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Overview of the First 5-years Study of the EGS Technology Development Using $ScCO_2$

Amane TERAI*, Toshiyuki TOSHA*, Takuya TERAOKA*, Shoko WATANABE*, Taro KABASHIMA*, Kenji OSAWA* and Norihito INADA*

JOGMEC(Japan Organization for Metals and Energy Security)*

terai-amane@jogmec.go.jp

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ABSTRACT

JOGMEC has been conducting a research project of EGS technology development using supercritical carbon dioxide ($ScCO_2$) from 2021 as an innovative geothermal power generation technology toward the goal of 2050 carbon neutral in Japan. This project aims to develop technology to generate electricity using $ScCO_2$ as a heat transfer medium instead of water in areas where a mature hydrothermal system does not exist, including creating an artificial heat exchange layer in a high-temperature area by CO_2 fracturing. The idea of using $ScCO_2$ for EGS has been announced since around 2000s (e.g. Brown, 2000; Pruess, 2009) and the previous research show the possibility of $ScCO_2$ to be a better heat transfer medium than water. However, the chemical properties of CO_2 were not fully taken into the flow simulation and there is less paper about the experiment and the simulation about mineralization and fracturing using CO_2 under the condition of high temperature and high pressure.

For the first five years (2021-2025), we have been trying to understand the underlying technology of three themes by laboratory experiment, small size field experiment and simulation. The three themes are; 1. Overall system design for CO_2 geothermal power generation, 2. Artificial geothermal reservoir formation technology using $ScCO_2$ as the fracturing fluid, 3. Technology for understanding CO_2 fluid behavior in geothermal reservoirs.

In this paper, we describe the major achievements gained through the basic study over first 5-years.

1 INTRODUCTION

To achieve Japan's 2030 energy mix and 2050 carbon neutrality goals, further promotion of geothermal power is essential. Conventional geothermal power relies on natural hydrothermal systems, but many high-temperature areas lack such systems, so that innovative geothermal power generation technologies that do not rely on natural hydrothermal systems are needed. To address this, JOGMEC (Japan Organization for Metals and Energy Security) launched a project in 2021 to develop Enhanced Geothermal Systems (EGS) using supercritical carbon dioxide ($ScCO_2$) as a heat transfer and fracturing fluid. This project has developed technology to generate electricity using $ScCO_2$ as a heat transfer medium instead of water in areas where a mature hydrothermal system does not exist, assuming volcanic geological settings (Figure1).

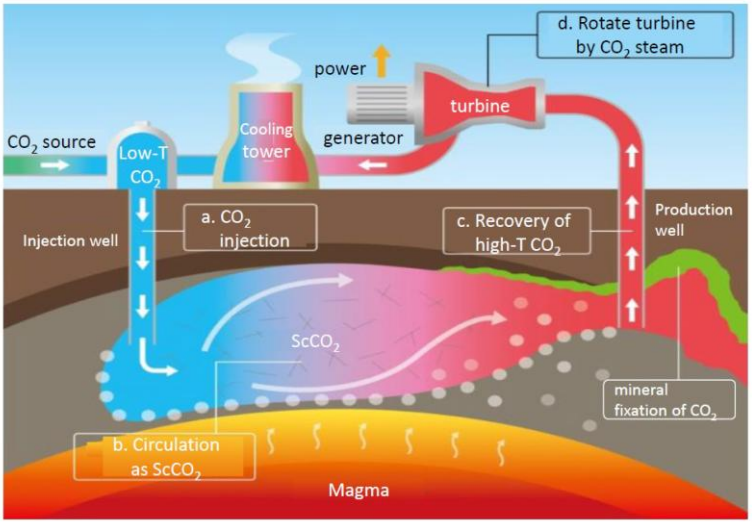


Figure 1. Concept of the project (circulation of $ScCO_2$ in the artificial reservoir and generate electricity)

The concept of using $ScCO_2$ in Hot Dry Rock (HDR) systems have been announced around 2000s (e.g. Brown, 2000; Pruess, 2009). While CO_2's thermophysical properties are favorable for power generation, its chemical reactivity is also significant. CO_2 can form acidic fluids underground, dissolving rocks and leading to carbonate mineralization, a process that can trap CO_2. Though it would take more than 100 years for CO_2 to be trapped in carbonate minerals, in Iceland, it was observed that 95 % of CO_2 mineralized within 2 years after injection (Matter et al., 2016), suggesting faster trapping in high-temperature geothermal zones especially at the mafic geological settings.

CO_2 has the following characteristics: supercritical under geothermal conditions, having high density and low viscosity as $ScCO_2$, and is interactable with rocks which should result in mineral fixation underground to create a "mineral cap". Therefore, the following advantages of $ScCO_2$ are expected: creation of complex, three-dimensional fracture networks, reduction of induced seismicity during fracturing, improved fluid return rate due to mineral fixation, and improved heat recovery. The project is structured in three phases:

- Phase 1 (2021–2025): Focuses on foundational technologies across three themes.
- Phase 2 (2025–2035): Field demonstration based on Phase 1 outcomes.
- Phase 3 (Post-2035): Technology transfer to the private sector via pilot plant construction and operation.

The three themes at Phase 1 are; 1.Overall system design for CO_2 geothermal power generation, 2.Artificial geothermal reservoir formation technology using $ScCO_2$ as the fracturing fluid, 3.Technology for understanding CO_2 fluid behavior in geothermal reservoirs. We first create artificial reservoir using $ScCO_2$ underground (Theme2), then inject $ScCO_2$ as a heat transfer medium and circulate (Theme 3), then finally generate electricity and $ScCO_2$ is recycled to injection well and to the reservoir(Theme1). Our main goal is to generate electricity such as tens of MW, not a small size generation, since it should be economically achievable despite it is predicted to be a costly technology. As a side effect, it can capture CO_2 underground both by physical trapping and mineral trapping and work as CCUS. If the mineral trapping occur like artificial cap-rock "around" the reservoir, the circulation could occur like semi-closed loop system and the fluid return rate would be improved. However, it is necessary to be careful that we don't intend to mineralize all of the reservoir since it would be just CCS not CCUS. At phase 1(2021-2025), JOGMEC contracted GERD and Taisei Corporation and there are several sub-contractors behind them (Figure 2). We have advanced the project with them.

The following sections will be described in the order of these progress assumption, which are theme2, 3 and 1.

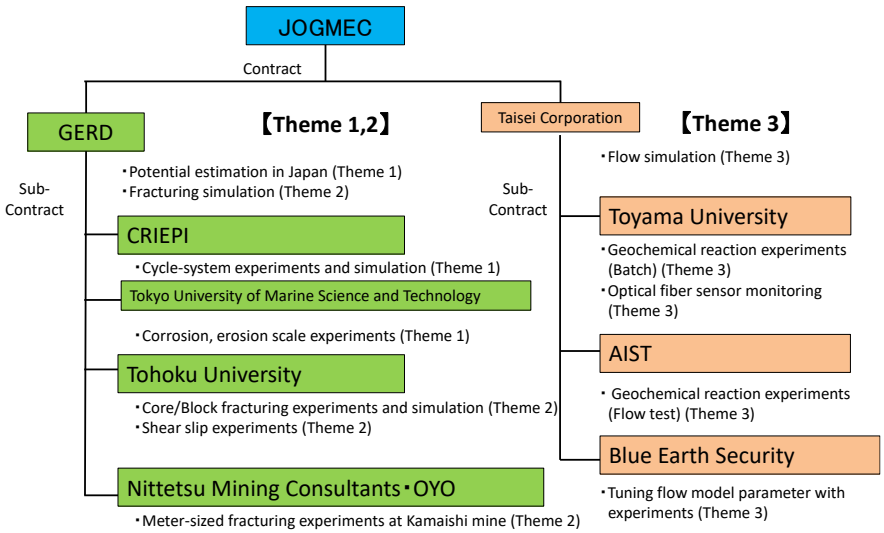


Figure 2. Substructure of the First 5-years project

2 THEME 2. ARTIFICIAL GEOTHERMAL RESERVOIR FORMATION TECHNOLOGY USING $SCCO_2$ AS THE FRACTURING FLUID

Theme II of this study aims to develop technologies for creating of artificial geothermal reservoirs using $ScCO_2$ as a fracturing fluid. The low viscosity of $ScCO_2$ facilitates its penetration into microfractures, thereby enabling more refined and complex fracturing. Laboratory-scale experiments are conducted to examine the fracturing behavior of volcanic rock under geothermal conditions, characterized by high temperature and pressure. These

experiments include comparative analyses with conventional hydraulic fracturing methods to evaluate the complexity of fracture and induced seismicity reduction effect by $ScCO_2$. A simulator capable of reproducing laboratory-scale fracturing experiments is developed and subsequently scaled up to enable meter-scale fracturing simulations for small-scale field testing. Subsequently, small-scale field tests are performed at a test site to validate the feasibility of $ScCO_2$ based reservoir creation (in the field experiment, nitrogen gas was used). During these trials, acoustic emissions and strain responses are continuously monitored to assess fracture propagation and reservoir development. To prepare for future large-scale field applications, operational guidelines are formulated to mitigate potential risks such as CO_2 leakage and induced seismicity. The detailed work item for Theme II is presented in Figure 3.

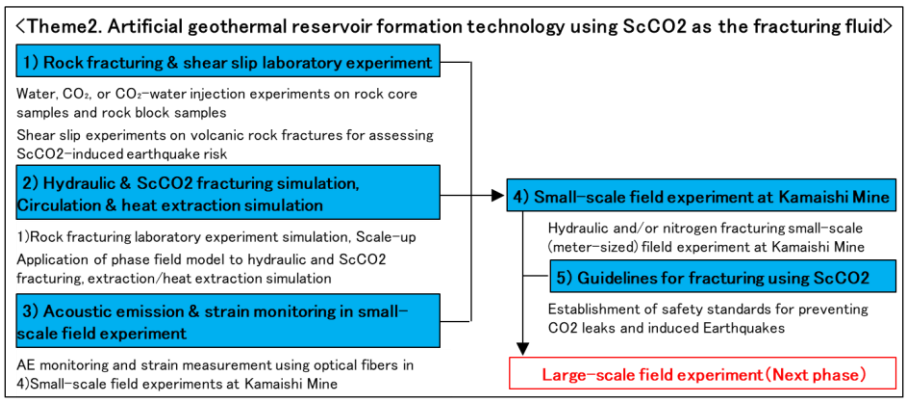


Figure 3. Work item in theme 2

Representative results in theme 2 will be presented in 2.1 and 2.2.

2.1 Rock fracturing experiment

To clarify the difference between fracturing with water and $ScCO_2$ as a fracturing fluid, the fracturing fluid is injected into a cylindrical rock sample (diameter 30 mm, length 25 mm) under confining pressure (30 MPa), axial pressure (100 Ma), and temperature (250°C). The changes in injection pressure and the occurrence of AE were observed (Takuma et al., 2024).

Table 1: Mechanical and hydraulic properties of Honkomatsu andesite

Porosity (%)	5
Permeability (m^2)	$1\sim4 \times 10^{-18}$
Tensile strength (MPa)	10
Uniaxial compressive strength (MPa)	242
Young's modulus (GPa)	26
Poisson's ratio	0.3
Cohesion (MPa)	40
Internal friction angle (degree)	58

The experiment was conducted by shaping samples from substitute volcanic rocks such as basalt and andesite. Here, we will describe an experiment using Honkomatsu Andesite, which is a pyroxene andesite flowed during the eruption of Hakone Volcano. The physical properties of the andesite are shown in Table 1. A small diameter hole was created at the centre of the sample to a depth of about half of the sample, and fluid was injected into the hole. The sample is covered with a gasket to prevent the leak of the pressure (Figure 4). The injection pressure and the AE were observed.

When water was injected and the injection pressure reached to about 60 MPa, the AE energy suddenly increased, and the fracture of the rock sample occurred. The surface of the core sample was identified using X-ray CT images after the experiment. The core, which was X-rayed after the water injection experiment, suggests that the fracture progressed in nearly one direction shown in Figure 5.

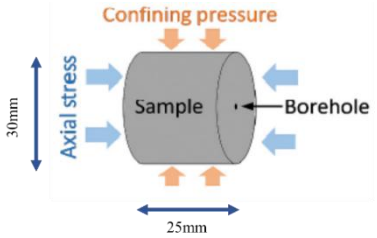


Figure 4: A rock sample for the fracturing experiment

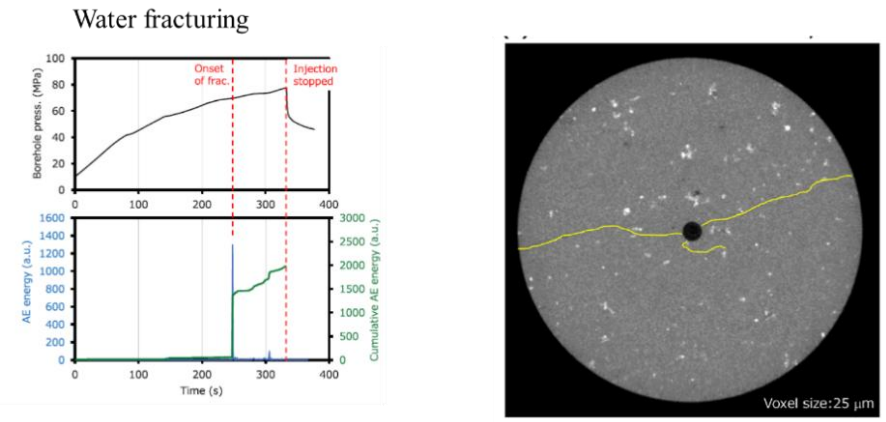


Figure 5: Changes in borehole pressure (upper left figure) and AE energy (lower left figure) with time in the water fracturing experiments and core X-ray CT image after the experiment (right figure)

In the other hand, when $ScCO_2$ is injected, AE begins to be generated when the injection pressure becomes to be about 40 MPa, suggesting that the fractures occur near this pressure. Core X-ray CT images taken after this experiment showed the fractures were spreading in multiple directions with small sizes. Many and fine fracture surfaces are generated by using $ScCO_2$ as a fracturing fluid, and this may be due to the low viscosity coefficient of $ScCO_2$ shown in Figure 6.

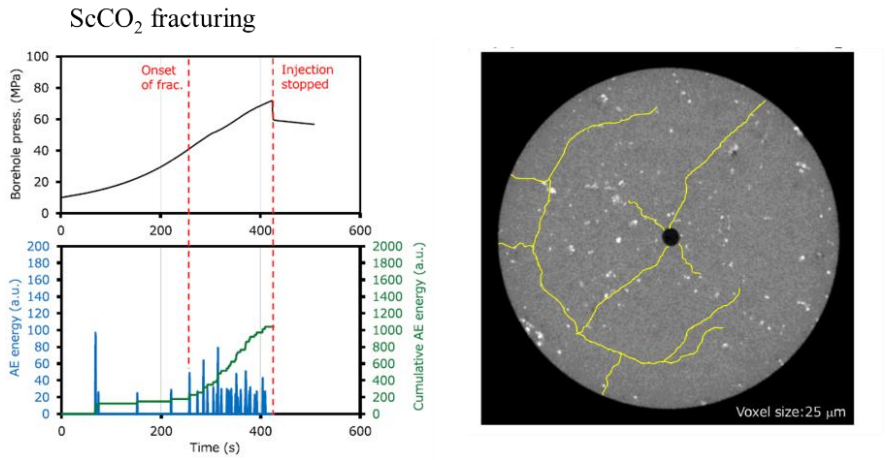


Figure 6: Changes in borehole pressure (upper left figure) and AE energy (lower left figure) with time in the $ScCO_2$ fracturing experiments and core X-ray CT image after the experiment (right figure)

Moreover, when $ScCO_2$-water is injected, AE begins to be generated when the injection pressure becomes to be about 20-40 MPa, suggesting that the fractures occur near this pressure. The rate of increase in the cumulative AE energy did not accelerate beyond the 240 sec when water reached the borehole. This finding, consistent with expectations from CO_2 hydraulic fracturing experiments, suggests that CO_2 primarily formed fractures, which water then opened and propagated. Core X-ray CT images taken after this experiment showed the fractures were complicated pattern shown in Figure 7.

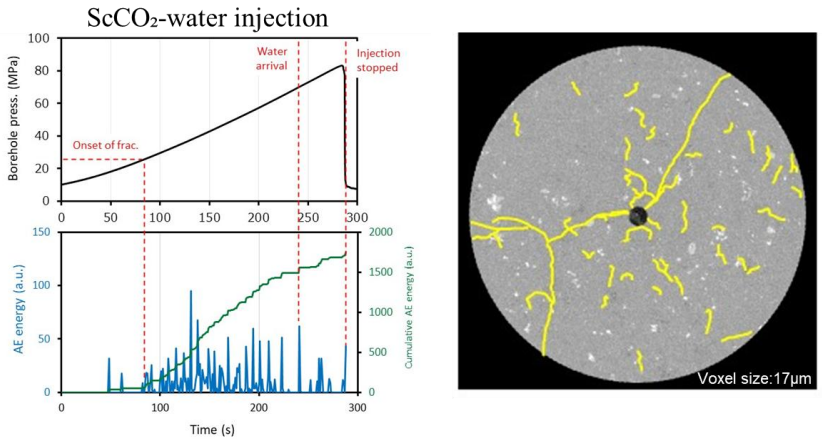


Figure 7: Changes in borehole pressure (upper left figure) and AE energy (lower left figure) with time in the $ScCO_2$-water fracturing experiments and core X-ray CT image after the experiment (right figure)

AE was also generated in experiments using $ScCO_2$ and $ScCO_2$-water as the fracturing fluid, but the AE energy was quite low. The energy released during fracturing will be small and dispersed. Earthquakes induced during fracture are one of the factors restraining the development of EGS technology. The use of $ScCO_2$ and $ScCO_2$-water as a fracturing fluid can reduce the risk of induced earthquakes during the creation of artificial reservoirs. Reducing the possibility of induced earthquakes will greatly contribute to the future development of EGS technology.

2.2 Hydraulic & $ScCO_2$ fracturing simulation

Due to the limitations of laboratory experiments in replicating fracturing pattern on a field scale, numerical simulations are necessary for scale-up. A two-dimensional simulator that can model fracture patterns within two-dimensional cross-sections of 30 mm-scale rock cores was previously developed (Takuma et al., 2024). This simulator successfully reproduced the characteristic fracture patterns observed in laboratory experiments conducted on cylindrical volcanic rock samples (30 mm in diameter and 25 mm in length) under axial and isotropic confining pressures, with water, CO_2, or CO_2-water injection. Although the validity of the simulator has been confirmed for core-scale fracture behaviors under isotropic confining conditions, its applicability to larger-scale fracture processes under anisotropic stress fields—such as those encountered in actual subsurface environments—remains unverified. Therefore, the next step involves establishing a simulator capable of modeling fracture experiments under true triaxial stress conditions at sub-meter scales, bridging the gap between core-scale and field-scale.

A three-dimensional fracture simulator equipped with parallel computing capabilities sufficient for numerical analysis of fracture experiments using large-scale samples under true triaxial stress conditions has been successfully developed. Utilizing this simulator, a three-dimensional numerical simulation was conducted to replicate a CO_2-water injection-induced fracturing experiment performed on a saturated cubic sample (10 cm per side) of Emochi andesite under true triaxial stress. The simulation results demonstrated that the simulator could reproduce key fracture characteristics observed in the experiment, such as reductions in fracture pressure and the pattern of generated fractures (Figure 8). These findings validate the applicability of the simulator to sub-meter scale fracture processes under true triaxial stress conditions, bridging the gap between core-scale and field-scale.

Moreover, it is necessary to implement the developed three-dimensional fracture simulator on high-performance computing platforms, such as supercomputers, to enable further scale-up to meter-scale simulations. This will facilitate the reproduction of field-scale fracture experiments and allow for predictive analyses aimed at geothermal reservoir development in actual geothermal fields.

2.3 Efficient heat exchange by complex fractures

Many complex fractures created by $ScCO_2$ are useful for preventing short-circuiting, where $ScCO_2$ flows along the shortest path between injection and production wells. In other words, by circulating $ScCO_2$ through various pathways, high heat exchange efficiency is maintained, preventing the reservoir from cooling and enabling long-term power generation.

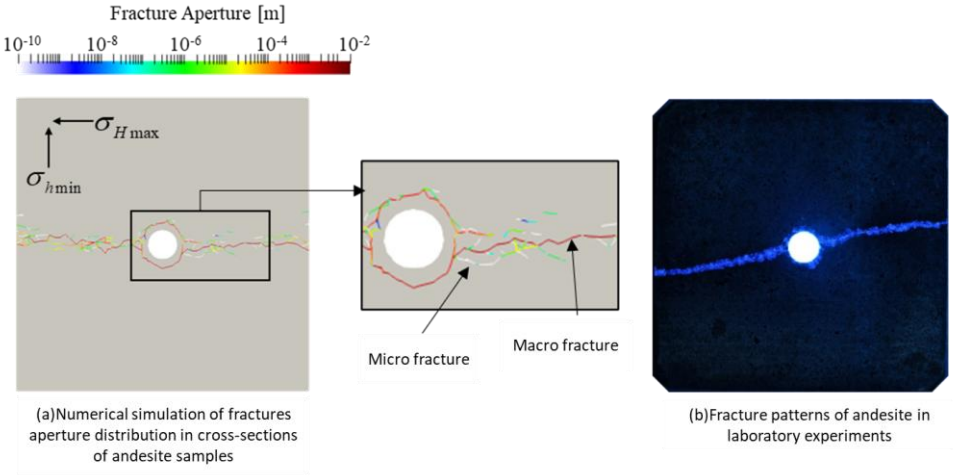


Figure 8: Comparison of fracture patterns in andesite sample

3 THEME 3. TECHNOLOGY FOR UNDERSTANDING CO_2 FLUID BEHAVIOR IN GEOTHERMAL RESERVOIRS

To understand the behavior of CO_2 as the working fluid in carbon-recycled CO_2 geothermal power generation, we first conducted laboratory tests using volcanic rock particles and cores, then we compiled those basic data on the reaction between $ScCO_2$ and the volcanic rocks in the geothermal reservoir. $ScCO_2$ will be to maintain an acidic state dissolved in brine near the injection well, but it is assumed to mineralize and deposit in formations by binding to cations in the volcanic rock when it becomes weakly acidic and be cool down at the reservoir periphery. This mineralization is expected as an impermeable barrier and cap rock around the reservoir, potentially forming an artificial reservoir with low leakage. However, depending on the conditions, there is a risk to mineralize in the reservoir and block the fracture network. Therefore, those basic data from these laboratory tests are extremely important for carbon-recycled CO_2 geothermal power generation.

Also, we conducted thermal - hydraulic simulations using $ScCO_2$, considering the chemical reactions resulting from these tests, to examine the heat extraction capacity. Here, we considered methods to appropriately incorporate the distribution and shape of the fracture network which would be created by the method considered in Theme II into the simulations. We also developed a monitoring system capable of detecting $ScCO_2$ and the scale produced by $ScCO_2$, which is considered necessary for laboratory tests and field tests.

Through these efforts, we attempted to develop the technology to understand the behavior of CO_2 fluids in reservoirs in carbon recycled CO_2 geothermal power generation.

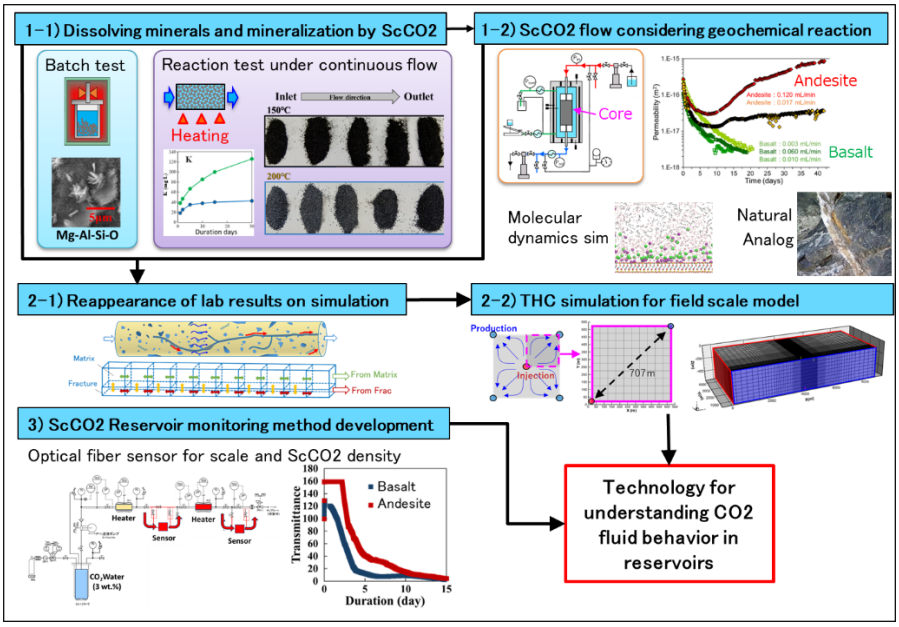


Figure 9. Work item in theme 3 with examples of the results

3.1 Laboratory tests on the behavior and mineralization of $ScCO_2$ at high temperature

3.1.1 Study of dissolving minerals and mineralization by $ScCO_2$

We conducted batch-type rock reaction tests using rock particles such as cuttings and $ScCO_2$. Additionally, we made a new experimental facility in which $ScCO_2$ passed through rock particles and we conducted continuous tests with it to know the temporal change of amount of dissolved minerals. We identified smectites deposited as a secondary mineral, and we are organizing about those reaction conditions such as temperature and so on.

3.1.2 Study on $ScCO_2$ flow considering chemical reaction

Here, we conducted some tests to flow $ScCO_2$ in core samples and recorded the permeability changes in each condition such as flow rate, temperature and rock type. We found that the basalt core showed a tendency to decrease the permeability over time in this test. On the other hand, the andesite core showed a similar decrease in permeability as the basalt core until the fifth day of this test, but it showed a tendency to increase in permeability after the fifth day. By microscopic and CT observations, we found that secondary minerals in the andesite did not completely block the fractures, but rather $ScCO_2$ made new passes and connected near pores.

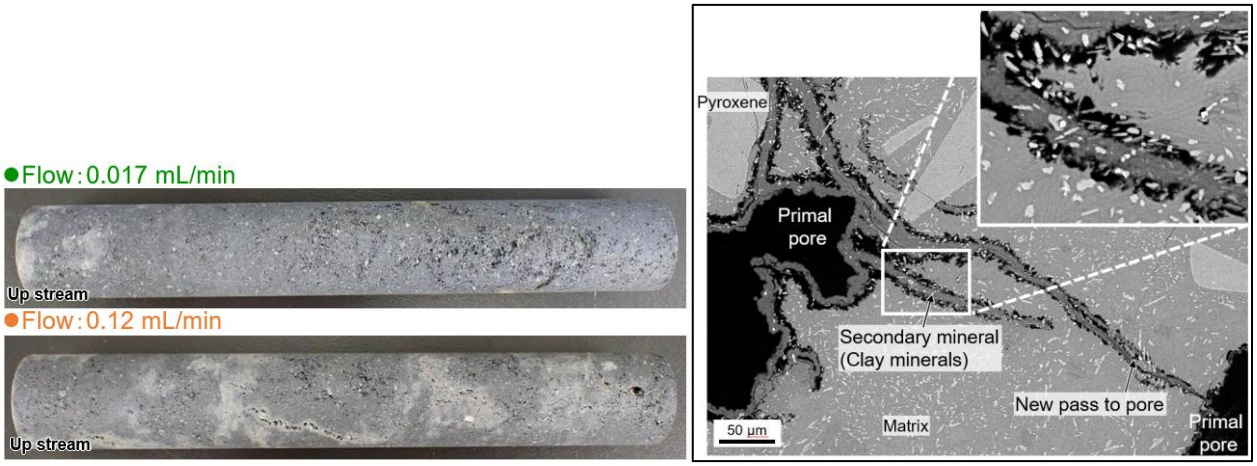


Figure 10. The andesite core after flow test with $ScCO_2$ and a microscopic picture of it

On the other hand, we thought to need to evaluate the influence on the CO_2 behavior in fractures by differences in interfacial physical properties. We conducted the calculation on the molecular dynamics of the CO_2-water-rock system for minerals and secondary minerals contained in each lithology of andesite, basalt, granite and so on as the parameters are temperature, pressure and salinity.

Furthermore, we could not laboratory tests for long term as a few years, so we researched the natural analogues and considered the parameters of flow-reaction simulation to improve the accuracy. We sampled from hot springs and mine tunnels where carbonate minerals deposited and compared those with the test results at the laboratory.

3.2 Thermal - Hydraulic simulation using $ScCO_2$ taking chemical reactions into account

3.2.1 Reappearance of laboratory results on simulation

Using TOUGHREACT, which handles thermal, hydraulics and chemical reactions, we reappeared the water quality changes obtained from batch tests and continuous $ScCO_2$ flow test and the permeability changes obtained from core-$ScCO_2$ flow tests, then we estimated conditions and parameters for the simulation.

3.2.2 Estimation of heat volume through THC simulation

We conducted field scaled THC simulation with the model which was thought for real field to estimate how heat volume we could get from carbon-recycled CO_2 geothermal power generation.

3.2.3 Development of $ScCO_2$ geothermal reservoir monitoring method

We have developed a fluoride optical fiber sensor (FT-IR) to detect CO_2 and $ScCO_2$. We have also developed an optical fiber sensor using surface plasmon resonance (SPR) as a silica scale sensor. These have enabled remote real-time measurement of fluid components and mineral precipitation phenomena under high temperature and pressure.

4 THEME 1. OVERALL SYSTEM DESIGN FOR CO_2 GEOTHERMAL POWER GENERATION

Theme 1 encompasses core technology of the area of ground-underground including turbine and well casing issue of scale and corrosion, while theme 2 and 3 encompasses core technology of the area of underground. It also encompasses a national geothermal resource map of non-hydrothermal systems and comprehensive analysis based on all themes. A work item is shown in Figure 11.

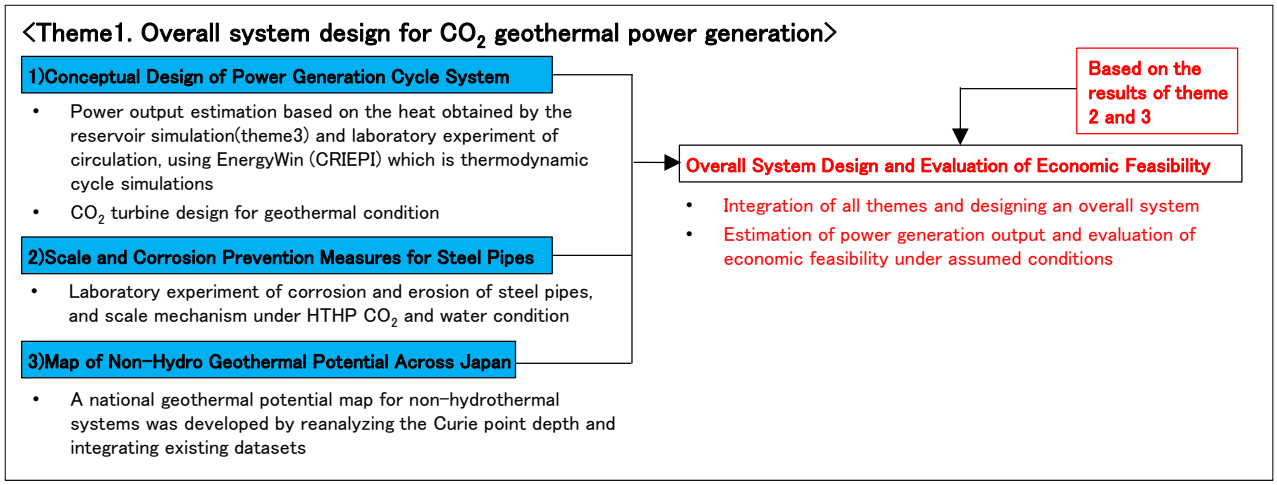


Figure 11. Work item in theme 1

Representative results in theme 1 will be presented in 4.1 and 4.2.

4.1 Conceptual design of power generation cycle system

The simulation of power generation cycle system was conducted using EnergyWin(CRIEPI) by an idealized semi-closed loop system based on the heat obtained by the reservoir simulation(theme 3) and the power generation efficiency obtained by the preliminary design of CO_2 turbine for geothermal condition. Before beginning this project, we thought it was a big issue to consider the power of pressurizing inlet CO_2 into the injection well since it might be a larger power than the power generated. As a result, the power generation can be larger than pressurizing power if the CO_2 phase is supercritical at least from production wells to injection wells since we need a huge power to pressurize CO_2 if it becomes gas phase. The power generation output becomes larger with the higher temperature, the deeper injection wells, and lower injection temperature (Nakao et al., 2024), the relationship is shown in Figure 13. It was estimated that a 1km square geothermal reservoir at a depth of 4km and a temperature of 300℃ is expected to generate approximately 10MW.

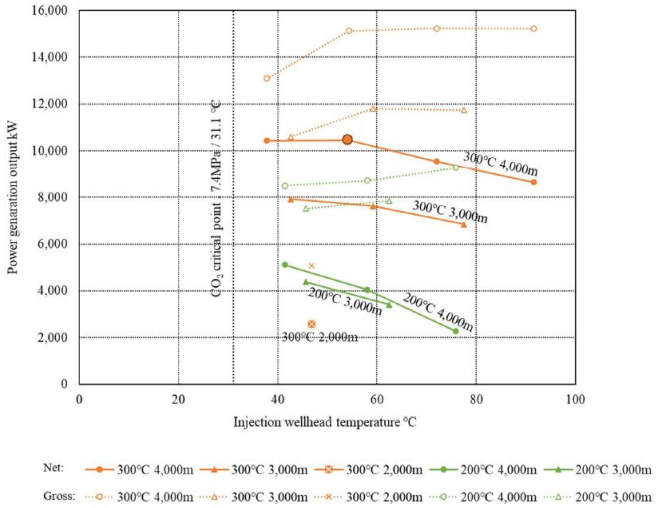


Figure 13. Relationship between the injection wellhead temperature and gross/net power generation output (Nakao et al.(2024))

In the current analysis, subsurface permeability is assumed to be constant. However, if geochemical reactions or other factors cause the permeability to change over time, additional compression power may be required

depending on the degree of clogging. In systems employing CO_2 turbines, it is necessary to consider the impact of impurities likely to be contained in the CO_2 entering the turbine. Depending on the ratio of CO_2 and water, a separation device might be required that extracts only CO_2.

4.2 Overall system design and evaluation of economic feasibility

We conducted a bunch of experiments using different kind of rocks with different temperature in theme 2 and 3, the result of laboratory experiment and THC simulation from theme 3 showed that there is a risk that whole of a reservoir would be blocked earlier by mineralization within basaltic settings. Therefore, this project targets high-temperature zones (approximately 200–300°C or more) within andesitic settings, which are prevalent in Japan's geothermal regions and offer promising potential for enhanced power generation (Figure 12). To ensure containment and prevent CO_2 leakage, the existence of an effective caprock layer upward a reservoir is a critical requirement.

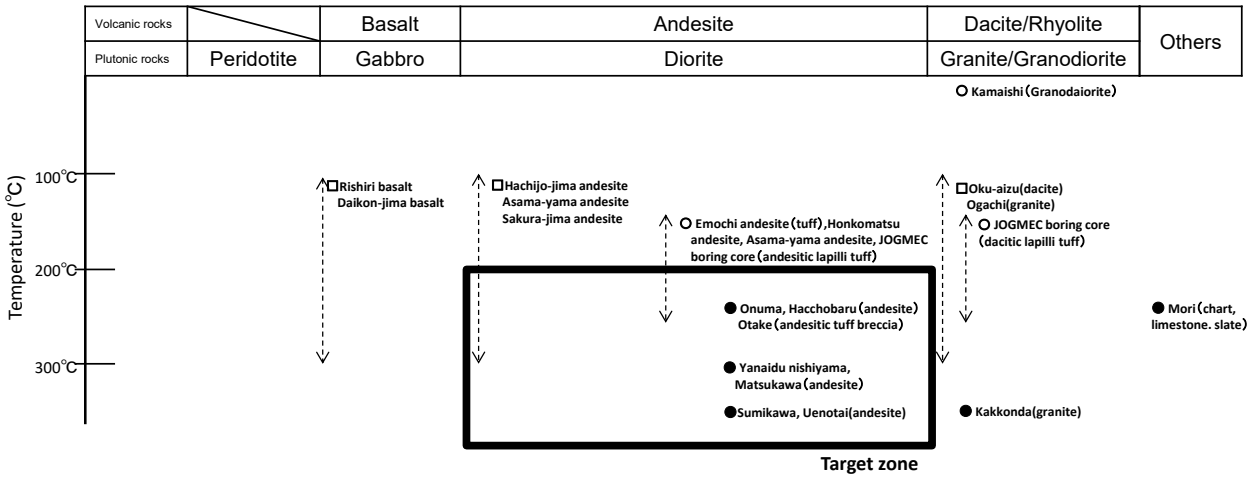


Figure 12. Target of this project (● : geothermal power plants in Japan, ○ : experiments(theme2), □ : experiments(theme3),arrow: temperature of experiments). Geothermal power plants in Japan are referred from Japanese geothermal survey (2000)

Under the large reservoir with HTHP conditions such as 2km square, 300℃ and 4km depth, four times larger than the simulation results of power generation cycle system (4.1) suggest the potential to achieve power output on the order of tens of megawatts. However, further discussions are required regarding the practically achievable reservoir size and methods for securing CO_2 supply.

In the last fiscal year, a comprehensive economic assessment is underway, incorporating the spatial relationship between CO_2 emission sources and candidate regions for deployment. The issue is that CO_2 emission sources are in coastal areas while candidate regions are in mountainous areas, and they are too far to carry CO_2 in Japan. Therefore, the cost tends to be high than conventional geothermal now and we might need to take the income from carbon credit by CCS effect into assumption.

5 CONCLUSION

To develop EGS technology using $ScCO_2$, we conducted a research dividing 3 themes at Phase 1 (2021-2025), which are; 1.Overall system design for CO_2 geothermal power generation, 2.Artificial geothermal reservoir formation technology using $ScCO_2$ as the fracturing fluid, 3.Technology for understanding CO_2 fluid behavior in geothermal reservoirs. Our main goal is to generate electricity such as tens of MW and the side effect is physical and mineral trapping of CO_2 underground, in other words, CCUS. The progress assumption of this project is theme 2,3 and 1 in order, and the major achievements and takeaways for 5-years are shown in Table 2.

Table 2: Major achievements and issues in 5-years project

Theme	Achievements	Takeaways for Next Phase
2	● As a result of laboratory experiment, $ScCO_2$ and $ScCO_2$-water showed lower AE energy, indicating less violent fracturing at rock fracturing experiment, the possibility of reducing the risk of induced	● Further scale-up to meter-scale simulations allowing predictive analyses in actual fields

	seismicity. Moreover, they create complex fracture systems than water ● Established a three-dimensional fracture simulator for sub-meter scale fracturing under true triaxial stress	
3	● $ScCO_2$ flow tests with basalt and andesite core samples showed clear difference of permeability changes. Andesite showed the increase of permeability due to the creation of new passes. This showed the possible sustainability of reservoir, not to be all blocked by mineralization ● Conducted field-sized THC simulation based on the parameters obtained from laboratory experiments and estimated heat volume and how mineralization occur	● Improve THC simulation model to reflect realistic fracture and shapes created by $ScCO_2$ fracturing (that is, more collaboration with theme 2), including the real size of artificial reservoir by fracturing
1	● Estimated a sustainable amount of electricity generated by an idealized semi-closed loop $ScCO_2$ system and showed that a 1km square geothermal reservoir at 4km depth and 300℃ is expected to generate approximately 11MW. By assuming the larger reservoir, the possibility of tens of MW is suggested	● In systems employing CO_2 turbines, it is necessary to consider the impact of impurities likely to be contained in the CO_2 entering the turbine ● Methods for securing supply of CO_2 in the potential area

We could suggest the feasibility of tens of MW in Phase 1 and understood there are some takeaways to follow up in Phase 2. Though it is important to keep updating the overall system (combining theme 1,2 and 3) for realizing the concept of this project for 2050 carbon neutral, in each theme, there were some new findings by considering the HTHP $ScCO_2$ situation in Phase 1. We expect our new findings would be useful for CCS and CCUS, too. In Phase 2, we would like to forward to the field size experiment based on the outcomes obtained.

Acknowledgements

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