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Recent Developments in Geothermal Scale Control

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ABSTRACT

Successful scale control treatment programs have been demonstrated and implemented for a variety of scale deposits encountered in the production of geothermal power, including calcite and metal silicates. More recently, inhibition of clay minerals has been demonstrated as well.

Control of amorphous silica scale has proved more challenging, and in many cases, is limited to pH modification. Chemical treatments developed to control metal silicates have limited effect against silica because formation of silica deposits involves different mechanisms and is controlled by different factors. A new class of inhibitors, different from the chemicals used to inhibit metal silicates, has been identified and is being qualified for field testing.

Computer modeling work suggests that returning carbon dioxide to flashed brine can control deposition of metal silicate scales in the heat exchanger of a combined cycle generating system while reducing or completely eliminating the need for silicate inhibitors.

1. INTRODUCTION

Scale deposition is a major problem in geothermal operations. The plugging and deposit problems caused by scale can significantly reduce power plant generation and cause expensive cleaning and maintenance costs. The reduction in power and increased operating costs caused from inadequate scale control will directly hurt a plant's financial performance.

Different types of scale are found in various geothermal areas and sometimes even among the various wells of the same field. The varieties of scale deposited from geothermal brines typically include calcium carbonate, a poorly crystallized magnesium-iron silicate, silica, and metal sulfides. Metal silicate, silica, and metal sulfide scales are often observed in higher temperature resources. Metals forming metal sulfide scales include zinc, iron, lead, and antimony. Silica and antimony sulfide, both covalent solids, pose particular difficulties because inhibitors developed against carbonates and silicates, which are ionic solids, have limited effect. Each of these scale varieties can present challenging operating problems for geothermal plants.

Calcium carbonate scale frequently causes operational problems in the brine production system. It typically forms as a result of the evolution of CO_2 from the liquid phase. CO_2 evolves any time a pressure drop occurs. Pressure drops occur in production well bores, flash vessels, and also in localized areas of production well pumps or elbows in surface piping. As CO_2 is evolved, the liquid phase experiences a corresponding pH increase. Under these conditions, even small amounts of calcium in the brine will precipitate as pH increases. A “hydrodynamic” component associated with the fluid flow to the well and lines can further aggravate calcite scaling conditions by creating local regions of low pressure and increased vapor fraction.

Likewise, increased pH caused by steam separation decreases solubility of metal silicates causing them to precipitate from the brine; for example, talc, which fairly represents magnesium silicate deposits actually formed:

$$3\ Mg^{+2} + 4\ Si(OH)_4 + 6\ OH^- \rightarrow Mg_3Si_4O_{10}(OH)_2 + 10\ H_2O$$

In addition to the powerful effect of increased pH, decreasing temperature further decreases the solubility of talc and most other metal silicates.

Silica scale is among the most difficult scales encountered in geothermal operation. Silica is present in all geothermal brines and its concentration increases with the temperature of the brine. As steam is separated from the brine and the temperature of the brine decreases, silica solubility drops. If the initial temperature of the brine, and therefore the concentration of silica, is high enough, the brine may become super-saturated in respect to amorphous silica. Under these conditions, silica may precipitate to form amorphous silica scale. These deposits are extremely tenacious and can occur throughout the production field, plant, and injection systems.

Metal sulfide scales are also encountered in geothermal operations, in high temperature as well as low/medium temperature resources. Metal sulfide scales have been observed in production wells with two-phase flow and have caused choking of the brine flow from the well. Antimony is sometimes present in low/medium temperature brines and can form antimony sulfide deposits in binary plant heat exchangers. Because antimony is extremely insoluble, as little as 100 parts per billion of antimony in brine can cause problems with antimony sulfide deposits.

2. SCALE CONTROL BY INHIBITORS

2.1 Calcite

Calcite inhibitors have proved very effective in controlling calcite scale in production wells. Several commercial inhibitors are available and the selection of the appropriate inhibitor is critical for a successful scale control program. Using the appropriate feed equipment is also crucial and allows for the delivery of the inhibitor to the appropriate location in the well bore.

PowerChem has successfully implemented calcite scale control applications in numerous plants and fields throughout the world-wide geothermal industry. A typical feed system equipment installation for a flash plant is illustrated in Fig. 1. In addition to selecting the appropriate scale inhibitor, the bundled equipment package is designed to include pumps, tanks, a lubricator assembly, capillary tubing (commonly 0.25 inch O.D.), sinker bars, and injection nozzles.

Figure 1: Bundled chemical feed equipment package showing pump skid, insulated tank, capillary tubing, and wellhead lubricator assembly.

2.2 Magnesium-Iron Silicates

While the concentration of magnesium in geothermal brines is always much less than the concentration of calcium and sometimes is undetectable, the very low solubility of magnesium silicate minerals after steam has been separated from the brine and temperature has decreased practically guarantees that magnesium silicate or a mixed magnesium-iron silicate will precipitate. Quantitatively, the magnesium-iron silicate deposits are small in proportion to the small amount of magnesium and iron present in the brine. However, they tend to form hard, tenacious scales causing rapid deterioration of heat exchanger performance in a binary bottoming cycle. Once formed, magnesium-iron silicate scales are hard to remove even when hydrofluoric acid is employed.

Magnesium silicate inhibitors are available which can prevent fouling of heat exchangers when properly applied. PowerChem has had good success at several locations using blended products that contain synergistic components which effectively inhibit calcite scale as well. The introduction of new products has provided greater success in allowing different local conditions to be targeted in a cost-effective manner. Further research is underway, aimed at increasing product effectiveness while decreasing treatment costs.

The problem of removing magnesium silicate scales once formed has also been addressed. A recently developed product, when added to hydrofluoric acid, allows complete removal of magnesium silicate deposits while avoiding the formation of pseudo-scale.

2.3 Clays

The concentration of aluminum in geothermal brine is governed by fluoride and pH. Geothermal brines that contain fluoride and a large amount of CO_2 in solution and are, therefore, unusually acidic, sometimes contain enough aluminum to precipitate clay minerals after steam has been separated and temperature reduced. Kaolinite clay (aluminosilicate) precipitates according to the following reaction:

$$2\ AlF_3(aq) + 2\ Si(OH)_4 + 6\ OH^- \rightarrow Al_2[Si_2O_5](OH)_4 + 5\ H_2O + 6\ F^-$$

While clays are soft and tend not to form tenacious scales, clay can damage injection wells if a substantial amount precipitates from the brine.

Fig. 2 is a Scanning Electron Microscope image of clay minerals precipitated from a geothermal brine which was being passed through two stages of filters with 2 micron pore size to remove suspended solids before being reinjected. The sample analyzed was soft material that accumulated on the face of the second filter; that is, after the brine had already been filtered to remove particles large than 2 microns.

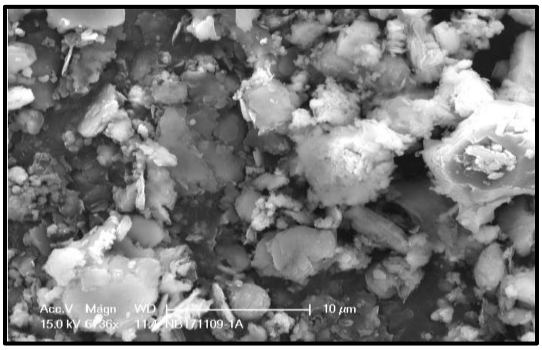


Figure 2: Scanning Electron Microscope (SEM) image of solids filtered from geothermal brine which was previously passed through a 2 micron filter. Large vaguely hexagonal plates are kaolinite precipitated from the brine. Fine particles are quartz silt carried up from the producing formation and a 3-layer clay precipitated from the brine.

X-ray diffraction analysis of the same sample indicated roughly equal amounts of quartz, kaolinite (a two-layer clay mineral), and an otherwise unidentified three-layer clay mineral to be present as the major constituents.

The large, vaguely hexagonal plates have morphology typical of kaolinite. The fact that kaolinite plates up to 10 micron in size were filtered from brine that had already passed through a 2 micron filter indicates that the kaolinite was actually precipitating from the brine, rather than preexisting material carried up from the producing formation. The imperfect, “fuzzy” appearance of the kaolinite plates also suggest recently precipitated material; natural kaolinite typically has a cleaner, more precisely hexagonal morphology.

The fine grained material is a mixture of very fine quartz silt carried up from the formation and three layer clay, which probably precipitated from the brine together with the kaolinite. Chemical modeling of the brine suggests this clay to be beidellite, a common, widespread member of the smectite group.

This sample came from a project where large amounts of sand carried up from the formation, together with clays precipitated from the brine required the brine be filtered prior to reinjection. The filter replacement costs were large, and filtration failed to adequately control the problem because the precipitation of the clays continued even after the brine was filtered. For many months, these problems limited brine production and the power generated to a fraction of the installations design capacity.

Once it was realized that the clays were actually precipitating from the brine, a metal silicate inhibitor was applied and the amount of clay precipitating from the brine was greatly decreased. Meanwhile, the amount of sand coming up from the formation dropped as the wells cleaned out. Together, these beneficial changes greatly reduced costs associated with filtering the brine, allowing power production to be progressively increased.

2.4 Metal Sulfides

There has been limited success in controlling metal sulfide scale deposited from geothermal brines. Some metal sulfides, for example ZnS, are sensitive to pH and can, in principle, be controlled by acidifying the brine. Unlike ZnS, antimony sulfide becomes less soluble at lower pH and reducing pH would increase scaling tendency. However, there has been some success controlling antimony sulfide using inhibitors.

By-and-large, control of metal sulfide deposits remains an unsolved problem.

2.5 Silica

The control of silica scale in geothermal operations has proved challenging and difficult. Chemical inhibitors are sometimes employed but have limited effect, because the molecular structure and chemical processes involved in deposition of amorphous silica scale are quite different from those involved in deposition of calcite and metal silicates. Products developed to control calcite and metal silicates typically are anionic, and act by binding to cations on the surface of a growing crystal. Because amorphous silica contains no cations, these inhibitors literally do not have anything to grab on to.

Adding acid to the brine to control silica scale (“pH Mod”) has been widely considered but rarely implemented. Decreasing pH slows the chemical kinetics of silica polymerization but has no effect upon the solubility of silica, and large amounts of acid are often required to neutralize alkalinity in the brine. Also, decreasing brine pH can aggravate corrosion, the acid is itself hazardous and highly corrosive, and a variety of operational problems are encountered.

A new class of silica inhibitors, unrelated to commercial products commonly recommended for that application have been identified and is being investigated in our laboratory. Laboratory test results are presented in Figures 3 and 4. In these experiments, colloidal silica is added to a simulated brine to provide a substrate of well-defined surface area for deposition of dissolved silica. These tests simulate the slow formation of a dense, glassy silica deposit on solid surfaces.

Figure 3 illustrates the effect of a product widely promoted for inhibiting deposition of silica and metal silicates, which is, in fact, effective against metal silicates. However, the inhibiting effect against silica itself is small. Figure 4 illustrates the strong inhibiting effect of a product representative of the new class of scale inhibitors

A number of related materials with similar strong inhibiting effect have been screened and identified. This test work is ongoing, and is being extended to include direct measurement of scale deposition rate on a metallic surface.

3.0 SCALE CONTROL USING CARBON DIOXIDE

Unlike silica itself, the solubility of silicate minerals decreases with increasing pH. Solubility also decreases with decreasing temperature. Therefore, separating steam from the brine causes silicates to precipitate, and magnesium-iron silicate scale is commonly observed in the heat exchanger of a steam-binary hybrid or combined cycle power generating unit as illustrated in Figure 5

Scale deposition in the heat exchanger is commonly controlled by adding a silicate inhibitor to the brine. This method is effective, but expensive. Because solubility of the silicate scale is sensitive to pH, scale deposition could in principle be controlled by adding an acid to the brine to decrease pH. However, this approach may not be practical and may be hazardous because of the large amount of acid that would be needed.

Happily, there is an acid available at no cost as a by-product of the power generating process: carbon dioxide. Figure 6 illustrates the use of CO_2 for this purpose in its simplest form. A small gas separator is added to the system before the high pressure (HP) steam separator and operated at a pressure just below the bubble point of the brine.

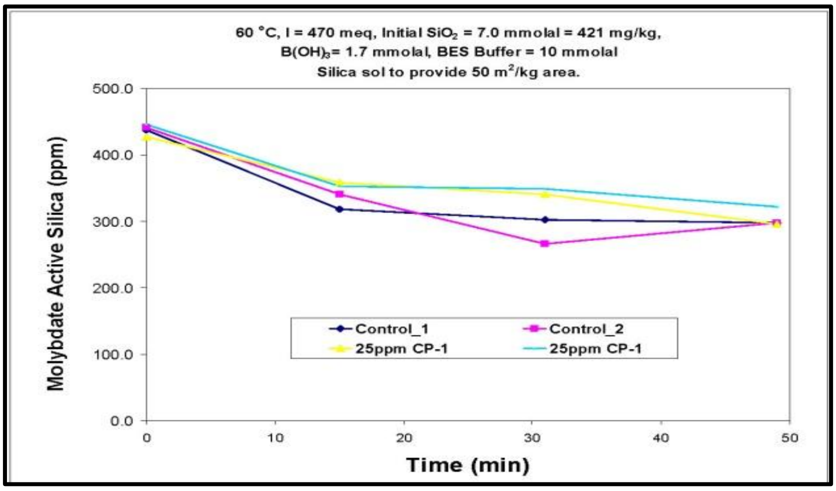


Figure 3. The effect of a silicate inhibitor against silica is small.

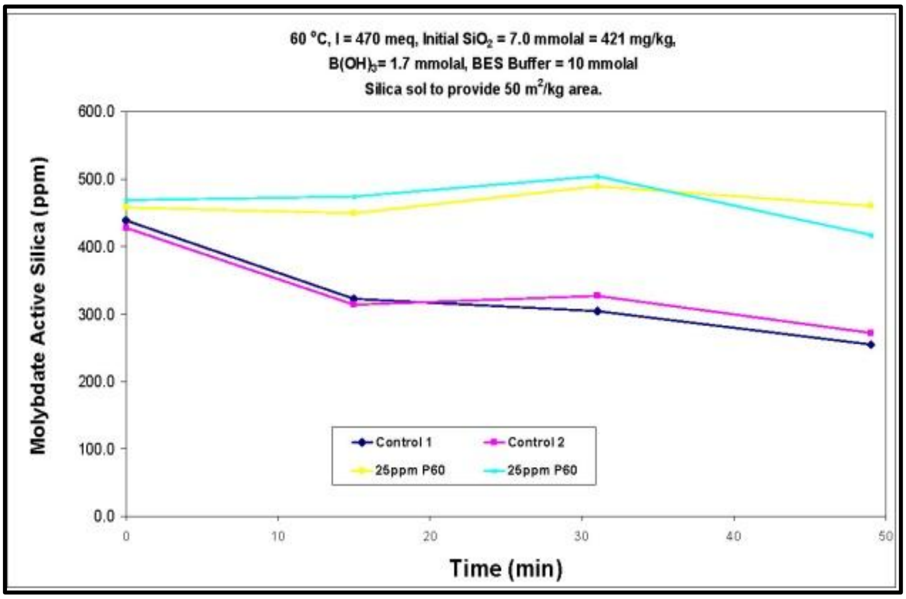


Figure 4. Silica deposition strongly inhibited by a chemical representative of a new class of inhibitors.

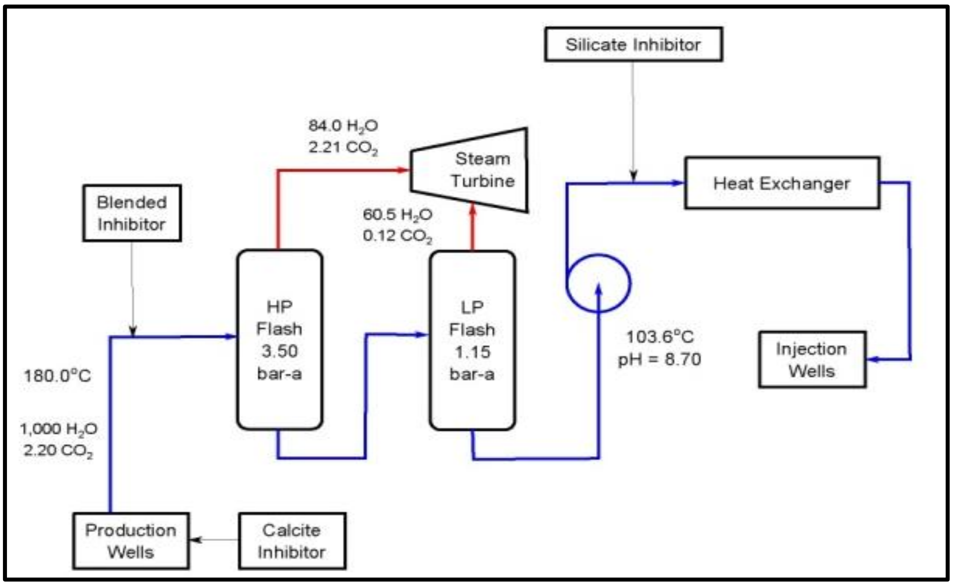


Figure 5. Baseline configuration: mass flows in kg/1,000 kg brine.

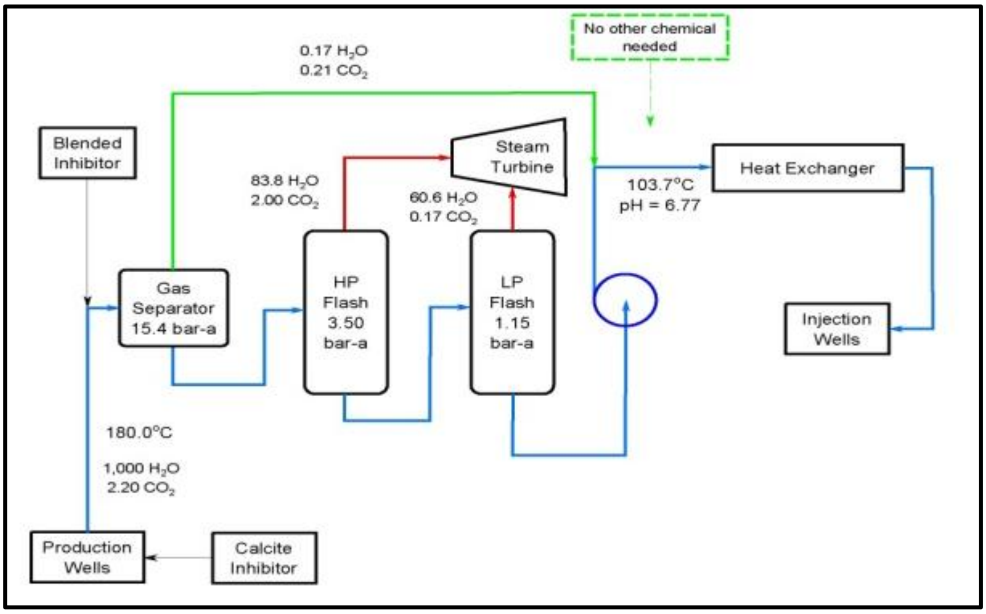


Figure 6. Scale inhibition using CO_2: Mass flows in kg/1,000 kg brine.

The small amount of vapor that separates from the brine at this pressure contains a large concentration of CO_2. This gas-rich vapor is added to the flashed brine between the low-pressure separator and the heat exchanger. The CO_2 thus added to the flashed brine decreases pH of the brine, preventing scale deposition.

In this way, the need for costly silicate inhibitors is reduced or completely eliminated.

3.1 Computer Modeling of Geothermal Fluids

The effect of returning CO_2 to the brine was investigated by modeling the chemistry of the brine.

An integrated approach is used to model the chemistry of geothermal brines, employing programs derived from the public domain program CNDSR together with the commercially available program Geochemist's Workbench.

CNDSR was originally developed by the second author nearly 30 years ago to model gas liquid-vapor partitioning and transport of gases in the condensers and cooling water system of a geothermal power plant. CNDSR is able to model complex systems of many parts with flow of liquid and vapor between them, where different pressures can be specified in the different parts of the system, and heat and chemical constituents can be added or removed as desired. CNDSR was written to run on a main frame computer at a time when punched cards were still in use, but has been transferred to PCs in several versions by different users, and remains the tool of choice for modeling condensate and cooling water chemistry in geothermal power plants.

A proprietary derivative of CNDSR called BRINE is used to calculate brine pH, steam separation, and liquid-vapor partitioning of gases in low-to-moderate salinity geothermal brines. Figure 7 illustrates a simple model system computed using BRINE. This model was used to study the installation depicted in Figures 5 and 6, and generated the mass flow values presented in these Figures. The amount of water and the enthalpy of the water coming into the system from the well is indicated, and the amount of heat removed in the heat exchanger. The pressure in each of the three separators is specified in bars-absolute.

Because CNDSR and BRINE were written to allow calculation of liquid-vapor partitioning and mass transport in complicated systems, simple chemical models were employed, which calculate only gas solubilities and acid-base equilibrium in the liquid phase. The only other chemical reaction modeled is the interconversion of carbon dioxide and carbonic acid. Solubility and precipitation of solid phases are not calculated by BRINE.

The solids that precipitate from geothermal brines are similar and sometimes identical to natural minerals. Therefore, computer programs developed to model mineral solubilities can profitably be employed, with due regard for the much shorter time scales and typically much greater deviations from chemical equilibrium encountered in processing geothermal fluids.

We employ the commercially available program Geochemist's Workbench to compute chemical equilibrium and reactions involving geothermal brine and the minerals that may exist in a geothermal reservoir or precipitate from the brine. The capabilities of Geochemist's Workbench (GWB) complement those of BRINE: GWB is able to calculate chemical equilibrium and dissolution/precipitation reactions for many minerals, but is very limited in respect to calculating liquid-vapor partitioning and mass transport among the different parts of a complex system. Therefore, we use BRINE together with GWB, taking advantage of their mutually complementary capabilities.

3.2 Reconstruction of the Initial Composition of the Brine

The initial step of the calculation involves reconstructing the brine as it originally existed down in the reservoir using GWB. The starting point is the reported chemical composition of the brine. In practice, the reported composition rarely, if ever, accurately portrays the initial composition of the brine. In particular, the reported concentrations of Mg and Al are rarely, if ever, reliable. These elements are important, because most of the Al or Mg present in the brine will precipitate, forming the respective silicate minerals after steam is separated from the brine. However, the initial concentrations usually are small, and are often lost between the time the brine sample is taken and the time it is analyzed.

Typically, the following procedure is employed to reconstruct the initial composition of the brine.

1. The initial temperature of the brine is calculated. In the rare event that the enthalpy of the total flow is known, it is used to fix the initial brine temperature, before separation of a vapor phase. More typically, the initial temperature is inferred based using the quartz geothermometer and allowing for the effect of steam separation.

2. The initial concentration of CO_2 is determined employing the reported concentration of calcium and alkalinity in the brine and the assumption that the brine was initially at equilibrium with calcite.

3. The initial concentrations of Mg and Al are calculated, assuming chemical equilibrium of the brine with minerals containing these metals which are predicted to be the least soluble and therefore most stable under conditions inferred to exist in the reservoir.

Table 1 presents an example of a reconstructed brine composition. This composition does not represent any specific geothermal project, but falls within the range of brine composition commonly encountered and thus may be considered typical.

	mmol/kg-H_2O	mg/kg
Na^+	150.0	3409
Mg^{+2}	0.025	0.61
Ca^{+2}	0.92	36.5
Zn^{+2}	4.1×10^{-6}	2.6×10^{-4}
Cl^-	145.9	5115
HCO_3^-	5.92	357
$SiO_2(aq)$	3.62	215
$B(OH)_3$	1.00	61
$H_2S(aq)$	0.20	6.7
$CO_2(aq)$	50.03	2176
Alkalinity as $CaCO_3$	5.95 meq/kg-H_2O	295
T(°C)	180	
pH	5.90	
P(bar)	16.0 at bubble point	

Table 1. Initial Composition of the Brine Modeled Brine composition before any vapor has been separated from it; that is, the brine as it exists down in the geothermal reservoir, in equilibrium with calcite, dolomite, quartz, and sphalerite.

3.3 Calculating the Effect of Steam Separation and Predicting Deposits

Once the initial composition of the brine has been reconstructed using GWB, the effect of steam separation on dissolved gas content and temperature is calculated using BRINE. Figures 5 and 6 illustrate the results obtained, using the model depicted in Figure 7.

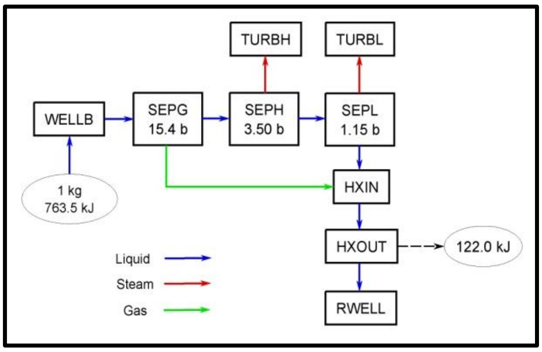


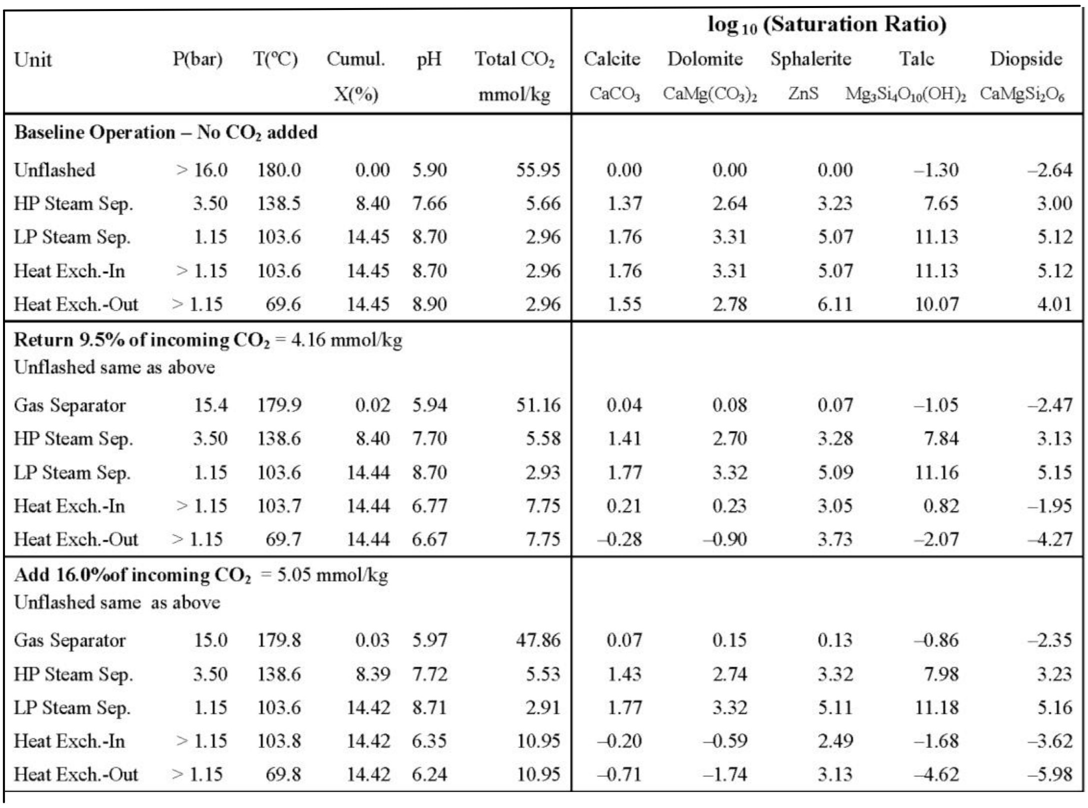
Figure 7. Simple brine model

Finally, the solubility and precipitation of minerals is calculated using GWB. Because the time available for reaction in a geothermal power generating system is small and the deviation from chemical equilibrium is large, the choice of minerals allowed to precipitate requires some discretion. Minerals of simpler structure are favored under these conditions; for example, calcite and amorphous silica. Silicate minerals with complex, three dimensional structures do not precipitate, because crystal defects quickly build up when the degree of supersaturation is large, resulting in structures that are amorphous or nearly so. Aside from amorphous silica, solubility data are not available for amorphous silicates. Therefore, the solubility and precipitation of clays and clay-like minerals are calculated as approximate stand-ins for the poorly defined silicate solids that do precipitate. Magnesium-iron silicate deposits are represented by the clay-like minerals talc and minnesotaite, which has the same structure as talc, with ferrous iron in place of Mg.

The results of typical calculations are presented in Table 2. The example presented in Tables 1 and 2, and Figures 5 to 7 actually summarizes development of this new method of scale control, which is now patent pending. That a new method of scale control was developed by computer modeling alone demonstrates the power of the computer programs and theoretical methods employed.

3.4 Effect of Returning Carbon Dioxide to the Flashed Brine

Table 2 summarizes the calculated results. “X” is the cumulative steam fraction; that is, the total amount of water that has been separated from the brine as steam up to that point in the system, expressed as a percentage of water initially in the brine. “Total CO_2” is the sum of CO_2 as such dissolved in the brine, plus bicarbonate and carbonate.



						$\log_{10}$ (Saturation Ratio)				
Unit	P(bar)	T(°C)	Cumul. X(%)	pH	Total CO_2 mmol/kg	Calcite $CaCO_3$	Dolomite $CaMg(CO_3)_2$	Sphalerite ZnS	Talc $Mg_3Si_4O_{10}(OH)_2$	Diopside $CaMgSi_2O_6$
Baseline Operation – No CO_2 added										
Unflashed	> 16.0	180.0	0.00	5.90	55.95	0.00	0.00	0.00	–1.30	–2.64
HP Steam Sep.	3.50	138.5	8.40	7.66	5.66	1.37	2.64	3.23	7.65	3.00
LP Steam Sep.	1.15	103.6	14.45	8.70	2.96	1.76	3.31	5.07	11.13	5.12
Heat Exch.-In	> 1.15	103.6	14.45	8.70	2.96	1.76	3.31	5.07	11.13	5.12
Heat Exch.-Out	> 1.15	69.6	14.45	8.90	2.96	1.55	2.78	6.11	10.07	4.01
Return 9.5% of incoming CO_2 = 4.16 mmol/kg Unflashed same as above										
Gas Separator	15.4	179.9	0.02	5.94	51.16	0.04	0.08	0.07	–1.05	–2.47
HP Steam Sep.	3.50	138.6	8.40	7.70	5.58	1.41	2.70	3.28	7.84	3.13
LP Steam Sep.	1.15	103.6	14.44	8.70	2.93	1.77	3.32	5.09	11.16	5.15
Heat Exch.-In	> 1.15	103.7	14.44	6.77	7.75	0.21	0.23	3.05	0.82	–1.95
Heat Exch.-Out	> 1.15	69.7	14.44	6.67	7.75	–0.28	–0.90	3.73	–2.07	–4.27
Add 16.0%of incoming CO_2 = 5.05 mmol/kg Unflashed same as above										
Gas Separator	15.0	179.8	0.03	5.97	47.86	0.07	0.15	0.13	–0.86	–2.35
HP Steam Sep.	3.50	138.6	8.39	7.72	5.53	1.43	2.74	3.32	7.98	3.23
LP Steam Sep.	1.15	103.6	14.42	8.71	2.91	1.77	3.32	5.11	11.18	5.16
Heat Exch.-In	> 1.15	103.8	14.42	6.35	10.95	–0.20	–0.59	2.49	–1.68	–3.62
Heat Exch.-Out	> 1.15	69.8	14.42	6.24	10.95	–0.71	–1.74	3.13	–4.62	–5.98

Table 2. The effect of adding CO_2 rich vapor from the gas separator to the flashed brine

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Calcite would be deposited from the flashed geothermal brine in nearly every case unless calcite inhibitor is applied. Talc and diopside are modeled as representative of magnesium silicate and calcium silicate deposits which typically are poorly crystallized and variable in composition, and sphalerite (ZnS) is representative of the sulfide minerals sometimes observed. Results for amorphous silica are not presented, because amorphous silica would not precipitate from this brine under any condition modeled here and its solubility is much less sensitive to pH.

In all cases, the brine starts out saturated with calcite, dolomite, sphalerite, and quartz (not shown) down in the geothermal reservoir (“Unflashed” in Table 2), but is initially undersaturated in respect to talc and diopside.

Separating steam from the brine in the HP (High-Pressure) Steam separator increases the saturation ratios calculated for all five minerals, and separating more steam from the brine in the LP (Low Pressure) Steam Separator further increases the saturation ratios.

Returning to the flashed brine an amount of CO_2 equal to 9.5% of the molecular CO_2 (that is, CO_2 as such) initially dissolved in the brine decreases the pH by nearly 2 units (the difference between “LP Steam Sep.” and “Heat Exch.-In”) and sharply decreases the saturation ratio for each mineral. The value of log S for diopside is now negative at the inlet of the binary heat exchanger. The values of log S for calcite, dolomite and talc are positive at the inlet of the binary heat exchanger but small, and negative at the outlet of the binary heat exchanger. Log S for sphalerite is decreased, but remains positive. Under these mild conditions, the calcite inhibitor added to the brine downhole probably would suffice to protect the binary heat exchanger as well as the steam separators. (Calcite inhibitors commonly inhibit precipitation of silicate minerals to some degree as well, though not as well as products specifically developed to inhibit silicate deposits.)

Thus, returning to the flashed brine just 9.5% of the CO_2 initially present in this brine would suffice to largely prevent deposition of carbonates and silicates in the binary heat exchanger. Deposition of sulfides would also be decreased and would in any case be small or insignificant in proportion to the small concentration of sulfide-forming metals in the brine. The precipitation of clay minerals, the solubility of which also drops with increasing brine pH, would also be inhibited.

Returning to the flashed brine 16% of the molecular CO_2 initially dissolved in the brine would decrease pH even further, resulting in undersaturation in respect to calcite, dolomite, talc and diopside at the inlet of the binary heat exchanger as well as the outlet. In this case, the CO_2 returned to the brine would by itself completely inhibit precipitation of carbonates and silicates in the binary heat exchanger and injection wells, with no reliance on scale inhibitors which may already be present in the brine.

The amount of CO_2 that must be returned to the brine to inhibit scale deposition would, of course, depend on the composition of the brine and operating conditions. However, in most cases much less than half of the CO_2 initially present in the brine would do the job.

3.5 Minimum Effect on Power Output

In the common situation where the brine is already two-phase when delivered to the power plant, most of the CO_2 initially dissolved in the brine will be in the vapor phase at that point. In that case, just a fraction of this initial vapor phase would be separated from the brine before it enters the high pressure steam separator and combined with the flashed brine before it enters the heat exchanger. Some amount of water vapor would necessarily go along with the CO_2, thereby slightly decreasing the amount of high pressure steam provided to the turbine and the amount of power generated by the high pressure turbine. However, detailed consideration of this issue indicates that the net effect on power generation would be small. First, enthalpy of the steam added to the flashed brine together with the CO_2 would increase the temperature of the brine entering the heat exchanger, thereby increasing the power output of the bottoming cycle. Second, removing a fraction of the CO_2 and other noncondensible gases from the brine before it enters the steam separator would decrease the gas content of the steam provided to the turbines, thereby decreasing the amount of steam consumed to power the gas ejectors. Together, all of these effects practically cancel out, and the net effect on power generated is small, and may even be slightly beneficial.

Of course, preventing fouling of heat exchange surfaces would increase power output; thus, the overall effect upon power output would be positive and substantial.

4.0 CONCLUSION

Deposition of calcite scale from geothermal brines is a familiar, practically universal problem that can be readily controlled by appropriate application of chemical inhibitors.

Metal silicates can also be controlled using chemical inhibitors, but the high cost of the inhibitors employed is a serious concern.

A new method of controlling metal silicates using carbon dioxide separated from the brine has been developed and shows considerable promise.

Because the chemical factors that control the solubility and precipitation of amorphous silica are quite different from metal silicates, inhibitors used to control metal silicates have limited effect against silica itself. However, a new class of inhibitors specifically active against silica has been identified and is being investigated. Although decreasing pH has no effect upon the solubility of silica, it does slow down the chemical reactions involved in forming silica deposits. Therefore, carbon dioxide can be used to decrease the precipitation of silica as well.

Controlling the precipitation of metal sulfides remains challenging with limited progress to date. In some cases, for example ZnS, returning carbon dioxide to the brine may be effective, but additional control methods and a better understanding of the chemical parameters controlling precipitation of metal sulfides are needed.

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