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Siliceous scaling aspects of geothermal power generation using binary cycle heat recovery

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ABSTRACT

Siliceous scaling potential of geothermal brines has long been an obstacle to the efficient energy recovery from some geothermal resources. In classical flash geosteam plant the brine for disposal was separated at high enough temperature in order to avoid «silica oversaturation)) which might lead to scaling on further cooling for additional power generation through heat recovery.

Recent years binary cycle heat recovery experience involved cases of brine cooling leading to «silica oversaturation)) which did not cause extensive fouling in the heat exchanger part of the plant. Some case histories of such successful applications are presented.

Kinetics of siliceous precipitation, being overlooked in the past, is nowadays tackled through various design and/or operation approaches in order to keep fouling within acceptable limits.

KEYWORDS

Power generation, silica, binary-cycle, geothermal brine

Introduction

Deposition and related phenomena were considered a major constraint on the development of geothermal energy worldwide (GUDMUNDSSON 1983). Among the different minerals susceptible to deposit, silica and calcite are the most common and the most difficult to remove. However, while calcite has been mostly troublesome for production wells management, silica is considered «dangerous» for reinjection wells and some parts of the surface conducts transporting the brine. The scaling problem is inherent to most liquid dominated geothermal resources. Generally as aquifer temperatures rise, scaling problems would be more expected along the extraction system.

In steam operating geopower plants silica deposition by steam carryover, became sometimes very troublesome to the operation (when even in small concentrations it affected steam turbines, valves and separators). This aspect, however, is beyond the scope of our paper.

The fear of silica deposition after separation of two phase geofluids induced conservative approach for the design of geothermal power plants. The result of such approach was the limitation of the lower obtainable temperature and hence, a severe restriction on the power capacity output.

After a short review of the silica problem sometimes encountered, in production wells, this paper will concentrate on the silica scaling aspects of separated brine handling, with special emphasis on power production from such a brine as presented by some case histories.

Earlier designs of two phase beat resources exploitation were bothered by scale formation (CORSI **1987)** from single phase fluids (reinjection pipelines) and from flashing fluids (wells, separators, two phase pipelines) and of course by steam carryover deposition (not dealt in this paper). Scaling from single phase fluids, being mostly related to the liquid phase, («spent brine))) was frequently associated with siliceous species depositing as amorphous or semi-amorphous silica or silicates. Empirical silica saturation curves and equations derived from laboratory research *on* pure and saline waters at different temperatures (up to about 350°C), served as guidelines for the definition of silica «supersaturation» (FOURNIER et al. **1983,** FOURNIER et al. **1977),** and hence, for the drawing of the temperature limit for brine disposal.

The development of the Organic Rankine Cycle (O.R.C. or otherwise ((binary))) technology for geothermal power plant application at the beginning of the **80's** was limited to those cases where silica scaling would not be expected like in medium to low enthalpy sources. At East-Mesa (USA) pumped geothermal brines produced light *iron* carbonate and iron sulfide scales **(GRASSIANI 1988)** mostly protective against C. steel corrosion, while iron silicate was scarcely present on cooling to temperatures lower than **90°C.** At the same time scientists and field exploiting people started to be more confident about the site specific nature of the silica deposition and about the importance of the kinetics of such deposition which might permit further thermal use of spent brines issuing from medium to high enthalpy geothermal two phase resources. The interest shifted from Silica Index (actual concentration to «supersaturation» concentration ratio) to «induction (or incubation) period to polymerisation))wbicb is a major prerequisite to colloidal amorphous silica generation and further massive deposition. Induction periods may vary from several minutes to several hours and in many cases long enough to permit normal **flow** and heat transfer inside the critical heat exchanger part of the binary plant unit. Further more design and operation experience has allowed in recent years to bring scaling rate to a reasonable extent.

Experimental work at different locations worldwide was fust aimed at the handling of silica bearing brines and their eventual reinjection (e.g. plugging of reinjection wells). It lead eventually to the costly on line treatment of separated brines resulting in silica removal (from hypersaline brines at the Salton Sea plants). The emergence of brine convective beat recovery technology has added to the incentive of looking for other practical solutions and for more insight (RIMSTIDT et al. **1978)** *on* the practical rate of deposition.

Exceptional fast silica scaling cases

In some cases steam operating power plants were built on initially known «problematic» sites where silica scaling appeared before or right after first flash separation. The following two examples shortly **summarize** such cases.

Silica (among other species) has been encountered in scaling events of some production wells in the Cerro Prieto I plant (Mexico). It occurred on the production line (MERCADO et al. 1989). Further reports on other wells confirmed this phenomenon of «major abundance of amorphous silicates))(HURTADO et al. 1983). The scaling in the production line (including also some calcite and sulfides) was considered bearing «an enormous impact on the cost of power generation)). Due to the eventual decrease **of** steam production following scaling and to the decrease of availability, following maintenance, the plant would need a greater number of supporting wells at an extra economic toll. Furthermore the cost of such wells maintenance involving descaling would not be negligible, not mentioning the serious risk of well collapse during such operation. Most of the brine at Cerro Prieto is disposed in ponds (where partial «cold» injection has been considered).

The late Milos (Greece) power plant (DELLIOU, 1989) had severe silica scaling taking place in the flash/separation and brine transmission systems at the designed 8 bars separator pressure (silica concentration at 1150 ppm!).

In other cases high silica deposition rate drove to expensive engineering solutions of separating the silica before brine handling (Salton Sea projects) or even to the decision to stop further development like in the case **of** the Assal field in Djibouti (where at different **pressures** different scales occurred).

As one can find out, even at fast silica scaling conditions of upstream the classical geosteam plants, engineering solutions were adopted (provided economic incentives were attractive), to overcome the problem of the silica deposition in the spent brine handling. Ponding, like in the Svartsengi plant (Iceland) turned to be beneficial through creating a tourism resort (in spite of the heavy **H_2S** smell).

However, these *fast* silica deposition cases caused high reluctance among geopower plant designers from further **use** of the hot separated brine, sticking to the barrier of the supersaturation point (derived from literature as mentioned above), while in many other cases the scaling kinetics are such as to permit such a use. Going into further heat to power use after the first separation, the idea of second flash in order to produce lower pressure steam, drove to higher supersaturation values on further concentration of the brine in addition a certain rise of pH, due to the pressure drop release of some acidic still dissolved gases (CO_2, H_2S) occurs; all of which further boost polymerization faster than if the brine was cooled without flashing.

Brine pH effect on silica deposition kinetics

The strong relation between pH and precipitation rate of amorphous silica from a ((supersaturated, solution was observed in quite a few cases. At the Fushima field in Kyushu Japan (AKAKU 1990) it was observed that the acidic water discharged from Well C (pH = 3.9) having the highest silica concentration generated relatively small silica-rich scale while the neutral pH water containing only moderate silica concentration (from Well F) continuously precipitated amorphous silica from upstream through downstream sections of the flow test equipment. It was considered that in Fushima waters the pH controls the precipitation rate of amorphous silica more than the supersaturation degree.

At Svartsengi (Iceland), early tests (GUDMUNDSSON 1983) carried on spent brine, did not show any polymerisation «for at least 60-80 minutes)) when values **of** pH ≤ 5.5 (the natural pH of the brine **was** 7.8 at 20°C). The titration results (in a test of added acid and caustic as 0.1 N to cover a pH range of 2 to 10.7) indicated «that lowering the brine pH to prevent deposition/polymerisation may be practical)). Later test at 80°C (GUDMUNDSSON et al. 1984) carried on a mixture of brine (630 ppm silica) 80% and steam condensate 20% with resultant pH = 6.7 and silica content **of** 490 ppm.

The degree of polymerization was tested through measuring the residual monometric silica versus time. **The** test clearly showed the common beneficial effect **of** both dilution and pH decrease (from 7.8 to 6.7) on **the** rate of silica polymerization, which at the original brine conditions, double flashed to vacuum (70-75°C), was fast while after dilution became slow enough to keep the monometric silica in solution for 60 minutes.

In New Zealand silica scaling test was carried at the Broadlands field (BROWN et al. 1983) using «doubly flashed) 100°C separated brine at about 810 ppm initial monometric silica content. Here too, polymerization rate was measured (through monometric silica decrease titration). «Oversaturation» was calculated to be 2.2 to 2.5. Fast polymerization was observed at pH = 6 while at pH = 5 nearly no polymerization occurred up to 200 minutes. Nevertheless since acidification «only delays silica deposition)), the authors do not recommend reinjection of such treated brine because of the risk that «some silica must precipitate in the well)).

By the end of 1989 a field silica scaling test on hot (about 180°C) spent reinjection brine (at about 860 ppm S_iO_2 content) was attempted at the Mak-Ban (Philippines) geosteam power plant in view of a future installation of an O.R.C. heat recovery repowering system using that brine. This joint study (Ormat Inc., PGI and N.P.C.) was carried on a reinjection line bypass steam going through a pilot heat exchanger where it cooled down by about 40°C. At the initial stage with no acid addition the first amorphous silica scale appeared on the stagnant part of heat exchanger inlet, suggesting that some silica was already in suspension at 180°C. The carbon steel tubes were frst fouled by corrosion products and then buildup of powdery white silica started to deposit towards the cooler end of the tubes. Corrosion coupons were also put in the pipe connected to the heat exchanger (cooled with water). Further tests with acid injection to the test pilot, described elsewhere (GALLUP 1996), showed that a slight acidification (using HCl or H_2SO_4) reduced scaling rate by an order of magnitude and can delay polymerization at convective cooling and thus prevent further scaling in the reinjection pipes.

The Mak-Ban (Philippines) case history

About 70 km away from Manila the Bulalo field produced about 300 MWe geopower using a conventional steam plant and injecting the separated brine (at about 180°C) into the reservoir (GALLUP 1996). A project of repowering of the plant with extra 16 MWe using the heat of the spent brine, flowing through a binary cycle (Organic Rankine Cycle), was cautiously examined because of the risk of excessive silica scaling. Following a test scheme (mentioned previously) for the application of a pH modification, the plant has been erected, commissioned and BTO operated by Ormat Inc. Philippines ever since 1994.

On cooling the brine throughout the plant heat exchangers from a slightly silica oversaturated condition at 173-180°C to 137-140°C, the saturation index rises to about 1.7. As a result of the earlier conclusions drawn from the pH modification study, an acid injection system was applied by the brine supplier (PGI) to the brine inlet of the power plant where insitu continuous pH control to 5.5 ± 0.5 is performed. The Mak-Ban geopower bottoming cycle using air cooled Ormat Energy Converters (OEC's) was first in the world to introduce acid treatment in order to prevent (eventually by reduction of the silica polarization rate) silica scaling by bringing down pH from 6.3 to about 5.5. As such, special design precautions were made in order to anticipate the event of too efficient scale control (leading to corrosion) or the event of partial lack of brine supply leading to low flow velocity fouling and the subsequent adhesion of suspended silica created at the hot flash stage. A general view of the Ormat Mak-Ban plant is presented on figure 1.

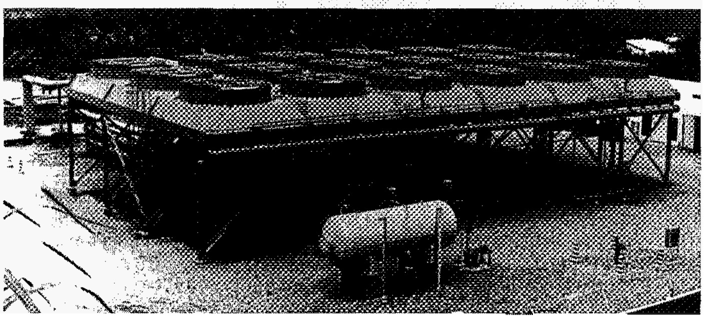

Figure 1: 15.73 MWe Modular Ormat Power Plant in Mak-Ban (Philippines)

The Los Azufres (Mexico) case history

Although having similar silica content (900 –1150 ppm) the brines produced at Los Azufres are by far less depositing than those produced at Cerro Prieto (which is the largest geothermal field in Mexico). This phenomenon was attributed to the lower salinity and higher boron content at Los Azufres (MERCADO 1984). Some preliminary fouling tests (camed in a pilot heat exchanger with 160°C inlet brine temperature, exiting at about 90 - 100°C) made by the IIC in cooperation with the CFE, lead to the conclusion «that it might be economically feasible to design heat exchangers exploiting the thermal energy of geothermal fluids similar to the ones produced by Los Azufres» (HERNANDEZ-GALAN 1989).

As of 1993, two OEC's producing each 1.5 MWe were installed (in two separate locations) on separated brine of Los Azufres geosteam power plant (OEC inlet temperature 174°C and outlet temperature 108°C). At the outlet temperature the silica supersaturation index is at least 2. Only once a year maintenance with standard acid cleaning has been sufficient to maintain the normal power production of the units. An air cooled such OEC module (1.5 MW_e) is shown on figure 2.

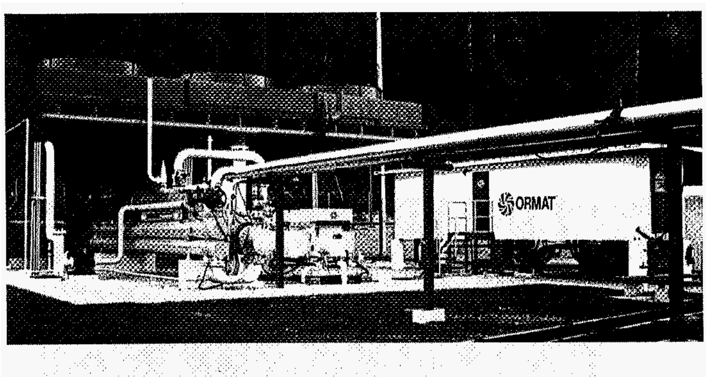

Figure 2: One of the 2 OEC 1.5 MWe air cooled modules repowering the Los Azufres geopower plant

Rotokawa (New Zealand) case history

The Rotokawa 24 MWe net capacity geothermal power plant using an Ormat modular combined cycle technology (OCCM) was turnkey supplied by Ormat group on end of 1997. By this technology both the steam and the brine are used for power generation.

Steam is separated from the brine at 23 bar, and processed through a 14 MWe hack pressure steam turbine, exiting this turbine at about 1.5 bar and further condensed and cooled in two binary units of 5 MWe power output each. The separated brine rich in silica (about 1000 ppm at separation pressure) is processed into a third binary unit (brine OEC of 5 MWe) where it cools from 219°C to 150°C. Supersaturation silica index at this stage would be already about 1.6, however kinetics show that induction period for polymerization is long enough to avoid scaling in the heat exchanger. Mixing the brine with the steam condensate from the OCCM would result a supersaturation **S.I.** of about 1.4 at injection temperature of about 130°C. One year since startup of operation, no silica related problem was encountered.

The Kawerau (New Zealand) field binary plants case history

The fist TOI #1 (Tarawera Ormat Installation) 2.6 MW. plant comprising two air cooled OEC modular units operates since 1990 with a separated brine at about 180°C. The brine (at about 700 ppm silica content), previously entirely disposed to the Tarawera river, is now mostly reinjected at approximately 120°C **(S.I.** 1.4 – 1.5) ((surprisingly, no silica scaling has been reported to form in the heat exchangers or the injection wells)) (GALLUP 1996).

TG2 is another binary plant of 3.4 MWe using an air cooled dual OEC. Convectively cooled **from** about 172°C to about 85°C **(S.I.** ≈ 2). Operating (by the Bay of Plenty Utility), since end of 1993, only once in two years heat exchangers cleaning is performed.

Conclusions

Growing experience has been gained in recent years with handling and heat extracting out of silica ((supersaturated)) brines. In some cases, when properly designed, the induction time for polymerization is long enough for the brine which flows through the critical heat recovery part of the O.R.C. power unit and **further** to disposal, without serious scaling. In others, a total heat to power taylor-made design for both brine and steam (like the one used at Rotokawa N.Z.) has been successful controlling silica scaling at enough low rate, so to allow smooth operation. Even for fast scaling (on separation) brines, suitable design can minimize adherence to metallic walls of already existing silica colloids, while suitable operation can delay further polymerization of monomeric silica (on cooling).

Case histories of some Ormat designed (and built) geopower plants, where silica «supersatured» brines are used at reasonable operating costs, were presented.

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