformly deposited along the length of the gravel beds.

DISCUSSION

The rate of deposition on a known surface area has been studied experimentally by Bohlmann et al. (1980) using packed columns of various forms of silica. The rate of linear growth of amorphous silica in cm/min was given by;

$$R = 3.1 ([S1(0H_4)] - [Si(0H)_4]_{eq})^* [0H"]0.7$$

in 1 m NaCl in the pH range 5-8 and temperatures from 60 to 120°C. They found no significant effect of salinity between 0.09 and 1 molal. In all cases monomeric silica was found to be the depositing species. There was little or no tendency for deposition of previously polymerised silica and no dependence on flow rate was found.

Although their equation is only valid to 120°C the calculated deposition rates are similar to the experimentally determined deposition rates listed in Table 1. At 180 and 160°C the calculated deposition rates are 40 and 110 mg/cm^2 year respectively. Reducing the monomer concentration by 5% at 160°C reduces the calculated deposition rate to 84 mg/cm^2 year. At 140°C, assuming 10% polmerisation at the inlet, the deposition rate is calculated to be 123 mg/cm2 year. At 120°C with the inlet and outlet monomer concentrations of 20 and 50% of the total silica, the deposition rates were calculated to be 133 and 9 mg/cm^2 year respectively. This suggests that the drop in scaling rates along the pipe at 140 and 120°C may be attributed to the decrease in monomeric silica concentration causing a corresponding decrease in the molecular scaling rate. Deposition rates were lowest when the monomeric silica concentration was close to the amorphous silica solubility value even though between 40-50% of the total silica was present in polymeric form.

The lack of overlap between the two sets of deposition results in the pipe runs at 140°C are difficult to interpret because of the problems previously discussed. The 3 1/min results at 140°C are indicative of a fluid with decreasing monomer concentration across the pipe length while the 30 1/min results are similar to the results at 180 and 160°C. In this experiment the induction time before the onset of rapid polymerisation was short, less than 1 minute. The pipe at 3 1/min was attached to the end of the manifold so that the extra residence time, before entry into the pipe, may have been about the order of the induction time.

Recently Jamieson (1984) presented a model for scale formation from geothermal brines. With this model calculated mass transfer rates of silica particles, together with monomer deposition rates, have been used to rationalise the observed scaling rates in various field tests. That the observed scaling results for steam pipes were close to that predicted for monomeric deposition and did not appear to be greatly enhanced by the presence of a high concentrations of rapidly polymerizing silica may be explained by assuming the formation of large colloidal particles (up to 500 nm). Particles of this size would have low velocity and inertia and in addition may be charged and size stabilised. A direct comparison with the model could not be made because the size and number density of the particles was not known. The changes in total silica between inlet and outlet were usually within the uncertainties of the silica determination so that the identity of the depositing species could not be determined.

Turbulence and hydrodynamic factors are known to affect the deposition rate. The flow was considered to be turbulent at both rates. There appeared to be little dependence on flow rate at 180 and 160°C which may be expected if the mechanism was assumed to be dominated by molecular deposition. At 120°C the exponential decrease in deposition as a function of time can be explained by continuous removal of monomer by polymerisation and direct chemical deposition rather than a flow effect.

However, greater hydrodynamic effects, if any, would be expected to be observed in the gravel beds. At the 1" inlet to the bed a small amount of gravel was in direct contact with the full fluid flow and overall the area of rock in direct contact with fluid was far greater than with the walls in the 1" pipes. These bed conditions would be more conducive for particle deposition than those in the pipe runs. The observation of uniform deposition on the chips along the length of the beds at 180 and 160°C is consistent with the results in pipes. However at 140 and 120°C at 30 1/min the beds rapidly blocked with a soft, porous, loosely adhering silica deposit right at the fluid entrance. The chips at 30 1/min and 140°C were also solidly cemented together along the pipe length to the outlet. In this case it appears that particulate plugging at the bed inlet and direct chemical (monomeric) deposition were occurring together. Little deposition took place at 3 1/min. The porous nature of the deposits suggests that there was little monomer available for cementation or that the particle deposition rate was greater than the monomer deposition kinetics. There appeared to be slightly less deposition at 140 than at 120°C at 3 1/min. This may have occurred because of the larger more stable colloidal particles present at 140°C.

Recently Itoi et al. i.1984) studied the deposition of silica scale in a porous column using Otake water at an experimental temperature of 92°C. This fluid had a silica concentration of 552 ppm (supersaturation ratio about 1.4) and a pH of 8 at this temperature. The results showed that silica deposited mainly in the upper part of the porous column with a decrease in permeability by an order of two compared with the initial value. In the deeper portions, the change was insignificant. At a given flow rate .the amount of silica deposited decreased rapidly with depth and progressively increased with increasing flow rate. Their results are in good agreement with the behaviour observed at 140 and 120°C respectively.

SUMMARY

1. Deposition in the 1" pipe runs at all temperatures was found to be related to the monomeric silica concentration. There appeared to be little tendency for deposition of polymeric silica and the deposition rate was not greatly enhanced even with relatively high concentrations of both polymer and monomer.

2. Colloidal particles deposited in the gravel bed mainly at the pipe inlet. The greater rock/fluid ratio and increased turbulence meant a significant difference in deposition at different flow rates.

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