UTILISATION AND SEQUESTRATION OF SUPERCRITICAL CARBON DIOXIDE IN THE GEOTHERMAL FIELD

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ABSTRACT

Geothermal energy is expected as one of the renewable energies against the global warning, which we have to overcome in this century. However, the conventional geothermal development that pumps up and uses the subsurface hot water has not been much promoted because of the objection of the local residents. The Hot Dry Rock (HDR) method, which does not pump up underground hot water, was studied but suspended by economical and other reasons.

The HDR technology creates an artificial reservoir by hydraulic fracturing at the area where natural geothermal system is not or poorly developed, and pressurises water into the reservoir to extract subsurface heat. Several demerits have been pointed out such as the outflow of water from the reservoir, and the low temperature due to the bypass of injected water (Short Circuit). The induced earthquake during the hydraulic fracturing and the water circulation is another matter of concern.

Carbon dioxide (CO_2) in the supercritical condition ($ScCO_2$) has better thermal properties as the heat transport fluid than water. $ScCO_2$ inhibits the dissolution from host rocks and the sedimentation of minerals in the fractures. Large buoyancy can be expected to reduce the pumping energy. Also, $ScCO_2$ can penetrate into narrow micro-cracks due to its small viscosity. An output of about 1.5 times that of water can be expected with use of $ScCO_2$ as a working fluid.

$ScCO_2$ that migrates from the flow path would be expected to be sequestered and fixed as carbonate minerals in HDR. In addition, the formation of the Short Circuit and the scale production might be overcome by controlling CO_2. The induced earthquakes at the reservoir creation can be also suppressed by using CO_2 as a fracturing fluid. There are many advantages in use of CO_2 but are also many subjects to be solved. We will progress a new geothermal research program using CO_2. In this paper, subjects on the use of CO_2 in the geothermal field and the processes to the implementation will be discussed.

1. INTRODUCTION

The 21st century is believed to be the era of the environment. The world before the 20th century consumed a lot of fossil fuels after the Industrial Revolution, and the temperature in the polar regions increased due to CO_2, a major component of the Green House Gases (GHGs), emitted along with it, resulting in the melting of snow and ice, and the rise of sea level, which affected the atmospheric condition of the entire earth. The era of the environment is due to the reflection that we have fallen into a situation where CO_2 emissions affect the entire earth.

It is clear that limiting the use of fossil fuels that emit CO_2 into the atmosphere the most effective against the global warming. In order to sustain sustainable development and economic activity, it is also necessary to use fossil fuels by reducing CO_2 emissions into the air and/or transform energy supply structures that rely on fossil fuels.

As a technology that uses fossil fuels while suppressing CO_2 emissions into the atmosphere, CO_2 is separated from other gases while burning. And it will be transferred and sequestered into the underground. The technology is called CCS (Carbon Capture and Storage). In Japan, a demonstration test plant was conducted for three and a half years, and ended in November 2019, in which CO_2 of 100,000 tons per year separated from an oil refining plant was injected and stored in a saline, coastal aquifer off the Tomakomai, Hokkaido (JapanCCS, 2020).

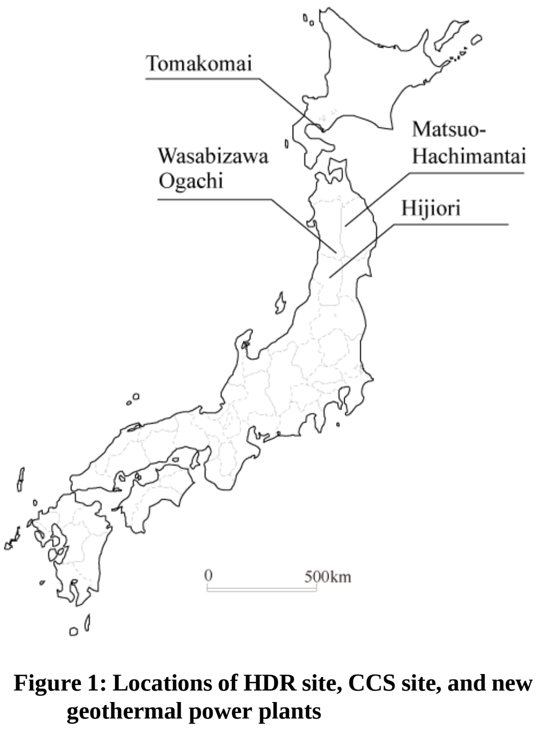

Figure 1: Locations of HDR site, CCS site, and new geothermal power plants

On the other hand, there are renewable energies such as geothermal resources, which does not depend on fossil fuels. The Wasabizawa geothermal power plant (the approval and authorised certificate output of 46,199 kW) in Yuzawa City, Akita Prefecture, started operation in May 2019, which is a large-scale geothermal power plant with a capacity of 10,000 kW or more in twenty-three years in Japan. In January 2019, the Matsuo-Hachimantai power plant (the output of 7,499 kW) started operation in Hachimantai City, Iwate Prefecture. As of May 2019, the power generation scale is 24 units at 21 locations with the output is 543,813kW.

The small-scale power generation with an output of 1,000 kW or less was recorded as 47 units of 7,135 kW at 46 locations as of March 2019 (Thermal and Nuclear Power Engineering Society, 2019). The total geothermal power output of Japan is about 550 MW and is ranked 9th in the world (Huttrer, 2020).

Efforts to reduce GHGs at the atmosphere have begun since the 1990s. The international conference on global environment (United Nations Conference on Environment and Development, UNCED) organised by the United Nations in 1992 in Rio de Janeiro, Brazil is also called "Earth Summit", where the United Nations Framework Convention on Climate Change (UNFCCC) was signed against the global warming with the participation of 172 countries.

Under the UNFCCC, the Kyoto Protocol was proposed at the Third Conference of Parties (COP3, 160 countries and NGOs, etc.) held in Kyoto in 1997. This protocol is an international agreement for the prevention of the global warming, and set specific reduction target of GHGs for each country. The effectiveness was, however, questioned because developing countries (including China and India) were not obliged to reduce the emissions and the United States left on the way. For this reason and the commitment period of the treaty ended in 2020, a new framework agreement was adopted at COP21 in 2015 at Paris, France, with the participation of all 196 countries of UNFCCC. The new agreement is called the Paris Agreement. By 2030, Japan will reduce its greenhouse gas emissions by 26% compared to that in 2013 (Fig. 2). We need to promote CCS projects and geothermal energy use to reduce atmospheric CO_2 emissions.

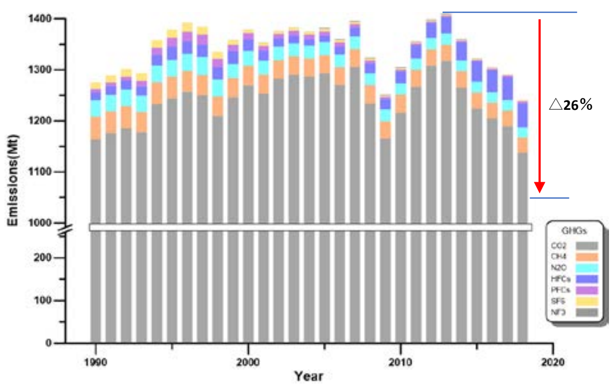

Figure 2: GHGs emissions by year in Japan.

2. HISTORY OF HDR PROJECT

Research on HDR power generation technology started in 1971 at the Los Alamos National Laboratory in the United States, and continued until 1995 (NEDO, 2002). At that time, Wairakei geothermal power plant commenced to operation of the power generation in 1958 as the second geothermal power plant in the world and other power plants started commercial electricity generation in the United States and Japan. Such novel ideas have already been proposed in the dawn of geothermal power generation in the world.

After drilling two wells (GT-2: 2,932m, EE-1: 3,064m), major vertical fractures and small fractures with various directions were created in a full-scale field test at Fenton Hill, New Mexico. In order to improve the continuity between wells, GT-2 was re-drilled twice and hydrofracturing were performed using EE-1. Heat output of 2~5MWt was achieved in 288 days, the 60kW binary generator was intermittently operated for several weeks at the rated capacity. In the United States, HDR technology attracted attention for its enormous amount of resources, triggered by the oil crisis of the 1970s, and international joint research and development program was started in Europe, Japan and the United States.

A research on HDR began in 1975 in Japan, and a small-scale field experiment was conducted in the Yakedake area of Gifu prefecture. From 1986 to 2002, the research was carried out in the Hijiori area of Yamagata prefecture. Research and development were promoted for the purpose of developing elemental technology for creation. In parallel with this research and development at Hijiori, experiments were carried out at Ogachi, as well as participation in full-scale field experiments at Fenton Hill, New Mexico, and experiments at Soults, France, to create a reservoir by hydraulic fracturing, AE Efforts were made to acquire new technologies such as grasping reservoirs and evaluating reservoirs.

Since Fenton Hill was the only study site at the beginning of the research, the target of the development was a rock type that has few cracks and is uniformly filled with minerals such as granitic rocks. However, homogeneous rock bodies do not exist in the crustal deformation area such as Japan, and existing cracks have already developed. Figure 3 shows the characteristics of HDR around the world classified by the reservoir temperature and the distance between the injection well and the production well (Niitsuma, 2004).

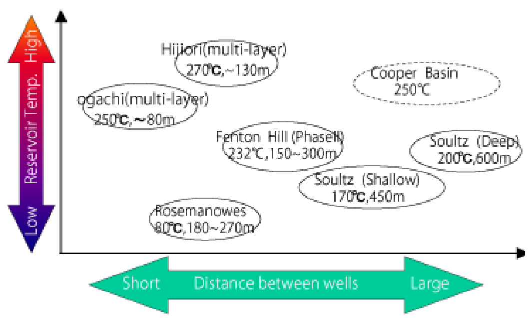

Figure 3: Reservoir temperatures and well distances for HDR sites

HDR projects were discontinued due to several reasons except that in Soults in France, which began the commercial operation in 2008 with an output of 1.5MW binary cycle power generation. The HDR project in the US ended in 1995 and moved to a more conceptual EGS technology. In Japan, R&D was completed in 2002 against the backdrop of budget cuts for geothermal technology development.

3. HDR WITH CO_2 AS WORKING FLUID

The HDR project in the US ended in 1995 and moved to a more conceptual EGS technology. Brown (2000) proposed the idea of using ScCO2 as the working fluid in HDR just five years after the end of the experiment at Fenton Hill. The advantages of using $ScCO_2$ are listed below.

1. The large density difference of $ScCO_2$ between low and high temperatures would make a large buoyancy force. This buoyance allows the circulation of fluid without a pump which has to be surprised and save the electrical power used in a power plant.

2. Minerals that generate scale are not dissolved and transported result in the avoid of scale problem for wells and ground facilities such as a heat exchanger.

3. The high temperature of the HDR reservoir ranging exceeding the critical temperature of water (374℃) can be developed without problems such as scale.

It is also pointed out that the smaller mass heat capacity of $ScCO_2$ should be one of disadvantages of the CO_2 HDR as the CO_2 mass would be necessary more than water. However, the viscosity of $ScCO_2$ is only 40% that of water and $ScCO_2$ may be able to penetrate even into small cracks of the host rock. The normalised flow rate (density/viscosity) was estimated to be 0.72 for water and 1.10 for $ScCO_2$ at the temperature of 260℃ and the depth of 4km, implying that the HDR system using $ScCO_2$ as flow fluid would be 1.53 times more efficient (Brown, 2000).

Generally, it should take a long period of time for CO_2 to become a mineral and be fixed. However, Matter et al. (2016) demonstrated CO_2 will be fixed at a temperature of 20-50°C within 2 years in the field experience. CO_2 mineral storage, which CO_2 combines with Ca^{++} or Mg^{++} cations and converted into $CaCO_3$ (calcite) or $MgCO_3$ (dolomite) and is permanently confined in the subsurface layer as a mineral, is being developed. This mineral fixation technology can be applied to geological formations that have not previously been considered as a feasible geological storage.

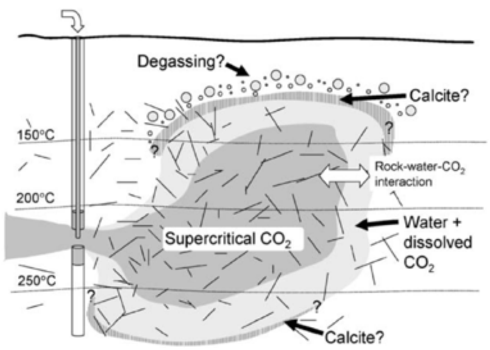

Figure 4: conceptual model for mineral carbonation at HDR area after Ueda (2009)

Since the chemical reaction will be accelerated when the temperature rises, CO_2 mineral storage is expected to apply it in the geothermal field, where volcanic rock to be rich to positive ions. Ueda (2009) observed the growth of minerals at high temperature by observing the growth of minerals by putting solid CO_2s (dry ices) into the well at the Ogachi HDR experiment site. In HDR that uses water as the working fluid, it was necessary to take care of the leaked water, but in HDR using CO_2 as the working fluid, non-circulating CO_2 may be fixed as minerals.

CO_2 is expected to mix with water and separate into H^+ ions and $CO3^-$ ions around the injection well. Then, the mineral carbonation will not occur but dissolution will take place. The water content in HDR will decrease by increasing the distance from the injection well, where CO_2 is expected to become calcite and dolomite. These minerals prevent CO_2 from escaping and leaking. CO_2 mineral carbonations contribute to the soundness of the geothermal reservoir.

4.DISCUSSIONS

Global warming is one of the biggest issues to be solved in the 21st century, and the development and the use of geothermal energy, which emits less CO_2, is expected. However, conventional geothermal development that uses hot water in the subsurface has not been much promoted in Japan, as the consent of the local residents may not be obtained. For this reason, the HDR method, which does not pump up underground hot water, is being studied. Several papers have been published on geothermal systems using CO_2, and all of them focus on the physical and chemical characteristics of $ScCO_2$ (eg. Gupta and Vashistha, 2016; Esteves et al., 2019).

At least two wells are required in the HDR power generation, and an artificial reservoir for heat extraction is formed between them by hydraulic fracturing technology. Rocks with many existing cracks have to be used instead of uniform rocks without cracks in Japan. it is desirable to create an artificial reservoir for the HDR system by the following procedure (Niitsuma, 2004, Fig. 5).

1. Drilling of injection well

2. Implementation of hydraulic fracturing and observation of micro-earthquakes showing fractures

3.Estimation of the direction and the size of the artificial reservoir based on the micro-earthquake observation and drilling of production wells to the estimated reservoir

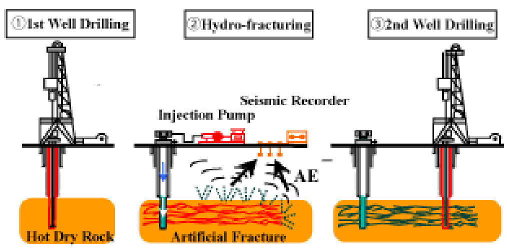

Figure 5: procedures to create HDR reservoir after Niitsuma (2004)

The HDR system will be developed in the procedures mentioned above. After the creation of the artificial reservoirs and wells, water or CO_2 will be injected into the injection well to generate hot steam or CO_2 from the production well, and power generation is performed. If the artificial reservoir is detected to many directions, multiple production wells in a radial pattern centred on the injection well will be expected to increase the recovery rate.

We will start the HDR technology development using CO_2 as the circulation fluid from the next fiscal year. For the first 5 years, we will try to understand the basic physical properties and examine how CO_2 remains in the geothermal reservoir and can be reused again. In addition, we will confirm the condition of the CO_2 mineral storage around the geothermal reservoir (CCS).

If reuse of CO_2 is feasible in the reservoir, we will start to design of the CO_2 HDR where CO_2 will be extracted and used for power generation in the next phase (CCUS). The closed circuit using an existing well will also be examined in the next phase.

The following themes will be set up and research will be conducted on basic issues for the first five years.

- Understanding CO_2 fluid behaviour at high temperature

- Understanding CO_2 mineral carbonation characteristics

We will also promote technological development for hydrofracturing technology using CO_2 (Jian et al., 2020).

- CO_2 utilization rock crushing technology

This technology is a method that uses CO_2 in the formation of an artificial reservoir in HDR, and there is a possibility that the size of an earthquake during fracturing will be reduced by using highly incompressible CO_2 because smaller increase of the pore pressure will be expected (Fig. 6).

For practical HDR technology using CO_2, it is necessary to examine the ground facilities such as turbines, but since this technical development is planned to be carried out by NEDO (New Energy and Industrial Technology Development Organization, a governmental enterprise), we will incorporate those results and proceed with the project. After accumulating basic knowledge for 5 years, it will be also necessary to examine the circulation method such as an open circulation method like HDR or a closed method like a DCHE (Double Coaxial Heat Exchange) system. The system using closed circulation has been established in US and several experiments are being conducted (Amaya et al.,2020).

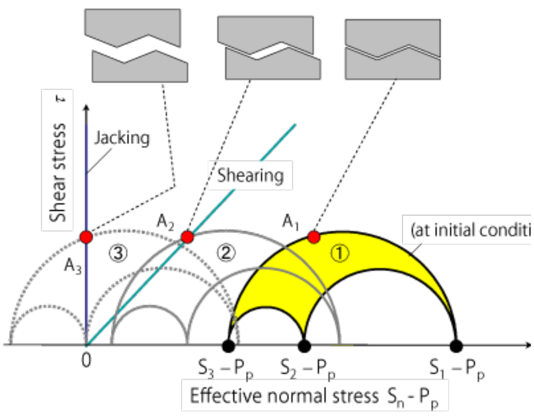

Figure 6: mechanism of the earthquake by the hydrofracturing after Niitsuma (2004) When the pore pressure (Pp) increases, Mohr circle will shift leftward (from stage1 to stage 2). Smaller pore pressure rise will expect to make smaller dislocation causing the smaller magnitude of the earthquake. Water will make a bigger pore pressure than ScCO₂.

With the closed method, it is possible to circulate by controlling the temperature and pressure of CO_2, but the extraction heat may not be sufficient to sustain economic power generation using DCHE. On the other hand, it also has the advantage of heat extraction from existing wells without the need for well drilling.

Schedule		Select suitable site for			
	(1)Establishment of basic technology 2021～2025FY		(2)Consideration for practical application 2026-2035FY		(3)Examination of social implementation 2036-2045FY
1.Understanding CO_2 fluid behaviour at high temperature	Understanding of technology based on literature research, behavior analysis experiment in laboratory, development and behavior analysis of behavior analysis simulator, examination of surrounding monitoring method, selection of area for implementation of verification test	Consideration of development and implementation toward commercialization of carbon recycle CO_2 geothermal power generation technology based on	Technical understanding from the laboratory level for practical application study based on the optimum experimental location	Carbon recycling CO_2 geothermal power generation	Construction of demonstration plants at multiple locations with different geological conditions
2.Understanding CO2 mineral carbonation characteristics	Literature research, laboratory experiments for mineral fixation, establishment of monitoring methods, grasp of technology based on field verification tests				
3.CO2 utilization rock crushing technology	Literature research, laboratory crushing experiments, examination of monitoring methods, understanding of technology based on field verification tests				

Table 1: schedule for the project

4.CONCLUSION

As for the method of using CO_2 as the working fluid of HDR, various ideas with a closed circuit and an open circuit have been proposed. Also, CO_2 is used during the hydro-fracturing for creating an artificial reservoir in the geothermal system. When the open circuit is adopted, the created reservoir would be used as a heat exchange surface for CO_2, and it can also be used for storage and isolation as the CCS technology. The CO_2 storage and sequestration will take place in the marginal area of the created reservoir, and the retained CO_2 will be mineralized. On the other hand, CO_2 in the central part of the reservoir is not mineralized but maintains fluidity, and heat is obtained at the heat exchange surface. CO_2 reaches at a high temperature state. CO_2 in high temperature can be enough to rotate a turbine to generate electricity. One of the big problems in the hydraulic geothermal system such as scale will be ameliorated.

We are planning a new research project using CO_2 in the geothermal field starting from 2021FY. There are many unknown fields such as CO_2 behaviour under high temperature and mineral fixation, and we are actively seeking cooperation with overseas countries. We would be happy if the geothermal and CCS study groups in NZ could join us.

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