Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

Case Study of Calcium Carbonate Scale at EGS and Hot Spring Binary System

Norio Yanagisawa

Institute for Geo-Resources and Environment, AIST, 1-1-1 Higashi, Tsukuba, Ibaraki, Japan

n-yanagisawa@aist.go.jp

Keywords: scale, calcium carbonate, EGS, hot spring, heat exchanger, pipeline

ABSTRACT

Calcium carbonate is one of the major scales in geothermal systems. Not only in conventional systems but in new concept geothermal systems, EGS (Enhanced Geothermal System) and hot spring binary systems, calcium carbonate scale precipitate in wells, pipelines and heat exchangers.

For example, at Hijiori EGS test site, calcium carbonate scales on pipelines of HDR-2 increased after thermal breakthrough of the reservoir due to the temperature decreasing and Ca concentration increasing. For one of the scaling prevention methods at EGS, the scale inhibitor injection to injection well was carried out. This resulted in about 20% decrease in calcium carbonate scale with 20 ppm inhibitor with decreasing anhydrite dissolved in the reservoir.

In another case, at Otari hot spring, calcium carbonate precipitates not only in hot spring water path due to degas from fluid but in the cooling water path due to increasing temperature. Recently, many hot spring sites have expressed interest in small binary systems and the prevention of calcium carbonate scaling is very important. According to estimation of scaling, high Mg and HCO_3 concentration are the cause of calcium carbonate and silica scaling.

1. INTRODUCTION

In many geothermal fields, mineral scales such as calcium carbonate and silica tend to precipitate if there are changes in fluid temperature and/or pressure, leading to fluid flow problems. To overcome the operational problems associated with scaling, mechanical and chemical methods have been developed to eliminate and/or reduce the amount of mineral deposition. It is however important to further investigate and understand the mechanisms involved and the relation between mineral scaling and the physical and geochemical characteristics of the rocks and fluids in the geothermal system under exploitation.

Recently, research and development for new concept geothermal systems such as EGS and hot springs (about 100 degree C) binary system tests were carried out in Japan. For example, at Hijiori EGS test site in caldera region, a long-term circulation test (LTCT) was conducted from November 2000 to August 2002 and scaling such as calcium carbonate and silica was also observed in the production wells and surface installations (Yanagisawa et al., 2008).

Several small (about 50 kW) binary project using high temperature hot springs (Onsen) are progressing. The concept of these systems is shown in Figure 1. The small-scale Kalina cycle power generation system is built into the upper stream of the high-temperature hot springs, to obtain electricity and adjust the bath temperature without any dilution (Osato et al., 2005, Muraoka et al., 2008). One of the problems of this system was corrosion and scaling on the plate heat exchanger between hot spring fluid and ammonia-water fluid, similar to usual geothermal system. On the hot fluid side and also on the cooling water side (where cooled geothermal water was used for cooling) of the heat exchanger, calcium carbonate scale precipitated (Yanagisawa et al., 2012).

This paper presents the results of calcium carbonate scaling at EGS and hot spring binary system, describes properties compareed with conventional geothermal systems and shows the method of preventing calcium carbonate scaling based on calculated scaling indicies.

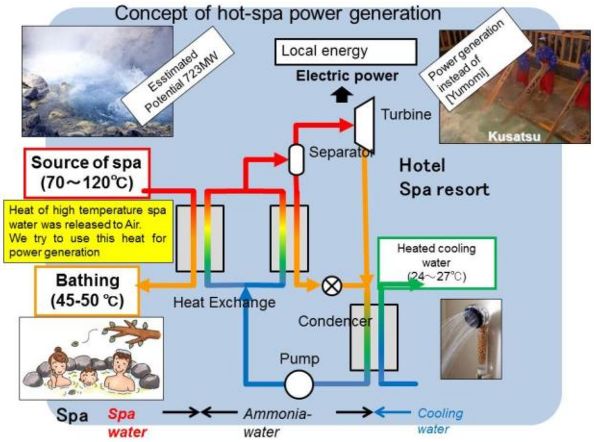


Figure 1: The concept of power generation using hot spring fluid.

2. CALCIUM CARBONATE SCALING

Calcite or aragonite ($CaCO_3$) scaling is a well known problem in conventional geothermal systems. Calcite scale occurs near the flash point in the production wells due to a decrease in calcite solubility.

Calcium solubility varies with the pressure of CO_2 (P_{CO_2}) and temperature of the fluid. Figure 2 shows the calcium solubility curve as a function of P_{CO_2} and temperature by Fournier (1985). It is noted from this curve that under the same temperature condition, calcite solubility is higher with respect to an increase of P_{CO_2}. This explains why it is common to observe scaling at the flash point. During flashing where vapor is release and thus P_{CO_2} decreases, calcite solubility would therefore decrease and thus calcite scale precipitates. Furthermore, as calcite solubility is lower at high temperature conditions, calcite precipitation tends to occur in mid-section or shallow areas of production wells where flashing occurs and could be a serious problem. Many geothermal fields with high calcium or bicarbonate concentrations experience calcite scale problems. In Japan, Mori and Yanaizu-Nishiyama geothermal power plant have serious calcite scaling,

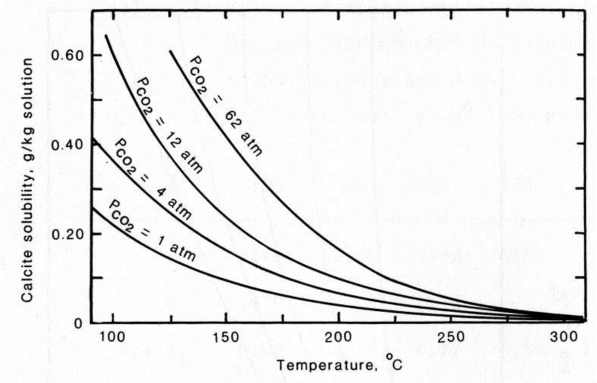


Figure 2: Solubility of calcite as a function of temperature and pressure of CO_2.

To prevent calcite scaling in wells, various chemical inhibitors have been used in many geothermal fields. For example, sodium polyacrylate, C_2H_3COONa, has been used for several Japanese geothermal fields and hot spas. Similar chemicals have been used around the world. At high fluid temperature, sodium polyacrylate reacts with calcium ion to make a calcium complex. Calcium complex cannot react with bicarbonate ion (HCO_3) to precipitate calcite. Thus, this sodium polyacrylate inhibitor is effective to prevent calcite scaling. For production wells, a capillary tube is inserted into well until it reaches the depth of flashing point and chemical inhibitor is then directly injected to this point and prevents scaling.

Similarly, solubility of anhydrite ($CaSO_4$) is lower at higher temperature and tends to precipitate at deep points of production wells and at shallow high temperature points (i.e. higher temperature shallow reservoir fluid feed points in the wells). In both cases, the temperature of fluid is s high and anhydrite precipitates due to decreasing solubility. It has been reported that in Japan, Mori and Sumikawa geothermal fields experience anhydrite scaling.

3. CALCIUM CARBONATE SCALING IN EGS

3.1 The Circulation Test at Hijiori EGS Site

Hijiori is located in the Yamagata Prefecture, in the northern part of Honshu Island, Japan. The topography of the area is dominated by an approximately 1.5-2 km diameter volcanic caldera. The test site is at the southern rim of the Hijiori caldera where four boreholes (HDR-1, HDR-2a, HDR-3 and SKG-2) were drilled with true vertical depths ranging between 1800 and 2300 m. All these wells penetrated the basement rocks, which consist of Cretaceous granodiorite that has been intensively altered by hydrothermal processes. Based the geological data gathered from the deep Hijiori wells, the granodiorite basement is unusually overlain by the sedimentary rock at depth of 1500 m. The mineral composition of core samples of granodiorite of HDR-2a at about 2,000 meters depth shows about 5 % anhydrite existence as a vein mineral due to volcanic activity.

The fluid circulation system at the Hijiori EGS site is shown schematically in Figure 4 (Oikawa et al., 2001). A multi-stage centrifugal pump (ESP TJ9000) was used to inject the fluid at a constant flow rate of 16.66 kg/s. The long-term circulation test (LTCT) was conducted from November 2000 to August 2002. In the first stage of the LTCT, this fluid was directly injected into lower reservoir HDR-1 and SKG-2 was used for monitoring pressure of the upper reservoir (Tenma et al., 2002). In the second stage, the injection fluid was separated into two lines after being pressurized by the pump. One was connected HDR-1, which was used as an injection well for the deep reservoir, and the other to SKG-2. Figure 4 shows the change of wellhead temperature during LTCT. Wellhead temperature of production wells, HDR-2a and HDR-3, was about 160 degree C in early stages of the LTCT. But after half a year since the start of circulation, the wellhead temperature of HDR-2a rapidly decreased from 160 to 120 degree C.

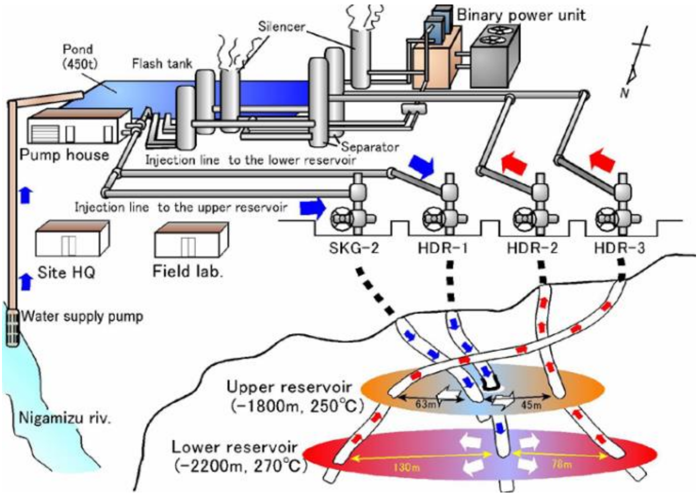


Figure 3: The system of Hijiori EGS test field.

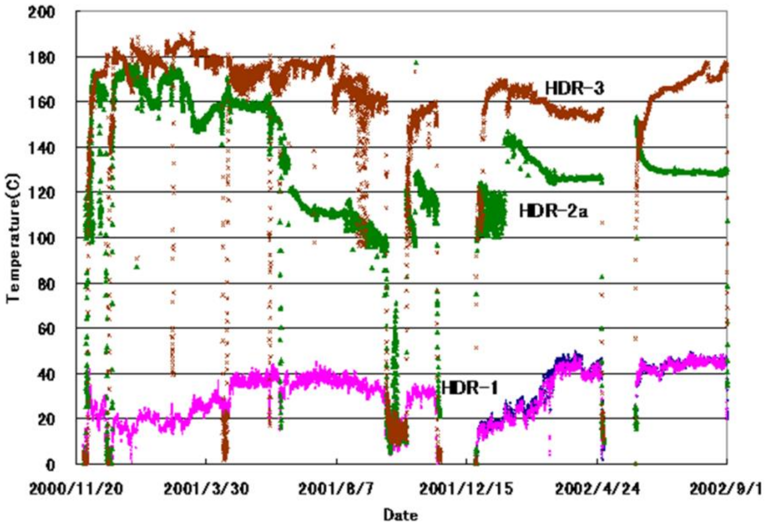


Figure 4: The wellhead temperature during circulation test.

3.2 Scale and fluid analysis

Figure 5 shows the change of the X-ray powder diffraction of scale samples with circulation progress at the fluid sampling pool of HDR-2a. These scales were collected in May 2001 and October 2001 during the single well injection test and in February 2002 and August 2002 during the dual injection test. Scale analysis methods were as follows: a) major metal elements were analyzed by Inductively Coupled Plasma Emission Spectrometry (ICP-ES) and b) sulfur and carbon were analyzed using the high-frequency burning infrared absorption method.

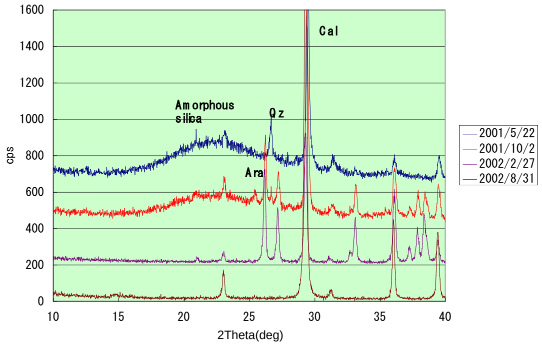


Figure 5: Change of X-ray diffraction pattern of scale sample at fluid sampling pool in HDR-2 at several times during Long time Circulation test.

Table 1: Chemical composition of scale sample at fluid sampling pool in HDR-2 at several times during Long time Circulation test (based on ICP-ES analysis),

	SiO_2	Al_2O_3	FeO	CaO	SO_4	CO_2
2001/5/22	68.2	1.9	3.2	10.4	1.6	9.1
2001/10/2	47.1	1.6	2.5	22.4	2.6	17.7
2002/2/27	0.8	0.2	0.0	53.8	2.1	42.1
2002/8/31	3.5	0.2	0.8	51.2	3.7	38.6

Table 1 shows the chemical composition of these samples. During the single injection test, silica content decreased and calcium increased. The last two samples contained mainly calcium carbonate. Samples collected in February contained calcite and aragonite but those from August contained mostly calcite.

With circulation progress, scale species changed from amorphous silica to calcium carbonate at HDR-2a. And the fluid composition was analyzed by ion-chromatography. This change was related with the temperature decrease and Ca and SO_4 increase as shown in Figure 6 (NEDO, 2003). At HDR-2a, thermal breakthrough occurred on June 2001 and temperature decreased, the fluid composition changed and tracer response changed to quick and sharp (Yanagisawa et al., 2002). The scale species change corresponded with the decreasing temperature.

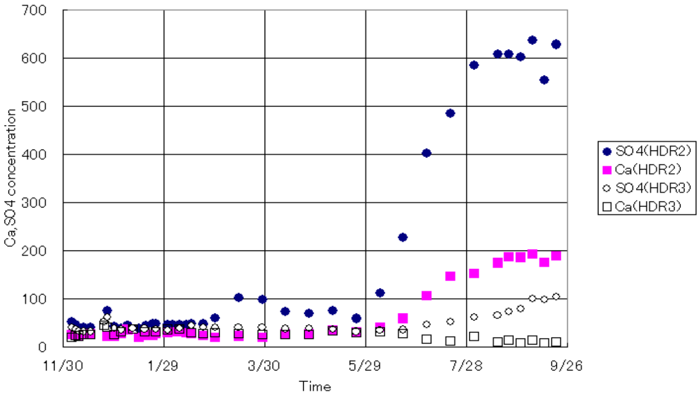


Figure 6: Change of Ca and SO_4 concentration of HDR-2 and HDR-3 during LTCT of 2001.

The temperature depth profile at May 2001, prior to thermal breakthrough, and the profile after breakthrough case at July 2001 are shown in Figure 7. The scales precipitated at the deep part of the production well and consisted mainly of anhydrite. Because the solubility of anhydrite decreases with higher temperature, the reverse of usual scale compositions such as silica, anhydrite precipitates at higher temperature zones in the flow path. In the case of EGS, injection water is about 70°C when the water reaches the reservoir, at the injection point, the water dissolves anhydrite veins in the granite reservoir rock.

Dissolved anhydrite was transported with fluid flow in the reservoir to the production well, the water was then heated by granite around the reservoir, and the heated fluid became supersaturated with anhydrite. As shown in the temperature curve in Figure 7, high temperature exists at 500m depth, and a step change is seen at 2,000m. Anhydrite precipitated around this temperature and the steep change zone was detected by the PTS logging tool. The HDR-3 temperature is higher than at HDR-2a and gradually increases with depth until 1,950m where there is a slight decrease at the deeper zone. The PTS logging tool did not penetrate beyond 2,000m depth due to anhydrite scale at the high temperature zone. Anhydrite scaling at high temperature zones in production wells is found in other geothermal fields, for example, at Sumikawa geothermal field (Kato et al., 2000).

In HDR-2a, the lower temperature well, calcium carbonate is the major scale component. Ca and SO_4 content of the HDR-2a fluid were higher than HDR-3 due to higher anhydrite solubility at lower temperature. The high content of Ca reacted with CO_2 at the surface facilities to deposit calcium carbonate. On the other hand, in HDR-3, the higher temperature well, there was slight amorphous silica deposition. The Ca content of HDR-3 was too low to precipitate calcium carbonate. The SiO_2 content was higher than HDR-2a but lower than other geothermal fields and silica precipitated slightly.

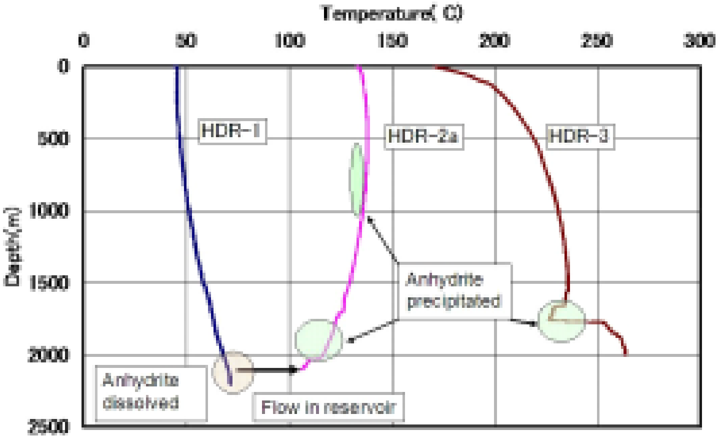


Figure 7: Temperature depth profile of HDR-1, injection well, HDR-2a and HDR-3, production well obtained by PTS survey at June 2001, after thermal breakthrough.

3.3 Idea of Scale Prevention for EGS

In the case of EGS, calcium carbonate scaling depends on Ca concentration increasing due to reservoir temperature and water-rock interaction in reservoir. This means that Ca concentration and temperature control is important for scaling prevention.

To prevent calcite scaling, there are several methods as follows:

1) Estimation of Ca content in reservoir from geological conditions. For example, Hijiori EGS field exists in the volcanic caldera region with several carbonic acid springs and the reservoir rock includes anhydrite veins. Then, calcium carbonate scale would precipitate easily.

2) Consider the circulation system of EGS. For example, the well distance of Hijiori EGS is about 70 metres, but that of developing other EGS would be longer (about 500 metres). Control of the injection temperature and rate may provide another method. The temperature of injection well at Hijiori is too low to dissolve anhydrite. The period of circulation may also be a considerable factor.

3) If anhydrite scaling was more serious than calcium carbonate scaling then reverse circulation, exchanging between injection well and production well, is one method.

4) Similar to a conventional geothermal system, a scale inhibitor (Sodium Polyacrylate) can be injected to the circulation system.

5) Control of CO_2 degas is one method.

Among these methods, the scale inhibitor test was carried out at Hijiori EGS site.

3.4 Scale Inhibitor Test

Sodium polyacrylate, C_2H_3COONa, is a commonly used scale inhibitor to prevent calcite precipitation (Ramos-Cardelaria et al., 2000). In Japan, sodium polyacrylate is used in several geothermal plants and hot spas, for example Mori and Oku-aizu geothermal plants. At high fluid temperatures, sodium polyacrylate reacts with calcium ion to produce a calcium complex. Calcium complex cannot react with bicarbonate ion, HCO_3, to precipitate calcite. However, it is not clear if it is effective for other kinds of scale, for example anhydrite. We tested using sodium polyacrylate for anhydrite because other inhibitors have not been developed for anhydrite and sodium polyacrylate has the possibility to affect the calcium ions of anhydrite and is used in many calcite scaling geothermal fields.

The inhibitor injection test was carried out two times at difference concentrations of inhibitor. We checked Ca, SO_4 and HCO_3 concentration changes to estimate the effect of the inhibitor. Table 2 shows the maximum and minimum concentration and change rate of Ca, HCO_3 and SO_4 with inhibitor injection during two inhibitor injection tests. This table shows the dependence of inhibitor concentration to Ca, HCO_3 and SO_4 concentration change. SO_4 concentration decreased 6.5%, from 765 to 715ppm, at 4.7ppm inhibitor test and the decreasing rate changed to 16.7%, from 540 to 450ppm at 18.2ppm inhibitor test. HCO_3 showed an increasing rate with inhibitor addition but with a lesser dependence than SO_4. HCO_3 concentration increased 45.5%, from 70 to 102ppm, at 4.7ppm inhibitor and 55.5%, from 70 to 100ppm, at 18.2ppm inhibitor. Ca decreased with inhibitor concentration similar to SO_4.

Table 2: Maximum and minimum concentration and change rate with inhibitor injection of Ca, HCO_3 and SO_4.

TEST	Inhibitor	SO4(ppm)		Change	HCO3(ppm)		Change	Ca(ppm)		Change
NO.	(ppm)	Max	Min	Rate(%)	Max	Min	Rate(%)	Max	Min	Rate(%)
1	4.7	765	715	-6.5	102	70	45.5	180	175	-3
2	18.2	540	450	-16.7	110	70	55.5	107	96	-10

The increasing HCO_3 concentration with inhibitor shows the effect of inhibitor to prevent precipitation of calcite as in many geothermal plants. But as SO_4 decreased in contrast to HCO_3, the effect on anhydrite by the inhibitor was not the same as for calcite to prevent precipitation. To identify the reason of SO_4 decreasing and whether the decrease of dissolution would occur at the low temperature region or precipitate prevention occurs in the production well, a flow and anhydrite dissolution test was done using the inhibitor in laboratory conditions.

The result of testing is shown in Figure 8. Firstly, distilled water was flowed into an anhydrite cell. Ca and SO_4 concentration reached 600ppm and 1400 ppm, respectively, during the first 15 minutes and was constant during the 1 hour of flow. After distilled water was flowed for 1 hour, 20ppm inhibitor solution was flowed into the anhydrite cell. As soon as inhibitor reached the cell, Ca and SO_4 concentration rapidly decreased and Ca and SO_4 concentration reduced to 300ppm and 700ppm respectively. This concentration change shows that the inhibitor prevents to dissolution of anhydrite at room temperature.

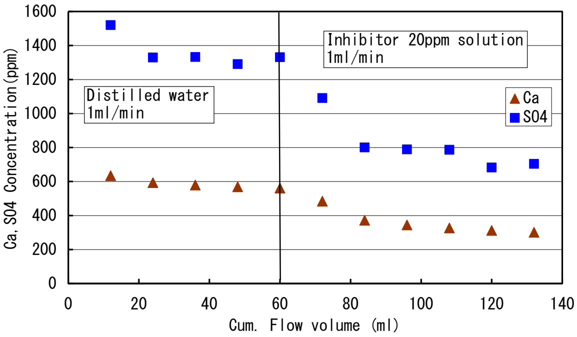


Figure 8: Ca and SO_4 concentration at anhydrite flow cell. After distilled water flowed for 1 hour, 20ppm inhibitor including water flowed.

Figure 9 shows the effect of inhibitor on calcite precipitation and anhydrite dissolution. Therefore, in EGS, sodium polyacrylate inhibitor prevents the dissolution of anhydrite in the reservoir near the injection well. Ca and SO_4 concentration of reservoir fluid decrease than no inhibitor condition. This leads to lower anhydrite scaling in the production well and lower calcite scaling in surface pipeline by Ca ion effect of inhibitor.

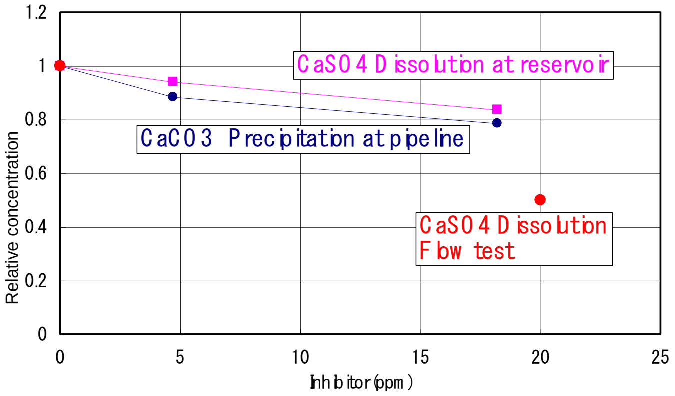


Figure 9: Effect of inhibitor on calcite precipitation and anhydrite dissolution.

4. CALCIUM CARBONATE SCALING IN HOT SPRING BINARY SYSTEM

4.1 Scaling Test at Otari Site

As shown in Figure 1, several hot spring binary projects are progressing in Japan including Matsunoyma (Yanagisawa et al., 2012), Beppu, Obama, Tsuchiyu hot spring region etc. The first survey in Otari site is north of Nagano prefecture. Using the OT-2 well, a scaling test was carried out (Yanagisawa et al., 2012).

The scaling test was carried out from 20 January to 8 February 2008. During testing, the temperature of hot spring fluid increased from 51.2 ºC to 69.2 ºC and flow rate increased from 10 L/min to 18 L/min. The temperature of cooling water increased from 20.1 ºC to 35.2 ºC but the flow rate decreased from 20 L/min to 13 L/min. The fluid chemistry of hot spring fluid from OT-2 is shown in Table 3, unit of chemical composition from Na to SiO2 is mg/l. Samples were collected at the inlet and outlet of the heat exchanger at the end of the test.

Table 3: Geochemistry (mg/l) of inlet and outlet of heat exchanger of OT-2 hot spring fluid at end of test (units for Na to SiO_2 in mg/l).

	Temp	pH	EC	Na	K	Mg
Inlet	69.2	7.1	8.2	1906	30	11
Outlet	51.8	6.9	7.9	1849	29	11
	Ca	F	HCO3	Cl	SO4	SiO2
Inlet	84	0.55	2167	1487	559	112
Outlet	85	0.56	2182	1450	545	95

After 20 days of testing, scale precipitated on the plates of the heat exchanger. Figure 10 shows the hot spring fluid side of heat exchanger. About 0.4g scale precipitated on one plate. The scale formed consided mainly of amorphous silica, calcite, aragonite and iron oxide.

Cooled geothermal water was used as the cooling water supply)refer Figure 1). Figure 11 shows the cooling water side of the heat exchanger. The main composition of the scale was calcite and aragonite. Scaling depends on temperature and there was considerable precipitation at the high temperature region at the inlet of hot spring fluid and outlet of cooling water. The range of scaling weight is from 1 g to 10g per plate and was dependent on flow rate and temperature on the plate. Due to scaling, the flow rate of cooling water decreased from 20 L/min to 13 L/min. This scaling is due to lower solubility of calcium carbonate as show in Figure 2 when the cooling water temperature is increased. High Ca and HCO_3 fluid, cooled hot spring fluid, as shown in Table 3, was used and caused the high amounts of scale precipitation. Scale prevention technology is needed for not only the hot spring water path but also the cooling water path if cooled hot spring water is the used for cooling.

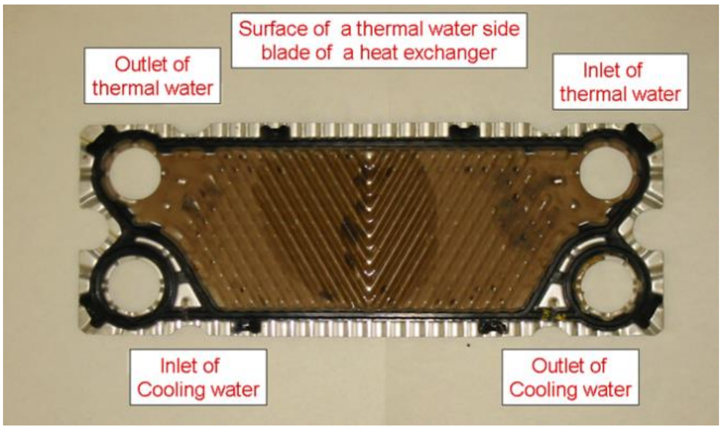


Figure 10: Scale on hot spring fluid side on heat exchanger.

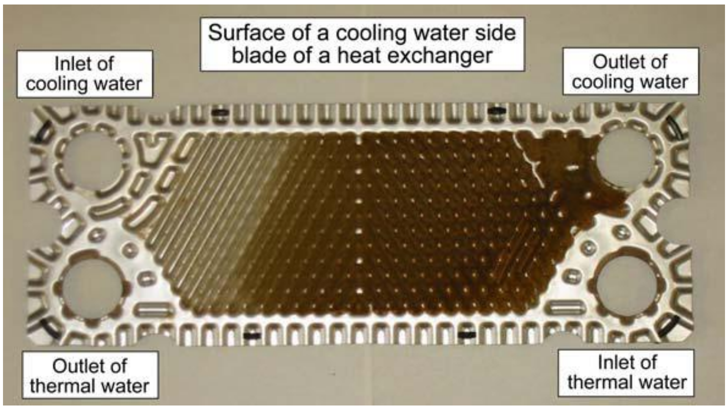


Figure 11: Scale on cooling water side on heat exchanger.

4.2 Idea of Scale Prevention for Hot Spring Binary System

In the binary system for hot springs, three times as much cooling water is needed than hot spring fluid. Therefore, the calcite scaling at the cooling water flow path poses a big problem. To prevent calcite scaling, we have to use pure water or low Ca concentration fluid, for example, river water for cooling water.

A scaling prevention system, for example, electrode method (Yanagisawa et al., 2006) or scale inhibitor, is useful to prevent calcite scaling. One method is by using an air cooling system but the cooling rate is slower than a water cooling system which influences power generation.

The calcium carbonate scaling occurs on the hot fluid path due to high chemical composition as shown in Figure 10. A conventional system scale inhibitor is very useful in preventing calcite scaling. However, for hot spring owners, scale inhibitor is expensive and several owners dislike injecting inhibitor into water used for bathing. Other methods are being considered for development.

In order to promote hot spring binary systems, especially with bathing, it is important to estimate scaling before designing the system. Several estimations were carried out in our test field Otari and Matsunoyama.

4.3 Estimation of Scaling at Otari Field

The estimation of the possibility of scaling in hot spring system is carried out by calculating equilibrium of silicate and carbonate minerals using Solveq-Chiller by Reed (1982). The estimation of scaling at Otari is carried out using chemical composition data of Table 3. The result is shown in Figure 12.

In Figure 12, during the cooling process of hot spring fluid from 100 to 40 ºC, in the heat exchanger, magnesium silicates, tremolite, is super-saturated above 50ºC. Dolomite is also super-saturated and the log(Q/K) value is more than 2 above 50ºC. The log(Q/K) of calcite at Otari is from 1 to 1.5 between 60 and 100 ºC. This log(Q/K) is high due to a high HCO_3 concentration of 2162mg/l. Therefore at Otari, calcite and silica precipitated on plates of the heat exchanger is predicted.

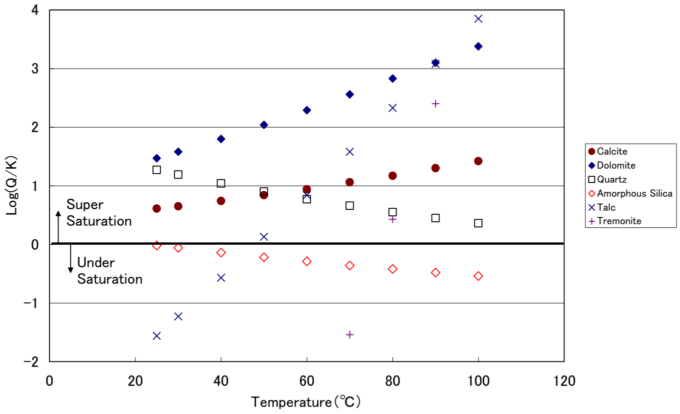


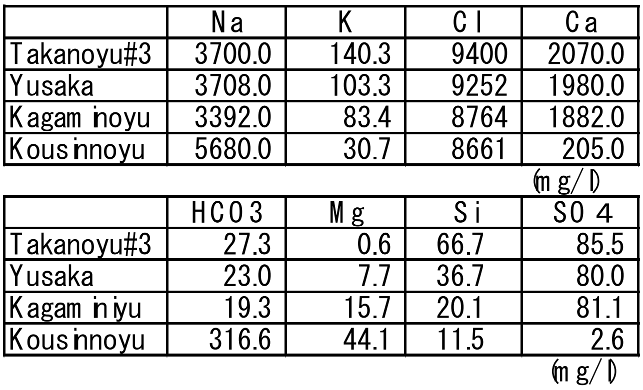
Figure 12: Estimation of equilibrium of scale minerals of Otari fluid.

4.4 Estimation of Scaling at Matsunoyama Field

After material tests at Otari site, the Ministry of the Environment (MOE) of Japan started to support hot spring power generation project from fiscal year 2010 (FY2010). In this project, power generation testing by implementing a 50kW class Kalina cycle system using about 100 ^{o}C hot spring water was carried out at Matsunoyama hot spring field (Yanagisawa et al., 2012, Welch et al., 2011). At Matsunoyama, a new hot spring well, Takanoyu#3, was drilled at a depth of approximately 1,200 meters in 2007.During the first production test, the fluid temperature was about 97 ºC and flow rate about 630 l/min.

Table 4 shows the fluid composition of Matsunoyama wells with high Cl concentration, about 9,000 mg/l, in all wells measured during November 2010. Takanoyu#3 has about 3,700 mg/l Na, 140mg/l K, 2,070 mg/l Ca and 27.3 mg/l HCO_3 and did not change from the start of production at September 2007.

Table 4: Geochemistry of hot spring of Takanoyu#3 and surrounding wells (mg/l).



	Na	K	Cl	Ca
Takanoyu#3	3700.0	140.3	9400	2070.0
Yusaka	3708.0	103.3	9252	1980.0
Kagaminoyu	3392.0	83.4	8764	1882.0
Kousinnoyu	5680.0	30.7	8661	205.0

(mg/l)

	HCO3	Mg	Si	SO4
Takanoyu#3	27.3	0.6	66.7	85.5
Yusaka	23.0	7.7	36.7	80.0
Kagaminiyu	19.3	15.7	20.1	81.1
Kousinnoyu	316.6	44.1	11.5	2.6

(mg/l)

The estimation of scaling at Takanoyu#3 of Matsunoyama was carried out using the chemical composition data of Table 4. Results are shown in Figure 13.

The equilibrium graph illustrated in Figure 13 is during the cooling process of hot spring fluid from 100 to 40 ºC on the heat exchanger. Quartz (SiO_2) and calcite ($CaCO_3$) are supersaturated, but other minerals such as dolomite ($MgCaCO_3$), talc ($Mg_3Si_4O_{10}(OH)_2$), tremolite ($Ca_2Mg_5Si_8O_{22}(OH)_2$) and amorphous silica (SiO_2) are under saturation. This suggests the scaling problem will not beserious because silica scaling usually appears as amorphous silica under saturation over 40ºC at Matsunoya#3 and the degree of super saturation of calcite decreases as temperature decreases. Therefore, to prevent scaling we have to take care to prevent vaporized fluid and pH changes in the heat exchanger.

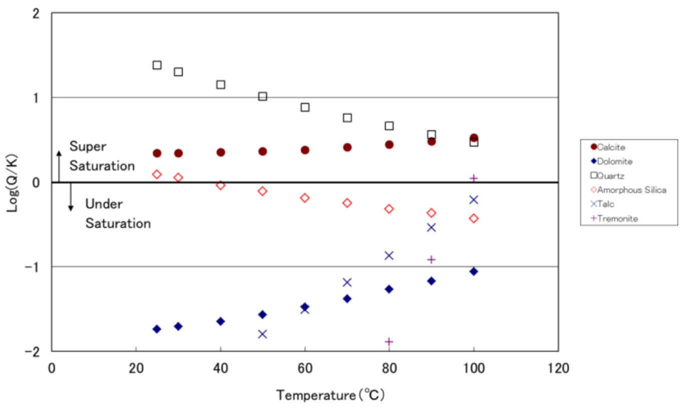


Figure 13: Estimation of equilibrium of scale minerals of Takanoyu#3 fluid.

In the Matsunoyama region, Ca, HCO_3 and Mg concentrations have a wide range, even though Na and Cl are almost similar. In particular at Kousinnoyu, Mg concentration is 44.1 mg/l and about 70 times that of Takanoyu#3 which is 0.6mg/l. HCO_3 concentration is 316mg/l and about 10 times that of Takanoyu#3. The log(Q/K) of minerals of Kousinnoyu is shown in Figure 14. Several minerals, including Mg and HCO_3, show high log(Q/K) values similar to the Otari field.

The reason for the low risk of scaling at Takanoyu#3 is due to low HCO_3 and Mg concentrations. However the scaling risk will increase in high HCO_3 and Mg fluids as found at Otari and obserfed at Kousinnoyu.

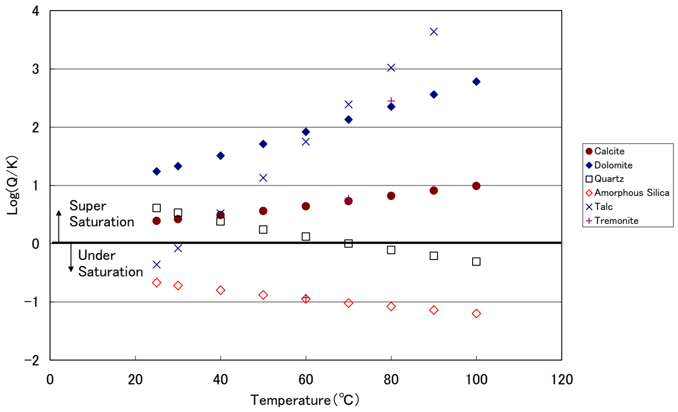


Figure 14: Estimation of equilibrium of scale minerals of Kousinnoyu of Matsunoyama field.

5. CONCLUSIONS

The scaling of calcium carbonate was observed in Hijiori EGS test site and hot spring binary test site. The mechanism of scaling and prevention ideas are as follows;

1) At Hijiori EGS site, calcium carbonate scaling depends on fluid temperature and chemical composition. In the case of HDR-2 nearer to the injection well, due to low wellhead and well temperature, calcium carbonate scaling occurred due to anhydrite dissolution in the reservoir and high Ca concentrations.

2) Scale inhibitor is useful to prevent the precipitation of calcite on pipelines and to decrease anhydrite dissolution in reservoir.

3) During the hot spring heat exchange test, calcium carbonate and silica precipitated on the hot spring fluid path of the heat exchanger. In the cooling water path, aragonite precipitated, especially in the higher temperature area, due to super-saturation by heating of the cooled hot spring water used for cooling.

4) According to the estimation of scaling, the scaling problem at Takanoyu#3 of the Matsunoyama region is less than the Otari test site due to low HCO_3 and Mg concentrations at Takanoyu#3. The scaling at Kousinnoyu is predicted to be similar to that at Otari.

REFERENCES

Fournier, R. O.: Carbonate transport and deposition in the epithermal environment; in Berger, B. R., and Bethke, P. M. (eds.), Geology and geochemistry of epithermal systems: *Reviews in Economic Geology*, **2**, (1985), 63–72.

Kato, H., Kamei, J. and Kitao, K.: Fluid Flow-Precipitation Model of Anhydrite Scale in Wellbore-Case Study of the Sumikawa Production Well, SC-1, *Journal of the geothermal research society of Japan*,**22**,(2000),171-185. (In Japanese with English abstract).

Muraoka, H., Sasaki, M., Yanagisawa, N. and Osato, K.: Development of small and low-temperature geothermal power generation system and its marketability in asia, *Proceedings*, 8th Asian Geothermal Symposium (2008), CD-ROM.

NEDO: Summary of Hot Dry Rock Geothermal Power Project of FY2002, (2003) (in Japanese)

Oikawa, Y., Tenma, N., Yamaguchi, T., Karasawa, H., Egawa, Y. and Yamauchi, T.: Heat Extraction Experiment at Hijiori Test Site, *Proceedings*, 26th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA (2001), 255-258.

Osato, K.: Applicable condition of Kalina cycle for geothermal power plant, *Journal of the Geothermal Energy Research & Development,* **30**, (2005), 53-61. (in Japanese)

Ramos-Candelaria, M., Cabel, A.C. Jr., Buñing, B.C. and Noriega, M.T.: Calcite inhibition field trials at the Mindanao Geothermal Production Field (MGPF), Philippine, *Proceedings*, World Geothermal Congress 2000,(2000),2171-2176.

Reed, M.H.: Calculation of multicomponent chemical equilibria and reaction process in systems involving minerals, gasses and an aqueous phase, *Geochimica Cosmochimica Acta*, **46**, (1982), 513-528

Welch, P., Boyle, P., Murillo, I. and Sells, M.: Construction and Startup of Low Temperature Geothermal Power Plants, *Geothermal Resources Council Transaction*, **35**, (2011), 1351-1356.

Yanagisawa, N., Matsunaga, I., Sugita, H. and Tao, H.: Reservoir Monitoring by Tracer Test of a 2001 Long Term Circulation Test at the Hijiori HDR site, Yamagata, Japan, *Geothermal Resources Council Transactions*, **26**, (2002), 267-271.

Yanagisawa, N. and Matsumura, T.: Analysis of the electrolytic precipitation rate of calcite, *Journal of Mineralogical and Petrological Sciences*, **101**, (2006), 319-323

Yanagisawa, N., Matsunaga, I., Sugita, H., Sato, M. and Okabe, T.: Temperature dependent scale precipitation in the Hijiori Hot Dry Rock system, *Geothermics*, **37**, (2008), 1-18

Ynagisawa, N., Sasaki, M., Muraoka, H. and Osato, K.: Scale and corrosion of kalian power generation system using hot spring water, *Proceedings* , 34th New Zealand geothermal workshop, (2012), CD-ROM