



## **AN EXPERIMENT ON MONOMERIC AND POLYMERIC SILICA PRECIPITATION RATES FROM SUPERSATURATED SOLUTIONS**

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### **ABSTRACT**

Experimental solutions initially supersaturated with amorphous silica were allowed to polymerize while being pumped through a column packed with silica gel. The concentrations of silica monomers and polymers in the solutions were monitored at the inlet and outlet of the column. Results of experimental runs conducted at 50°C with pure water and saline solutions (0.1 M, 0.2 M, 0.3 M and 0.4 M NaCl) showed shorter induction time and faster polymerization with increasing salinity, consistent with theory and past studies. In all runs, monomeric silica dropped to saturation for amorphous silica in the column whereas the concentration of polymerized silica changed little. A solution of 0.3 M NaCl at 90°C also showed a lesser tendency for polymeric silica than monomeric silica to precipitate on the surface of the silica gel in the packed column. However, higher temperature and salinity allowed polymers to grow large enough to deposit in the source tank. In the column, some of the polymeric silica was lost either by precipitation or filtration from solution in the void spaces of the column. The experiment demonstrated that amorphous silica scaling from geothermal brine can be mitigated by allowing dissolved silica in excess of amorphous silica solubility to polymerize, provided that factors affecting polymerization rate and polymer deposition rate are known.

### **1. INTRODUCTION**

Harnessing geothermal energy entails overcoming the difficulties encountered in its various stages of development. Whereas geothermal projects are spurred forward after establishing the heat source and permeability, addressing problems associated with the chemical composition of the geothermal fluids is just as critical for successful exploitation. Geothermal water undergoes cooling and degassing during the process of extracting heat. These changes favour the formation of different scales along the fluid path (Arnórsson, 2004) which are often detrimental to geothermal operations. Amorphous silica is one of the major and most common scaling problems as its solubility decreases with decreasing temperatures. Depending on the conditions, amorphous silica scales may form anywhere from the production wells, surface facilities to downstream of injection wells.

Injecting the fluids back into the reservoir is either an integral part of field management and/or compliance to environmental regulations. As spent geothermal waters are injected, silica may precipitate to cause mild to severe decline in the injectivity of wells (Messer et al., 1978; Hauksson and Gudmundsson, 1986; Itoi et al., 1989; Malate and O'Sullivan, 1993; Alcober et al., 2005). High costs, both in drilling wells and treatment to restore well injectivity, make it important to maintain injection well capacities for a sustainable period. In this study, we establish potential amorphous silica scale formation in the aquifer receiving brine in the Malitbog sector of Tongonan geothermal field, Philippines with the aid of the speciation program WATCH. The scale formation, which deteriorates the injectivity of the wells, provided the motivation to investigate the precipitation rates of the different silica species in a controlled experiment.

## 2. BACKGROUND

The theory and mechanism of amorphous silica scaling, studies conducted in the past and their applications to address problems encountered in the geothermal industry are reviewed. As silica is the most abundant oxide in the earth's crust coupled with the need to understand its behaviour as applied to science and engineering, it is a subject of considerable study through the years. For detailed and comprehensive discussions on silica chemistry, readers are referred to Iler (1979) and Dove and Rimstidt (1994). General information on Malitbog geothermal operations and field tests in relation to the study topic is provided in this report.

### 2.1 Silica scaling

The term silica is a short convenient form of silicon dioxide ( $\text{SiO}_2$ ) and may refer to any of its nine natural or engineered earth system forms (polymorphs). In studying geothermal fluids, the silica phases of most interest are quartz, its microcrystalline form chalcedony and amorphous silica. Quartz is the most stable and common form in nature and is invariably present as a secondary mineral of most geothermal systems. The reaction of quartz with aqueous solution can be expressed as:



In most high-temperature reservoirs, aqueous silica concentrations are controlled by quartz solubility (Fournier and Rowe, 1966). Quartz solubility is temperature dependent. Accordingly, aqueous silica concentrations in geothermal reservoirs are determined by the reservoir temperature (point 1 on Figure 1). As the reservoir water rises to the surface, it boils by depressurization and cools down and in the process it gives off heat to the steam that forms. The steam formation increases the silica concentration of the water. This causes the water to become quartz supersaturated. Experience shows, however, that quartz

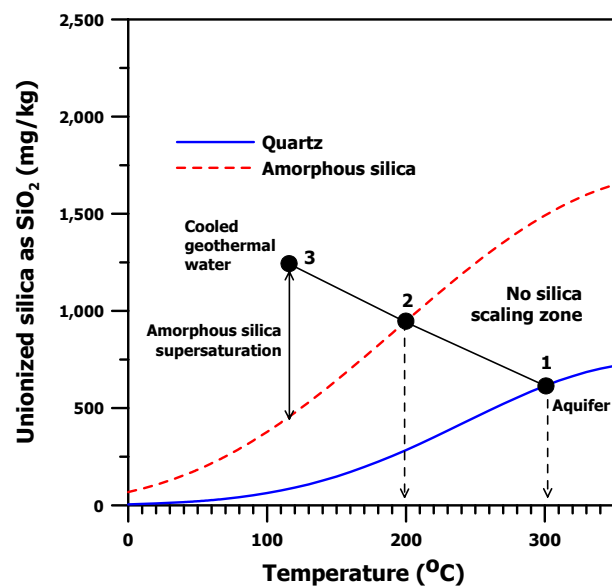
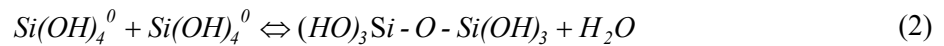


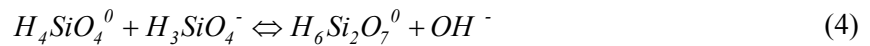
FIGURE 1: Solubility curves of quartz and amorphous silica as a function of temperature: Point 1 is the silica concentration in an aquifer initially in equilibrium with quartz. During adiabatic boiling and subsequent cooling of the aquifer water, aqueous silica concentration increases and amorphous silica saturation is reached in Point 2. Further adiabatic boiling and cooling of the aquifer water will lead to supersaturation with respect to amorphous silica at Point 3

precipitation from supersaturated solution is very slow. Silica only precipitates at an appreciable rate if the effects of cooling and steam formation are sufficient to produce amorphous silica supersaturated solution (point 2 on Figure 1). In order to prevent the deposition of amorphous silica in geothermal installations, it is common to keep its temperature above that corresponding with saturation for amorphous silica. This limits the amount of heat that can be extracted from the fluid discharged from production wells. It is therefore also common to cool the water past the saturation levels (point 3 in Figure 1), making it supersaturated with respect to both quartz and amorphous silica. Quartz and amorphous silica solubilities have been investigated numerous times over a wide range of temperatures, pressures, and solution compositions which are summarized in the works of Chan (1989) and Gunnarsson and Arnórsson (2000).

Dissolved silica in typical conditions of geothermal reservoir waters (<600°C, 6-8 kbar) was determined by Zotov and Keppler (2002) to be of monomeric form (monosilicic acid),  $H_4SiO_4^0$ . A monomer may also be written as  $Si(OH)_4^0$  showing a central Si atom with 4 separate bonded -OH, or silinol, groups. The silinol groups between two monomers form the Si-O-Si bonding into dimers, an initial step called a condensation reaction towards the formation of higher molecular weight polymers:



Since Equation 2 shows no ionized species, it is alternatively written in two reactions to manifest the effects of cations and pH (Fleming, 1986):



When the monomeric concentration exceeds the amorphous silica saturation level, the growth of polymers and scale formation are functions of combined chemical and physical processes following two dominant and essentially competing pathways: (1) molecular deposition upon solid surfaces and (2) particle deposition which follows homogenous nucleation and growth of suspended particles (Weres and Apps, 1981; Klein et al., 1991). The two mechanisms compete for the supply of excess  $Si(OH)_4$  in solution such that the dominant one tends to slow down the other.

Molecular deposition involves not just chemical bonding of dissolved silica directly to solid surfaces like pipe walls, forming hard, dense, difficult to remove, vitreous, and often dark-coloured scale. It also refers to the mechanism in which the growing polymer surface is a solid to which the monomer and silicate ions migrate by circulation and diffusion (heterogeneous nucleation). This mechanism is a slow process and dominant at a supersaturation ratio <2 (silica concentration/equilibrium solubility at the given condition) or at high-flow velocity such that nucleation occurs further downstream. The rate of molecular deposition of monomeric silica is a function of temperature and the density of silinol groups ionized to -Si-O<sup>-</sup> on the solid growth surface, or to an -OH group in a corroded iron. Salinity accelerates deposition by increasing the extent of surface ionization and decreasing the solubility of amorphous silica.

In particle deposition, the starting process is termed homogenous nucleation since the polymers develop spontaneously in solution. The decline of monomeric silica concentrations in solution (from initial supersaturation to saturation level) as analyzed by the molybdate method has been the principal method for studying polymerization processes. The rate of decline of monomeric silica is a strong function of initial supersaturation such that it is often instantaneous or very rapid if the ratio is >2.5 but exhibits a plateau called an induction period which can last from minutes to hours if the ratio is <2.5. The induction period and polymerization rate are subjects of many studies (summarized by Chan, 1989; Gunnarsson and Arnórsson, 2005). In general, at a given supersaturation level, induction will be shorter at a lower temperature, higher salinity, and higher pH (except in very basic solution when solubility of amorphous silica is high). The rate by which the monomers disappear to form

polymers (polysilicic acid) is usually expressed as (Bohlmann et al., 1980; Weres et al., 1982; Fleming, 1986):

$$-\frac{dC}{dt} = k(C - C_e)^n \quad (5)$$

where  $C$  = Monomeric silica concentration;  
 $C_e$  = Concentration corresponding to amorphous silica saturation at the reaction temperature;  
 $k$  = Reaction constant;  
 $n$  = Reaction order.

However, results are not consistent and reaction orders from 1 to 8 have been reported for the maximum rate at  $6 < \text{pH} < 9$ . Others also propose different mechanisms on how the monomers polymerize leading to the development of different forms of polymerization rate equations (summary in Chan, 1989). Despite the differences, most authors agree that polymerization continues until the monomeric silica concentration falls to the solubility of amorphous silica.

Polymers continue to grow until they reach a critical size ( $< 50 \text{ \AA}$  but sometimes down to  $10\text{-}20 \text{ \AA}$ ) for them to be considered colloidal particles. The colloids may deposit to a solid surface driven by transfer processes such as diffusion, flow turbulence and gravity. When the colloids are deposited along with monomeric silica (Iler, 1979), deposition rates are much faster than deposition involving monomers only, and the deposits are much denser and harder than those formed by coagulated colloids only. Simultaneous deposition of colloids and monomeric silica creates worse scaling problems than the deposition of monomeric silica only, as the depositing colloids are cemented together by the monomers (Weres and Apps, 1982). If the solution is static or flowing very slowly, the colloids may coagulate and form flocs which could either precipitate or remain suspended as a semi-solid material. In some cases, the colloids are very stable in solution and do not precipitate (Klein et al., 1991).

## 2.2 Previous studies and mitigating measures

Similar studies on silica chemistry have recently been carried out with objectives and methodology similar to those of the present study. Bohlmann et al. (1980) simulated geothermal brines under controlled conditions at specified supersaturation, pH, temperature and salinity and passed through columns with various substrates. They observed that once thoroughly coated with silica, the deposition behaviour was identical and independent of the type of substrate. They also observed that more than half the silica removed from solution was deposited as monomers. Polymerized silica had little tendency to deposit. Weres et al. (1982) studied experimentally and theoretically silica polymerization with the purpose of predicting its pattern under conditions typical of geothermal brines. Fleming (1986) studied condensation polymerization between monomer and silica surfaces in the absence of nucleation (seeding with colloidal amorphous silica particles of known surface area). Amorphous silica precipitation behaviour was investigated by Carroll et al. (1998). They observed slower rates in laboratory tests than in field experiments. The cause was considered to be due to chemical impurities in the geothermal brine. Gallup (1998) demonstrated that Fe and Al silicate scales were significantly less soluble than pure amorphous silica. It may require higher brine temperature to mitigate them.

Conducting local field experiments is common as results using actual geothermal brines often deviate from laboratory experiments. In their study of injection problems caused by downhole silica scaling, Nishiyama et al. (1985) observed the scale deposition was concentrated at the upstream part of the column only and that brine with high polysilicic acid concentration caused a small decrease in permeability. Axtmann and Grant-Taylor (1986) recognized that in slightly silica-supersaturated brine, monomeric silica initially deposited on growing colloidal surfaces so they concluded that it was

favourable to use a fluidized bed prior to injection. Mroczek and McDowell (1990) found that with rapidly polymerizing brine, deposition rates across gravel beds were lower compared to brine containing only monomeric silica. Mroczek et al. (2000) allowed brine with excess monomeric silica only to pass across a column packed with zirconia beads and used the results to numerically model and predict the lifetime of reinjection aquifers. The tests of Rothbaum et al. (1979) showed that deposition of polymerized silica only changed the physical appearance of the scale but had no effect on the chemical content. It was however argued that these observations were probably due to the high turbulence of the flowing brine. Dunstall and Brown (1998) and Zipfel et al. (1998) explored how hydrodynamics affect the behaviour of silica scaling.

The results of these studies helped develop other approaches to controlling silica precipitation from geothermal brines, aside from avoiding supersaturation. The exact fields utilizing the methods are widely cited in Weres and Apps (1982) and Arnórsson (2004). These include: (1) lowering the pH by acidification, (2) brine aging to convert monomeric silica to colloidal silica, (3) use of inhibitors, (4) precipitation of the silica with lime or by bubbling CO<sub>2</sub> through the solution, (5) mixing the brine with steam condensate and (6) removal of colloidal silica by coagulation and settling. There is no single standard solution to all silica scaling problems. Often a combination or slight modification of any of these methods has been adapted depending on the experience gained.

### 2.3 Operation difficulties and field tests

Malitbog is located south of the Tongonan geothermal field (Figure 2). This field forms the northern reservoir of the 1,076 km<sup>2</sup> geothermal reservation called Greater Tongonan Geothermal field in the island of Leyte, Central Philippines. Malitbog is the major outflow region of the Tongonan reservoir (Alvis-Isidro et al., 1993) and its artificial recharge by injected brine helps maintain the average well discharge enthalpies in this sector below 1,600 kJ/kg (Dacillo and Siega, 2005). All spent geothermal brine from Malitbog is injected into 3 wells (5R1D, 5R4 and 5R7D). As of August 2006, flow measurements using tracers showed that 73% of the total brine (~250 kg/s) flows into wells 5R1D and 5R4 of Pad 5R1 at a temperature ~160°C. Most of the Malitbog brine is distributed to Pad 5R1 injection wells with a lesser flow to injection well 5R7D of Pad 5R7 to counteract the observed decline in output of the central and eastern Malitbog production wells (Herras, 2006). Thus, maintaining high injection capacities in Pad 5R1 wells is of utmost importance not only for environmental compliance but also to achieve field management objectives.

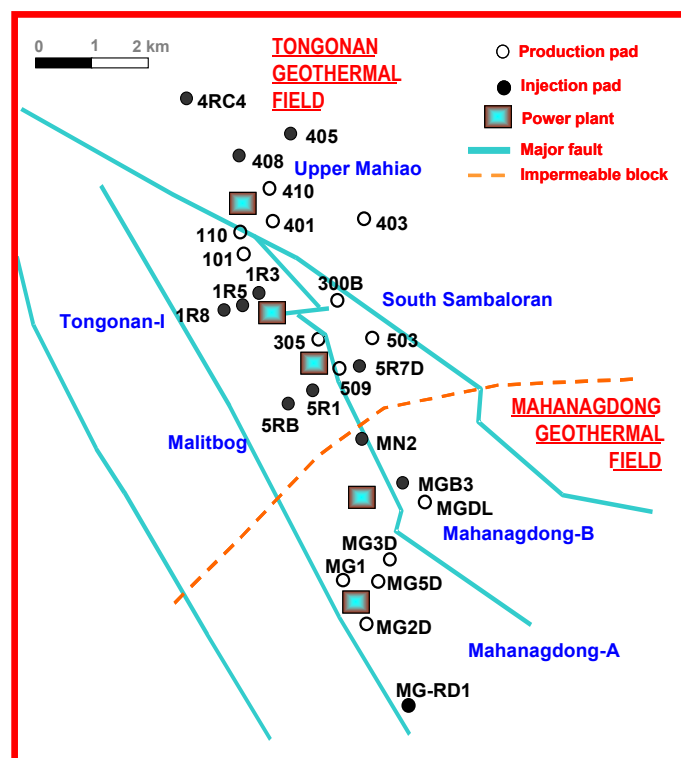


FIGURE 2: Map of the Greater Tongonan geothermal field, Leyte, Philippines

Limited silica scale (3-8 mm/yr) forms in the surface facilities conveying the brine from the steam separators to the injection wells. Observations show decreased injectivity in wells 5R1D and 5R4 (Figures 3 and 4). The steep decline seen in Figures 3 and 4 after workover of these wells is attributed

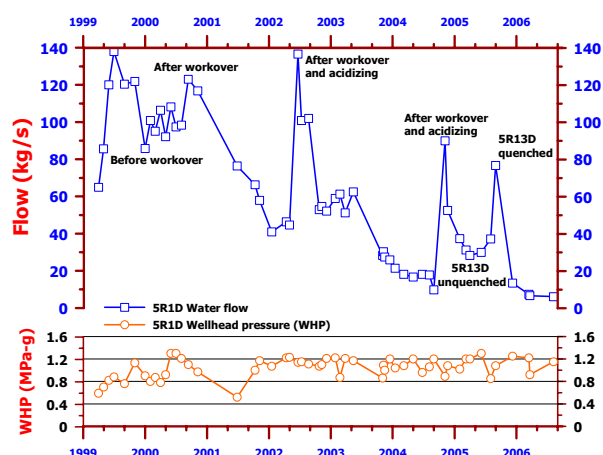


FIGURE 3: Malitbog injection well 5R1D water flows and wellhead pressures

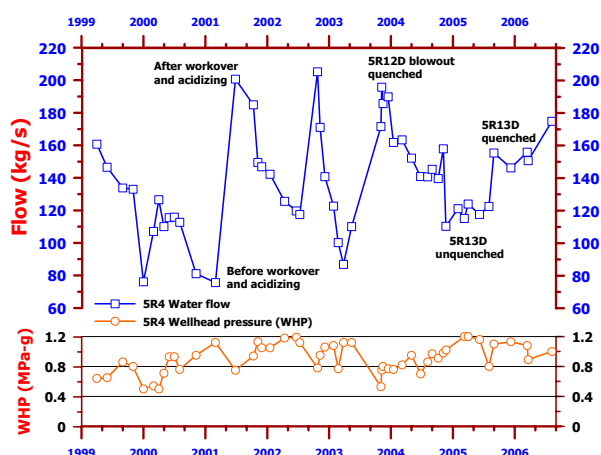


FIGURE 4: Malitbog injection well 5R4 water flows and wellhead pressures

to pressure build-up in a shallow two-phase permeable zone. This behaviour was initially observed in 2003 when well 5R4 acceptance improved after quenching the blow-out of well 5R12D that was eventually controlled through relief well 5R13D. Starting in March 2005, continuous quenching was done by injecting into well 5R13D a mixture of river water, main power plant condensate and brine dumped from the main brineline to Pad 5R1. However, it has been observed lately that only well 5R4 responds positively to quenching. The gradual decline is attributed to deterioration of permeability by deposition of amorphous silica in the receiving formation; but the brine injected in Pad 5R1 is slightly amorphous silica-supersaturated (oversaturation ratio of 1.1-1.2). The idea of silica deposition was substantiated when mechanical cleaning coupled with leaching by acid (HCl and HF) of the injection wells showed significant improvements in injectivity compared to mechanical cleaning alone.

Studies of silica scaling in Malitbog started in 1996 by tests using a chemical inhibitor to keep polymerized silica suspended in solution (Garcia et al., 1996). The residence time from the nearest separator station to the shallowest Pad 5R1 wellbore loss zone is 23 min. Using a polymerization vessel, it was determined that the fluid onset of silica polymerization in untreated brine was 45-55 min. In 2004, the above conditions were simulated in a field test set-up that allowed brine to flow through a column packed with broken rocks. The field test set-up was used to evaluate different mitigating measures (Alcober et al., 2005; Angcoy et al., 2005) which included: (1) brine pH modification by the addition of  $H_2SO_4$  and (2) addition of silica inhibitors. Acidification yielded clean rock formations but posed an increased risk of corrosion while the inhibitors reduced deposition by 80-85%.

### 3. DESCRIPTION OF WORK

#### 3.1 Assessment of scaling in Malitbog sector

This section aims to establish the type of scales that may precipitate from Malitbog brine as it is disposed of into injection wells. The use of geochemical tools is emphasized (analyses retrieved from PNOC-EDC integrated computer databases) but data on injection wells (from Reservoir Engineering Department of PNOC-EDC) are also presented to support the results obtained from the geochemical evaluation.

##### 3.1.1 Scaling potential evaluation

The saturation state of the geothermal fluids from Malitbog with respect to some common scale-forming minerals was assessed with the aid of the speciation program WATCH 2.3 (Arnórsson et al.,

1982 and Bjarnason, 1994). The detailed background and calculation methods of the program are discussed in Arnórsson et al. (1982). In general, the program computes the chemical composition of the aquifer fluid based on the chemical analyses of water and steam samples collected at the surface. The program can also be used to compute the resulting chemical composition when a fluid is cooled conductively or by adiabatic boiling from a reference temperature. During adiabatic boiling, the geothermal fluid may undergo varying degrees of degassing. A sample of the printout of calculations from WATCH is shown in Appendix I.

Figure 5 is a simplified flow diagram of the geothermal fluid collection and injection system in Malitbog. Table 1 shows the physical characteristics of representative wells 510D and 513D (fed to Separator Stations 51 and 52, respectively) and their discharge chemistry as analyzed from samples obtained using a double-wellhead Webre separator. Starting with the known chemical composition of water and steam samples collected at the wellhead, the fluid composition was calculated at: (1) reservoir conditions taking the quartz equilibrium temperature ( $T_{\text{quartz}}$ ) to represent the aquifer temperature, (2) at 10 bar-g assuming adiabatic flashing of the reservoir liquid, (3) at 5 bar-g assuming adiabatic flashing of the separated brine at 10 bar-g. The objective of these calculations was to see how the liquid chemistry derived at 5 bar-g compared with analytical data on samples collected at these conditions. The calculated composition was almost identical to the analytical data, demonstrating that the model used for the calculations was reliable.

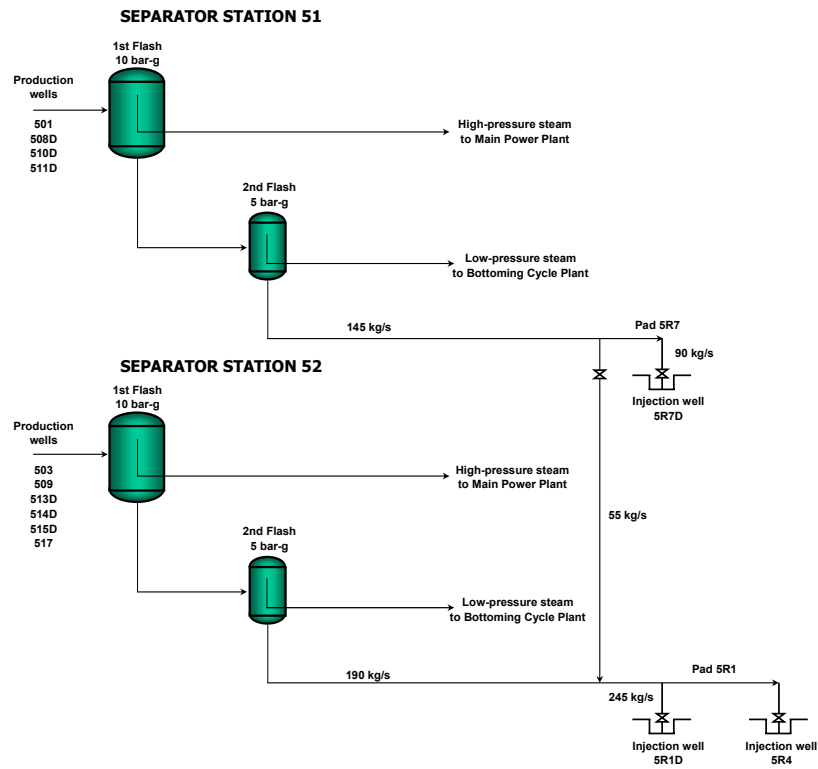


FIGURE 5: Simplified diagram of Malitbog fluid collection and injection system

The objective of these calculations was to see how the liquid chemistry derived at 5 bar-g compared with analytical data on samples collected at these conditions. The calculated composition was almost identical to the analytical data, demonstrating that the model used for the calculations was reliable.

The calculated liquid compositions are compared with the analyses of brine samples in Table 2 (further details in Appendices II and III). The results were obtained by assuming degassing to be 14% and 35% of maximum of geothermal fluids in separator stations 51 and 52, respectively, showing good agreement in the components, and dissolved gases (except  $\text{NH}_3$ ) and pH. If the samples were not immediately acidified upon collection, some  $\text{NH}_3$  may have escaped which could explain why the  $\text{NH}_3$  concentrations were consistently higher in the simulation than in the actual analyses. Acidification helps keep  $\text{NH}_3$  in the aqueous solution as it drives the reaction shown below to the right:



At each stage where the compositions of the geothermal water were calculated, the saturation index,  $\log(Q/K)$ , of a mineral was obtained from the activity product ( $Q$ ) and solubility constant ( $K$ ). A saturation index value equal to 0 represents equilibrium,  $<0$  undersaturation and  $>0$  supersaturation of

the mineral in the solution. As the geothermal water boils and degasses, it becomes supersaturated with respect to many hydrothermal minerals known to be present in geothermal reservoirs, such as quartz, albite and K-feldspar. However, the kinetics of their formation is very slow and poses no concern to operations. Also, the amount of metallic sulphides that precipitate as a consequence of boiling and degassing, such as pyrite, marcasite and pyrrhotite, is limited by the low concentrations of Fe and heavy metals in most geothermal waters. Thus, the troublesome scale-forming minerals are those that can form in quantity due to both fast kinetics and high availability of all their components. These minerals include amorphous silica, calcium carbonate (calcite or aragonite) and anhydrite.

TABLE 1: Physical and chemical characteristics of selected Malitbog production wells

|                                              | 510D <sup>a</sup> | 513D <sup>b</sup> |
|----------------------------------------------|-------------------|-------------------|
| <b>Physical data</b>                         |                   |                   |
| Wellhead pressure (bar-g)                    | 12.9              | 14.4              |
| Sampling pressure (bar-g)                    | 12.1              | 13.9              |
| Discharge enthalpy (kJ/kg)                   | 1,376             | 1,390             |
| Water flow (kg/s)                            | 33.50             | 42.60             |
| Steam flow (kg/s)                            | 13.70             | 18.00             |
| <b>Vapour chemistry (in mmole/100 moles)</b> |                   |                   |
| CO <sub>2</sub>                              | 251               | 435               |
| H <sub>2</sub> S                             | 19.30             | 23.10             |
| NH <sub>3</sub>                              | 1.35              | 1.90              |
| He                                           | 0                 | 0                 |
| H <sub>2</sub>                               | 1.94              | 3.35              |
| Ar                                           | 0.12              | 0.03              |
| N <sub>2</sub>                               | 10.63             | 2.77              |
| CH <sub>4</sub>                              | 1.73              | 2.25              |
| Cl                                           | 0                 | 0                 |
| Na                                           | 2.42              | 1.09              |
| <b>Water chemistry (in mg/kg except pH)</b>  |                   |                   |
| pH (25°C)                                    | 6.34              | 6.01              |
| Li                                           | 20.30             | 21.10             |
| Na                                           | 5,105             | 5,225             |
| K                                            | 994               | 1,114             |
| Ca                                           | 285               | 223               |
| Mg                                           | 0.14              | 0.13              |
| Fe                                           | 0.18              | 0.33              |
| Cl                                           | 9,074             | 9,232             |
| SO <sub>4</sub>                              | 20.50             | 19.90             |
| HCO <sub>3</sub>                             | 20.20             | 19.70             |
| B                                            | 159               | 208               |
| NH <sub>3</sub>                              | 3.06              | 2.34              |
| SiO <sub>2</sub>                             | 660               | 667               |
| H <sub>2</sub> S                             | 3.59              | 6.47              |
| CO <sub>2</sub> -total                       | 21.20             | 33.80             |

<sup>a</sup> Physical data as of 9 Jan 2006, chemistry as of 19 Aug 2005, representative of 4 production wells fed to separator station 51,

<sup>b</sup> Physical data as of 13 Jan 2006, chemistry as of 18 Aug 2005, representative of 6 production wells fed to separator station 52.

The saturation indices for amorphous silica, calcite and anhydrite in variably boiled geothermal water of wells 510D and 513D are shown in Figures 6 and 7, respectively (other production wells in Appendix IV). At aquifer

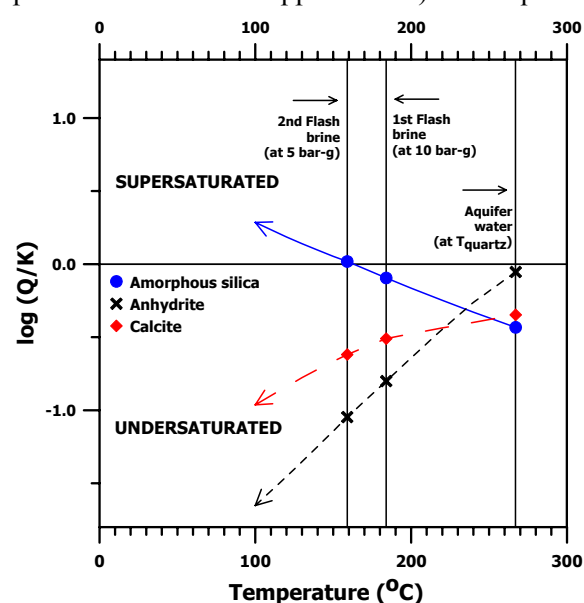


FIGURE 6: Saturation indices of Malitbog production well 510D at 14% degassing

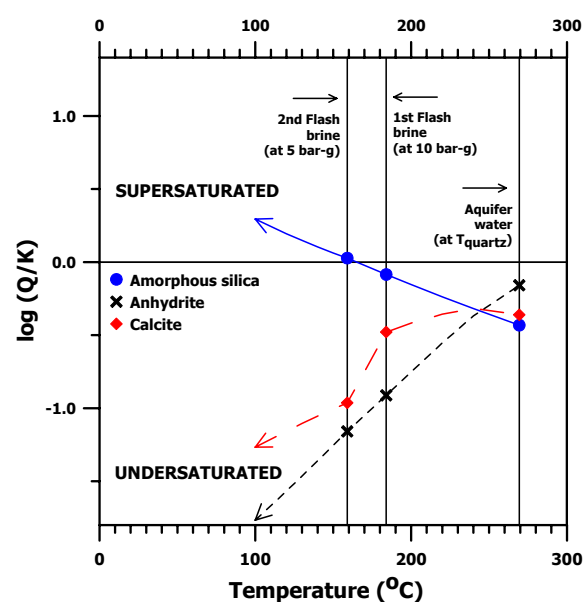


FIGURE 7: Saturation indices of Malitbog production well 513D at 35% degassing

conditions, the waters are at saturation with respect to both anhydrite and calcite within the anticipated limit of error, but significantly amorphous silica undersaturated. The calcite saturation index curve of well 513D shows a more pronounced “hump” than well 510D due to the selection of a higher degassing coefficient used in the calculations (0.35 vs. 0.14). Cooling, either by adiabatic boiling or conduction, makes the water more undersaturated with calcite and anhydrite because of their retrograde solubility with respect to temperature, but more supersaturated with amorphous silica.

After 2<sup>nd</sup> flashing at 5 bar-g, the brine of well 510D lies just within the amorphous silica saturation level while well 513D is at a slightly higher level. Due to its prograde solubility, only amorphous silica scaling is expected towards temperatures <160°C. The scaling potentials of the brine samples injected into wells 5R1D and 5R7D (Figures 8 and 9, respectively) were also evaluated using WATCH assuming their conductive cooling or heating in the receiving formation. The results indicate undersaturation levels of the minerals in the brine injected at 5R1D at temperature ranges of about 160°-250°C, and in brine injected at 5R7D at 160°-200°C. Above these temperature ranges, anhydrite or calcite may precipitate from the brine whereas temperatures below the ranges may lead to precipitation of amorphous silica in the formation.

TABLE 2: Comparison of brine sample analyses and liquid chemistry as calculated using WATCH<sup>a</sup>

| Analysis <sup>b</sup> | Well 5R7D           |                      | Well 5R1D           |                      |
|-----------------------|---------------------|----------------------|---------------------|----------------------|
|                       | Sample <sup>c</sup> | Calcul. <sup>d</sup> | Sample <sup>c</sup> | Calcul. <sup>e</sup> |
| pH                    | 6.41                | 6.16                 | 6.34                | 6.29                 |
| B                     | 199                 | 204                  | 219                 | 228                  |
| SiO <sub>2</sub>      | 675                 | 688                  | 707                 | 718                  |
| Na                    | 5,822               | 5,800                | 5,616               | 5,941                |
| K                     | 1,239               | 1,180                | 1,166               | 1,209                |
| Mg                    | 0.05                | 0.13                 | 0.12                | 0.13                 |
| Ca                    | 326                 | 325                  | 280                 | 340                  |
| F                     | NA <sup>f</sup>     | 1.60                 | NA <sup>f</sup>     | 1.51                 |
| Cl                    | 10,632              | 10,668               | 10,379              | 10,578               |
| SO <sub>4</sub>       | 27.50               | 22.79                | 26.55               | 24.50                |
| Fe                    | 0.30                | 0.34                 | 0.69                | 0.40                 |
| CO <sub>2</sub>       | 15.40               | 15.88                | 6.94                | 6.41                 |
| H <sub>2</sub> S      | 5.02                | 5.37                 | 3.26                | 2.11                 |
| NH <sub>3</sub>       | 0.77                | 6.17                 | 1.71                | 4.95                 |

<sup>a</sup> Details in Appendices II and III,

<sup>b</sup> In mg/kg except pH,

<sup>c</sup> Total composition in water phase at 159°C,

<sup>d</sup> Separator station 51 wells 14% degassing,

<sup>e</sup> Separator station 52 wells 35% degassing, separator station 51 to Sep. Station 52 brine flow ratio = 22:78,

<sup>f</sup> No analysis available.

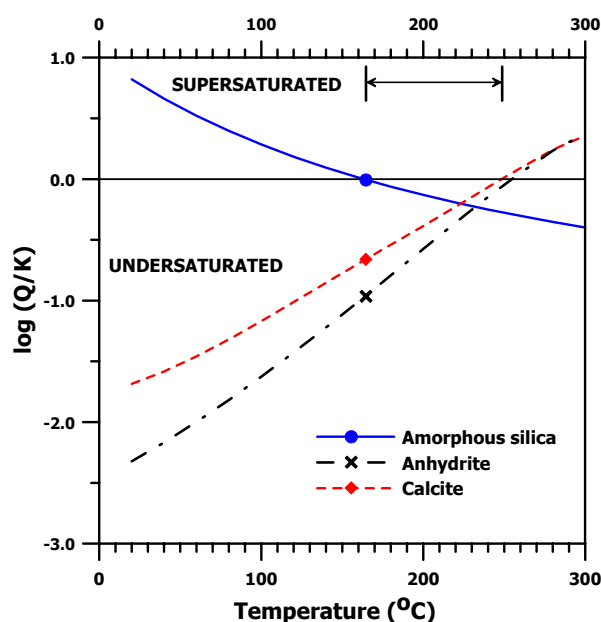


FIGURE 8: Saturation indices of brine injected into Pad 5R1

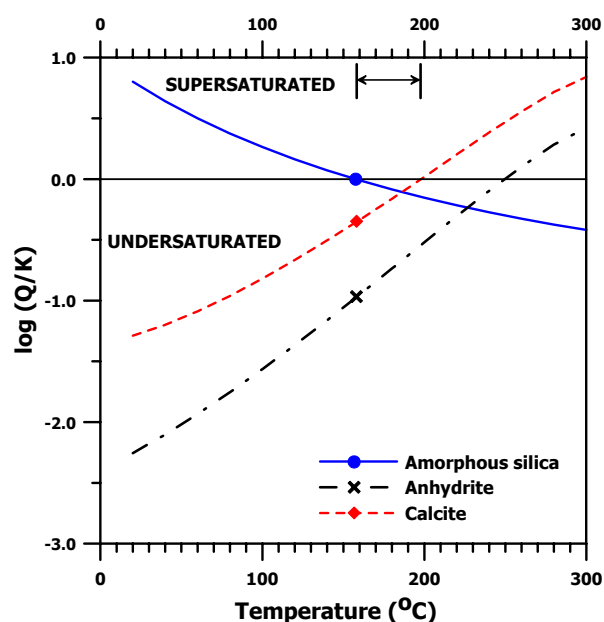


FIGURE 9: Saturation indices of brine injected into Pad 5R7

### 3.1.2 Data on injection wells

Injection well 5R1D was directionally drilled and completed on 1 August 1982 to a total depth of 952.2 m MD (measured depth from casing head flange). It intersected the Mamban formation, which is a thick sequence of predominantly biotite-bearing hornblende-pyroxene andesite lavas, hyaloclastites and tuff breccias (Delfin et al., 1995). Petrologic analysis of the rock formations showed the Mamban formation to be volcanic breccia intensely altered to quartz + drusy anhydrite + opaques + smectite + vermiculite + illite + chalcopryrite (Alcober et al., 2005). Originally targeted as a deep well, continued drilling was not possible due to complete loss of circulation at shallower depth (Sarmiento, 1986). The well had one of the highest original injectivities in the field, estimated at 192 l/s-MPa. During its last mechanical cleaning with acid stimulation in 2004, all obstructions cleared were below the production casing shoe and within the sections of the perforated liner (565-601 m MD, 815-857 m MD). In 2000, mechanical cleaning of well 5R1D resulted in minimal capacity recovery (from 98 to 123 kg/s) whereas acidizing registered significant improvements (from 44 to 137 kg/s in 2002 and from 9.8 to 89.9 kg/s in 2004). Again, two years after its last cleaning, it now has a capacity of 6 kg/s only. Figure 10 shows that at its major and minor permeable zones (553-658 m MD and 767 m MD, respectively) the temperature in 2001 was between 158° and 165°C, favourable to the precipitation of amorphous silica only.

Well 5R4 was vertically drilled and completed on 25 April 1980 to a total depth of 2,342 m (all vertical depths from casing head flange). It was initially tested as a producer and eventually turned into an injector in 1996. Its open section starts at 999.9 m intersecting the Mamban formation, but its minor and major permeable zones (1,900-2,000 m and 2,140-2,320 m, respectively) intersect the Mahiao sedimentary complex, which is described as a sedimentary breccia/conglomerate containing fragments of altered microdiorite, quartz monzodiorite, and minor volcanics. Within the conglomeratic unit, minor interbeds of sandstone, siltstone and claystone exist and these interbeds usually mark the contact of Mahiao sedimentary complex with the Mamban formation (Caranto and Jara, 2006). Figure 11 shows that starting at 600 m depth, it has an almost isothermal temperature. At

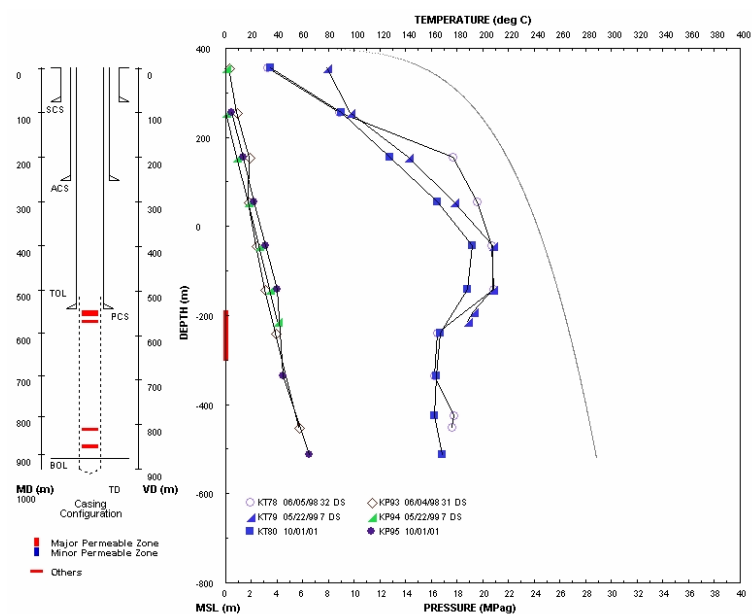


FIGURE 10: Temperature and pressure profiles of injection well 5R1D

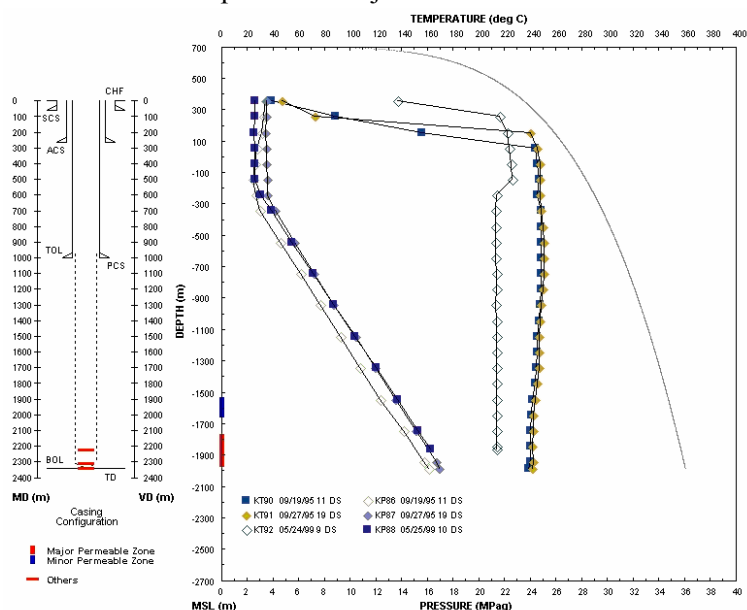


FIGURE 11: Temperature and pressure profiles of injection well 5R4

this temperature, scaling of amorphous silica, calcite or anhydrite is not expected. But in March 1999, blockage was tagged at 2,224 m using a 3" Go-Devil tool, which is within its major permeable zone. It is possible, however, that the scales were formed when it was still used as a production well. The encouraging results of mechanical cleaning with acidizing in 5R1D was duplicated in 5R4 in 2001, increasing capacity from 76 to 201 kg/s and suggesting that acid-soluble scales in near-wellbore formation are decreasing its injectivity.

Lower downhole temperatures in 5R1D may possibly explain the more frequent decline in injectivity due to amorphous silica deposition (Figure 3). Logging of well 5R4 conducted on June 1996 and June 2001 indicated casing discontinuities in the cased-off sections of ~300-350 m and ~550-580 m. These levels were also intersected during the blow-out of 5R12D in 2003 and eventually were targeted by relief well 5R13D to quench the shallow two-phase high-pressure zone. Since March 2005, cold fluids have been injected into 5R13D to maintain quenching. These casing breaks were probably the breakthrough of cold fluids to 5R4, thus generating a positive response to quenching. However, this may also lower its downhole temperature to promote amorphous silica supersaturation since a gradual decline in its injectivity is still observed at quenched conditions (Figure 4).

### 3.2 Silica experiment

In view of the results from the preceding section, an experiment was conducted to provide useful information on amorphous silica scaling in Malitbog. The objective of the experiment was to obtain data on relative precipitation rates of monomeric versus polymeric silica from amorphous silica supersaturated solution. Two sets of experiments were carried out. The first set was conducted at fixed temperature (50°C), atmospheric pressure, initial silica concentration (500 mg/kg) and pH of 6-7, but salinity was varied by adding 5 M NaCl solution to the initial test solution (0 M, 0.1 M, 0.2 M, 0.3 M and 0.4 M). The second set of experiments was conducted at 90°C, atmospheric pressure, initial silica concentration of 500 mg/kg, 0.3 M NaCl and pH of 6-7. This second experiment simulates well conditions at Malitbog.

#### 3.2.1 Experimental design

The experimental runs were performed using an oven set at the experimental temperature (Figure 12). The silica-supersaturated solution was pumped from a container across a column packed with washed silica gel. The solution was pumped against gravity to prevent channelling in the column. Pumping across the column from an experimental solution was continuous for at least 30 minutes before sampling the discharge. The same column was used in other experimental solutions. After the column, a three-way valve was manipulated to direct the outlet solution either for sampling or for pH measurement. The solution did not come into contact with any glass material in order to prevent leaching of silica. Residence time in the column was fixed by regularly monitoring the flow rate at 1 ml/min. The determination of residence time was conducted using an inert visual tracer after completing all experimental runs. The initial and final weights of the dried column were measured.

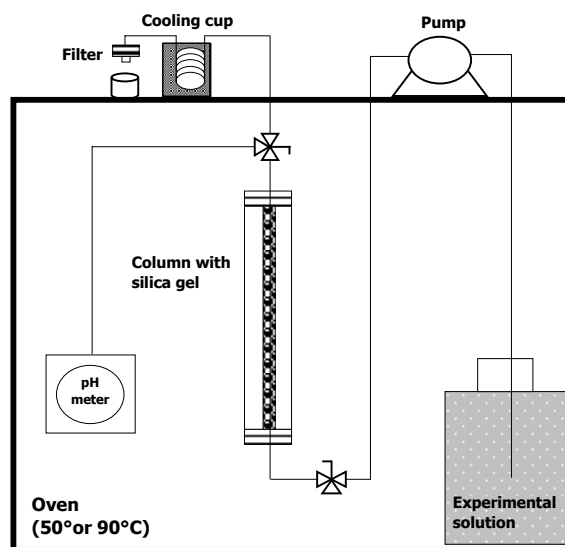


FIGURE 12: Set-up of silica experiment

The procedures in preparing the solutions and reagents were taken from another silica polymerization experiment (Gunnarsson and Arnórsson, 2005). Silica stock solution was prepared by dissolving silica gel in 0.1 N NaOH and filtered using 0.2  $\mu\text{m}$  cellulose acetate filter paper at room temperature. In all runs, 1 litre of experimental solution with a target concentration of 500 mg/kg  $\text{SiO}_2$  was prepared by diluting the stock solution with deionised water and adding variable amounts of 5 M NaCl solution depending on the desired ionic strength. The experimental solution after these steps was very basic ( $\text{pH} \approx 11$ ). At this pH, all silica species present in the solution were molybdate active and undersaturated with respect to amorphous silica. The undersaturated solution was kept inside the oven at the experimental temperature for at least 12 hours.

The pH of the thermally stabilized experimental solution was lowered to a target value of 6.97 by adding concentrated HCl to oversaturate it with respect to amorphous silica. Prior to acidification, the experimental solution was buffered with TRIS,  $(\text{HOCH}_2)_3\text{CNH}_2$ , to stabilize its pH. Polymerization of the silica-supersaturated solution proceeded in the source tank as the solution was pumped across the column. The solutions at the inlet and outlet of the column were monitored for active molybdate and total silica concentrations to determine the relative amount of monomeric and polymeric silica in the solution.

### 3.2.2 Sampling and analytical methods

The sample from the column inlet was extracted from the experimental solution container using a 10 ml syringe while the sample at the column outlet was collected into a small vial after passing it through a 0.2  $\mu\text{m}$  cellulose acetate filter. For analysis of monomeric silica concentration, the samples were immediately brought to room temperature through a cooling spiral and aliquots were drawn using a pipette. The entire sampling procedure was completed in less than 30 seconds to minimize the effect of cooling to polymerization. For analysis of total dissolved silica, all samples were diluted at least 10 times and acidified with concentrated  $\text{HNO}_3$ . In the first set of experiments, all samples were passed through 0.2  $\mu\text{m}$  cellulose acetate filter while in the second set of experiments a run was conducted where filtered samples were duplicated with unfiltered ones.

Monomeric silica concentration was determined using the yellow molybdate method (Franson, 1985). The absorbance was measured at 410 nm using a Cary, 1E UV-visible spectrophotometer. In theory, the molybdic acid will react only with monomeric silica in the solution. However, since the samples in the analytical procedure were diluted to become undersaturated with respect to amorphous silica, some of the monomers forming the yellow molybdosilicic complex may have also been formed from the breakdown of silica dimers and trimers (Iler, 1979). Thus, in this study, all monomeric silica is referred to as molybdate active silica. Total dissolved silica concentration was measured using Inductively Coupled Plasma-Atomic Emission Spectrometry (ICP-AES). Solution pH was measured with a buffer-calibrated pH meter.

### 3.2.3 Results

The results of the experiment are presented in Figures 13-21 and tabulated in Appendix V. After completing all the experimental runs, the retention time of the solution in the column was determined visually, using a coloured tracer, to be  $\sim 9$  minutes. The first trial of the 90°C run (Figure 19) showed almost equal total and monomeric silica levels of the inlet solution with time. To determine whether the polymers grew to sizes large enough to be filtered by the 0.2  $\mu\text{m}$  cellulose acetate filter membrane or were actually depositing in the tank, the experiment was repeated and the filtered samples were duplicated with unfiltered samples (Figures 20-21). The initial and final dry weights of the column containing the silica gel did not differ significantly.

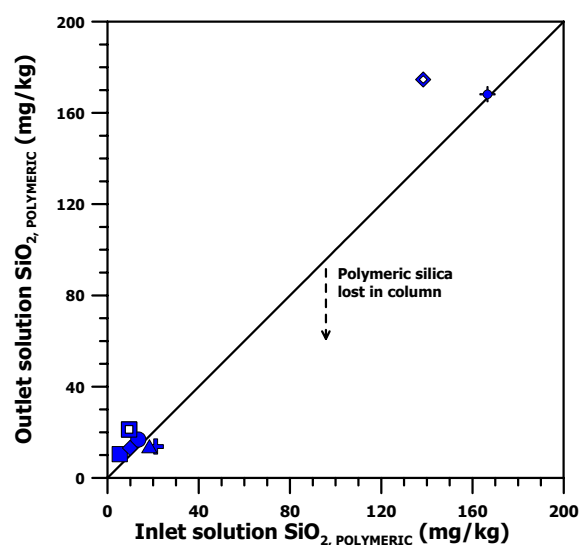
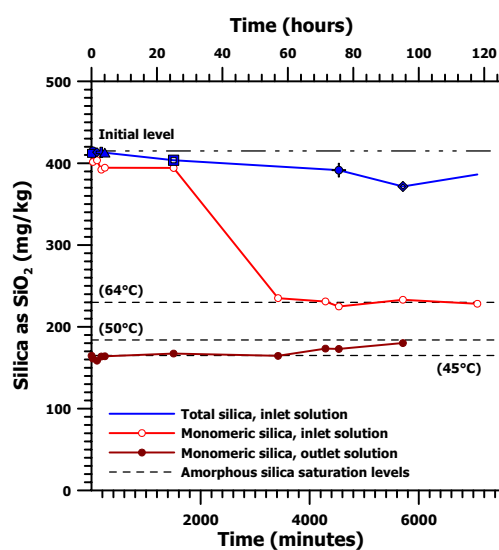


FIGURE 13: Experiment results at 50°C, 1 atm, pure water, pH~7.00, 9 minutes retention time, filtered samples

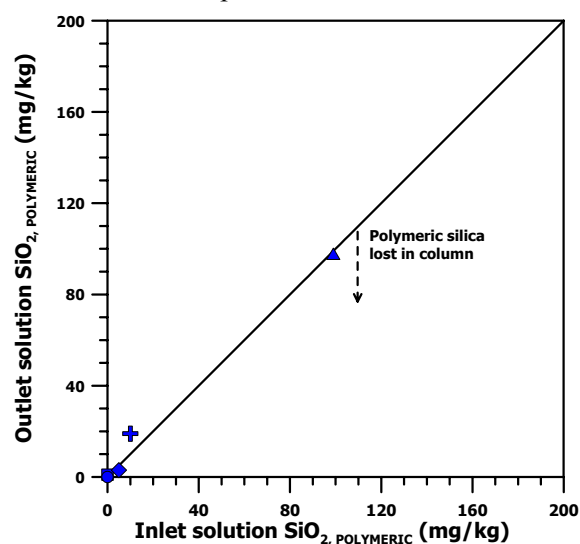
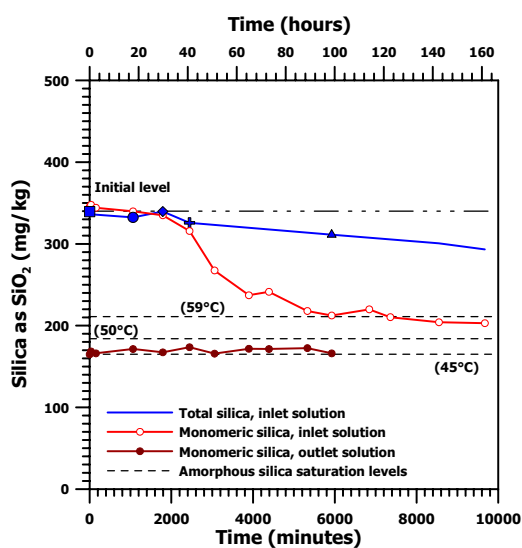


FIGURE 14: Experiment results at 50°C, 1 atm, 0.1 M NaCl, pH~7.00, 9 minutes retention time, filtered samples

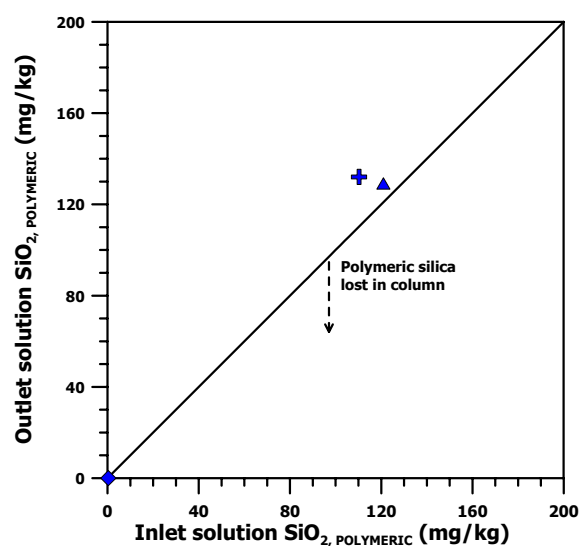
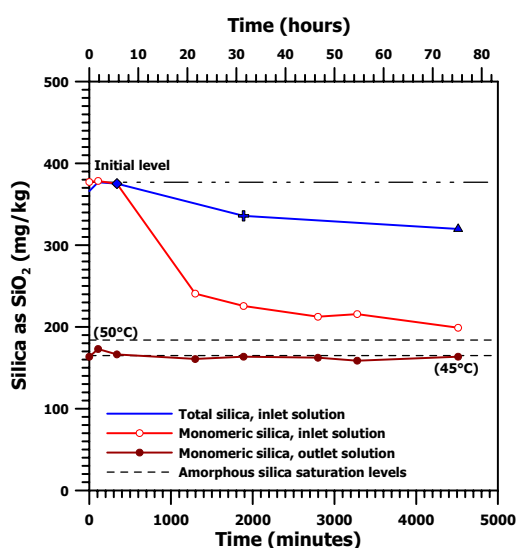


FIGURE 15: Experiment results at 50°C, 1 atm, 0.2 M NaCl, pH~7.00, 9 minutes retention time, filtered samples

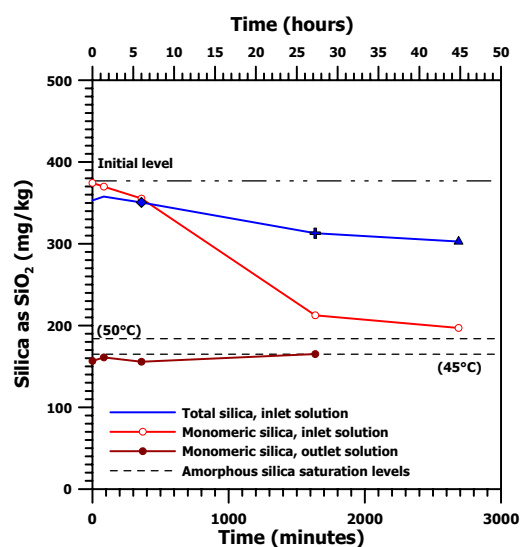


FIGURE 16: Experiment results at 50°C, 1 atm, 0.3 M NaCl, pH~7.00, 9 minutes retention time, filtered samples

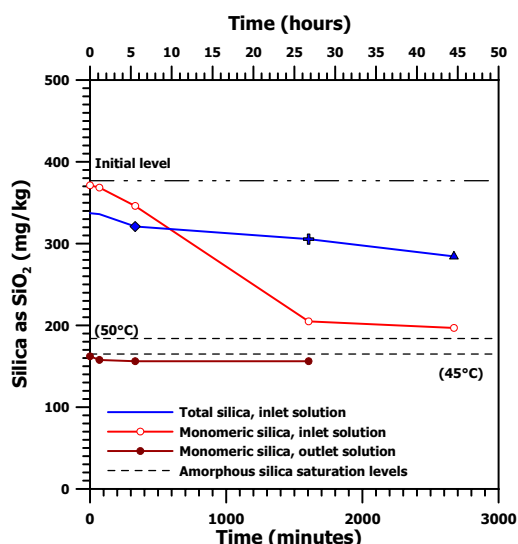


FIGURE 17: Experiment results at 50°C, 1 atm, 0.4 M NaCl, pH~7.00, 9 minutes retention time, filtered samples

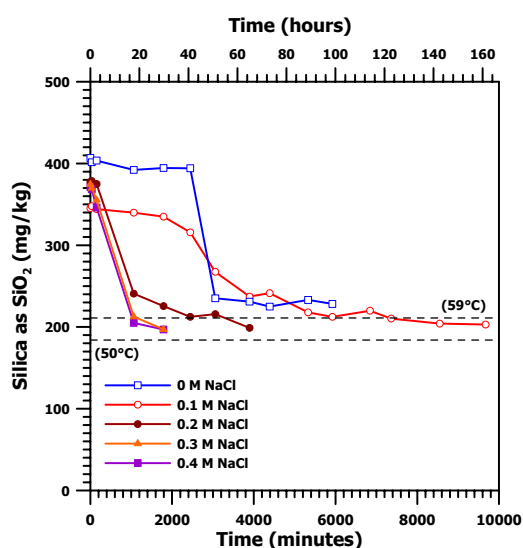


FIGURE 18: Polymerization of tank solutions (starting solutions) at 50°C, 1 atm, pH~7.00, varying salinities, filtered samples

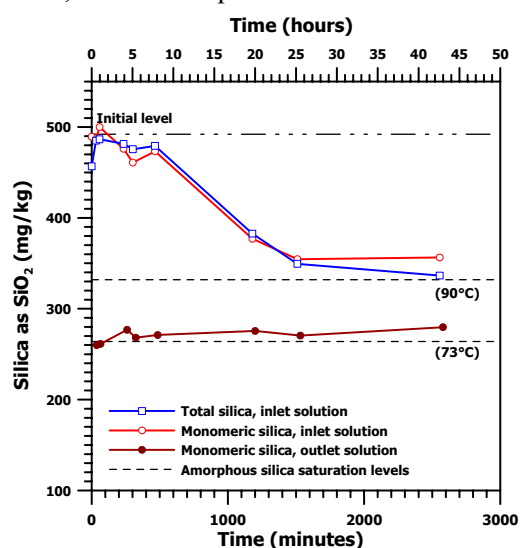


FIGURE 19: Experiment 1 results at 90°C, 1 atm, 0.3 M NaCl, pH~7.00, 9 minutes retention time, filtered samples

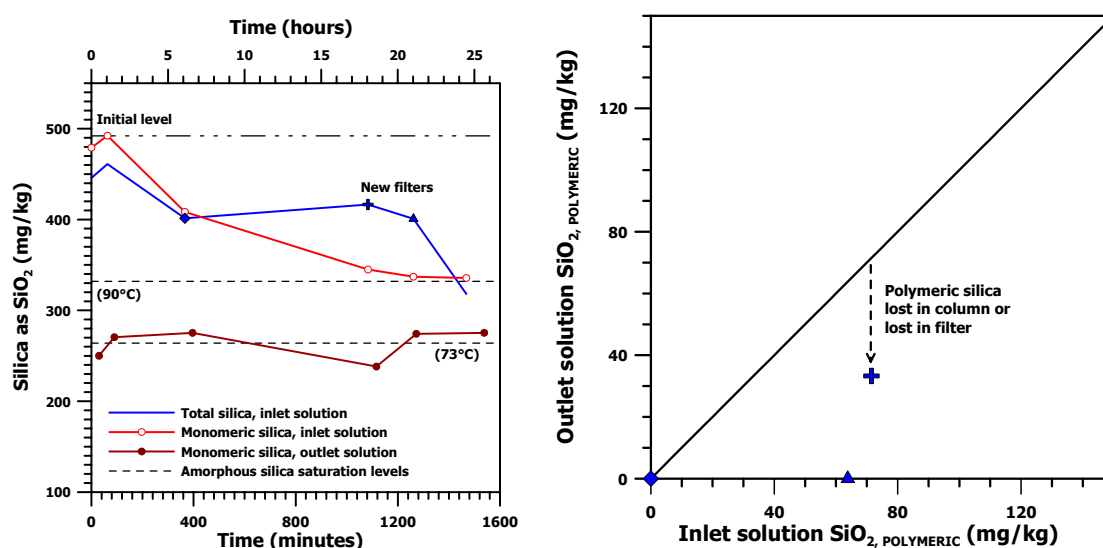


FIGURE 20: Experiment 2 results at 90°C, 1 atm, 0.3 M NaCl, pH~7.00, 9 minutes retention time, filtered samples

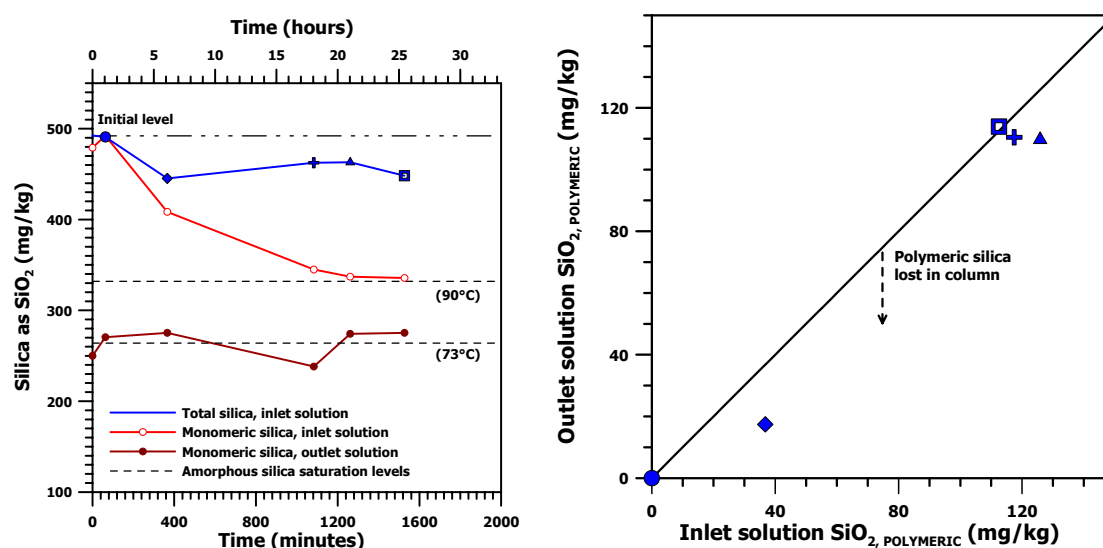


FIGURE 21: Experiment 2 results at 90°C, 1 atm, 0.3 M NaCl, pH~7.00, 9 minutes retention time, unfiltered samples

## 4. DISCUSSION

### 4.1 Results of experiment

The results show that monomeric silica concentrations in the solutions flowing from the column were always at the same concentration. This indicates that monomeric silica easily precipitates on the surface of the silica gel in the packed column. However, the concentration levels approached corresponded to temperatures significantly lower than the experimental temperatures. Since it is unlikely that a more stable silica polymorph other than amorphous silica precipitated in the column, the results were taken to indicate that cooling of the outlet solution occurred with the result that amorphous silica equilibration was attained at the lower temperature. The column was kept at oven temperature except during sampling of the inlet solution. Thus, it is not likely that the solution cooled across the column. Significant cooling only occurred when the sample was brought to room temperature to ensure accuracy of the volumes measured by the pipettes. Probably due to a larger

temperature difference, the monomeric silica level in the outlet solutions approached saturation of amorphous silica at lower temperatures in the 90°C runs (73°C) than in the 50°C runs (45°C).

In contrast to the monomers, the polymerized silica formed in the inlet solutions and pumped across the column had little tendency to precipitate in the column. Most of it remained in solution when pumped through the column. In the experiments at 90°C and saline solution, the analyses of the filtered samples indicated that the polymers grew to a large enough size to be filtered from solution by the 0.2 µm cellulose acetate filter membrane (Figures 19-20), as confirmed by the analyses of the duplicate unfiltered samples. In the experiment at 90°C, analyses of unfiltered samples indicated some polymeric silica (20 mg/kg maximum) was lost either by precipitation or filtration in the void spaces of the column (Figure 21). But compared to the losses of monomeric silica across the column, the amount of polymeric silica retained in the column was significantly less.

The experiment confirms the results of previous studies that at about a constant degree of supersaturation, pH (buffered solutions) and temperature, polymerization of monomeric silica in excess of amorphous silica saturation, is a strong function of salinity. Experiments carried out at 50°C show that increasing salinity increases silica polymerization rate in the tank solution (Figure 18). The monomers polymerized about 10 times faster in the 0.3 and 0.4 M NaCl saline solutions than in pure water. Silica polymerization rate is also a strong function of supersaturation. In the 50°C run, the 0.1 M NaCl solution was inadvertently prepared with a lower supersaturation (~165 ppm) than the solution in pure water (~220 ppm). The effect of salinity was offset by the low level of supersaturation such that the two solutions exhibited almost the same induction time but more time was required to closely approach amorphous silica saturation for the 0.1 M NaCl solution (Figure 18). At the salinity of 0.3 M NaCl (50°C and 90°C), it was anticipated that increased polymerization rate due to higher temperature would also be counteracted by the higher saturation level of amorphous silica. Thus, supersaturation was increased in the 90°C, 0.3 M NaCl run by starting at a higher initial silica level to achieve a reasonable onset of polymerization of the excess monomers after about 5 hours.

The experiment demonstrated that precipitation of amorphous silica from supersaturated solutions is decreased if the monomers in excess of saturation are allowed to polymerize. However, the successful application of this method in order to mitigate silica scaling requires a balance between both the silica polymerization rate and the deposition rate. Silica polymerization is regarded as a precursor to the precipitation of silica gel (Iler, 1979). At pH~7, the growing polymers in pure water tend to repel each other because of their negatively charged surfaces. But in saline solutions, the presence of ions reduces the repulsive forces allowing the polymers to aggregate and gel (Figure 22). In the experiment, increased salinity increased both silica polymerization and deposition rates. In all saline solutions of the experiment, the total silica concentration of the inlet solutions slightly declined from the initial silica levels indicating that some polymers had grown large enough to deposit in the tank. Growth and precipitation of the silica polymers were enhanced by the presence of electrolytes in solution. Marshall (1980) observed that the nature of cations and not the anions has greater effect. The decreasing effect of cations is  $Mg^{2+} > Ca^{2+} > Sr^{2+} > Li^+ > Na^+ > K^+$  (Chan, 1989).

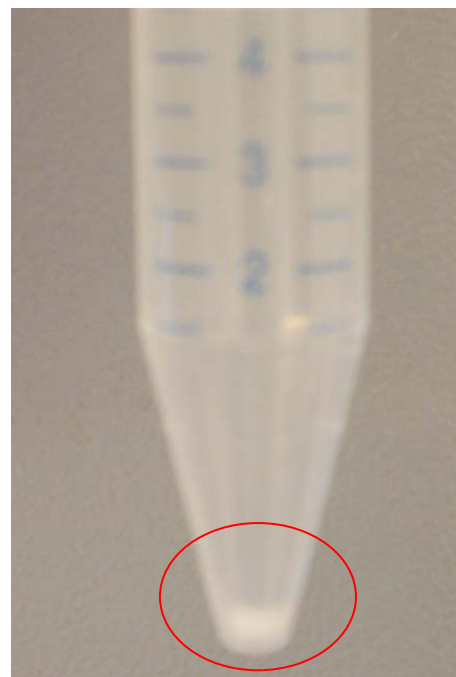


Figure 22: Experiment: Silica gel precipitated in the tank at 90°C, 1 atm, 0.3 M NaCl, pH~7

## 4.2 Relevance of experimental results to Malitbog

Amorphous silica scaling during the injection of Malitbog brine to Pad 5R1 wells is probably dominated by the deposition of both monomeric and polymeric silica. The conditions that favour the mechanism of deposition of both forms of silica are: (1) a low degree of supersaturation (not more than 1.2); (2) an induction period of about 1 hour (Alcober et al., 2005), long enough for the brine to travel away from the wellbore to the receiving aquifer in the injection well before the onset of polymerization and (3) the presence of cations that may coagulate the polymerized silica to a solid surface rather than to the colloidal particles in suspension. Monomeric silica deposition and reheating in the formation are not rapid enough to relieve the slight supersaturation of the brine and to prevent polymerization. In relatively saline waters, deposition of both monomeric and polymeric silica is relatively fast and forms hard but microporous scales (Iler, 1979) similar to that observed in the field test of Malitbog (Alcober et al., 2005). The declining maximum well injectivity achieved after workovers (Figures 3-4) suggests that the removal and dissolution of the scales is becoming more difficult, especially in areas that can no longer be accessed by acid leaching.

The method demonstrated by the experiment to mitigate amorphous silica scaling can be applied with greater confidence if (1) silica polymerization is very fast so that no induction period is observed and (2) the conditions allow the polymers not to precipitate or, if precipitated, remain suspended in solution. To retain the maximum 300 kg/s of Malitbog brine for about 1 hour, in order to polymerize the silica in the brine prior to injection, requires an impractically large volume (~1,000 m<sup>3</sup>). At the surface, rapid polymerization of the brine is possible by increasing the level of oversaturation by either brine flashing to low pressure or rapid cooling. Either way, it opens opportunities to cascade the energy of Malitbog brine for further utilization. If cooling the Malitbog brine is not an option due to an adverse impact on field management, heterogeneous nucleation may be induced by seeding or brine transit through fluidized or packed beds, with the objective of stripping the excess silica monomers from the solution before injecting the brine.

## 4.3 Future work

The experimental procedure needs to be improved so as to allow direct sampling and analyses of samples without cooling. Analyses of monomeric silica concentrations may also be carried out using the more sensitive blue molybdate method. After these improvements, silica polymerization and deposition rates may be investigated with more confidence at various conditions. Laboratory tests need to be confirmed by field tests to validate the results. For instance, since the silica polymers in Malitbog brine are likely to precipitate by gravity due to a high ionic strength of the brine (~0.3), field tests will help gauge the increased risk of deposition. Polymerization and deposition rates may further be complicated by the influence of trace amounts of iron, aluminium and manganese in the brine (Gallup, 1998; Yokoyama et al., 1989).

## 5. SUMMARY AND CONCLUSIONS

Potential amorphous silica scale formation in the aquifer receiving brine in the Malitbog sector of Tongonan geothermal field, Philippines was established with the aid of the speciation program WATCH. A laboratory experiment showed that polymeric silica has lesser tendency than monomeric silica to precipitate from the solution in a column packed with silica gel. Thus allowing the monomers in excess of the amorphous silica saturation level to polymerize before injection will possibly mitigate the declining injectivity of wells. Successful application of this method should consider the conditions that will allow deposition of polymeric silica precipitated due to dissolved salts in the solution.

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## APPENDIX I: Sample of WATCH print-out to determine scaling potential of Malitbog production wells

ICELANDIC WATER CHEMISTRY GROUP

Program WATCH, version 2.3 / 2004

### STEP 1: Calculation of aquifer conditions from steam and water samples.

Malitbog production well 510D

| Water sample (mg/kg) |            | Steam sample       |                                              |
|----------------------|------------|--------------------|----------------------------------------------|
| pH/deg.C             | 6.34/ 25.6 | Gas (volume %)     | Reference temperature deg.C : 267.1 (Quartz) |
| CO2                  | 21.20      | CO2                | 0.00                                         |
| H2S                  | 3.59       | H2S                | 0.00                                         |
| NH3                  | 3.06       | NH3                | 0.00                                         |
| B                    | 159.0000   | H2                 | 13.57                                        |
| SiO2                 | 660.00     | O2                 | 0.00                                         |
| Na                   | 5105.00    | CH4                | 12.09                                        |
| K                    | 994.00     | N2                 | 74.33                                        |
| Mg                   | 0.140      |                    |                                              |
| Ca                   | 285.00     | Liters gas per kg  |                                              |
| F                    | 1.340      | condensate/deg.C   | 0.19/25.0                                    |
|                      |            | Condensate (mg/kg) |                                              |

Reference temperature deg.C : 267.1 (Quartz)

Sampling pressure bar abs. : 13.1

Discharge enthalpy kJ/kg : 1171. (Calculated)

Discharge kg/s : 47.2

Steam fraction at collection : 0.1797

Measured temperature deg.C :

|     |         |                     |          |           |      |
|-----|---------|---------------------|----------|-----------|------|
| Cl  | 9074.00 |                     | pH/deg.C | 0.00/ 0.0 |      |
| SO4 | 20.50   | Total steam (mg/kg) | CO2      | 0.00      |      |
| Al  | 0.0000  | CO2                 | 6131.92  | H2S       | 0.00 |
| Fe  | 0.1800  | H2S                 | 365.11   | NH3       | 0.00 |
| TDS | 0.00    | NH3                 | 12.76    | Na        | 0.00 |

Ionic strength = 0.26580

Ionic balance : Cations (mol.eq.) = 0.26106104

Anions (mol.eq.) = 0.25596878

Difference (%) = 1.97

Liquid phase components (mg/kg)

|      |          |     |         |
|------|----------|-----|---------|
| B    | 130.4218 | CO2 | 1119.52 |
| SiO2 | 541.37   | H2S | 68.57   |
| Na   | 4187.44  | NH3 | 4.80    |
| K    | 815.34   | H2  | 0.39    |
| Mg   | 0.115    | O2  | 0.00    |
| Ca   | 233.77   | CH4 | 2.77    |
| F    | 1.099    | N2  | 29.72   |
| Cl   | 7443.06  |     |         |
| SO4  | 16.82    |     |         |
| Al   | 0.0000   |     |         |
| Fe   | 0.1476   |     |         |
| TDS  | 0.00     |     |         |

Aquifer steam fraction = 0.0000

Vapor phase (mg/kg)

|       |           |
|-------|-----------|
| CO2   | 0.00      |
| H2S   | 0.00      |
| NH3   | 0.00      |
| H2    | 0.00      |
| O2    | 0.00      |
| CH4   | 0.00      |
| N2    | 0.00      |
| H2O   | 0.526E+02 |
| Total | 0.554E+02 |

Gas pressures (bar-abs.)

|     |           |
|-----|-----------|
| CO2 | 0.213E+01 |
| H2S | 0.652E-01 |
| NH3 | 0.823E-03 |
| H2  | 0.635E-01 |
| O2  | 0.506E-36 |
| CH4 | 0.462E-01 |
| N2  | 0.465E+00 |

Ionic strength = 0.19629

1000/T (Kelvin) = 1.85

Ionic balance : Cations (mol.eq.) = 0.19268577

Anions (mol.eq.) = 0.18851227

Difference (%) = 2.19

Oxidation potential (volts) : Eh H2S= -0.424 Eh CH4= -0.498 Eh H2= -0.496 Eh NH3= -0.487

Chemical geothermometers (degrees C)

Quartz 267.1 (Fournier &amp; Potter, 1982)

Chalcedony 254.3 (Fournier, 1977)

Na/K 273.0 (Arnorsson et al., 1983)

Activity coefficients in water

|          |       |           |       |           |       |
|----------|-------|-----------|-------|-----------|-------|
| H+       | 0.650 | K+        | 0.489 | FeSO4+    | 0.557 |
| OH-      | 0.508 | Ca++      | 0.120 | FeCl++    | 0.099 |
| H3SiO4-  | 0.525 | Mg++      | 0.163 | FeCl2+    | 0.557 |
| H2SiO4-- | 0.107 | CaHCO3+   | 0.585 | FeCl4-    | 0.525 |
| H2BO3-   | 0.469 | MgHCO3+   | 0.525 | FeCl+     | 0.525 |
| HCO3-    | 0.525 | CaOH+     | 0.585 | Al+++     | 0.022 |
| CO3--    | 0.088 | MgOH+     | 0.597 | AlOH++    | 0.107 |
| HS-      | 0.508 | NH4+      | 0.469 | Al(OH)2+  | 0.568 |
| S--      | 0.099 | Fe++      | 0.120 | Al(OH)4-  | 0.542 |
| HSO4-    | 0.542 | Fe+++     | 0.022 | AlSO4+    | 0.542 |
| SO4--    | 0.078 | FeOH+     | 0.557 | Al(SO4)2- | 0.542 |
| NaSO4-   | 0.568 | Fe(OH)3-  | 0.557 | AlF++     | 0.107 |
| KSO4-    | 0.568 | Fe(OH)4-- | 0.099 | AlF2+     | 0.568 |
| F-       | 0.508 | Fe(OH)++  | 0.099 | AlF4-     | 0.542 |
| Cl-      | 0.489 | Fe(OH)2+  | 0.568 | AlF5--    | 0.088 |
| Na+      | 0.525 | Fe(OH)4-  | 0.568 | AlF6---   | 0.004 |

Chemical species in water - ppm and log mole

|          |         |         |           |         |         |           |      |         |
|----------|---------|---------|-----------|---------|---------|-----------|------|---------|
| H+       | 0.01    | -5.037  | Mg++      | 0.11    | -5.336  | Fe(OH)3   | 0.15 | -5.865  |
| OH-      | 0.05    | -5.503  | NaCl      | 1193.30 | -1.690  | Fe(OH)4-  | 0.00 | -8.238  |
| H4SiO4   | 865.66  | -2.045  | KCl       | 103.91  | -2.856  | FeCl+     | 0.03 | -6.518  |
| H3SiO4-  | 0.17    | -5.745  | NaSO4-    | 3.58    | -4.521  | FeCl2     | 0.00 | -8.852  |
| H2SiO4-- | 0.00    | -11.412 | KSO4-     | 3.91    | -4.539  | FeCl++    | 0.00 | -15.288 |
| NaH3SiO4 | 0.19    | -5.804  | CaSO4     | 4.65    | -4.467  | FeCl2+    | 0.00 | -16.157 |
| H3BO3    | 745.78  | -1.919  | MgSO4     | 0.01    | -7.200  | FeCl3     | 0.00 | -17.439 |
| H2BO3-   | 0.19    | -5.505  | CaCO3     | 0.01    | -6.953  | FeCl4-    | 0.00 | -18.695 |
| H2CO3    | 1560.09 | -1.599  | MgCO3     | 0.00    | -11.306 | FeSO4     | 0.00 | -9.956  |
| HCO3-    | 6.83    | -3.951  | CaHCO3+   | 17.73   | -3.756  | FeSO4+    | 0.00 | -17.701 |
| CO3--    | 0.00    | -9.342  | MgHCO3+   | 0.00    | -7.928  | Al+++     | 0.00 | 0.000   |
| H2S      | 68.02   | -2.700  | CaOH+     | 0.05    | -6.068  | AlOH++    | 0.00 | 0.000   |
| HS-      | 0.53    | -4.794  | MgOH+     | 0.00    | -7.459  | Al(OH)2+  | 0.00 | 0.000   |
| S--      | 0.00    | -13.713 | NH4OH     | 5.53    | -3.802  | Al(OH)3   | 0.00 | 0.000   |
| H2SO4    | 0.00    | -10.809 | NH4+      | 2.24    | -3.906  | Al(OH)4-  | 0.00 | 0.000   |
| HSO4-    | 1.85    | -4.719  | Fe++      | 0.01    | -7.040  | AlSO4+    | 0.00 | 0.000   |
| SO4--    | 6.03    | -4.202  | Fe+++     | 0.00    | -20.242 | Al(SO4)2- | 0.00 | 0.000   |
| HF       | 0.63    | -4.502  | FeOH+     | 0.00    | -8.859  | AlF++     | 0.00 | 0.000   |
| F-       | 0.50    | -4.579  | Fe(OH)2   | 0.00    | -10.091 | AlF2+     | 0.00 | 0.000   |
| Cl-      | 6669.78 | -0.726  | Fe(OH)3-  | 0.00    | -16.714 | AlF3      | 0.00 | 0.000   |
| Na+      | 3717.27 | -0.791  | Fe(OH)4-- | 0.00    | -19.877 | AlF4-     | 0.00 | 0.000   |
| K+       | 759.72  | -1.712  | Fe(OH)++  | 0.00    | -12.709 | AlF5--    | 0.00 | 0.000   |

Water pH is 5.223

|                                                                                               |         |         |              |         |         |             |         |         |
|-----------------------------------------------------------------------------------------------|---------|---------|--------------|---------|---------|-------------|---------|---------|
| Ca++                                                                                          | 225.34  | -2.250  | Fe(OH)2+     | 0.08    | -6.057  | AlF6---     | 0.00    | 0.000   |
| Logarithms of mineral solubility product constants (K) and ion activity products (Q) in water |         |         |              |         |         |             |         |         |
|                                                                                               | log K   | log Q   |              | log K   | log Q   |             | log K   | log Q   |
| Adularia                                                                                      | -14.372 | 99.999  | Albite, low  | -13.938 | 99.999  | Analcime    | -11.563 | 99.999  |
| Anhydrite                                                                                     | -8.425  | -8.479  | Calcite      | -13.219 | -13.566 | Chalcedony  | -1.928  | -2.045  |
| Mg-Chlorite                                                                                   | -86.296 | 99.999  | Fluorite     | -11.052 | -12.916 | Goethite    | 3.237   | -2.686  |
| Laumontite                                                                                    | -24.709 | 99.999  | Microcline   | -14.998 | 99.999  | Magnetite   | -15.258 | -24.927 |
| Ca-Montmor.                                                                                   | -72.582 | 99.999  | K-Montmor.   | -33.869 | 99.999  | Mg-Montmor. | -74.087 | 99.999  |
| Na-Montmor.                                                                                   | -34.152 | 99.999  | Muscovite    | -17.838 | 99.999  | Prehnite    | -37.927 | 99.999  |
| Pyrrhotite                                                                                    | -11.288 | -52.071 | Pyrite       | -29.035 | -55.697 | Quartz      | -2.046  | -2.045  |
| Wairakite                                                                                     | -24.894 | 99.999  | Wollastonite | 7.203   | 5.231   | Zoisite     | -38.758 | 99.999  |
| Epidote                                                                                       | -38.383 | 99.999  | Marcasite    | -12.809 | -55.697 | Talc        | 8.084   | 4.786   |
| Chrysotile                                                                                    | 14.233  | 8.877   | Sil. amorph. | -1.612  | -2.045  |             |         |         |

## STEP 2: Calculation of brine composition from 1<sup>st</sup> separator vessel (10 bar-g).

Aquifer liquid boiled to 184.0 °C

Degassing coefficient is 0.1400

| Liquid phase components (mg/kg) |          |                                 |       | Vapor phase (mg/kg) |         | Gas pressures (bar-abs.) |           |
|---------------------------------|----------|---------------------------------|-------|---------------------|---------|--------------------------|-----------|
| B                               | 162.0251 | CO2                             | 76.42 | CO2                 | 5424.24 | CO2                      | 0.244E-01 |
| SiO2                            | 672.56   | H2S                             | 13.04 | H2S                 | 297.77  | H2S                      | 0.173E-02 |
| Na                              | 5202.13  | NH3                             | 5.43  | NH3                 | 2.22    | NH3                      | 0.258E-04 |
| K                               | 1012.91  | H2                              | 0.00  | H2                  | 1.99    | H2                       | 0.195E-03 |
| Mg                              | 0.143    | O2                              | 0.00  | O2                  | 0.00    | O2                       | 0.000E+00 |
| Ca                              | 290.42   | CH4                             | 0.03  | CH4                 | 14.08   | CH4                      | 0.174E-03 |
| F                               | 1.365    | N2                              | 0.16  | N2                  | 151.69  | N2                       | 0.107E-02 |
| Cl                              | 9246.64  |                                 |       |                     |         | H2O                      | 0.110E+02 |
| SO4                             | 20.89    |                                 |       |                     |         | Total                    | 0.110E+02 |
| Al                              | 0.0000   |                                 |       |                     |         |                          |           |
| Fe                              | 0.1834   |                                 |       |                     |         |                          |           |
| TDS                             | 0.00     | Aquifer steam fraction = 0.1951 |       |                     |         |                          |           |

Ionic strength = 0.26041

1000/T (Kelvin) = 2.19

Ionic balance : Cations (mol.eq.) = 0.25576815

Anions (mol.eq.) = 0.25057867

Difference (%) = 2.05

Oxidation potential (volts) : Eh H2S= -0.379 Eh CH4= -0.419 Eh H2= -0.398 Eh NH3= -0.447

Chemical geothermometers (degrees C)

Quartz 299.2 (Fournier & Potter, 1982)

Chalcedony 280.5 (Fournier, 1977)

Na/K 271.2 (Amorsson et al., 1983)

Activity coefficients in water

|          |       |           |       |           |       |
|----------|-------|-----------|-------|-----------|-------|
| H+       | 0.691 | K+        | 0.542 | FeSO4+    | 0.606 |
| OH-      | 0.560 | Ca++      | 0.173 | FeCl++    | 0.147 |
| H3SiO4-  | 0.577 | Mg++      | 0.224 | FeCl2+    | 0.606 |
| H2SiO4-- | 0.158 | CaHCO3+   | 0.632 | FeCl4-    | 0.577 |
| H2BO3-   | 0.522 | MgHCO3+   | 0.577 | FeCl+     | 0.577 |
| HCO3-    | 0.577 | CaOH+     | 0.632 | Al+++     | 0.045 |
| CO3--    | 0.134 | MgOH+     | 0.643 | AlOH++    | 0.158 |
| HS-      | 0.560 | NH4+      | 0.522 | Al(OH)2+  | 0.617 |
| S--      | 0.147 | Fe++      | 0.173 | Al(OH)4-  | 0.592 |
| HSO4-    | 0.592 | Fe+++     | 0.045 | AlSO4+    | 0.592 |
| SO4--    | 0.120 | FeOH+     | 0.606 | Al(SO4)2- | 0.592 |
| NaSO4-   | 0.617 | Fe(OH)3-  | 0.606 | AlF++     | 0.158 |
| KSO4-    | 0.617 | Fe(OH)4-- | 0.147 | AlF2+     | 0.617 |
| F-       | 0.560 | Fe(OH)++  | 0.147 | AlF4-     | 0.592 |
| Cl-      | 0.542 | Fe(OH)2+  | 0.617 | AlF5--    | 0.134 |
| Na+      | 0.577 | Fe(OH)4-  | 0.617 | AlF6---   | 0.011 |

Aquifer liquid boiled to 184.0 °C

Degassing coefficient is 0.1400

| Chemical species in water - ppm and log mole |         |        |         |        |         | Water pH is 5.813 |      |
|----------------------------------------------|---------|--------|---------|--------|---------|-------------------|------|
| H+                                           | 0.00    | -5.652 | Mg++    | 0.14   | -5.241  | Fe(OH)3           | 0.00 |
| OH-                                          | 0.09    | -5.291 | NaCl    | 603.24 | -1.986  | Fe(OH)4-          | 0.00 |
| H4SiO4                                       | 1071.81 | -1.953 | KCl     | 44.10  | -3.228  | FeCl+             | 0.18 |
| H3SiO4-                                      | 1.96    | -4.687 | NaSO4-  | 4.60   | -4.413  | FeCl2             | 0.00 |
| H2SiO4--                                     | 0.00    | -9.346 | KSO4-   | 3.09   | -4.641  | FeCl++            | 0.00 |
| NaH3SiO4                                     | 2.50    | -4.674 | CaSO4   | 4.10   | -4.521  | FeCl2+            | 0.00 |
| H3BO3                                        | 925.45  | -1.825 | MgSO4   | 0.01   | -6.981  | FeCl3             | 0.00 |
| H2BO3-                                       | 1.27    | -4.680 | CaCO3   | 0.03   | -6.478  | FeCl4-            | 0.00 |
| H2CO3                                        | 90.32   | -2.837 | MgCO3   | 0.00   | -10.406 | FeSO4             | 0.00 |
| HCO3-                                        | 10.64   | -3.758 | CaHCO3+ | 10.68  | -3.976  | FeSO4+            | 0.00 |

|       |         |         |           |      |         |           |      |       |
|-------|---------|---------|-----------|------|---------|-----------|------|-------|
| CO3-- | 0.00    | -7.878  | MgHCO3+   | 0.00 | -7.951  | Al+++     | 0.00 | 0.000 |
| H2S   | 11.13   | -3.486  | CaOH+     | 0.04 | -6.176  | AlOH++    | 0.00 | 0.000 |
| HS-   | 1.86    | -4.250  | MgOH+     | 0.00 | -8.060  | Al(OH)2+  | 0.00 | 0.000 |
| S--   | 0.00    | -13.209 | NH4OH     | 2.84 | -4.092  | Al(OH)3   | 0.00 | 0.000 |
| H2SO4 | 0.00    | -13.357 | NH4+      | 4.29 | -3.624  | Al(OH)4-  | 0.00 | 0.000 |
| HSO4- | 0.07    | -6.174  | Fe++      | 0.07 | -5.899  | AlSO4+    | 0.00 | 0.000 |
| SO4-- | 12.02   | -3.903  | Fe+++     | 0.00 | -20.049 | Al(SO4)2- | 0.00 | 0.000 |
| HF    | 0.06    | -5.538  | FeOH+     | 0.00 | -8.284  | AlF++     | 0.00 | 0.000 |
| F-    | 1.31    | -4.161  | Fe(OH)2   | 0.00 | -9.548  | AlF2+     | 0.00 | 0.000 |
| Cl-   | 8859.67 | -0.602  | Fe(OH)3-  | 0.00 | -15.680 | AlF3      | 0.00 | 0.000 |
| Na+   | 4963.44 | -0.666  | Fe(OH)4-- | 0.00 | -19.534 | AlF4-     | 0.00 | 0.000 |
| K+    | 988.89  | -1.597  | Fe(OH)++  | 0.00 | -13.614 | AlF5--    | 0.00 | 0.000 |
| Ca++  | 284.94  | -2.148  | Fe(OH)2+  | 0.00 | -8.155  | AlF6---   | 0.00 | 0.000 |

Logarithms of mineral solubility product constants (K) and ion activity products (Q) in water

|             | log K   | log Q   |              | log K   | log Q   |             | log K   | log Q   |
|-------------|---------|---------|--------------|---------|---------|-------------|---------|---------|
| Adularia    | -14.997 | 99.999  | Albite, low  | -14.468 | 99.999  | Analcime    | -11.767 | 99.999  |
| Anhydrite   | -6.931  | -7.732  | Calcite      | -11.151 | -11.661 | Chalcedony  | -2.298  | -1.953  |
| Mg-Chlorite | -80.977 | 99.999  | Fluorite     | -10.657 | -11.735 | Goethite    | -1.126  | -4.060  |
| Laumontite  | -24.766 | 99.999  | Microcline   | -15.900 | 99.999  | Magnetite   | -22.950 | -25.866 |
| Ca-Montmor. | -74.047 | 99.999  | K-Montmor.   | -35.138 | 99.999  | Mg-Montmor. | -75.470 | 99.999  |
| Na-Montmor. | -35.349 | 99.999  | Muscovite    | -18.265 | 99.999  | Prehnite    | -35.894 | 99.999  |
| Pyrrhotite  | -56.973 | -70.121 | Pyrite       | -87.795 | -78.512 | Quartz      | -2.454  | -1.953  |
| Wairakite   | -23.824 | 99.999  | Wollastonite | 8.710   | 6.764   | Zoisite     | -35.810 | 99.999  |
| Epidote     | -37.856 | 99.999  | Marcasite    | -68.613 | -78.512 | Talc        | 11.224  | 9.395   |
| Chrysotile  | 18.114  | 13.301  | Sil. amorph. | -1.858  | -1.953  |             |         |         |

## APPENDIX II: Data for calculation of mixed brine in separator stations 51 and 52 at 10 bar-g

TABLE 1: Determination of brine mixture chemistry from 1st separator vessel of separator station 51

|                                                                   | Unit    | W501                 | W508D                | W510D                | W511D                | Composition at 1 <sup>st</sup> separator |
|-------------------------------------------------------------------|---------|----------------------|----------------------|----------------------|----------------------|------------------------------------------|
| Mass flow at wellhead pressure                                    | kg/s    | 41.2                 | 38.6                 | 47.2                 | 51.8                 |                                          |
| <b>First separator vessel brine (10 bar-g, 184°C)<sup>a</sup></b> |         |                      |                      |                      |                      |                                          |
| Water flow                                                        | kg/s    | 33.95                | 31.86                | 37.99                | 41.33                | 145.13                                   |
| pH (at 184°C )                                                    |         | 6.01                 | 5.51                 | 5.81                 | 5.42                 | 5.67                                     |
| B                                                                 | mg/kg   | 203                  | 160                  | 162                  | 239                  | 193                                      |
| SiO <sub>2</sub>                                                  | mg/kg   | 616                  | 613                  | 673                  | 694                  | 652                                      |
| Na                                                                | mg/kg   | 5,793                | 4,809                | 5,202                | 6,048                | 5,495                                    |
| K                                                                 | mg/kg   | 1,197                | 1,023                | 1,013                | 1,224                | 1,118                                    |
| Mg                                                                | mg/kg   | 0.12                 | 0.10                 | 0.14                 | 0.10                 | 0.12                                     |
| Ca                                                                | mg/kg   | 376                  | 246                  | 290                  | 315                  | 308                                      |
| F                                                                 | mg/kg   | 1.64                 | 1.70                 | 1.37                 | 1.44                 | 1.52                                     |
| Cl                                                                | mg/kg   | 10,805               | 8,728                | 9,247                | 11,389               | 10,107                                   |
| SO <sub>4</sub>                                                   | mg/kg   | 23.33                | 20.77                | 20.89                | 21.45                | 21.59                                    |
| Fe                                                                | mg/kg   | 0.44                 | 0.34                 | 0.18                 | 0.33                 | 0.32                                     |
| CO <sub>2</sub>                                                   | mg/kg   | 60.3                 | 75.76                | 76.42                | 162.03               | 96.88                                    |
| H <sub>2</sub> S                                                  | mg/kg   | 9.78                 | 11.5                 | 13.04                | 20.63                | 14.10                                    |
| NH <sub>3</sub>                                                   | mg/kg   | 3.81                 | 5.3                  | 5.43                 | 8.82                 | 5.99                                     |
| H <sub>3</sub> SiO <sub>4</sub> <sup>-</sup>                      | moles   | 3.0×10 <sup>-5</sup> | 9.2×10 <sup>-6</sup> | 2.1×10 <sup>-5</sup> | 8.8×10 <sup>-6</sup> | 1.7×10 <sup>-5</sup>                     |
| H <sub>2</sub> BO <sub>3</sub> <sup>-</sup>                       | moles   | 4.3×10 <sup>-5</sup> | 1.0×10 <sup>-5</sup> | 2.1×10 <sup>-5</sup> | 1.3×10 <sup>-5</sup> | 2.1×10 <sup>-5</sup>                     |
| HCO <sub>3</sub> <sup>-</sup>                                     | moles   | 2.0×10 <sup>-4</sup> | 9.2×10 <sup>-5</sup> | 1.7×10 <sup>-4</sup> | 1.7×10 <sup>-4</sup> | 1.6×10 <sup>-4</sup>                     |
| CO <sub>3</sub> <sup>-2</sup>                                     | moles×2 | 5.0×10 <sup>-8</sup> | 6.7×10 <sup>-9</sup> | 2.6×10 <sup>-8</sup> | 1.1×10 <sup>-8</sup> | 2.3×10 <sup>-8</sup>                     |
| HS <sup>-</sup>                                                   | moles   | 6.3×10 <sup>-5</sup> | 2.6×10 <sup>-5</sup> | 5.6×10 <sup>-5</sup> | 4.0×10 <sup>-5</sup> | 4.6×10 <sup>-5</sup>                     |

<sup>a</sup> Degassing at 14% was selected to calculate the composition of individual well discharges.

TABLE 2: Determination of brine mixture pH from 1st separator vessel of separator station 51

| Molar concentrations of anions of weak acids in brine mixture at 184°C |                                              |                                             |                               |                                    |                      |                      |                                   |                       |
|------------------------------------------------------------------------|----------------------------------------------|---------------------------------------------|-------------------------------|------------------------------------|----------------------|----------------------|-----------------------------------|-----------------------|
| pH                                                                     | H <sub>3</sub> SiO <sub>4</sub> <sup>-</sup> | H <sub>2</sub> BO <sub>3</sub> <sup>-</sup> | HCO <sub>3</sub> <sup>-</sup> | CO <sub>3</sub> <sup>-2</sup> (×2) | HS <sup>-</sup>      | Sum                  | Target                            | Delta                 |
| 5.67                                                                   | 1.4×10 <sup>-5</sup>                         | 1.8×10 <sup>-5</sup>                        | 1.7×10 <sup>-4</sup>          | 1.9×10 <sup>-8</sup>               | 4.6×10 <sup>-5</sup> | 2.5×10 <sup>-4</sup> | 2.5×10 <sup>-4</sup> <sup>a</sup> | -3.8×10 <sup>-7</sup> |

<sup>a</sup> Total moles of anions of weak acids in brine mixture.

TABLE 3: Determination of brine mixture chemistry from 1st separator vessel of separator station 52

|                                                                    | Unit    | W503                 | W509                 | W513D                | W514D                | W515D                | W517                 | Comp. at 1 <sup>st</sup> separator |
|--------------------------------------------------------------------|---------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|------------------------------------|
| Mass flow at well head pressure                                    | kg/s    | 40.70                | 42.00                | 60.60                | 31.80                | 35.10                | 24.70                |                                    |
| <b>First separator vessel brine (10 bar-g, 184°C) <sup>a</sup></b> |         |                      |                      |                      |                      |                      |                      |                                    |
| Water flow                                                         | kg/s    | 32.35                | 35.18                | 48.43                | 23.38                | 27.81                | 20.52                | 187.67                             |
| pH (at 184°C)                                                      |         | 6.06                 | 5.91                 | 5.97                 | 5.83                 | 5.67                 | 6.17                 | 5.93                               |
| B                                                                  | mg/kg   | 220                  | 226                  | 215                  | 188                  | 247                  | 246                  | 223                                |
| SiO <sub>2</sub>                                                   | mg/kg   | 703                  | 577                  | 689                  | 884                  | 710                  | 597                  | 688                                |
| Na                                                                 | mg/kg   | 5,069                | 5,825                | 5,401                | 5,459                | 5,588                | 7,307                | 5667                               |
| K                                                                  | mg/kg   | 1,047                | 1,036                | 1,151                | 1,248                | 1,186                | 1,371                | 1153                               |
| Mg                                                                 | mg/kg   | 0.05                 | 0.19                 | 0.13                 | 0.15                 | 0.15                 | 0.14                 | 0.13                               |
| Ca                                                                 | mg/kg   | 189                  | 535                  | 231                  | 204                  | 228                  | 681                  | 326                                |
| F                                                                  | mg/kg   | 1.64                 | 1.28                 | 1.39                 | 1.47                 | 1.35                 | 1.25                 | 1.40                               |
| Cl                                                                 | mg/kg   | 8,749                | 10,376               | 9,542                | 9,571                | 9,794                | 13,143               | 9996                               |
| SO <sub>4</sub>                                                    | mg/kg   | 19.43                | 26.25                | 20.57                | 19.55                | 30.91                | 28.25                | 23.68                              |
| Fe                                                                 | mg/kg   | 0.60                 | 0.34                 | 0.34                 | 0.36                 | 0.48                 | 0.27                 | 0.40                               |
| CO <sub>2</sub>                                                    | mg/kg   | 18.42                | 44.30                | 54.07                | 47.31                | 50.83                | 36.26                | 42.82                              |
| H <sub>2</sub> S                                                   | mg/kg   | 0.75                 | 5.81                 | 7.03                 | 5.96                 | 6.46                 | 4.61                 | 5.24                               |
| NH <sub>3</sub>                                                    | mg/kg   | 3.33                 | 4.74                 | 4.76                 | 6.68                 | 5.75                 | 3.08                 | 4.71                               |
| H <sub>3</sub> SiO <sub>4</sub> <sup>-</sup>                       | moles   | 3.8×10 <sup>-5</sup> | 2.3×10 <sup>-5</sup> | 3.0×10 <sup>-5</sup> | 2.8×10 <sup>-5</sup> | 1.6×10 <sup>-5</sup> | 4.4×10 <sup>-5</sup> | 2.9×10 <sup>-5</sup>               |
| H <sub>2</sub> BO <sub>3</sub> <sup>-</sup>                        | moles   | 5.0×10 <sup>-5</sup> | 3.8×10 <sup>-5</sup> | 4.0×10 <sup>-5</sup> | 2.6×10 <sup>-5</sup> | 2.3×10 <sup>-5</sup> | 7.9×10 <sup>-5</sup> | 4.1×10 <sup>-5</sup>               |
| HCO <sub>3</sub> <sup>-</sup>                                      | moles   | 6.8×10 <sup>-5</sup> | 1.2×10 <sup>-4</sup> | 1.7×10 <sup>-4</sup> | 1.2×10 <sup>-4</sup> | 8.9×10 <sup>-5</sup> | 1.5×10 <sup>-4</sup> | 1.2×10 <sup>-4</sup>               |
| CO <sub>3</sub> <sup>-2</sup>                                      | moles×2 | 1.8×10 <sup>-8</sup> | 2.4×10 <sup>-8</sup> | 3.7×10 <sup>-8</sup> | 1.5×10 <sup>-8</sup> | 9.9×10 <sup>-9</sup> | 5.8×10 <sup>-8</sup> | 2.7×10 <sup>-8</sup>               |
| HS <sup>-</sup>                                                    | moles   | 5.1×10 <sup>-6</sup> | 3.1×10 <sup>-5</sup> | 4.1×10 <sup>-5</sup> | 2.7×10 <sup>-5</sup> | 2.1×10 <sup>-5</sup> | 4.0×10 <sup>-5</sup> | 2.8×10 <sup>-5</sup>               |

<sup>a</sup> Degassing at 35% was selected to calculate the composition of individual well discharges.

TABLE 4: Determination of brine mixture pH from 1st separator vessel of separator station 52

| Molar concentrations of anions of weak acids in brine mixture at 184°C |                                              |                                             |                               |                                    |                       |                      |                                   |                      |
|------------------------------------------------------------------------|----------------------------------------------|---------------------------------------------|-------------------------------|------------------------------------|-----------------------|----------------------|-----------------------------------|----------------------|
| pH                                                                     | H <sub>3</sub> SiO <sub>4</sub> <sup>-</sup> | H <sub>2</sub> BO <sub>3</sub> <sup>-</sup> | HCO <sub>3</sub> <sup>-</sup> | CO <sub>3</sub> <sup>-2</sup> (×2) | HS <sup>-</sup>       | Sum                  | Target                            | Delta                |
| 5.93                                                                   | 2.81×10 <sup>-5</sup>                        | 3.86×10 <sup>-5</sup>                       | 1.23×10 <sup>-4</sup>         | 2.55×10 <sup>-8</sup>              | 2.88×10 <sup>-5</sup> | 2.2×10 <sup>-4</sup> | 2.2×10 <sup>-4</sup> <sup>a</sup> | 4.1×10 <sup>-7</sup> |

<sup>a</sup> Total moles of anions of weak acids in brine mixture.

**APPENDIX III: Data for calculation of mixed brine from separator stations 51 and 52 at 5 bar-g**

TABLE 1: Determination of brine mixture chemistry at 5 bar-g (injection to Pad 5R1)

|                                                      | Unit     | From separator station 51 <sup>a</sup> | From separator station 52 <sup>b</sup> | Brine mixture to pad 5R1 |
|------------------------------------------------------|----------|----------------------------------------|----------------------------------------|--------------------------|
| <b>First separator vessel brine (5 bar-g, 159°C)</b> |          |                                        |                                        |                          |
| Water flow                                           | kg/s     | 55                                     | 190                                    | 245                      |
| pH                                                   | at 159°C | 6.33                                   | 6.16                                   | 6.29 <sup>b</sup>        |
| B                                                    | mg/kg    | 235                                    | 204                                    | 228                      |
| SiO <sub>2</sub>                                     | mg/kg    | 726                                    | 688                                    | 718                      |
| Na                                                   | mg/kg    | 5,982                                  | 5,800                                  | 5,941                    |
| K                                                    | mg/kg    | 1,217                                  | 1,180                                  | 1,209                    |
| Mg                                                   | mg/kg    | 0.14                                   | 0.13                                   | 0.13                     |
| Ca                                                   | mg/kg    | 344                                    | 325.                                   | 340                      |
| F                                                    | mg/kg    | 1.48                                   | 1.60                                   | 1.51                     |
| Cl                                                   | mg/kg    | 10,551                                 | 10,668                                 | 10,578                   |
| SO <sub>4</sub>                                      | mg/kg    | 25.00                                  | 22.79                                  | 24.50                    |
| Fe                                                   | mg/kg    | 0.42                                   | 0.34                                   | 0.40                     |
| CO <sub>2</sub>                                      | mg/kg    | 3.67                                   | 15.88                                  | 6.41                     |
| H <sub>2</sub> S                                     | mg/kg    | 1.16                                   | 5.37                                   | 2.11                     |
| NH <sub>3</sub>                                      | mg/kg    | 4.6                                    | 6.17                                   | 4.95                     |
| H <sub>3</sub> SiO <sub>4</sub> <sup>-</sup>         | moles    | 7.5×10 <sup>-5</sup>                   | 4.8×10 <sup>-5</sup>                   | 6.9×10 <sup>-5</sup>     |
| H <sub>2</sub> BO <sub>3</sub> <sup>-</sup>          | moles    | 10.6×10 <sup>-5</sup>                  | 6.1×10 <sup>-5</sup>                   | 9.6×10 <sup>-5</sup>     |
| HCO <sub>3</sub> <sup>-</sup>                        | moles    | 2.8×10 <sup>-5</sup>                   | 9.5×10 <sup>-5</sup>                   | 4.3×10 <sup>-5</sup>     |
| CO <sub>3</sub> <sup>-2</sup>                        | moles×2  | 2.0×10 <sup>-8</sup>                   | 4.6×10 <sup>-8</sup>                   | 2.6×10 <sup>-8</sup>     |
| HS <sup>-</sup>                                      | moles    | 1.5×10 <sup>-5</sup>                   | 5.4×10 <sup>-5</sup>                   | 2.4×10 <sup>-5</sup>     |

<sup>a</sup> Calculated brine mixture in Table 1, Appendix II adiabatically boiled to 5 bar-g at 14% degassing.<sup>b</sup> Calculated brine mixture in Table 3, Appendix II adiabatically boiled to 5 bar-g at 35% degassing.

TABLE 2: Determination of brine mixture pH at 5 bar-g (injection to Pad 5R1)

| <b>Molar concentrations of anions of weak acids in brine mixture at 159°C</b> |                                              |                                             |                               |                                    |                      |                      |                                   |                       |
|-------------------------------------------------------------------------------|----------------------------------------------|---------------------------------------------|-------------------------------|------------------------------------|----------------------|----------------------|-----------------------------------|-----------------------|
| pH                                                                            | H <sub>3</sub> SiO <sub>4</sub> <sup>-</sup> | H <sub>2</sub> BO <sub>3</sub> <sup>-</sup> | HCO <sub>3</sub> <sup>-</sup> | CO <sub>3</sub> <sup>-2</sup> (×2) | HS <sup>-</sup>      | Sum                  | Target                            | Delta                 |
| 6.29                                                                          | 6.7×10 <sup>-5</sup>                         | 9.3×10 <sup>-5</sup>                        | 4.6×10 <sup>-5</sup>          | 3.0×10 <sup>-8</sup>               | 2.6×10 <sup>-5</sup> | 2.3×10 <sup>-4</sup> | 2.3×10 <sup>-5</sup> <sup>a</sup> | -1.2×10 <sup>-5</sup> |

<sup>a</sup> Total moles of anions of weak acids in brine mixture.

## APPENDIX IV: Malitbog production wells scaling potential

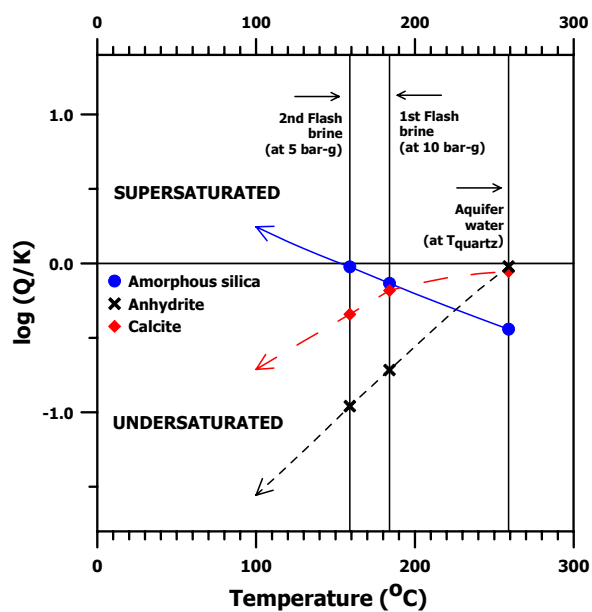


FIGURE 1: W501 saturation indices, 14% degassing

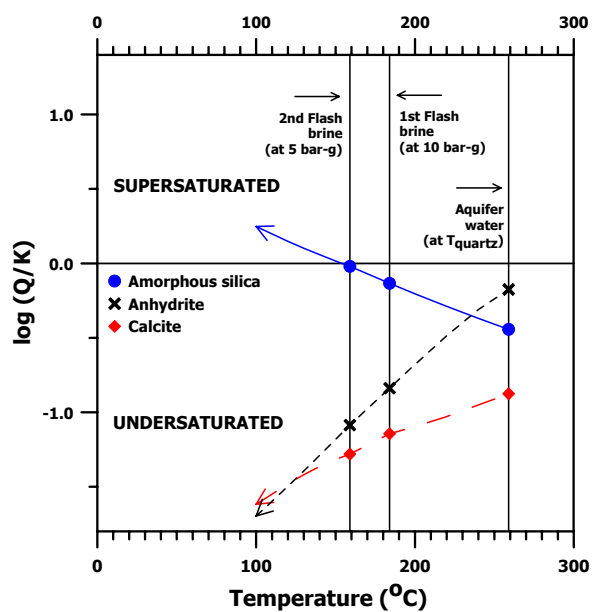


FIGURE 2: W508D saturation indices, 14% degassing

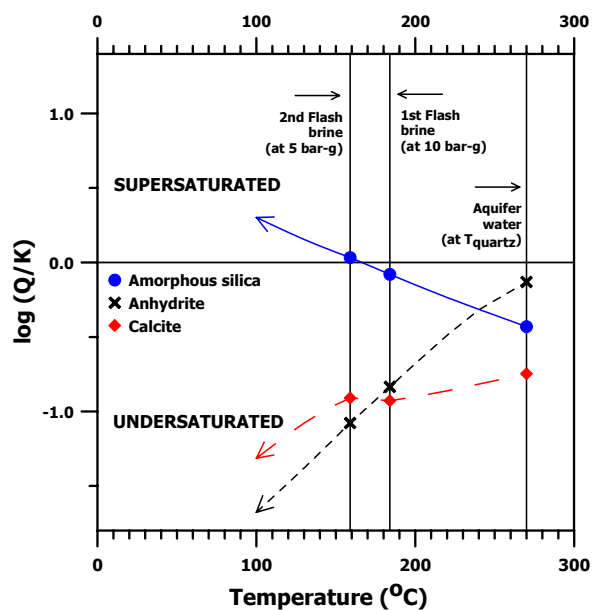


FIGURE 3: W511D saturation indices, 14% degassing

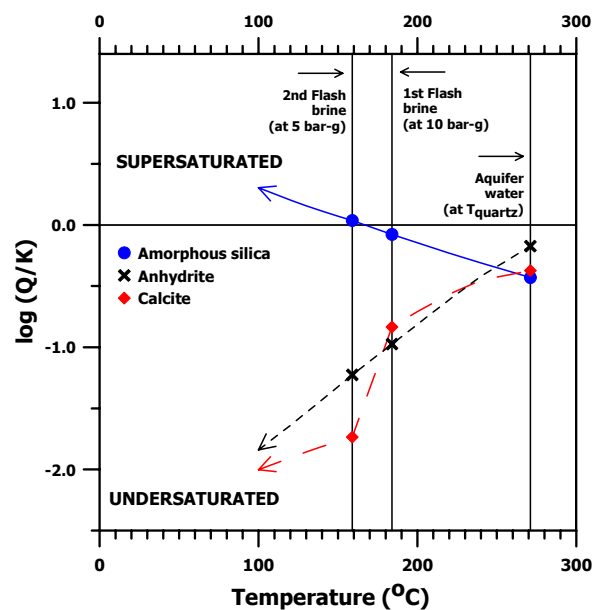


FIGURE 4: W503 saturation indices, 35% degassing

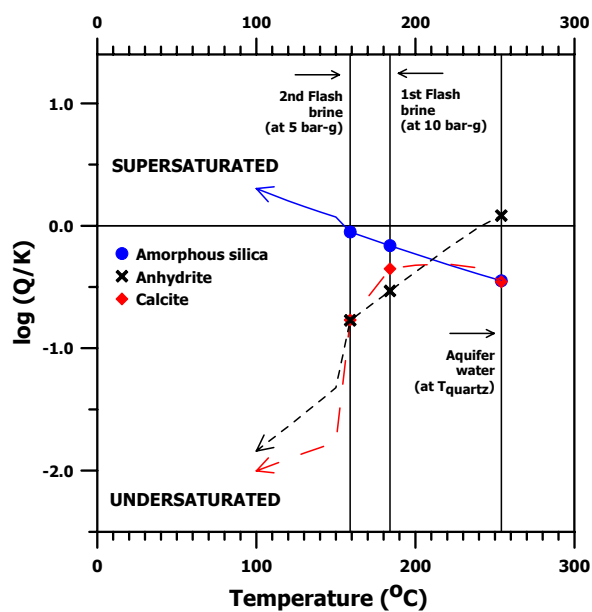


FIGURE 5: W509 saturation indices, 35% degassing

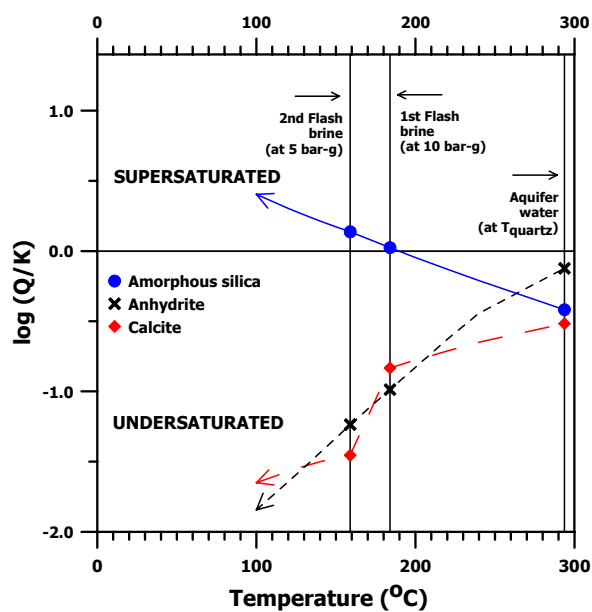


FIGURE 6: W514D saturation indices, 35% degassing

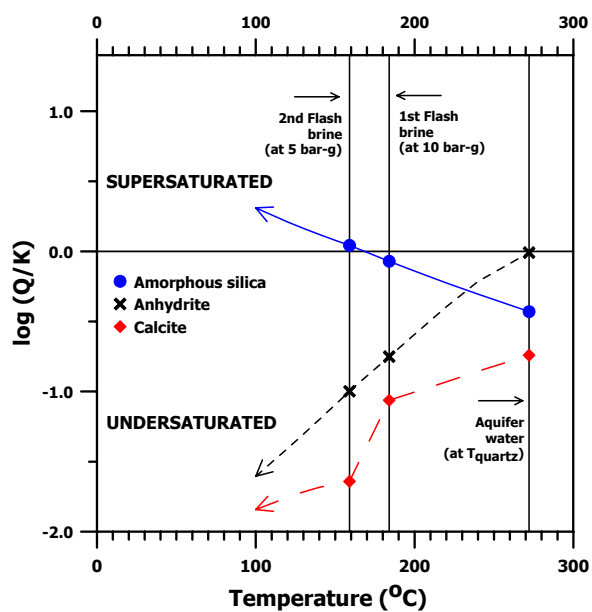


FIGURE 7: W515D saturation indices, 35% degassing

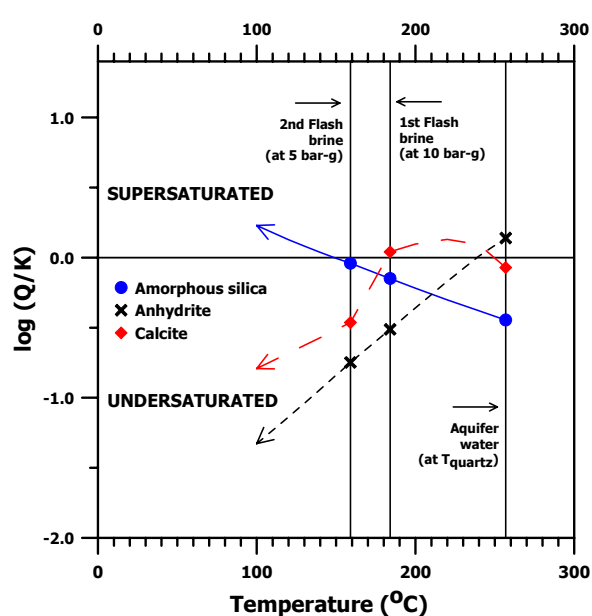


FIGURE 8: W517 saturation indices, 35% degassing

**APPENDIX V: Silica experiment results**

TABLE 1: 50°C, pure water, 1 atm, pH~7, 9 minutes retention time, filtered samples

| <b>Inlet solution</b> |                                           |                                       |                                           | <b>Outlet solution</b> |                                           |                                       |                                           |
|-----------------------|-------------------------------------------|---------------------------------------|-------------------------------------------|------------------------|-------------------------------------------|---------------------------------------|-------------------------------------------|
| <b>Time (min)</b>     | <b>SiO<sub>2</sub>, monomeric (mg/kg)</b> | <b>SiO<sub>2</sub>, total (mg/kg)</b> | <b>SiO<sub>2</sub>, polymeric (mg/kg)</b> | <b>Time (min)</b>      | <b>SiO<sub>2</sub>, monomeric (mg/kg)</b> | <b>SiO<sub>2</sub>, total (mg/kg)</b> | <b>SiO<sub>2</sub>, polymeric (mg/kg)</b> |
| 0                     | 407                                       | 412                                   | 5 <sup>d</sup>                            | 11                     | 165                                       | 175                                   | 10 <sup>d</sup>                           |
| 24                    | 402                                       | 415                                   | 13 <sup>d</sup>                           | 44                     | 161                                       | 178                                   | 17 <sup>d</sup>                           |
| 100                   | 404                                       | 413                                   | 10 <sup>d</sup>                           | 114                    | 159                                       | 172                                   | 13 <sup>d</sup>                           |
| 179                   | 392                                       | 413                                   | 21 <sup>d</sup>                           | 189                    | 164                                       | 177                                   | 14 <sup>d</sup>                           |
| 244                   | 394                                       | 413                                   | 18 <sup>d</sup>                           | 254                    | 164                                       | 178                                   | 14 <sup>d</sup>                           |
| 1,504                 | 394                                       | 404                                   | 9 <sup>d</sup>                            | 1,514                  | 167                                       | 189                                   | 21 <sup>d</sup>                           |
| 3,420                 | 235                                       | 311 <sup>a</sup>                      | 76 <sup>a</sup>                           | 3,429                  | 164                                       | 312                                   | 147 <sup>b</sup>                          |
| 4,289                 | 231                                       | 335 <sup>a</sup>                      | 104 <sup>a</sup>                          | 4,301                  | 173                                       | 339                                   | 165 <sup>b</sup>                          |
| 4,534                 | 225                                       | 392                                   | 167 <sup>d</sup>                          | 4,534                  | 173                                       | 341                                   | 168 <sup>d</sup>                          |
| 5,709                 | 233                                       | 371                                   | 138 <sup>d</sup>                          | 5,739                  | 180                                       | 355                                   | 175 <sup>d</sup>                          |
| 7,074                 | 228                                       | 386                                   | 158                                       |                        |                                           |                                       |                                           |

<sup>a</sup> Removed in plot due to low values,<sup>b</sup> Excluded in plot since no equivalent analyses from inlet,<sup>c</sup> Set to zero if plotted,<sup>d</sup> Used in inlet vs. outlet polymeric silica plots.

TABLE 2: 50°C, 0.1 M NaCl, 1 atm, pH~7, 9 minutes retention time, filtered samples

| <b>Inlet solution</b> |                                           |                                       |                                           | <b>Outlet solution</b> |                                           |                                       |                                           |
|-----------------------|-------------------------------------------|---------------------------------------|-------------------------------------------|------------------------|-------------------------------------------|---------------------------------------|-------------------------------------------|
| <b>Time (min)</b>     | <b>SiO<sub>2</sub>, monomeric (mg/kg)</b> | <b>SiO<sub>2</sub>, total (mg/kg)</b> | <b>SiO<sub>2</sub>, polymeric (mg/kg)</b> | <b>Time (min)</b>      | <b>SiO<sub>2</sub>, monomeric (mg/kg)</b> | <b>SiO<sub>2</sub>, total (mg/kg)</b> | <b>SiO<sub>2</sub>, polymeric (mg/kg)</b> |
| 0                     | 345                                       | 339                                   | -6 <sup>c,d</sup>                         | 47                     | 165                                       | 166                                   | 1 <sup>d</sup>                            |
| 34                    | 348                                       | 337                                   | -11 <sup>c</sup>                          | 1,074                  | 168                                       | 167                                   | -1 <sup>c,d</sup>                         |
| 154                   | 344                                       | 336                                   | -9 <sup>c</sup>                           | 1,809                  | 166                                       | 169                                   | 3 <sup>d</sup>                            |
| 1,062                 | 340                                       | 332                                   | -7 <sup>c,d</sup>                         | 2,479                  | 171                                       | 190                                   | 19 <sup>d</sup>                           |
| 1,791                 | 335                                       | 340                                   | 5 <sup>d</sup>                            | 3,057                  | 167                                       | 228                                   | 61 <sup>b</sup>                           |
| 2,445                 | 316                                       | 326                                   | 10 <sup>d</sup>                           | 3,929                  | 174                                       | 259                                   | 85 <sup>b</sup>                           |
| 3,057                 | 268                                       | 282 <sup>a</sup>                      | 14 <sup>a</sup>                           | 4,434                  | 166                                       | 255                                   | 89 <sup>b</sup>                           |
| 3,897                 | 237                                       | 257 <sup>a</sup>                      | 20 <sup>a</sup>                           | 5,404                  | 172                                       | 269                                   | 97 <sup>b</sup>                           |
| 4,389                 | 241                                       | 274 <sup>a</sup>                      | 33 <sup>a</sup>                           | 5,999                  | 171                                       | 268                                   | 97 <sup>d</sup>                           |
| 5,329                 | 218                                       | 299 <sup>a</sup>                      | 81 <sup>a</sup>                           | 6,899                  | 172                                       | 283                                   | 110 <sup>b</sup>                          |
| 5,924                 | 212                                       | 311                                   | 99 <sup>d</sup>                           | 7,366                  | 166                                       | 266                                   | 100 <sup>b</sup>                          |
| 6,844                 | 220                                       | 282 <sup>a</sup>                      | 62 <sup>a</sup>                           |                        |                                           |                                       |                                           |
| 7,360                 | 210                                       | 273 <sup>a</sup>                      | 63 <sup>a</sup>                           |                        |                                           |                                       |                                           |
| 8,549                 | 204                                       | 301                                   | 97                                        |                        |                                           |                                       |                                           |
| 9,672                 | 203                                       | 293                                   | 90                                        |                        |                                           |                                       |                                           |

<sup>a</sup> Removed in plot due to low values,<sup>b</sup> Excluded in plot since no equivalent analyses from inlet,<sup>c</sup> Set to zero if plotted,<sup>d</sup> Used in inlet vs. outlet polymeric silica plots.

TABLE 3: 50°C, 0.2 M NaCl, 1 atm, pH~7, 9 minutes retention time, filtered samples

| Inlet solution |                                      |                                  |                                      | Outlet solution |                                      |                                  |                                      |
|----------------|--------------------------------------|----------------------------------|--------------------------------------|-----------------|--------------------------------------|----------------------------------|--------------------------------------|
| Time (min)     | SiO <sub>2</sub> , monomeric (mg/kg) | SiO <sub>2</sub> , total (mg/kg) | SiO <sub>2</sub> , polymeric (mg/kg) | Time (min)      | SiO <sub>2</sub> , monomeric (mg/kg) | SiO <sub>2</sub> , total (mg/kg) | SiO <sub>2</sub> , polymeric (mg/kg) |
| 0              | 377                                  | 366                              | -11 <sup>c</sup>                     | 23              | 164                                  | 164                              | 0                                    |
| 108            | 379                                  | 377                              | -1 <sup>c</sup>                      | 108             | 173                                  | 159                              | -14 <sup>c</sup>                     |
| 338            | 375                                  | 375                              | 0 <sup>d</sup>                       | 356             | 166                                  | 163                              | -4 <sup>c,d</sup>                    |
| 1,296          | 241                                  | 301 <sup>a</sup>                 | 60 <sup>a</sup>                      | 1,318           | 161                                  | 273                              | 112 <sup>b</sup>                     |
| 1,888          | 226                                  | 336                              | 110 <sup>d</sup>                     | 1,908           | 164                                  | 296                              | 132 <sup>d</sup>                     |
| 2,798          | 212                                  | 232 <sup>a</sup>                 | 19 <sup>a</sup>                      | 2,818           | 162                                  | 304                              | 142 <sup>b</sup>                     |
| 3,278          | 216                                  | 304 <sup>a</sup>                 | 88 <sup>a</sup>                      | 3,288           | 159                                  | 298                              | 140 <sup>b</sup>                     |
| 4,513          | 199                                  | 320                              | 121 <sup>d</sup>                     | 4,558           | 164                                  | 292                              | 128 <sup>d</sup>                     |

<sup>a</sup> Removed in plot due to low values,<sup>b</sup> Excluded in plot since no equivalent analyses from inlet,<sup>c</sup> Set to zero if plotted,<sup>d</sup> Used in inlet vs. outlet polymeric silica plots.

TABLE 4: 50°C, 0.3 M NaCl, 1 atm, pH~7, 9 minutes retention time, filtered samples

| Inlet solution |                                      |                                  |                                      | Outlet solution |                                      |                                  |                                      |
|----------------|--------------------------------------|----------------------------------|--------------------------------------|-----------------|--------------------------------------|----------------------------------|--------------------------------------|
| Time (min)     | SiO <sub>2</sub> , monomeric (mg/kg) | SiO <sub>2</sub> , total (mg/kg) | SiO <sub>2</sub> , polymeric (mg/kg) | Time (min)      | SiO <sub>2</sub> , monomeric (mg/kg) | SiO <sub>2</sub> , total (mg/kg) | SiO <sub>2</sub> , polymeric (mg/kg) |
| 0              | 374                                  | 353                              | -21 <sup>c</sup>                     | 32              | 157                                  | 152                              | -4 <sup>c</sup>                      |
| 84             | 370                                  | 358                              | -12 <sup>c</sup>                     | 472             | 161                                  | 164                              | 3 <sup>d</sup>                       |
| 360            | 355                                  | 351                              | -5 <sup>c,d</sup>                    | 1,636           | 156                                  | 273                              | 117 <sup>d</sup>                     |
| 1,619          | 213                                  | 313                              | 100 <sup>d</sup>                     | 2,797           | 165                                  | 276                              | 110 <sup>d</sup>                     |
| 2,688          | 197                                  | 303                              | 106 <sup>d</sup>                     |                 |                                      |                                  |                                      |

<sup>a</sup> Removed in plot due to low values,<sup>b</sup> Excluded in plot since no equivalent analyses from inlet,<sup>c</sup> Set to zero if plotted,<sup>d</sup> Used in inlet vs. outlet polymeric silica plots.

TABLE 5: 50°C, 0.4 M NaCl, 1 atm, pH~7, 9 minutes retention time, filtered samples

| Inlet solution |                                      |                                  |                                      | Outlet solution |                                      |                                  |                                      |
|----------------|--------------------------------------|----------------------------------|--------------------------------------|-----------------|--------------------------------------|----------------------------------|--------------------------------------|
| Time (min)     | SiO <sub>2</sub> , monomeric (mg/kg) | SiO <sub>2</sub> , total (mg/kg) | SiO <sub>2</sub> , polymeric (mg/kg) | Time (min)      | SiO <sub>2</sub> , monomeric (mg/kg) | SiO <sub>2</sub> , total (mg/kg) | SiO <sub>2</sub> , polymeric (mg/kg) |
| 0              | 371                                  | 337                              | -34 <sup>c</sup>                     | 47              | 162                                  | 151                              | -11 <sup>c</sup>                     |
| 69             | 368                                  | 336                              | -33 <sup>c</sup>                     | 328             | 158                                  | 142                              | -16 <sup>c,d</sup>                   |
| 332            | 346                                  | 321                              | -25 <sup>c,d</sup>                   | 1,672           | 156                                  | 268                              | 112 <sup>c,d</sup>                   |
| 1,605          | 205                                  | 306                              | 101 <sup>d</sup>                     | 2,705           | 156                                  | 278                              | 122 <sup>c,d</sup>                   |
| 2,672          | 197                                  | 284                              | 87 <sup>d</sup>                      |                 |                                      |                                  |                                      |

<sup>a</sup> Removed in plot due to low values,<sup>b</sup> Excluded in plot since no equivalent analyses from inlet,<sup>c</sup> Set to zero if plotted,<sup>d</sup> Used in inlet vs. outlet polymeric silica plots.

TABLE 6: Experiment 1 results at 90°C, 0.3 M NaCl, 1 atm, pH~7,  
9 minutes retention time, filtered samples

| Inlet solution |                                      |                                  |                                      | Outlet solution |                                      |                                  |                                      |
|----------------|--------------------------------------|----------------------------------|--------------------------------------|-----------------|--------------------------------------|----------------------------------|--------------------------------------|
| Time (min)     | SiO <sub>2</sub> , monomeric (mg/kg) | SiO <sub>2</sub> , total (mg/kg) | SiO <sub>2</sub> , polymeric (mg/kg) | Time (min)      | SiO <sub>2</sub> , monomeric (mg/kg) | SiO <sub>2</sub> , total (mg/kg) | SiO <sub>2</sub> , polymeric (mg/kg) |
| 0              | 489                                  | 457                              | -33 <sup>c</sup>                     | 37              | 260                                  | 256                              | -4 <sup>c</sup>                      |
| 32             | 486                                  | 485                              | -1 <sup>c</sup>                      | 65              | 261                                  | 256                              | -5 <sup>c</sup>                      |
| 58             | 500                                  | 487                              | -13 <sup>c</sup>                     | 260             | 277                                  | 280                              | 4                                    |
| 234            | 476                                  | 481                              | 5                                    | 324             | 268                                  | 271                              | 3                                    |
| 302            | 461                                  | 476                              | 15                                   | 485             | 271                                  | 281                              | 10                                   |
| 465            | 473                                  | 479                              | 6                                    | 1,200           | 276                                  | 262                              | -13 <sup>c</sup>                     |
| 1,180          | 377                                  | 383                              | 6                                    | 1,532           | 270                                  | 297                              | 27                                   |
| 1,510          | 355                                  | 349                              | -5 <sup>c</sup>                      | 2,579           | 280                                  | 316                              | 36                                   |
| 2,555          | 356                                  | 337                              | -20 <sup>c</sup>                     |                 |                                      |                                  |                                      |

<sup>a</sup> Removed in plot due to low values,

<sup>b</sup> Excluded in plot since no equivalent analyses from inlet,

<sup>c</sup> Set to zero if plotted,

<sup>d</sup> Used in inlet vs. outlet polymeric silica plots.

TABLE 7: Experiment 2 results at 90°C, 0.3 M NaCl, 1 atm, pH~7,  
9 minutes retention time, filtered samples

| Inlet solution |                                      |                                  |                                      | Outlet solution |                                      |                                  |                                      |
|----------------|--------------------------------------|----------------------------------|--------------------------------------|-----------------|--------------------------------------|----------------------------------|--------------------------------------|
| Time (min)     | SiO <sub>2</sub> , monomeric (mg/kg) | SiO <sub>2</sub> , total (mg/kg) | SiO <sub>2</sub> , polymeric (mg/kg) | Time (min)      | SiO <sub>2</sub> , monomeric (mg/kg) | SiO <sub>2</sub> , total (mg/kg) | SiO <sub>2</sub> , polymeric (mg/kg) |
| 0              | 479                                  | 446                              | -33 <sup>c</sup>                     | 30              | 250                                  | 237                              | -13 <sup>c</sup>                     |
| 63             | 492                                  | 461                              | -31 <sup>c</sup>                     | 90              | 270                                  | 251                              | -20 <sup>c</sup>                     |
| 366            | 408                                  | 401                              | -7 <sup>c,d</sup>                    | 396             | 275                                  | 273                              | -3 <sup>c,d</sup>                    |
| 1,083          | 345                                  | 416                              | 71 <sup>d</sup>                      | 1,116           | 238                                  | 271                              | 33 <sup>d</sup>                      |
| 1,261          | 337                                  | 401                              | 64 <sup>d</sup>                      | 1,272           | 274                                  | 245                              | -29 <sup>c,d</sup>                   |
| 1,468          | 336                                  | 318                              | -18 <sup>c</sup>                     | 1,538           | 275                                  | 262                              | -14 <sup>c</sup>                     |

<sup>a</sup> Removed in plot due to low values,

<sup>b</sup> Excluded in plot since no equivalent analyses from inlet,

<sup>c</sup> Set to zero if plotted,

<sup>d</sup> - Used in inlet vs. outlet polymeric silica plots.

TABLE 8: Experiment 2 results at 90°C, 0.3 M NaCl, 1 atm, pH~7,  
9 minutes retention time, unfiltered samples

| Inlet solution |                                      |                                  |                                      | Outlet solution |                                      |                                  |                                      |
|----------------|--------------------------------------|----------------------------------|--------------------------------------|-----------------|--------------------------------------|----------------------------------|--------------------------------------|
| Time (min)     | SiO <sub>2</sub> , monomeric (mg/kg) | SiO <sub>2</sub> , total (mg/kg) | SiO <sub>2</sub> , polymeric (mg/kg) | Time (min)      | SiO <sub>2</sub> , monomeric (mg/kg) | SiO <sub>2</sub> , total (mg/kg) | SiO <sub>2</sub> , polymeric (mg/kg) |
| 0              | 479                                  | 492                              | 13                                   | 30              | 250                                  | 239                              | -11 <sup>c</sup>                     |
| 63             | 492                                  | 491                              | -1 <sup>c,d</sup>                    | 90              | 270                                  | 257                              | -14 <sup>c,d</sup>                   |
| 366            | 408                                  | 445                              | 37 <sup>d</sup>                      | 396             | 275                                  | 293                              | 17 <sup>d</sup>                      |
| 1,083          | 345                                  | 462                              | 117 <sup>d</sup>                     | 1,116           | 238                                  | 349                              | 110 <sup>d</sup>                     |
| 1,261          | 337                                  | 463                              | 126 <sup>d</sup>                     | 1,272           | 274                                  | 384                              | 110 <sup>d</sup>                     |
| 1,527          | 336                                  | 448                              | 113 <sup>d</sup>                     | 1,538           | 275                                  | 389                              | 114 <sup>d</sup>                     |

<sup>a</sup> Removed in plot due to low values,

<sup>b</sup> Excluded in plot since no equivalent analyses from inlet,

<sup>c</sup> Set to zero if plotted,

<sup>d</sup> Used in inlet vs. outlet polymeric silica plots.