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Ca and CO_2 Transport and Scaling in the Hijiori HDR System, Japan

Norio Yanagisawa

AIST Tsukuba Central 7, Higashi 1-1-1, Tsukuba, Ibaraki, Japan

n-yanagisawa@aist.go.jp

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ABSTRACT

Carbon dioxide (CO_2) and calcium (Ca) transport in underground water or geothermal reservoirs is an important topic in water-rock interactions, especially for estimating effects on CO_2 storage or scaling in engineering geothermal systems (EGS) or hot dry rock (HDR) systems.

In the Hijiori HDR test field, dissolved anhydrite near the injection well is the primary source of calcium that leads to calcite precipitation in pipelines. HDR-2 has a lower temperature, and about 2.7 tons of calcite precipitated in the pipeline and well during the 3 months of CO2 circulation. HDR-3 has a higher temperature and about 0.6 tons of calcite precipitated in the deep well.

The transport of CO_2 in HDR system including river water and atmosphere was estimated. From river water, production well and atmosphere, about 6 tons of CO_2 were injected over a 3 month period. Of the CO_2 that reached HDR-2, 68% was precipitated as calcite and 3% CO_2 was discharged as gas by the atmosphere. In HDR-3, 20% CO_2 precipitated as calcite and 30% CO_2 was discharged as gas to the atmosphere.

1. INTRODUCTION

Recently, CO_2 geological storage has become an important strategy for decreasing the release of CO_2, a greenhouse gas, to the atmosphere. It is important to estimate the effect of CO_2 geological storage, including transport rates and reactions of CO_2 with Ca and other elements.

One method of geological storage is to inject CO_2 into high temperature (about 200^{o}C) granitic rock. Calcite ($CaCO_3$) tends to precipitate at high temperature, so injected CO_2 will likely change to calcite early (Ueda et al., 2005). CO_2 injection tests are currently ongoing at the Ogachi site, northeast of Japan, into high temperature geothermal fields (Kaieda et al., 2009).

Until 2002, the Ogachi site was used for research and development of Hot Dry Rock (HDR) systems, after which time the site was used to test CO_2 injection. The CO_2 injection technology is similar to a HDR system. Recently the idea of CO_2-EGS was described by Pruess (2006) where understanding CO_2 transport and reaction processes in the reservoir becomes important.

In Japan, the other HDR project was carried out at Hijiori, Yamagata. At the Hijiori site a long term circulation test was carried out until 2002 where calcite and anhydrite scaling was observed in pipelines and deep wells (Yanagisawa et al., 2008).

Mineral precipitation was a result of Ca and CO_2 transport within the HDR reservoir circulation system. In order to consider the possibility of CO_2 storage in a HDR circulation system, it is important to estimate the behavior of Ca and CO_2 to prevent scaling.

2. HIJIORI HDR SITE

2.1 Circulation and Fluid Chemistry

The Hijiori HDR field test was created through a series of hydraulic stimulation experiments and is located in Yamagata Prefecture of Japan. A heating reservoir was created at 2000 m depth, after which river water was injected fractured reservoir, heated in reservoir and returned to installations on the ground surface. The circulation system is shown in figure 1.

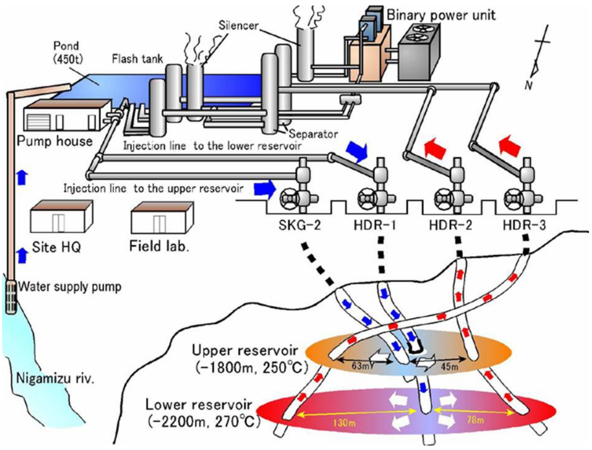

Figure 1: Schematic diagram of circulation system at Hijiori HDR site

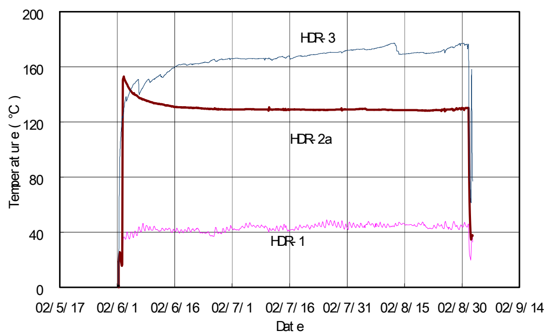

Figure 2: Wellhead temperature of injection and production well

At the Hijiori site, a long term circulation test was carried out from November 2000 to August 2002. During circulation, the injection water ratio between SKG-2 and HDR-1 was changed in December 2001 and April 2002. Also, pipeline scale was removed in May 2002 before conducting a binary power generation test.

From June 2002 to August 2002, fluid circulation was carried out along with a binary power generation test. During this 3 month period, fluid chemistry, injection and production temperatures were almost constant (figure 2). Table 1 shows the mean chemical composition of fluids in river water, injection water (HDR-1) and production water (HDR-2 and HDR-3).

Table 1. Total Water and Vapor Mass During 3 Month Binary Power Plant Test.

	Water mass	Vapor mass
HDR-1	129000	
HDR-2	53600	1930
HDR-3	16500	1350
River water	58900	

Table 2. Average Fluid Chemical Composition of River Water, HDR-1, HDR-2 and HDR-3 During 3 Month Test.

	River water	HDR-1	HDR-2	HDR-3
pH	6.43	7.74	8.7	9.03
Na	6.0	118.6	166.4	373.9
K	1.0	17.0	26.8	54.6
Ca	4.7	64.7	145.8	8.3
Mg	5.7	4.5	3.4	0.1
SiO_2	5.8	111.4	164.5	370.5
Cl	5.4	96.2	119.4	391.4
SO_4	13.2	246.6	563.6	202.1
HCO_3	53.0	64.8	32.7	125.0

2.2 Scaling in HDR System

Scaling at surface installations and in deep wells (HDR-2 and HDR-3) are shown in figure 3. Anhydrite deposited in the deeper parts of the production wells, while silica and calcium carbonate precipitated at the surface downstream of the wellhead. Amounts of precipitation depended on the temperature and chemical composition of the produced fluid. In HDR-2, which is closer to the injection well, most of the scale was calcium carbonate; in HDR-3, which is further away from the injection well, there was slight precipitation of amorphous silica. As fluid circulation progressed and temperature decreased, scaling in the flow line of well HDR-2 changed from amorphous silica to calcium carbonate.

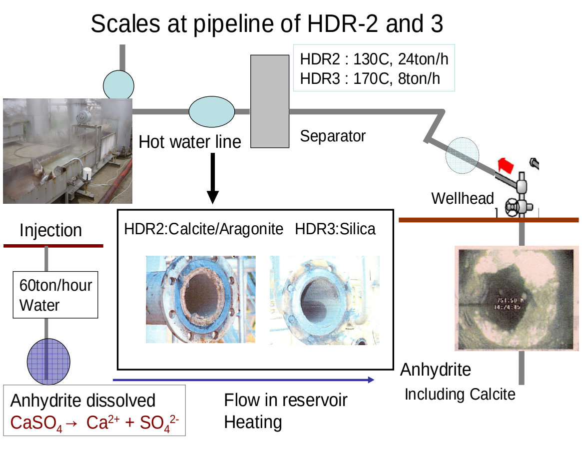

Figure 3: Scale sampling site and photo

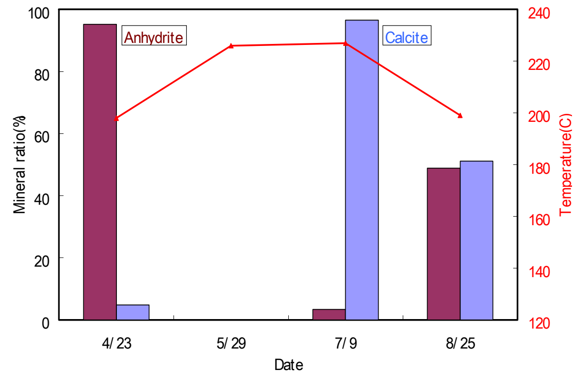

Figure 4: Temperature at 1750 m depth (red line) and the ratio of anhydrite to calcite in deep well scale at HDR-3

Figure 4 shows the temperature in HDR-3 at 1750 m depth and the ratio of anhydrite to calcite of the deep well scale. During a 1 month circulation interruption, temperature increased from 200 to 230°C, after which calcite mainly precipitated in the deep well. With continued circulation, temperature decreased again and the anhydrite ratio increased. At HDR-2, the anhydrite precipitation ratio is above 90% during the 3 month circulation test.

Figure 5 shows the depth temperature profile. As water was injected anhydrite dissolved around the injection well, the water heated as it flowed through the reservoir, and anhydrite precipitated due to lower solubility at higher temperatures.

As fluid reaches the production well, scaling depends on temperature. In HDR-2, maximum temperature was 130°C and Ca remained in solution. On ground pipeline of HDR-2, Ca reacts with CO_2 and calcite precipitated. In contrast, in HDR-3, with a maximum temperature was 260°C, led Ca to precipitate as anhydrite and calcite in the reservoir and deep well and not in the surface pipeline.

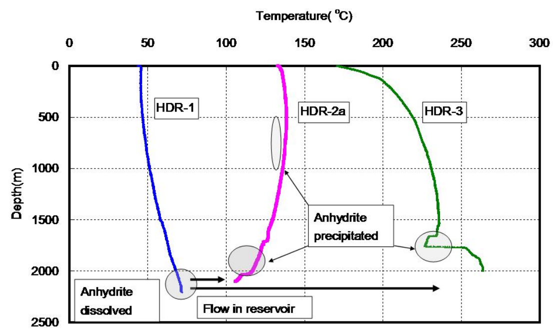

Figure 5: Temperature profiles in the Hijiori wells measured in July 2002

3. MASS BALANCE IN HDR SYSTEM

3.1 Ca Transportation

Table 3 shows the thickness of scale and chemical composition in pipeline of HDR-2. From this thickness and pipeline length, the weight of calcium in calcite scale in HDR-2 was estimated at about 1.04 ton. From the difference of SO_4 and Ca between injection well and production well, we can estimate the mass of calcium for calcite precipitation in circulation system.

Table 3. Chemical Ratio and Thickness of Several Sampling Points in HDR-2 Well.

	Chemical ratio (%)			
	CaO	SO_4	CO_2	Thickness
Wellbore	40.6	53.8	4.0	
Swivel Joint	54.94	1.25	42.30	45mm
Two phase line	55.25	1.38	42.50	40-60mm
Hot water line	52.99	2.75	40.30	20mm
Sampling pool	51.2	3.7	38.6	

In the case of HDR-2 the difference of calcium concentration between HDR-1 and HDR-2 is 81 ppm and that of SO_4 is 317 ppm. From this, about 51 ppm of calcium precipitated as calcite and the total mass of calcium is estimated to be 2.7 ton from total production fluid, or 53,600 ton during the 3 month test period.

By using same method, about 0.56 tons of calcium were precipitated as mostly calcite in the production well HDR-3, which is a higher temperature than HDR-2.

And total mass of calcium in fluid is calculated from concentration and total flow mass.

Figure 6 shows the diagram of calcium mass balance (in tons) with transportation during the 3 month circulation. From the pond, 8.29 tons of calcium were injected into the reservoir. Calcium concentration increased by dissolving anhydrite and decreased via precipitation in the reservoir and deep wells. After anhydrite precipitated, the total mass calcium in production fluid is about 2.66 ton to injection fluid. And in HDR-2, total calcium mass for calcite and fluid is 10.23 ton due to lower temperature. In contrast, only 0.72 ton in higher temperature HDR-3.

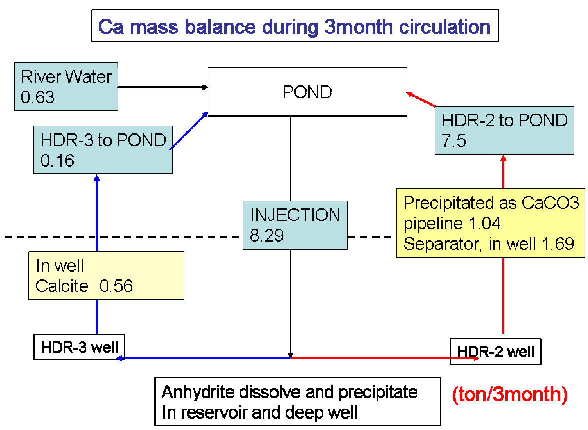

Figure 6: Calcium transportation mass (in tons) during 3 month circulation test

3.2 CO_2 Transportation

The mass transport of CO_2 in HDR systems including river water and atmosphere was estimated (results are shown in figure 7).

Firstly, CO_2 concentration in production vapor gas was measured at 75 ppm in HDR-2 and 682 ppm in HDR-3. From this value and total vapor mass (Table 1), about .143 ton and 0.923 ton CO_2 gas mass was released to atmosphere.

In terms of fluid chemistry, the mass balance of HCO_3 conversion to CO_2 were calculated. About 6 ton CO_2 were injected via the fluid from the pond. But total dissolved CO_2 in fluids from HDR-2, HDR-3 and river water was about 5 tons. Then the pond water is estimated to absorb about 1 ton CO_2 from atmosphere.

Secondly, injected CO_2 dispersed in reservoir and to HDR-2 and HDR-3. Also, CO_2 gas in reservoir added to fluid to production well. In total, about 1.4 tons CO_2 was added from the reservoir. After fluid flow through the reservoir, 4.41 tons CO_2 reached HDR-2 and 3.02 tons CO_2 reached HDR-3 during the 3 month circulation test.

Of the CO_2 that reached HDR-2, 68% CO_2 precipitated as calcite and 3% CO_2 was discharged as gas to the atmosphere. In HDR-3, 20% CO_2 precipitated as calcite and 30% CO_2 was discharged as gas to the atmosphere.

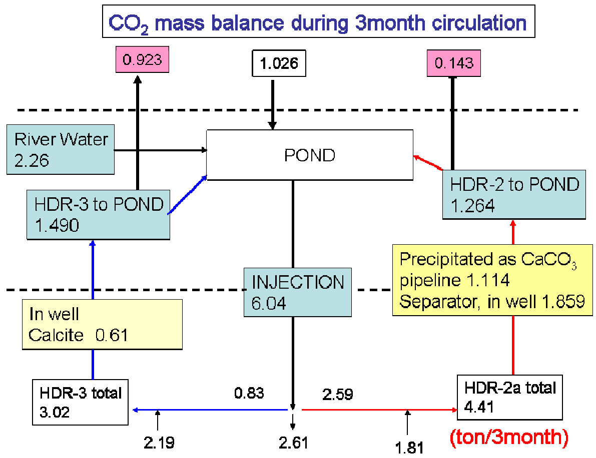

Figure 7: Carbon dioxide transportation mass balance (in tons) during 3 month circulation test

4. DISCUSSION

4.1 CO_2 Release and Calcite

In the HDR-2 line, about 2.97 tons of CO_2 precipitated as calcite that is about 20 times the mass that was released to atmosphere. This means the fluid chemistry and temperature of HDR-2 is favorable to calcite precipitation.

The equilibrium of calcite and CO_2 gas was calculated using SOLVEQ-CHILLER (Reed, 1982). The relation between temperature and pH is shown in figure 8. Before CO_2 release, pH is about 6.5 at temperatures lower than 130°C in pipelines of HDR-2. With CO_2 release, pH increased to 7.7 at temperatures of 130°C. After decreasing temperature, pH increased to 8.7, which is higher than injection waters.

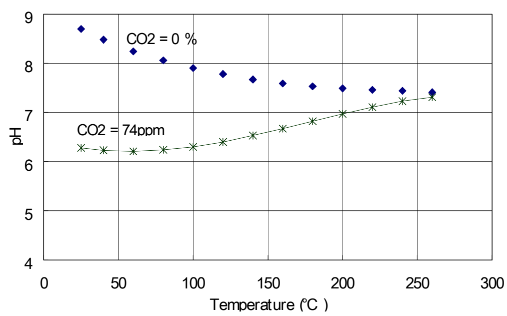

Figure 8: Change of pH profile of HDR-2 by CO_2 release

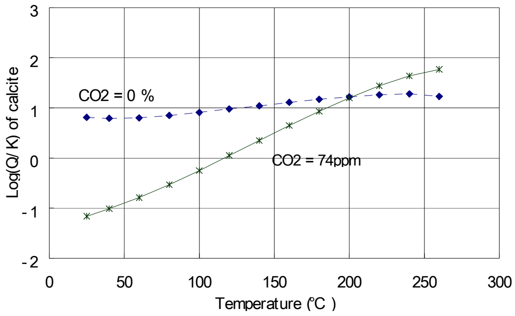

Figure 9: Change of Log (Q/K) of calcite of HDR-2 by CO_2 release

And the relation between temperature and mineral saturation states, log (Q/K), of calcite is shown in figure 9. Before CO_2 release, log (Q/K) of calcite is 0 at 120°C and almost at equilibrium between the fluid and calcite. After release of CO_2 gas, log (Q/K) increases to 1. This means about 10 times super-saturation of calcite for fluid in HDR-2 and calcite will easily precipitate.

CO_2 gas affects the log (Q/K) of calcite and pH in production well, and calcium concentration is important for calcite precipitation. In HDR-3, CO_2 gas concentration is 682 ppm, higher than that of HDR-2. In HDR-3, the pH and log (Q/K) diagram is similar to HDR-2 but calcite did not precipitate in the surface pipeline due to low calcium concentration. In HDR-3, calcite appeared in the deep well.

The log (Q/K) of calcite with dissolved CO_2 is higher than after CO_2 release at temperatures higher than 200°C. As temperatures at the deep well of HDR-3 is around 250°C, calcite precipitated before CO_2 release. This suggests that CO_2 will precipitate at high temperatures and high Ca concentrations from anhydrite dissolution.

4.2 Virtual CO_2 Injection to Hijiori HDR Site

As mentioned above, calcite precipitation in geothermal system shows the possibility of CO_2 storage in high temperature reservoirs.

In the case of the Hijiori HDR site, injection fluid has potential to dissolve CO_2 gas. We then considered the virtual CO_2 injection at Hijiori site and calculate pH and log (Q/K) of calcite with 0, 0.01, 0.1 and 1% dissolved CO_2 in the HDR-1 injection fluid.

Figure 10 shows the dependency of virtual storage CO_2 ratio to pH of HDR-1 fluid. After 0.01% CO_2 added, pH decreased from 7.7 to 6.2 at 25°C. But at about 260°C, pH remained constant at 7.5, for both concentrations of 0.01% and 0% CO_2.

Figure 11 shows log (Q/K) of calcite. In the case of the original HDR-1 fluid, log (Q/K) was greater than 0. But with 0.01% CO_2 added and log (Q/K) = 0, the temperature is about 120°C. At log (Q/K) = 0, the temperature was observed to increase with increasing CO2 concentrations. At temperatures over 200°C, log (Q/K) shows higher value with 0.01% CO_2 than original fluid. This shows the potential of CO_2 storage as calcite under 64 ppm of calcium fluid at HDR-1 and especially over 200°C 0.01% CO_2 injection is desirable for storage.

Actual river water will be used for CO_2 injection, therefore figure 12 shows log (Q/K) of calcite in the case of river water. The temperature at log (Q/K) = 0 is higher than the case of HDR-1 and at 180°C, log (Q/K) reach 0 at 0.01% CO_2 case. And at over 140°C, log (Q/K) shows higher value with 0.01% CO_2 than original fluid.

Then, from the equilibrium of calcite in the case of CO_2 injection to HDR system, 0.01% CO_2 injection is desirable for storage because log (Q/K) is higher than without CO_2 at high temperature conditions.

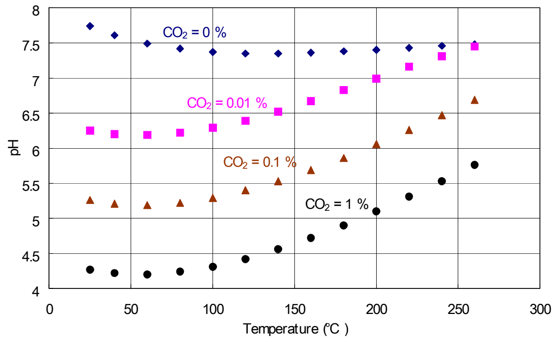

Figure 10: Temperature and virtual storage CO_2 ratio dependence of pH in the case of HDR-1

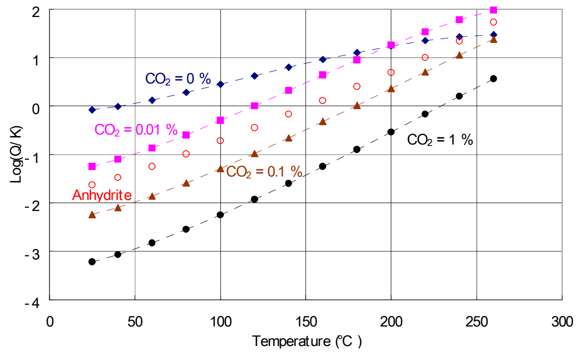

Figure 11: Temperature and virtual storage CO_2 ratio dependence of log (Q/K) in the case of HDR-1

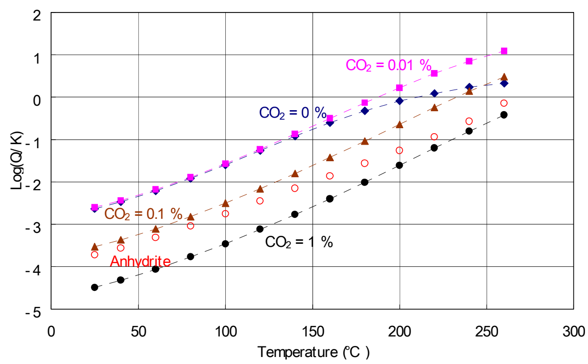

Figure 12: Temperature and virtual storage CO_2 ratio dependence of log (Q/K) in the case of river water

CONCLUSIONS

1) At the Hijiori HDR test field, anhydrite dissolution near the injection well is the primary source of calcium for calcite precipitation in pipelines. In lower temperature HDR-2, about 2.7 tons of calcium precipitated as calcite in the pipeline and well during the 3 month circulation test. In higher temperature HDR-3, about 0.6 ton calcium precipitated as calcite in the deep well.

2) The transport of CO_2 including river water and atmosphere was estimated. From river water, production well and atmosphere, a total of about 6 tons CO_2 was injected over 3 months. Of the CO_2 that reached HDR-2, about 68% CO_2 precipitated as calcite and 3% CO_2 was discharged as gas to the atmosphere. In HDR-3, about 20% CO_2 precipitated as calcite and 30% CO_2 was discharged as gas to the atmosphere.

3) Virtual CO_2 injection scenarios at the Hijiori HDR system were considered. The system has the possibility for CO_2 storage and 0.01% CO_2 injection is desirable for storage because log (Q/K) is higher than without CO_2 at high temperature conditions.

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