LOW TEMPERATURE WASTE WATER INJECTION EXPERIMENTS AT THE BAC-MAN GEOTHERMAL FIELD, PHILIPPINES

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ABSTRACT

Strict environmental standards for disposal of waste geothermal brine to surface waters has severely constrained testing of production wells at the Bacman geothermal field The alternative is to reinject waste brine but this is constrained by the high potential for silica deposition in pipelines and the receiving injection wells, even at relatively high temperatures (e.g 160 C) By taking into account the kinetics of silica polymerisation and precipitation, it has proven possible to control deposition to occur where physical removal of siliceous solids can be conveniently undertaken Experiments in reinjecting waste brine at low (ambient) temperature have been successfully undertaken at Bacman based on these concepts Of particular importance to the process is (1) maximising the amorphous silica supersaturation of the separated water, (2) cooling the fluid as rapidly as possible, and (3) maximising the fluid residence time prior to reinjection.

KEYWORDS

Injection, Geochemistry, Philippines, Corrosion, Silica

INTRODUCTION

The Bacman geothermal power project is located on the boundary of the towns of Bacon, Sorsogon and Manito in Albay Province in the Philippines. A first stage geothermal power development of 110MW in the Palayan Bayan field sector and a 20 MWe extension in the Cawayan sector have been commissioned in 1994. A further 20 MWe plant is currently being developed in the Botong sector and is expected to be in commercial operation by early 1996 (Figure 1).

As with any field development, the wells at Botong have had to be discharge tested to characterise mass flow, enthalpy and fluid chemistry to confirm resource characteristics and optimum power plant size. Conventionally, testing of exploration and delineation wells is achieved by flowing the wells to atmospheric silencers with separated steam and brine discharged to atmosphere. Because of strict environmental standards that exist in the Philippines, it was readily recognised that not all of the waste brine could be discharged directly to surface water ways. Two alternatives for disposal of brine from well testing were then considered - hot or cold piped reinjection

Hot injection was not favoured at Botong because of the need to build a welded and supported pressurised injection line ahead of any commitment to develop the sector This thus stimulated interest in disposal of brine initially cooled by flash to atmosphere pressure and then piped in low pressure, unsupported, light weight piping systems to temporary injection wells. The most significant constraint on piping and injecting geothermal effluent at relatively low temperatures is from silica deposition which readily occurs in surface piping and reinjection wellbores. This occurs because high temperature geothermal brine is invariably saturated with respect to quartz and as the temperature of the brine decreases upon flashing the brine becomes progressively more supersaturated with respect to amorphous silica or other silica polymorphs (see for example Barnett and Garcia, 1993)

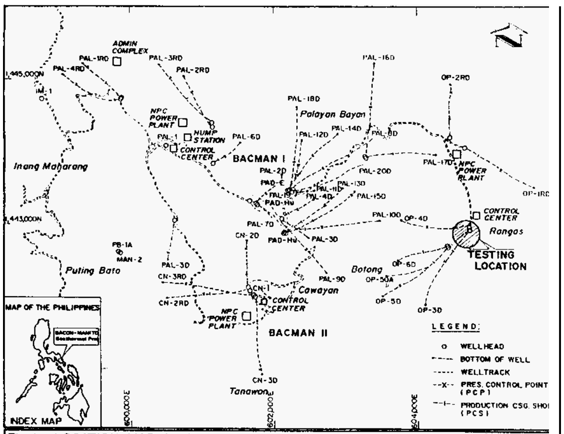


Fig. 1 LOCATION MAP OF BGPF WELL TARGETS
BACON MANITO GEOTHERMAL FIELD

The removal of silica from separated brine by precipitation prior to injection has been attempted at the Otake and Hatchobaru geothermal fields in Japan In both cases, full-scale injection was implemented but decreases in the injectivity of wells occurred (Inoue and Shimada, 1985). This has led to further experimentation on waste water injection at Otake (Itoi et al, 1989). Although for years the separated brine at Cerro Prieto, Mexico has been disposed of to a 16 sq km solar evaporation pond, reservoir pressure declines and mounting surface disposal problems have led to pilot scale experiments in brine treatment prior to injection (Hurtado et al., 1989, Weres and Tsao, 1981) In Iceland, controlled silica precipitation has been tried in Reykjavek (Gudmundsson and Einarson, 1989) and Svartsengi (Thordarson and Tomasson, 1989) geothermal fields.

KINETICS OF SILICA DEPOSITION

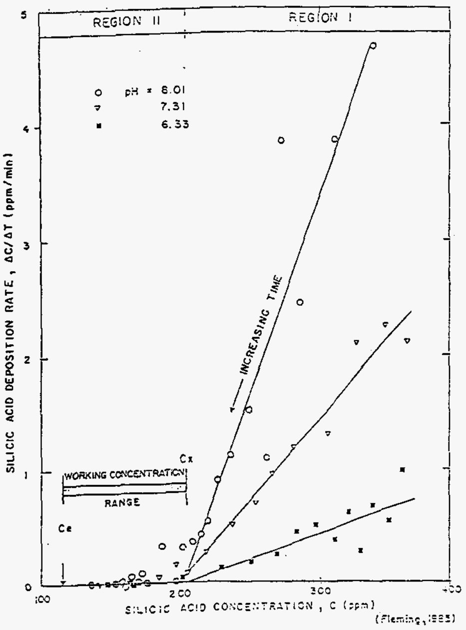
In conceptually designing a cooled brine injection scheme we initially felt that it should prove possible from a consideration of silica polymerisation and deposition kinetics to constrain silica deposition to occur in areas of the surface facilities where physical removal could be readily undertaken, rather than have deposition occur in an uncontrolled manner within surface piping and injection wells.

Current understanding on silica reaction kinetics suggests that overall deposition occurs in three distinct stages homogeneous nucleation of amorphous silica particles from silicic acid, continued growth of these particles via silicic acid polymerisation at their surfaces, and a surface rearrangement process whereby chemisorbed silicic acid molecules condense fully into solid silica At low initial silica supersaturation, S_0, the onset of polymerisation shows an induction period. This becomes progressively shorter with increasing supersaturation For the case of discharges from wells in the Botong sector, S_0 is very high (up to 1400 mg/kg in brine flashed to atmosphere) and the induction period is thus negligibly short

The amorphous silica kinetics model of Fleming (1986) was adopted in finalising a cold reinjection scheme for the Botong sector. The model recognises two distinct kinetic regimes as shown in Figure 2. In Region I, reaction rates are relatively fast and involve a condensation polymerisation reaction between a hydroxyl group on the amorphous silica surface and a dissolved silicic acid molecule. This polymerisation continues and approaches a pseudo equilibrium solubility value which is higher than the true thermodynamic solubility. In Region II there is a slower surface rearrangement, that proceeds from the pseudo equilibrium point, C_x to true equilibrium.

In the design of our cold reinjection scheme we have taken advantage of these different regimes in such a way as to have the bulk of the supersaturated portion of silica in the cooled brine polymerise and settle in surface ponds prior to injection, with hold-up time of brine in the ponds minimised on the basis of pseudo equilibrium considerations

Fig.2 Silicic Acid Deposition Rate at Pseudo-equilibrium Point (Cx)



(Fleming, 1983)

EFFLUENT REINJECTION SCHEME

The basic considerations that went into our design of the effluent disposal system (EDS) were to maximise the amorphous silica supersaturation of the separated water, to cool the fluid rapidly as possible, and to maximise the fluid residence time in sumps prior to reinjection

The design of our **EDS** at BacMan is shown in Fig 3 Two phase fluid from well OP-4D is flashed to an atmospheric silencer with the separated brine rapidly draining to sump 1 located on the same well pad At the outlet of sump 1, an oil trap was installed to filter out any solids, oil and other drilling wastes that may be discharged The effluent was then piped into a network of open canals and pipes to sump 2 located near the OP-2RD well pad at approximately 1 km distance from the OP-4D wellpad. Baffles were installed in the second sump to increase residence times. A flow of fresh water was tapped locally and piped to mix with the outflow from sump **2** to dilute the brine flow to the injection well OP2RD. The EDS was run for a number of months using initially well OP-4D as a source of brine and then several other production wells with different enthalpies, silica concentrations and brine flows

CHEMICAL SAMPLING AND ANALYSIS

Water samples were collected at different locations throughout the EDS as shown in Figure 3. Fluid pH was measured with a glass electrode while water temperature was determined using a digital thermometer. Chloride was determined by Mohr titration. Monomeric and total silica were measured colorimetrically using the standard silicomolybdate method. Monomeric silica was determined without digestion. Dissolved oxygen (DO) was measured using a specific-ion electrode.

The most important chemical parameter monitored during the effluent injection trial was the concentration of monomeric silica at various points in the EDS. In this work, the silica saturation index **(SSI)** is defined as the ratio of monomeric silica to the pseudo equilibrium solubility Cx, as calculated by Fleming (1986). For the cold EDS, a maximum **SSI** of 1.7 based on the amorphous silica solubility at a temperature range of 21-35 deg. C was found to be equivalent to an **SSI** of 1.0 at pseudo equilibrium conditions.

The equilibrium amorphous silica solubility C_e can be calculated from the equation of Fournier and Rowe (1977), which is valid from 0 to 250^0C, or the equation of Fournier and Marshall (1983) which is valid from 90 to 340^0C

RETENTION TIME

The retention time for waste brine within the EDS prior to reinjection was measured through each section of the system A total retention of 2 hours and 39 minutes was determined between the inlet to sump **1** and the outlet of sump 2 for an average brine flow from well OP-4D of 17 kg/sec During this period monomeric silica concentrations were reduced by polymerisation reactions down to the pseudo equilibrium concentration of 200 mgkg at 25^0C For the individual ponds, the longest effluent residence time t_r of approximately two hours was achieved in sump 2, attributable to the extensive baffling arrangement Sump 1 with no baffles had as much lower t_r of only 20 min

SUMP EFFICIENCY TEST

Tests were conducted to determine the efficiency of the EDS in reducing concentrations of monomeric silica prior to injection of waste brine, and silica polymerisation rates. Results are tabulated in Table 1 and are presented graphically in Figure 4 Three sections of the EDC were evaluated in this test - Sector **I** consisting of sump 1 (without baffles), Sector **II** consisting of the pipelines, open canals and catchments between sump 1 and 2 over a total distance of 1150m; and Sector III consisting of sump 2 (with baffles) located immediately upstream of the reinjection well OP-2RD

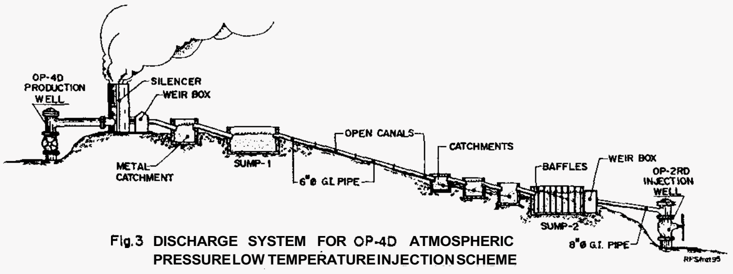


Fig.3 DISCHARGE SYSTEM FOR OP-4D ATMOSPHERIC PRESSURE LOW TEMPERATURE INJECTION SCHEME

Table 1 Polymerization and Sump Efficiency Test

SAMPLING POINT	WATER TEMP	Cl	$mSiO_2$[1]	$tSiO_2$[2]	SSI[3] (Cx)	NET $mSiO_2$	NET $tSiO_2$	% EFFICIENCY[4] POLYT'N	% EFFICIENCY[4] DEPT'N	POLYT'N RATE"	DEPT'N RATE"
	(°C)	ppm				ppm				ppm/min	
1. Sump No. 1-IN	84	11519	525	1285	1.19						
						283	220	53.9	17	14.2	11.0
2. Sump No 1-OUT	40	10749	242	1065	0.98						
						12	19	5.0	1 8	0.63	1.0
3. Sump No.2-IN	34	10728	230	1046	1.00						
						26	43	11 3	4.1	0 22	0 36
4. Sump No.2-OUT	30	101 11	204	1003	0.95						
OVERALL					0.24	321	282	61 1	21 9	2 00	1.8

Note: 1. $mSiO_2$ - **monomeric silica**

2. $tSiO_2$ - **total silica**

3. SSI (Cx) - **silica saturation index based** from **$mSiO_2$ at pseudo-equilibrium**

4. % Efficiency - **Net SiO_2** (mono **or total**) .... **x 100** **initial Si&** **(mono** or **total)**

5. **Polymerization**Rate **(Polyt'n)** - **Net $mSiO_2$** ------------- **Net Time**

6. **Deposition Rate (Dept'n)** - **Net $tSiO_2$** ------------- **Net Time**

In Sector I, the initial effluent temperature and monomeric [SiO_2] (concentrations are denoted by square brackets) at sump 1 inlet were 84^{0}C and 525 mg/kg respectively **A** large temperature drop of 24^{0}C was observed between the inlet and outlet of sump 1. This corresponds to a significant drop in [SiO_2] of approximately 54%. The polymerisation rate was also high at 14.2 mg/kg-min and a deposition rate of 11 kg/mg-min was calculated - the highest encountered in the trial These observations are attributed to the large temperature drop in the effluent and the high initial silica supersaturation, even though the retention time in sump 1 was only about 20 min. Petrographic analysis of precipitates collected from sump 1 showed these to be opal gel **(A.** G. Reyes, pers. comm).

In sector II, the [SiO_2] was further reduced by 12 mgkg, from 242 mg/kg which resulted in a low polymerisation efficiency of approximately 5%. Polymerisation rates (0.63 mgkg-min) and deposition rates (1 mg/kg-min) were much slower in this section of the EDS. The rates are interpreted to be due to the small temperature drop of only 6 C. and the short effluent retention time of only 19 minutes.

The second largest reduction in [SiO2] (of 11.3%) was found to occur in Sector III, even though the incoming effluent had an [SiO_2] of 230 mg/kg, was already substantially cooled .**(34^{0}C)** and was essentially at saturation with respect to C_X. Although a polymerisation rate of only 0.22 mg/kg-min was determined, the deposition efficiency in this sector was the second highest at 4.1%, with a deposition rate of 0.36 mg/kg-min We attribute the high polymerisation and deposition efficiency to the long retention times of effluent in this section of the EDS. This section is therefore considered the most efficient part of the EDS The high sump efficiency is mainly attributed to the extensive baffling system installed.

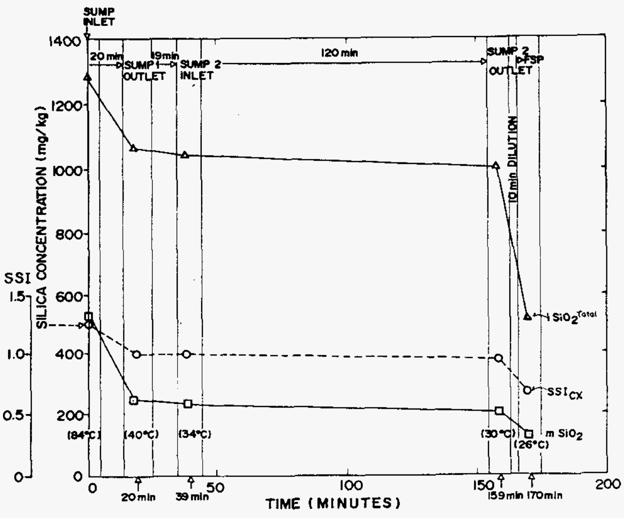


Fig.4 EFFLUENT RETENTION TIME AND SUMP EFFICIENCY TEST

The overall percentage of silica undergoing polymerisation and deposition in the EDS is calculated at 61% and 22% respectively. This corresponds to a polymerisation rate of 2.0 mg/kg-min and a deposition rate of 1.8 mgkg-min for total effluent residence time of 159 min (2.63 hr)..

CHEMICAL MONITORING OF REINJECTION FLUID

The discharge testing of well OP-4D was intermittent due to operational constraints. Atmospheric reinjection of well OP-4D effluent into OP-2RD commenced in November 1990. Routine chemical monitoring of the effluent being injected was maintained at the final sampling point (FSP) located on well OP2RD branchline.

Initially in November 1990, with only sump **1** in operation, the SSI at FSP ranged from 1.02-2.67 over an injection temperature range of 25-31^{0}C. These values vary from acceptable to unacceptable. **A** recalculation of the **SSI** based on a liquid temperature of 54°C measured just within the free standing liquid column in well OP-2RD indicated a range of 0.75-1.79. The high **SSI** values are attributed to slightly acidic pH's at this time which averaged 5.8 at sump no. 1. This acidity appears to have been caused by condensation of steam and oxidation of H2S from a submerged wellhead bleedline discharging into sump 1. This resulted in a significant reduction in the rate of polymerisation of silica polymerisation in sumps 1 and 2.

After sump 2 was commissioned and the wellhead bleed to sump1 was stopped, the SSI and FSP declined to acceptable levels from 1.27 to 1.02. At the top of the liquid level in OP-2RD, recalculated SSI values ranged from 0.73-0.89, all lower than for saturation of amorphous silica at pseudo equilibrium conditions.

OP-4D was re-discharged January 23-24, 1991 with a maximum injection rate to OP-2RD of 18 4 kg/s, a highest [SiO_2] of 163 mg/kg and an injection temperature of 26^{0}C at FSP **SSI** values at this time were all below saturation based on the pseudo equilibrium point, ranging from 0 47-0 80 Silica polymerisation was favoured during this period because of a slightly alkaline pH in FSP samples which ranged from 7 **87-8** 22 Dissolved oxygen (DO) ranged from 6 6-7 4 **mg/kg**, well within the expected concentration range.

During a further discharge of OP-4D on the January 26, 1991, the highest [SiO_2] was only 159 mgkg which corresponded to an SSI value of 1.07 or 0.65 at the OP-2RD water level. Thus, silica deposition was unlikely to have occurred in the well. A higher DO was measured in the range of 6.9-7.8 mgkg (7.4 mgkg average).

On January 31, 1991, the effluent at FSP was diluted by fresh river water to hrther reduce the [SiO_2] to an under saturated condition at which the SSI at FSP was between 0.69-0.71 Similarly, the injection temperature also declined to an average of 24 1^{0}C (range 23.6-245^{0}C) DO concentrations were, however, stable at this condition over a range between 7.3-7.6 mgkg (7 5 mg/kg average) The diluting component had a DO of 7 6-8.2 mgkg and the steady value is indicated to be due to a lower solubility in water with higher salinity The chloride concentration at the FSP ranged from 3800-4600 mgikg.

During discharges following February 4, 1991, the total water flow rate (effluent and fresh water) injected reached a maximum of 27 kg/s A maximum water flow rate of 59 kg/s was injected from February 13-18 and the well was then shut The discharge of OP-4D was resumed on February 20 with a maximurn cold water injection flow rate of approximately 65 kg/s recorded on February 23 comprised of brine production from wells OP-4D, 5D, and 6D and fresh dilution water The overall monomerıc silica concentration during this period was only 198 mg/kg at FSP, corresponding to under saturated effluent with an **SSI** of 0 93 at the injection temperature of 29 C The maximum injection rate that was attained further indicated that the well had not been damaged by silica deposition in this or earlier trials during which the total volume of fluid reinjected into OP-2RD was approximately 184,800 m^3

CORROSION TESTING AND MONITORING AT WELL OP-2RD

Dissolved oxygen (DO) concentrations ranged from 1 4-6 8 mg/kg during the various trials This is close to the maximum theoretical DO concentrations in the temperature range of 25-31' At these DO concentrations corrosion rates observed appear to be lower than expected.

Corrosion rates were assessed during the Botong cold injection trial by monitoring corrosion coupons placed in the injection flow from the outlet of sump 2. A first corrosion test was conducted in February 1991 with a total exposure time of 245 hours. **A** second test was undertaken from March 16 to April 5, 1991 for a total of 480 hours

Results from the first test suggested a corrosion rate of 12 7 kg/day at 25-30 C distributed over the entire internal surface area of the production casing and slotted liner in well OP2RD This rate is much lower than the theoretical value based on the equivalent weight ratio of iron and oxygen that could react The DO concentrations during the test range from 6 4-7 5 mg/kg at 23-29^{0}C water temperature

The second test was run longer, but the results indicated a lower corrosion rate of only 4 4 kg/day The DO concentration reached a maximum of 7 5 mg/kg at the 24-28°C injection temperature The large difference in the corrosion rate is probably caused by mud deposits on the corrosion ring giving inaccurate values The corrosion rate in OP-2RD is probably close to that measured at the surface (T=32 9°C) assuming that was no significant dissolution of oxygen from air which was clearly being sucked into OP-2RD during injection

IMPLICATIONS FOR DEVELOPMENT OF THE BOTONG SECTOR

The Botong sector of the BacMan geothermal field taps a high enthalpy, two-phase reservoir The characteristics of one of the Botong wells, OP-3D, has already been discussed elsewhere (Ruaya et al , 1991) From the recent output measurements obtained from the Botong wells, the estimated waste water flow rate for a 20 MWe power plant development is expected to be about 20 kg/sec in flow and to be significantly supersaturated with respect to amorphous silica The probability of silica scaling in the reticulation system and reinjection wells is thus high

The usual PNOC design practice is to separate brine from steam at a relatively high temperatures (e.g 160 to 170°C) in order to prevent brine becoming supersaturated with silica (Barnett and Garcia, 1993). This approach is not feasible for Botong because to maintain silica at or less than saturation condition requires that separator temperature be maintained at 200°C or above, at which the saturation pressure necessary to maintain this temperature is so high that well outputs are significantly reduced.

The only practical alternative is then to inject at low temperatures after allowing reactive silica to drop from solution The present results indicate that such a scheme is technically feasible

CONCLUSIONS

From the results of this study we conclude that the success of low temperature injection is dependent on. (a) the initial concentration of silica in flashed brine, (b) the magnitude and rate of temperature drop in the cooling brine, (c) the retention time of brine in ageing/ cooling ponds, and (d) dilution of aged brine with fresh water prior to injection.

Our results suggest a minimum number of two ponds; one close to the production wells, and the other close to the reinjection wells The ponds will require regular removal of solid silica which for Botong is expected to accumulate at the rate of approximately 250 tons/year or 0.7 ton/day (P.R. Barnett, pers comm). This could be done with a sludge pump, or by draining the ponds and then mechanically excavating the solids. This latter option would require a redundant pond in each location and thus an increase in the required number of ponds from 2 to 4. The minimum retention time provided by any two ponds in service should be around 2 5 hours.

Due to the amount of silica that will be continuously produced during cold injection, disposal may pose problems. Processing of silica for industrial use is an attractive option. Initial analyses of Botong silica products show it to be more than 95% pure. Geothermal silica sludge of this quality can be used in making construction materials, ceramics (Carpio-Obesco and Camos-Rodriguez, 1989), specialty glass (Beck, 1989), or as binders in epoxy floorings, or in high quality paper.

Corrosion prevention will be required to protect casing and liners in wells used for long term low temperature injection. This could be effected by (a) using sacrificial steel liners, (b) coatings, e.g., epoxy, concrete, silica, polymers, etc, or (c) using oxygen scavengers.

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