Binary plant retrofitting of a single-flash steam plant

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ABSTRACT

The edge of the Pacific Ocean is an area of strong tectonic activity marked by volcanoes and seismic activity. In all countries around the Ring of Fire, such as New Zealand, Japan, Indonesia, the Philippines and the western coastal Americas, harnessing the geothermal power potential capacity is of strategic importance for these countries growth. Developing a new steam field faces many challenges, takes time, costs a significant amount of equity, has mineral risk, and confronts environmental and regulatory issues. Existing steam fields frequently use single flash, steam turbine power generation plants. Although efficient and reliable, a significant part of the total thermal capacity is lost in the liquid-phase (hereinafter called brine). This paper describes in detail how it is possible to recover safely and efficiently the energy contained into the brine, otherwise wasted. In fact, just utilizing the energy contained in the existing brine, it is possible to add approximately 30% of the steam field rated electrical power output thanks to the Exergy GEX binary plant, based on its patented Radial Outflow Turbine (ROT). This type of design is in operation in different markets around the world, such as in Italy, Turkey and Portugal (the Azores Islands). The paper will focus on a case study where further issues are addressed, such as silica scaling, by applying state of the art geochemistry.

Keywords: Binary plant, ROT, Exergy S.p.A., bottoming, geothermal plants, power generation.

Reequipamiento de una planta a condensación de vapor con una planta binaria

RESUMEN

La periferia del Océano Pacífico es una zona de fuerte actividad tectónica con vulcanismo y sismos. En todos los países alrededor del Cinturón de Fuego, tales como Nueva Zelanda, Japón, Indonesia, Filipinas y la costa occidental de las Américas, aprovechar el potencial geotermoeléctrico resulta de importancia estratégica para su crecimiento. El desarrollo de un campo geotérmico nuevo enfrenta varios retos, requiere tiempo, cuesta una cantidad importante de capital de riesgo, tiene riesgos de incrustación mineral, y debe confrontar problemas ambientales y regulatorios. Los campos geotérmicos actuales usan frecuentemente plantas turbogeneradoras a condensación (de flasheo). Aunque estas son confiables y eficientes, una parte significativa de la capacidad térmica total se pierde en la fase líquida (a la que llamaremos salmuera). Este trabajo describe en detalle cómo es posible recuperar segura y eficientemente la energía contenida en la salmuera, que de otra manera se pierde. De hecho, utilizando sólo la energía contenida en la salmuera existente es posible agregar un 30% aproximadamente a la generación eléctrica producida por el campo, gracias a la planta binaria GEX de Exergy, que se basa en su Turbina de Flujo Radial (ROT: Radial Outflow Turbine) patentada. Este tipo de diseño está actualmente en operación en diferentes mercados del mundo, tales como Italia, Turquía y Portugal (las Islas Azores). Este trabajo se centra en un caso de estudio donde se abordan otros problemas, tales como la incrustación de sílice, mediante geoquímica de vanguardia.

Palabras clave: Planta Binaria, ROT, Exergy S.p.A., Bottoming, plantas geotérmicas, generación de energía eléctrica.

INTRODUCTION

Developing a new geothermal resource is a long and expensive process. Initial development steps are risky and upfront capital costs are important. The cost and risk of exploration and the development of geothermal energy has been an issue in determining the future of geothermal energy in many countries, as these are seen by private investors to have a major impact on the price of geothermal electricity. Once the resource has been proven, it is necessary to optimize the heat from geothermal energy both for generating electricity and for direct uses before the fluid is rejected, while it is still sellable and attractive to developers (Valdimarsson, 2011).

Mexico was among the earliest countries to operate a commercial geothermal power plant at a liquid-dominated resource, commissioning its first power plant in 1959 (Gutiérrez-Negrín and Quijano-León, 2003). The current installed geothermal electric capacity in the country, as of December 2013, is 1,017 MWe, distributed into the following four geothermal fields in operation, shown in Figure 1: Cerro Prieto (570 MWe), Los Azufres (191 MWe), Los Humeros (68.4 MWe), and Las Tres Virgenes (10 MWe) (in brackets the running capacities) (Gutiérrez-Negrín et al., 2015). All of them are owned and operated by the Mexican electric authority, the Comisión Federal de Electricidad (CFE). However, the running capacity is less because of production decline, mainly at Cerro Prieto geothermal field: so the total running capacity was only 839.4 MWe (Gutiérrez-Negrín et al., 2015).

Figure 1: Locations of Mexican geothermal fields under exploitation (Cerritos Colorados remains in stand-by).

Cerro Prieto is the oldest and largest field in operation in Mexico, and the second largest worldwide. The system is a liquid-dominated reservoir, with wells producing a mixture of fluids at surface conditions with approximately 60% water and 40% steam. At its natural state fluids presented reservoir temperatures from 275 to 310°C and excess steam values from -1 to 50% (Gutiérrez-Negrín, 2015).

Los Azufres is the second geothermal field operating in Mexico, with the first power units commissioned in 1982, and presently having 12 power units in operation. Commonly measured temperatures in the field range from 140 to 280°C, although fluids can reach temperatures as high as 320°C (Flores-Armenta et al., 2014, and Gutiérrez-Negrín, 2015).

Los Humeros geothermal field is characterized mainly by steam with high enthalpy and water with partial equilibrium at temperatures of 208-310°C (Gutiérrez-Negrín, 2015).

Las Tres Vírgenes is the most recent field in operation in Mexico: the reservoir is liquid-dominated with temperatures ranging from 250 to 275°C.

Cerritos Colorados has high temperature geothermal fluids, and it consists of a compressed liquid reservoir with an average temperature of 305°C and maximum of 356°C. No power plants have been installed in the field so far (Gutiérrez-Negrín, 2015).

Generally, in liquid-dominated areas, the energy conversion system that applies geothermal fluids to generate electricity uses single flash technology as the first step in development. Meanwhile, waste geothermal heat after flashing (brine) from the existing power plants could be better utilized, and the utilization efficiency of the plant could be increased, by using a bottoming binary plant.

In the existing flash power plants, after utilizing the separated steam, the brine from the separator is rejected to the earth through reinjection wells. The reinjected brine generally has a temperature higher than 150°C and a mass flow rate of one hundred tons per hour. The thermal energy of the brine can be recovered by transfer via a heat exchanger to working fluids used in other processes. Although the capacity is lower than the existing steam turbine, the upstream risk can be avoided and only two years are needed for complete project execution.

Previous studies have been made on the optimization of geothermal utilization for power production, using different cycles. It was concluded that a binary bottoming cycle using isopentane as a working fluid would give more power output than a second flash or other combined cycles, at discharged enthalpy below 1400 kJ/kg or at reservoir temperatures of 240°C or lower (Karlsdóttir, 2008; Bandoro, 2009; Nugroho, 2011). In those studies, a water-cooled condenser was used and different assumptions on silica scaling prevailed.

The present paper will show how much power can be recovered from the brine coming out of a separator vessel of a hypothetical single flash steam plant with a total capacity of approximately 110 MWe net. Geothermal fluid inlet conditions, as well as ambient ones, are calculated by averaging actual power plants (liquid-dominated system) operating conditions.

TECHNICAL OVERVIEW OF GEOTHERMAL POWER PLANTS

Flash cycle

A flash cycle is the simplest and most conventional form for high-temperature geothermal power generation. Most geothermal wells produce two-phase fluids, consisting of brine and steam. The fluids also contain non-condensable gases and solid particles.

The water and solid particles are separated from the steam and gases using a separator. Thus, the steam fraction of the geothermal fluid can be calculated based on the enthalpy and pressure. The process of an ideal separator is relatively simple, since the outlets are saturated steam and saturated brine. The saturated steam will go directly to the turbine that is coupled with a generator to produce power. Transferring heat from the exhaust steam into the cooling fluid causes the steam to condense. This creates a vacuum in the condenser due to the collapse of steam and creates a driving force for the steam flow. The effect is higher output from the turbine.

As there is no need to recover the condensate for reuse in the process cycle, direct contact condensers are generally preferred since they have lower initial capital cost and require less maintenance work. Fig. 2 shows a simplified schematic diagram of a flash cycle.

Binary plant

A binary system is a power plant consisting in two cycles: the first one is the heat exchange cycle of geothermal fluid, where the working fluid absorbs heat from the geothermal fluid via the heat exchanger; the second one is the ORC (Organic Rankin Cycle) working cycle, as seen in Fig. 3. These two cycles are separated, so only the heat transfer takes place through the heat exchangers; shell-and-tube heat exchangers are most common.

The working fluid is selected both from the optimizing power output view and the critical temperature requirement. The main components of a binary power plant are the following: heat exchangers (preheater, evaporator, condenser and recuperator), a feed pump, a turbine, a generator and a condenser (air or water cooled).

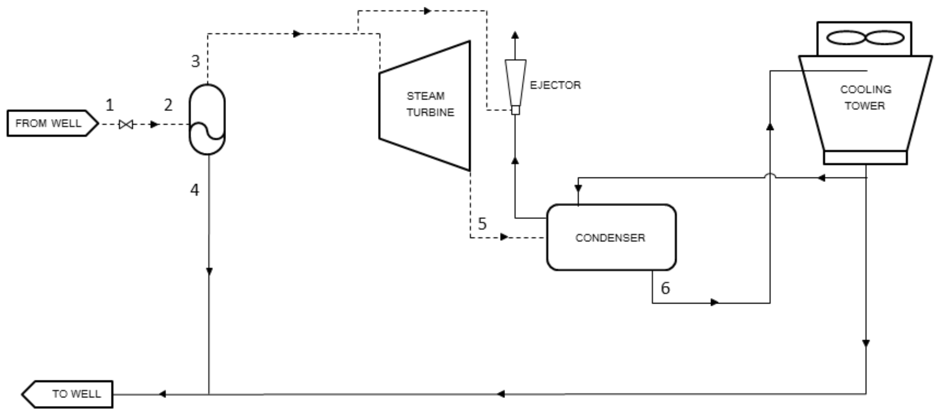

Fig. 2. Single flash cycle, plant typical simplified flow diagram.

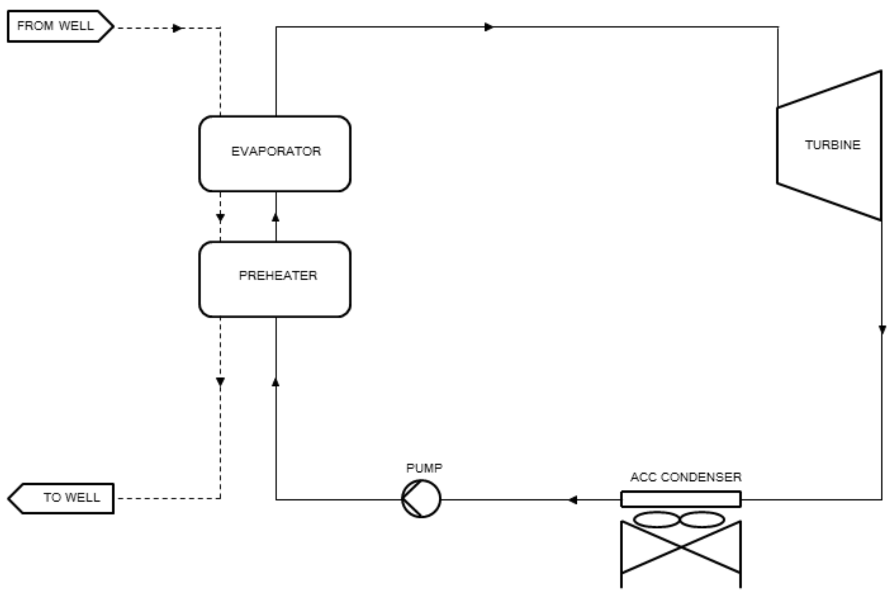

Fig. 3. Single pressure level binary cycle, plant typical simplified flow diagram.

Limitation of reinjection temperature

Reinjection is a very important part of any geothermal development and it may become the key factor in the success or failure of the field.

In order to achieve maximum conversion of geothermal energy into electricity, the geothermal fluid must be cooled to as low a temperature as possible. In many cases, the geothermal fluid becomes supersaturated with silica as it is cooled. A hotter resource temperature will lead to higher silica saturation in the disposal brine, the consequences of which could lead to greater silica scaling precipitation in reinjection wells, piping, heat exchangers and other production facilities (Di Pippo, 1985). At supersaturated conditions, silica and metal silicates take some time to equilibrate. The reactions are strongly influenced by pH, temperature and salinity. The lower values slow down the scaling rate of silica and this is often taken advantage of in process design. An example of this is the acidification of silica supersaturated solutions to lower the pH sufficiently (to approximately pH 4.5-5.5) to slow down scale formation, for example in the heat exchanger of binary units. This may increase the corrosion rate in the pipeline. It is relatively simple to inject sulfuric acid or hydrochloric acid by means of a chemical metering pump into the brine pipeline (Thórhallsson, 2005). To reduce silica concentration and keep a high enough temperature before reinjection, mixing between brine and condensate is a good idea, as experienced in some fields like at Svartsengi plant in Iceland (Thórhallsson, 2011).

Potential problem with silica scaling in high temperature geothermal system, such as the considered one, is very high. When the hot water is underground it is in equilibrium with quartz. However, when geothermal waters are driven to the surface, a considerable drop in temperature due to flashing occurs, and the difference in the solubility between quartz and amorphous silica allows the latter to be supersaturated in the solution. Hence, the form of silica that normally precipitates at the surface is amorphous silica, which has no crystalline structure and is more soluble than quartz. In addition, as the concentration of the other dissolved species is increased, the solubility of both quartz and amorphous silica decreased (Brown, 2011).

The potential for silica to precipitate is dependent on the degree of silica saturation in brine in respect to amorphous silica.

The silica limit temperature is the temperature below which the silica dissolved in geothermal fluid may be expected to precipitate and deposit. Silica deposits are formed first when the amorphous silica solubility curve is passed (**Figure 4**).

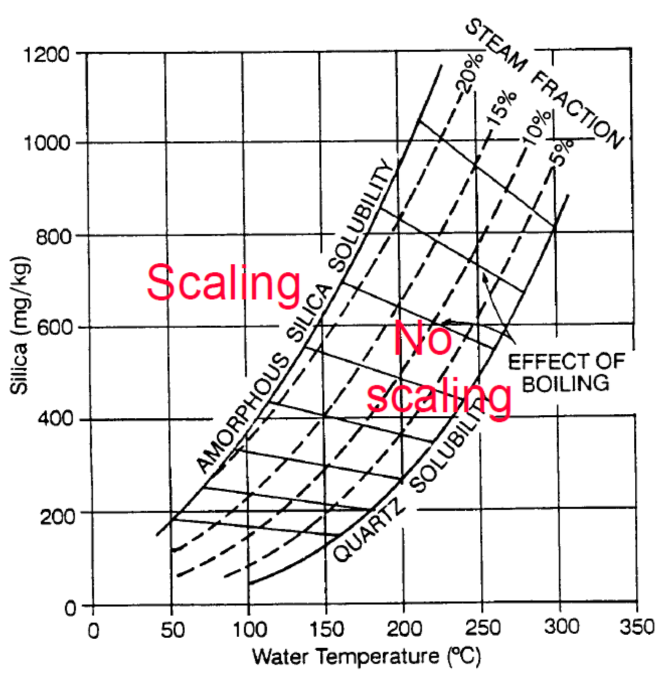

Figure 4. Solubility of silica in water.

It is possible to have an estimate of that temperature by using the following equations (Di Pippo, 2008):

(1) $Qc(t)$ = 41.598 + 0.23932 t_{water} − 0.011172 t^2_{water} + 1.1713 × 10^{-4} t^3_{water} − 1.9708 × 10^{-7} t^4_{water}

(2) $S = Qc(t) / (1 - x_1)$

(3) $\log_{10} S_{amorphous}$ = −6.116 + 0.01625 T_{water} − 1.758 × 10^{-5} T^2_{water} + 5.257 × 10^{-9} T^3_{water}

(4) $SSI = S / S_{amorphous}$

In all those equations:

$Qc(t)$: quartz solubility in reservoir [ppm]
t_{water}: reservoir temperature [°C]
SI: silica concentration in the brine after flashing [ppm]
x_1: steam quality from first flashing
$S_{amorphous}$: equilibrium solubility of amorphous silica for zero salinity [ppm] (must be multiplied by 58,000 to obtain ppm)
T_{water}: absolute reinjection temperature [K]
SSI: Silica Saturation Index

Amorphous silica and quartz solubility in water as a function of reservoir temperature are shown in **Figure 4**. To determine whether silica will tend to precipitate or not, the value of the silica concentration after flashing (S_{actual}) is compared with the equilibrium amorphous silica concentration given as the ratio in Equation 4. If SSI is higher than 1 the brine is supersaturated and a risk of silica scaling in the surface equipment, reinjection wells and reservoir will occur.

Together with the correct reinjection temperature, also the proper inhibition system has to be provisioned.

Many works have been already conducted in order to overcome the silica scaling problem. Silica precipitation on surface facility and possibly in reservoir could happen if geothermal fluid is not properly handled before reinjection. Brown (2011) suggests several treatments to cope with silica scaling. Among them, pH modification could be the most widely use now in geothermal industry. It reported that at pH about 4.5-5, the silica polymerization can be delayed for several hours, while at the normal pH, silica polymerization is very rapid.

In the same way, raising the pH to 9 by adding caustic, promotes the conversion of the dissolved silica to the silicate ion, preventing the silica scaling without problems with corrosion of steel. However, the major disadvantage is the cost of alkali.

Horie et al. (2010) reported successful application of pH modification by dosing the HP (high pressure) brine with sulfuric acid (H_2SO_4) in the double flash plant in Kawerau, New Zealand. The acid injection rate is precisely adjusted by variable speed dosing pump to target the LP (low pressure) brine to the reinjection system at pH 5. Gray (2010) also reported the same application in the triple flash plant Nga Awa Purua geothermal station in Rotokawa, New Zealand. However, extremely corrosive nature of sulfuric acid should be considered when selecting material for mixing.

Silica scaling mechanisms are fairly complex and poorly quantified; therefore it has been common to manage scale on the basis of local experiments.

BOTTOMING BINARY PLANT DESIGN

The brine is normally injected back into the reservoir, and then is possible to retrofit the existing steam plant with a bottoming binary plant, which will cool the brine down to a certain injection temperature (Fig. 5).

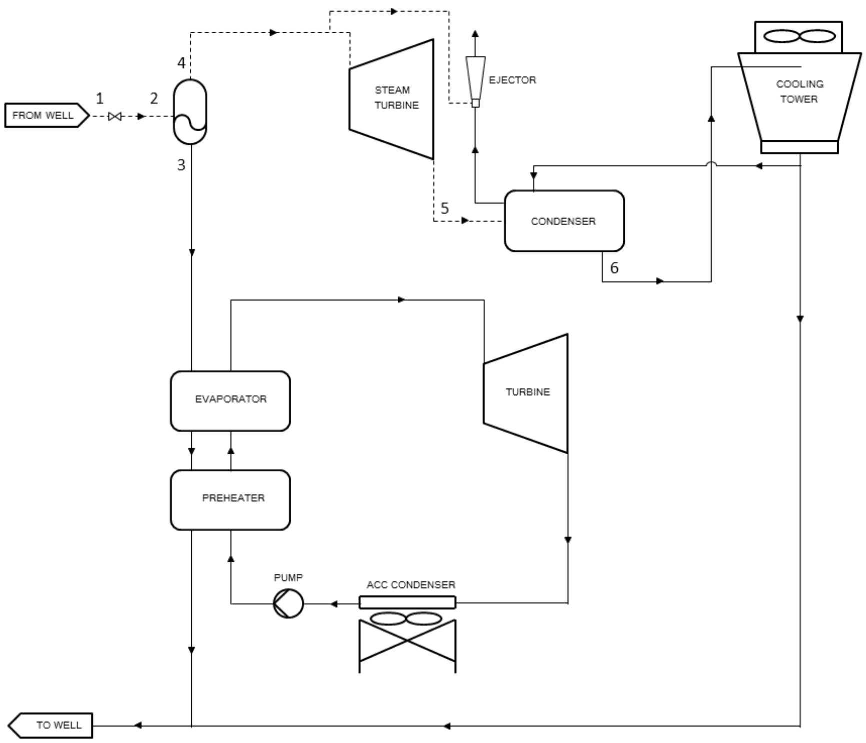

Fig. 5. Bottoming cycle, plant typical simplified flow diagram

As said, this temperature is mainly set according to the silica saturation curve. In fact, at lower the temperature, lower the silica solubility. Silica deposition must be foreseen accurately in order to prevent the whole system from rapidly depleting its performance. The minimum reinjection temperature is set considering the acidized water quality and it is equal to 90°C.

In order to maximize the power output, a two pressure level cycle, based on the unique Radial Outflow Turbine, is selected. As represented in Fig. 6, a two pressure level cycle recovers energy from the geothermal fluid more effectively than a single pressure level one, matching closely its heat release curve (red line). In fact, the recovered energy is graphically represented by the two colored regions below the red curve. The green region extension is bigger than the blue one, which means that for the same total heat input a two pressure level cycle will have higher conversion efficiency.

Both low pressure and high pressure turbines are directly coupled with a double ended synchronous generator. In order to ease the retrofitting, two twin modules are foreseen, each cooling half the brine flow down.

Boundary conditions

Based on general conditions of geothermal high-temperature and liquid-dominated areas, the design of the binary plant is conducted considering:

• Bottom hole temperature: 266.5°C
• Geothermal fluid mean enthalpy: 1167.5 kJ/kg

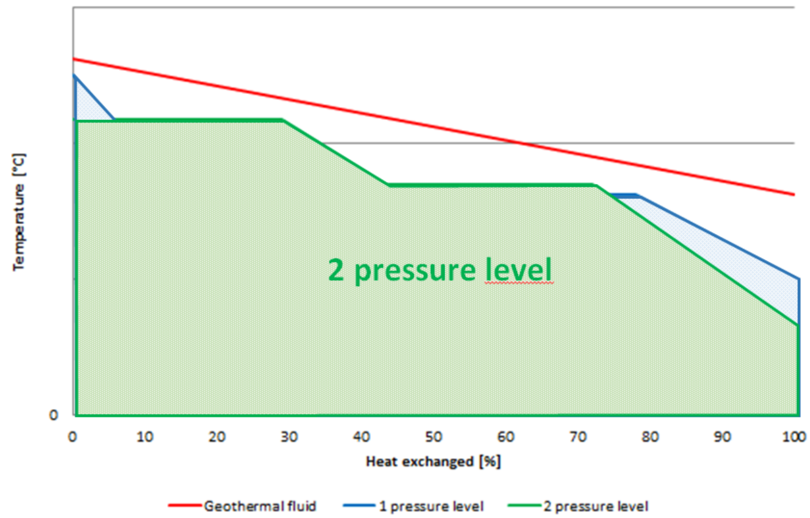

Fig. 6. Temperature-load diagram for binary plant.

• NCG (Non-condensable gases) content: 2% in weight (total geofluid flow)
• Average dry bulb temperature: 23°C
• Average wet bulb temperature: 21°C
• Reference atmospheric pressure: 0.93 bar (@810 masl)
• Cooling method: Air
• Limitation of reinjection temperature is calculated at SSI=1, considering acid dosing

Steam plant operative conditions

• Separation pressure: 9.3 bara
• Separation temperature: 175°C
• Total geothermal fluid mass flow rate: 3610 ton/hr
• Steam+NCG mass flow: 838 ton/hr
• Brine mass flow rate: 2772 ton/hr
• Condenser pressure: 0.12 bara
• Steam turbine isoentropic efficiency: 80%

Results

Description	Units	Steam plant	Binary plant
Gross power output	MWe	116	43.96
ORC auxiliaries power consumption	MWe	-	1.28
ACC auxiliaries power consumption	MWe	-	1.1
BOP auxiliaries power consumption	MWe	4.7	0.3
Step-up transformer power losses	MWe	1.16	0.440
Step-down transformers power losses	MWe	0.14	0.08

Net power output	MWe	110.0	40.8
Relative net power increase	%	-	37.1%

CONCLUSIONS

Power production increases gradually by decreasing the reinjection temperature. In order to obtain the maximum power output, the bottoming units must be designed at the minimum reinjection temperature level that is free from scaling issues, both in power plant components and the reinjection well itself.

A possible retrofitting configuration was studied in order to evaluate the power output produced at a given amount of heat source. The calculation indicates binary cycle produces 40.8 MW net, reinjecting at 90°C.

Relative to the presented case study of a 110 MW power plant, the bottoming cycle generates 37.1% more power from utilizing the hot brine. For liquid-dominated geothermal fields, such as the one considered in the present paper, the bottoming cycle contributes to a more efficient use of its resources.

Aside from the potential increase in output of each bottoming technology, financial aspects, environmental issues, land requirement, compactness, ease of operation and simplicity should be considered before making a final decision.

Concerns on the impact of reinjection of cooler fluid, such as cold brine influx, silica scaling in the surface facilities, reinjection wells and reservoir, should be thoroughly studied. Tracer test can be applied to analyze a proper injection strategy in order to prevent the cooling water breakthrough in reservoir, while pH modification is widely used to eliminate or to delay silica precipitation. Sulfuric acid (H_2SO_4) injection to maintain pH at 5 is already a common practice in geothermal power plant worldwide.

If modification of pH does not work, the brine can be simply disposed to retaining tank for a while to settle down the silica and then pumped into reinjection wells.

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