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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 plants, the brine for disposal is separated at a temperature high enough to avoid "silica oversaturation" which might lead to scaling on further cooling if additional power is generated by heat recovery.

Recent binary cycle heat recovery experience involved cases of brine cooling leading to "silica oversaturation" which did not cause extensive fouling in the plant heat exchanger. This paper presents some case histories of these successful applications.

Although kinetics of siliceous precipitation was overlooked in the past, it is now approached through various design and/or operational approaches in order to minimize fouling.

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 deposition, silica and calcite are the most common and the most difficult to remove. However, while calcite has been mostly troublesome for production well management, silica is considered "dangerous" for reinjection wells and some parts of the surface conduits transporting the brine. The scaling problem is inherent to most liquid dominated geothermal resources. Generally as aquifer temperatures rise, scaling problems would be expected to occur along the extraction system.

In steam operating geothermal power plants, silica deposition by steam carryover may become very troublesome. Even in small concentrations, silica affects steam turbines, valves, and separators. This aspect is, however, beyond the scope of this paper.

The prospect of silica deposition after separation of two phase geofluids inspired a conservative approach to the design of geothermal power plants. The result of this approach was the determination of the lowest operational temperatures which placed severe restrictions 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 brines as illustrated by some case histories.

The earliest designs of power plants using two phase fluids were hampered by scale formation (CORSI, 1987), from single phase fluids (reinjection pipelines), from flashing fluids (wells, separators, and two-phase pipelines), and by steam carryover deposition, which is not covered in this paper. Scaling from single phase fluids, largely tied to the liquid phase ("spent brine"), was frequently associated with siliceous species deposited 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 350ºC), served as guidelines for the definition of silica "supersaturation" (FOURNIER et al. 1983) (FOURNIER et al. 1977), and hence, for the determination of the temperature limit for brine disposal

The development of the Organic Rankine Cycle (ORC or "binary") technology for geothermal power plant applications at the beginning of the 1980's was limited to those cases where silica scaling would not be expected, such as in medium to low enthalpy sources. At East-Mesa, California, pumped geothermal brines produced light iron carbonate and iron sulfide scales (GRASSIANI 1988) reducing carbon-steel corrosion, while iron silicate was scarcely present on cooling at temperatures less than 90ºC. At the same time, scientists and developers started to become more confident about the site specific nature of silica deposition and about the importance of the kinetics of such deposition. An increased understanding might permit further use of spent thermal brines issuing from moderate- to high-enthalpy, two-phase geothermal resources. The interest shifted from Silica Index (actual concentration), to "supersaturation (concentration ratio), to "induction" (or incubation) period, to "polymerization" (which 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 are long enough to permit normal flow and heat transfer inside the critical heat exchanger of the binary plant unit. Furthermore, design and operational experience has evolved in recent years to a point where scaling is handled on a routine basis.

Experimental work at various locations worldwide was originally intended to deal with the problem of managing silica bearing brines and their eventual disposal (e.g. plugging of reinjection wells). It lead ultimately to the costly on-line treatment of separated brines, resulting, for example, in silica removal from hypersaline brines at the Salton Sea plants. The emergence of brine convective heat recovery technology has added to the incentive of investigating other practical solutions and for developing more understanding (RIMSTIDT et al. 1978) on the practical rate of deposition.

EXCEPTIONAL FAST SILICA SCALING CASES

In some cases, steam operating power plants were first built on known "problematic" sites where silica scaling appeared before or right after the first flash separation. The following two examples summarize such cases.

Silica (among other species) has been encountered in scaling events of some production wells in the Cerro Prieto I plant (Mexico), specifically in the production lines (MERCADO et al. 1989). Further reports on other wells confirmed the phenomenon of "major abundance of amorphous silicates" (HURTADO et al. 1983). The scaling in the production line (which includes calcite and sulfides) was found to have "an enormous impact on the cost of power generation". Due to the eventual decrease of steam production, following scaling, and the decrease of availability, following maintenance, the plant required additional wells at an increased cost. Furthermore the cost of well maintenance, including descaling, is significant and there is the serious risk of well collapse during such operations. Most of the brine at Cerro Prieto is disposed of in ponds, where partial "cold" injection has been considered.

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

In other cases, high silica deposition rates lead to expensive engineering solutions of separating the silica before brine handling (Salton Sea Projects). High rates of silica deposition played a part in the decision to put a stop to further development in the Assal Field in Djibouti, where at different pressures, different scales occurred.

The record shows that even for the rapid silica scaling conditions in the wellfields upstream of the classic geothermal power plants, engineering solutions were adopted (provided economic incentives were attractive) to overcome the problem of silica deposition in spent brine handling. Ponding, like in the Svartsengi plant (Iceland) turned out to be beneficial by creating a tourist resort, in spite of the intense H_2S smell.

However, these fast silica deposition cases created anxiety among geothermal power plant designers on the further use of the hot separated brine. They choose to observe the barrier of the supersaturation point (derived from literature as mentioned above) even though in many other cases the scaling kinetics permitted the use of brines. Increasing the heat-to-power ratio after the first separation, by use of a second flash, produced lower steam pressure, higher supersaturation values, increased mineral concentration in the brine, and a rise in the pH due to the pressure drop of some acidic dissolved gases (CO_2 and H_2O). All of these factors increase polymerization faster than if the brine were cooled without flashing.

BRINE PH EFFECT ON SILICA DEPOSITION KINETICS

The strong relationship 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 even though the acidic water discharged from well C (pH=3.9) has the highest silica concentration, it generated relatively small amounts of silica-rich scale. The neutral pH water, however, containing only moderate amounts of silica (from well F), continuously precipitated amorphous silica from both upstream and downstream sections of the test equipment. It was concluded that in the Fushima waters, the pH controls the precipitation rate of amorphous silica more than the degree of supersaturation.

At Svartsengi (Iceland), early tests (GUDMUNDSSON 1983) carried out on spent brine, did not show any polymerisation "for at least 60-80 minutes" for values of pH ≤ 5.5 (the natural pH of the brine was 7.8 at 20ºC). 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 reducing the brine pH to prevent deposition/polymerisation may be practical". Later tests at 80ºC (GUDMUNDSSON et al. 1984) were carried out 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 by measuring the residual monomeric silica versus time. The test clearly showed the beneficial effect of both dilution and pH decrease (from 7.8 to 6.7) on the rate of silica polymerization. At the original brine conditions, double flashed to vacuum (70-75ºC), polymerization was rapid, while after dilution, it became slow enough to keep the monomeric silica in solution for 60 minutes.

In New Zealand, silica scaling tests were performed at the Broadlands field (BROWN et al. 1983) using "doubly flashed" 100ºC separated brine with an initial monomeric silica content of about 810 ppm. Here too, the polymerization rate was measured using monomeric silica decrease titration. "Oversaturation" was determined to range from 2.2 to 2.5. Rapid polymerization was observed at pH = 6 while at pH = 5 nearly no polymerization

occurred for 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 (180°C) spent reinjection brine (860 ppm SiO_2) was attempted at the Mak-Ban, Philippines geothermal power plant in preparation for the future installation of an ORC heat recovery repowering system using that brine. This joint study (ORMAT, Inc., PGI, and NPC) was carried out on a steam reinjection line bypass going through a pilot heat exchanger where it was cooled to a temperature of 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 180ºC. The carbon steel tubes were first fouled by corrosion products and then by the buildup of powdery white silica at the cooler end of the tubes. Corrosion coupons were also put into the pipe connected to the heat exchanger (cooled with water). Further tests with acid injection, described elsewhere (GALLUP 1996), showed that a slight acidification (using HCl or H_2SO_4) reduced the scaling rate by an order of magnitude and can delay polymerization at convective cooling, preventing further scaling in the reinjection pipes.

THE MAK-BAN (PHILIPPINES) CASE HISTORY

About 70 km from Manila, the Bulalo field produced about 300 MWe of geothermal power using a conventional steam plant; the separated brine was injected back into the reservoir at a temperature of about 180°C (Gallup, 1996). A proposal to repower the plant with an extra 16 MWe, using the heat of the spent brine flowing through a binary cycle (Organic Rankine Cycle) was cautiously evaluated because of the risk of excessive silica scaling. Following a test scheme (mentioned previously) for the application of pH modification, the plant was constructed and commissioned in 1994. It is operated by ORMAT, Inc., under a BTO with the Philippine power agency

On cooling the brine throughout the plant heat exchangers from a slightly silica oversaturated condition at 173-180ºC to 137-140ºC, 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 installed by the brine supplier (PGI) at the brine inlet of the power plant, where in-situ continuous pH control (to 5.5 ± 0.5) is performed. The Mak-Ban geopower bottoming cycle using air cooled ORMAT® Energy Converters (OECs) was the first in the world to introduce acid treatment in order to prevent (eventually by reduction of the silica polarization rate) silica scaling by reducing the pH from 6.3 to about 5.5. Special design precautions were made in order to manage the problem of over-effective scale control (leading to corrosion) or the problem of partial lack of brine supply leading to decreased 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.

THE LOS AZUFRES (MEXICO) CASE HISTORY

Although they have similar silica content (900 to 1150 ppm), the brines produced at Los Azufres generate fewer deposits than those produced at Cerro Prieto, 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 (carried in a pilot heat exchanger with 160ºC inlet brine temperature, exiting at about 90 - 100ºC) 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 OECs, each producing 1.5 MWe, were installed at two distinct locations on the separated brine of the Los Azufres geothermal power plant. The OEC inlet temperature is 174°C and the outlet temperature is 108°C. At the outlet temperature, the silica supersaturation index is at least 2. Only once-a-year maintenance with standard acid cleaning is required to maintain the normal power production of the units. An air-cooled OEC module (1.5 MWe) is shown in Figure 2.

ROTOKAWA (NZ) CASE HISTORY

The Rotokawa 24 MWe net capacity geothermal power plant using ORMAT combined cycle unit technology (OCCU) was a turnkey project supplied by the ORMAT group at the end of 1997. With 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 14MWe back pressure steam turbine. The steam exits this turbine at about 1.5 bar and is further condensed and cooled in two binary units of 5MWe 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 5MWe), where it cools from 219°C to 150°C. The supersaturation silica index at this stage would be already about 1.6, however, kinetics show that the induction period for polymerization is long enough to avoid scaling in the heat exchanger. Mixing the brine with the steam condensate from the OCCUs would result in a supersaturation S.I. of about 1.4 at an injection temperature of about 130°C. One year after startup of operations, no silica related problems have been encountered

THE KAWERAU (NZ) FIELD BINARY PLANTS CASE HISTORY

The first TOI #1 (Tarawera ORMAT Installation) 2.6 MWe plant, comprised of two air-cooled OEC modular units, has operated since 1990 with a separated brine at about 180°C. The brine, at about 700 ppm silica content, was previously disposed

of in the Tarawera River. It is now mostly reinjected at approximately 120°C (S.I. ranges from 1.4 to 1.5). Surprisingly, no silica scaling has been reported forming in the heat exchangers or injection wells (Gallup, 1996).

TG2 is another binary plant of 3.4 MWe using an air-cooled dual OEC. Brine is convectively cooled from about 172°C to about 85°C (S.I. = 2). This plant has been operated by the Bay of Plenty Utility since late 1993. The heat exchangers require cleaning only once every two years.

CONCLUSIONS

Experience has been gained in recent years with handling of and heat extraction from silica supersaturated brines. In some cases, when properly designed, the induction time for polymerization is long enough for the brine to flow through the critical heat recovery part of the ORC power unit and to eventual disposal without serious scaling. In others, a total heat-to-power, tailor-made design for both brine and steam (like the one used at Rotokawa, NZ) has been successful in controlling silica scaling and allow smooth operation. Even for fast-scaling brines, a suitable design can minimize adherence of silica colloids to metallic walls, while suitable operation can delay further polymerization of monomeric silica on cooling. Case histories of some ORMAT designed and built geothermal power plants, where silica "supersaturated" brines are used at reasonable operating costs, were presented.

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Figure 1 – 15.73 MWe Modular ORMAT Power in Mak-Ban (Philippines)

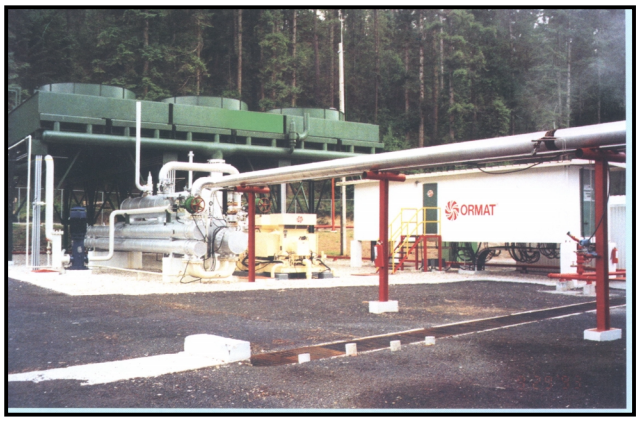

Figure 2 – One of the 2 OEC 1.5 MWe air-cooled modules repowering the Los Azufres geopower plant