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ESTIMATING THE QUANTITY OF SILICA DEPOSITED IN THE RESERVOIR *AROUND* AN INJECTION WELL

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SUMMARY – A month long silica-scaling trial, using waste fluid at 110°C determined quantitatively the silica deposited in SS pipes packed with zirconia beads. This data was used to derive the silica deposition rate, which was used to model silica deposition in the reservoir surrounding the injection well. The injection well had exhibited decreasing injectivity due to silica plugging. The results of the simulation showed that negligible silica was depositing greater than 40 m from the well. A new well was drilled **75 m** from the old injection well and there was no evidence of any recent silicification in the cuttings.

1. INTRODUCTION

Borefield shallow reinjection of 140 t/hr of effluent at about 110 °C into the reinjection well began on 7 June 1991. Over that time, injection has declined steadily to the present 30-40 t/hr, which is less than the required reinjection capacity. **A** replacement well was planned but operational requirements to minimise connection costs as well to facilitate easy access, necessitated drilling close to the present well site. The **risk** in doing so was that the bore may intersect the silica-plugged reservoir, which will have low permeability and consequently low injection capacity. The purpose of this study **was** to determine the minimum distance that the new well should be sited from the old injection well.

2. EXPERIMENTAL DESIGN

The experimental methodology is described fully by Mroczek et al., (2000) and is only briefly described here. Four 3 m long stainless steel (SS) pipes (31.8 mm OD, 28.5 mm ID), were packed with 2 mm diameter zirconia beads. The pipes were manifolded together and the flows through each pipe were regulated at the outlet. To ensure minimum fluid residence time in the manifold, a significantly greater volume of fluid was piped **to** the manifold than the combined flow through the packed pipes and the excess was piped to waste downstream of the manifold. The fluid was cooled at the pipe outlets to suppress flashing. A sampling port and thermocouple were placed at the end of each of the pipes. The pipes were insulated with aluminium-foil-covered fibreglass preforms. A schematic of the piping arrangement is shown in Figure 1.

The zirconia beads, which had previously been used for scaling experiments, were cleaned twice with hydrofluoric acid. This is did not completely remove all of the silica but the levels were much lower than what was subsequently deposited in the scaling test. The beads were held in place at both ends of the pipe by stainless steel gauze.

3. EXPERIMENTAL PROCEDURE

A portion of the fluid from the reinjection line at approximately 110°C and **4** bg, **was** diverted to the experimental equipment. The inlet temperature, outlet temperatures and volumetric flowrate out of each of the pipes were measured once a day. Fluid samples were collected only on the first day, shortly after the experiment commenced, and analysed for dissolved and total silica. The total silica was analysed by atomic absorption spectrometry while the molybdate active silica was measured using a W spectrophotometer using the yellow-β silicomolybdate method. The molybdate active silica was assumed to be equal to the dissolved monomeric silica.

After completion of the experiment the pipes were disconnected, cut in half longitudinally and the beads were sampled at selected positions from the inlet to the outlet. The quantity of silica deposited was determined by dissolving the silica in dilute hydrofluoric acid and analysing the washings.

4. RESULTS

The experiment successfully ran for **28** days without any shutdowns or other operational disturbances that may have affected the results. The fluid temperatures and mass flows are shown in Figure **2.** The mass flows decreased steadily over the duration of the experiment. The wire gauze holding the beads in were not blocked with pipe scale or fines and it is likely that the reduction in flow was primarily caused by scaling across the control valves which were only slightly cracked open to maintain the required flow rates.

The monomeric (dissolved) and total silica agree well (Table 1), which shows that no silica

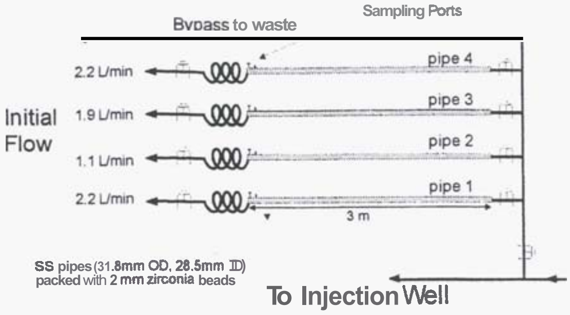

Figure 1. Experimental piping arrangement

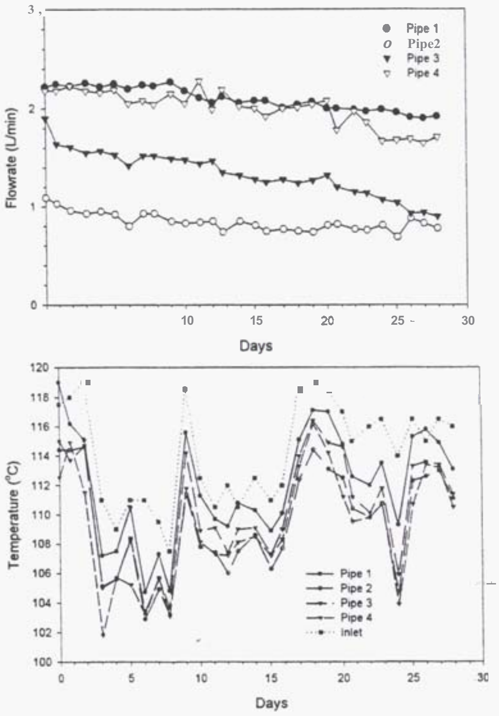

Figure 2. Fluid flows through the pipes and measured temperatures.

Figure 3. Amount of silica deposited down the pipes.

Table 1. Monomeric and total silica. The samples for monomeric silica were diluted 2x (*) and 7x(‡) and acidified with 1 N HCl to approx. pH 3-4.

	Monomeric mg/l	Total mg/l
Pipe 2	646*	646
Pipe 2	644‡	
Pipe 4	670*	669
Pipe 4	663‡	

Table 2. Amount of silica deposited down the pipes.

Pipe	Distance m	Silica mg/g beads
1	0.1	16.2
1	1	16.7
1	2	17.1
1	3	15.7
2	0.1	16.4
2	1	17.3
2	2	17.2
2	3	17.6
3	0.1	17.2
3	1	17.5
3	2	17.9
3	3	17.8
4	0.1	15.5
4	1	16.5
4	2	17.1
4	3	17.2
blank*		0.18

*The beads were washed twice with HF and the “blank” is beads prior to use in the scaling experiment.

polymerisation takes place in the time taken for the fluid to flow through the pipes. This is very important as it is assumed in the data reduction that the scaling is due to the direct deposition of dissolved silica, not polymers or colloidal particles. Difficult to explain is the large difference in silica measured between pipes 2 and 4. The data analysis shows that only a small fraction the silica is removed (less then the analytical error) so the outlet concentrations of the fluids should have been similar. Unfortunately it was not possible to sample the inlet fluids. The explanation may be that these water samples were collected soon after starting the experiment and the initial scaling rate on the “cleaned” beads

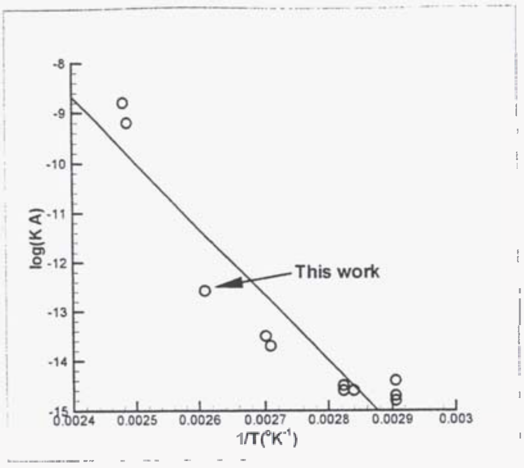

Figure 4. Deposition data plotted with earlier results using Wairakei fluid.

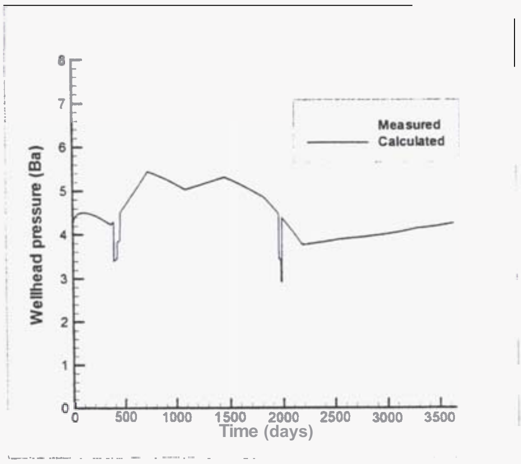

Figure 5. Match to injection wellhead pressure. Note that although the WHP is almost constant the injection rate drops from 44 kg/s to 7.5 kg/s over the simulation period.

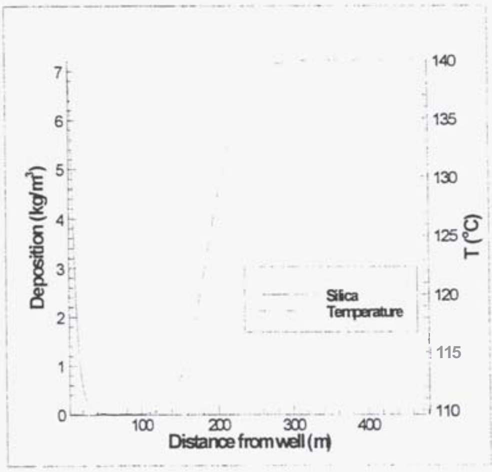

Figure 6. Silica deposition and reservoir temperature at the end of the simulation

may have been high until silica was depositing on silica.

The amount of silica deposited per gram of zirconia beads down the pipes is listed in **Table 2** and shown in Figure **3.** The amount deposited is very similar for all the pipes, irrespective of the flow rate, which again supports that silica polymers and colloidal particles are not depositing. It also shows that the concentration of dissolved silica is essentially the same throughout the pipe, i.e. the driving force for deposition is the constant from beginning to end. The beads were sampled over a ± 35 mm range of the distance given in Table **2.**

5. ANALYSIS OF SILICA DEPOSITION

The experimental silica deposition data in the pipes (Table 2) was analysed using the numerical methods described in Mroczek, et al., (2000) and the references therein, to fit a reaction rate of the form

$$R = sign(1-\frac{C}{C_{sat}})KA\left(1-\frac{C}{C_{sat}}\right)^2$$

where K is the reaction rate (moles/m^2/s), **A** the reactive surface area (m^2), **C** the silica concentration and **C$_{sat}$** the equilibrium silica concentration.

The results from this geothermal fluid appear in keeping with the results from Wairakei (Figure **4)** and for modelling we assume the same activation energy.

Based on the shallow geology of the field and well tests the reservoir about the injection well was modelled as a homogeneous reservoir with a thickness of **100** meters and **a** permeability of **0.3** Darcy initially at a temperature of **140°C and** a pressure of **14** bars with the fluid saturated in silica. The temperature comes from the original well testing

Fluid at **110°C** containing **662** ppm silica was injected at a rate taken from field annual measurement reports. Two properties of the reservoir control the change in permeability by silica deposition, the area available for deposition of silica per kg of fluid and a geometrical parameter ϕ_c that is a measure of porosity remaining when the permeability reaches **zero.** These parameters were estimated by matching modelled and measured wellhead pressure over the period **1996-2001**.

The best match was obtained with ϕ_c=0.02 and **A** (m^2/m^3) = **5.4.** This value of **A** is much smaller than one would expect for a porous media and suggests fluid is flowing in a small number of fractures. Figure 5 shows the pressure in the injection element offset to aid comparisons with measured WHP.

Figure *6* shows the density of silica precipitation about the injection well. The units are kg silica per cubic meter of rock. As can be seen most of the deposition takes place near the well and there is little deposition more than **40** m from the well.

6. DISCUSSION

The critical assumption **was** choosing the thickness of the reservoir. **A** 100 m reservoir thickness was chosen as a lower bound on the reservoir thickness based on local geology and loss zones in **the** well. Injection is into a rhyolite formation, which is around 100 m thick near the injection well but the permeable region is probably not limited to this. Nearby wells showed shallow permeability in the depth range 310 - 490 m and interference tests gave kh (permeability-depth) values of 500 - 1500 Darcy meters. Ten Darcy would be very much an upper bound on k with 1 Darcy more likely, giving a reservoir thickness between 50 - 1500 m. Using a conservative estimate of 100 m for the reservoir thickness means that the minimum safe drilling distance is **40** m out fiom the present site of the injection well.

Although the modelling shows that there is no silica depositing at **40** m, the reservoir temperature does not fully recover till *260* m out fiom the well. Simulation of injection into a cooler reservoir shows that reservoir temperature has only a small effect on the injectivity and lifetime of the injection reservoir.

The new injection well was sited and drilled 75 m fiom the old injection well. At the time of writing the well injectivity tests had not been completed but there was no evidence of any recent silicification in any of the cuttings.

7. CONCLUSIONS

The techniques developed by Mroczek et al. (2000) have been used for **the** first time to successfully site a new injection well close to the site of old well which had exhibited decreasing injectivity due to silica plugging in the surrounding aquifer. The experimental equipment, methodology and simulation are straightforward. However it must be certain that the silica plugging is primarily caused by the direct deposition of amorphous silica and not polymers or colloidal particles. Confidence in the result is strengthened by reliable information on the injection aquifer.

8. ACKNOWLEDGEMENTS

We would like to thank the field developers and owners for permission to publish this study.

9. REFERENCES

Mroczek E.K., White S.P. and Graham D., 2000. Deposition of silica in porous packed beds - Predicting the lifetime of reinjection aquifers. ***Geothermics*, 29**, 737-757.