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Field Test and History Matching of the CO_2 Sequestration Project in Coal Seams in Japan

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Global warming is one of the most important environmental problems facing the world and considered to be caused by an atmospheric greenhouse effect. The contribution of CO_2 to this greenhouse effect is estimated to equate approximately 50% of the effect of all greenhouse gases together, therefore the reduction of CO_2 emission is becoming extremely important. One of innovative technologies for CO_2 reduction in the atmosphere is CO_2 sequestration. In Japan, a six-years project on CO_2 sequestration in Japanese coal seams was started in 2002. This project involves several R&D items including a field test. A micro pilot test has been conducted in the Ishikari coal field since 2003. CO_2 was actually injected into coal seam in 2004 for the first time in Japan. A larger volume of CO_2 was injected in 2005. This paper investigates these field tests and discusses important results obtained through the history matching of these CO_2 sequestration field tests. It is concluded that CO_2 was sequestrated in coal seams and at the same time, the recovery of coalbed methane was enhanced.

Key Words : Global warming, Greenhouse gas, CO_2 Sequestration, Coal seams, History matching

1. INTRODUCTION

Global warming is one of the most important environmental problems facing the world and considered to be caused by an atmospheric greenhouse effect. The contribution of CO_2 to this greenhouse effect is estimated to equate approximately 50% of the effect of all greenhouse gases together, therefore the reduction of CO_2 emission is extremely important in these days. One possible contributory solution to CO_2 emission reduction is to collect and store CO_2 in underground formations. This process is known as CO_2 geo-sequestration. CO_2 geo-sequestration process includes several methods such as sequestration of CO_2 into oil and gas reservoirs, or aquifers, or coal seams. Among of these methods, CO_2 sequestration utilizing coal seams is considered to be more advantageous in the following points : 1) CO_2 is adsorbed to coal and fixed firmly, 2) Methane gas is produced as a by-product [1]. The revenue of methane gas production may offset the expenditures of the storage operation.

The Japanese Ministry of Economy, Trade and Industry began, in 2002, a six-years project on CO_2 sequestration in coal seams as one part of the "Carbon Dioxide Sequestration and Effective Use Program". The project was entitled "Japan CO_2 Geosequestration in Coal Seams Project (JCOP)". The purpose of this project is to develop a series of processes that can 1) extract the CO_2 discharged from thermal power plants and other large-scale emitters, 2) fix it within coal seams in a stable state, and 3) in the process, recover methane as a clean energy source. This project involves fundamental research into CH_4-CO_2-coal interaction, CO_2 monitoring technologies, cost reduction of CO_2 capture from flue gases, and the economics of sequestration [2]. This project also involves field tests, which have been conducted in the Ishikari coal field since 2003. Two wells were drilled in 2003 and 2004, and a CO_2 sequestration experiment utilizing coal seams was conducted for the first time in Japan.

This paper investigates these field tests and discusses important results obtained through the history matching of these CO_2 sequestration field tests.

2. FIELD TEST

In 2002, Japan Coal Energy Center (JCOAL) assessed the suitability for CO_2 sequestration of coal mining areas throughout Japan [3] and selected the Yubari district located in the southern part of the Ishikari coal field as the micro pilot test site (Figure 1). In 2003, a well named as Shuparo IW-1 was drilled to evaluate the geological character of the coal seams and associated formations, and to prepare for the subsequent pilot tests. In 2004, another well named as Shuparo PW-1 was drilled to conduct a multi well test.

2.1 Field Test in 2003

In 2003, IW-1 was drilled down to 932.60 m and encountered three major coal seams, namely the upper (H10), middle (Y68), and lower (Y10) coal seams, at depths of 742.00 to 743.75 m, 851.20 to 852.70 m, and 890.08 to 896.30 m, respectively. The target coal seam for CO_2 sequestration is the lower (Y10) coal seam, which is high volatile A bituminous coal. Cores of the mudstone cap rock and of the coal seams were taken at depths between 667.00 m and 932.60 m and analyzed to determine their CH_4 and CO_2 adsorption properties. Figure 2 shows a typical result of laboratory measurement on CH_4 and CO_2 adsorption characteristics. It is noted that adsorbed CO_2 volume is almost twice as much as adsorbed CH_4 volume. The coal rank was high volatile A bituminous based upon the moisture, ash free calorific value and vitrinite reflectance data. In situ adsorbed CH_4 volume was also measured for some coal seam core samples. The gas content data averaged 22.2 m^3/t, which was excellent for this rank coal.

A water-injection falloff test was performed in November 2003 to obtain estimates of the coal seam pressure, the absolute permeability of the coal natural fracture system, and the degree alteration to the near-well permeability caused by the injection test. The bottom hole pressure and temperature were measured during the test. Pressure analyses were conducted with radial model. Table 1 summarizes the analyzed results.

Table 1 Analyzed results of water-injection falloff test

Coal seam property	Estimated value
Coal seam pressure, kPa	10,214
Fracture opening pressure, kPa	15,800
Absolute permeability, md	1.0
Skin factor	1.0
Coal seam temperature, ℃	30

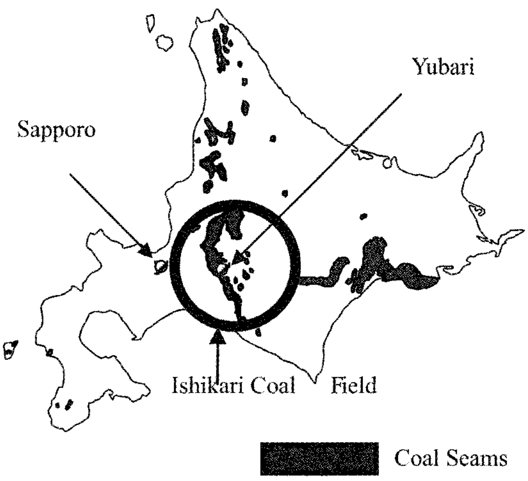

Figure 1 Map of the Ishikari coal field

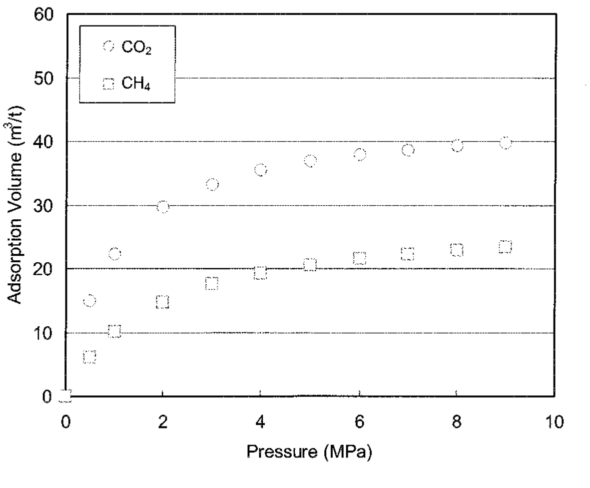

Figure 2 Adsorption isotherms

2.2 Field Test in 2004

In 2004, after the drilling of PW-1 and setting up CO_2 injection facilities, some preliminary production and CO_2 injection tests were performed. An initial production and shut-in test combination was conducted between late May and July 2004 to obtain gas composition and coal seam property data before CO_2 injection. Two one-day CO_2 injection tests were conducted in July to insure that CO_2 injection was possible. Photo 1 shows the CO_2 injection pump and CO_2 storage tank. Photos 2 and 3 show wellhead of the CO_2 injection well and the production well, respectively. As shown in Photo 3, a progressive cavity pump is used to produce water at the wellhead of the production well.

A multi well test with IW-1 and PW-1 commenced in October. CO_2 was injected at IW-1 and coalbed methane gas was produced

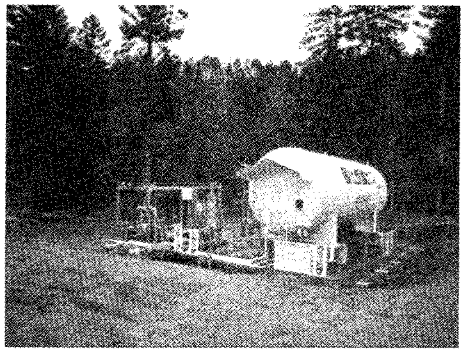

Photo 1 CO_2 Injection pump (Left) and CO_2 storage tank (Right)

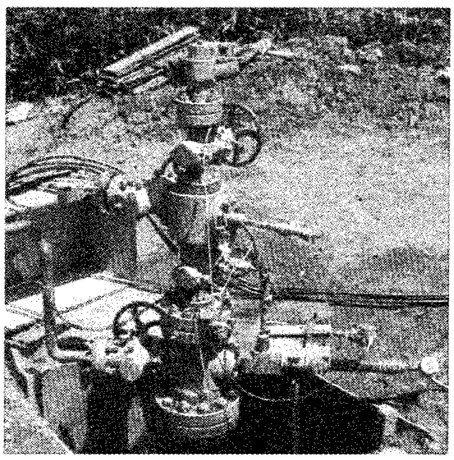

Photo 2 Wellhead of CO_2 injection well

Table 2 Schedule of the multi well test

Period	IW-1	PW-1
Oct.8 -- Oct.30	Shut in	Production
Oct.31-- Nov.8	Shut in	Shut in
Nov.9-- Nov.12	CO_2 Injection	Shut in
Nov.13-- Nov.24	CO_2 Injection	Production
Nov.25-- Dec.20	Shut in	Production

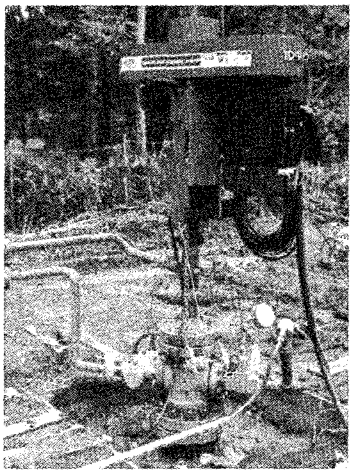

Photo 3 Wellhead of production well

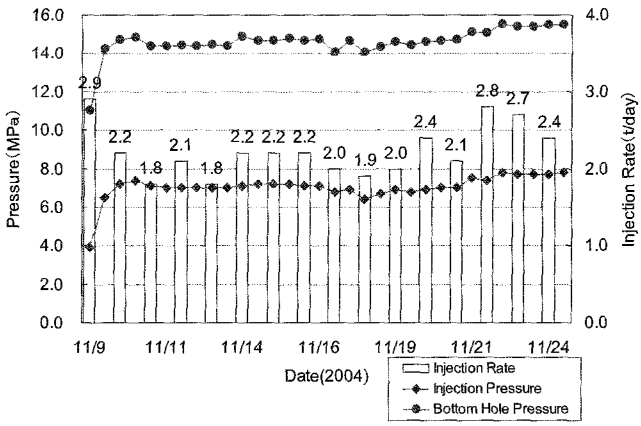

Figure 3 CO_2 injection performance at IW-1

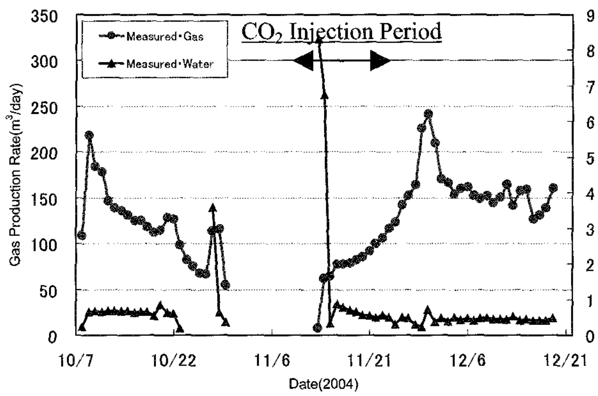

Figure 4 Gas and water production performance at PW-1

Table 3 Schedule of the multi well test

Period	IW-1	PW-1
Aug.1 -- Aug.25	Shut in	Production
Aug.26-- Oct.6	CO_2 Injection	Production
Oct.7 -- Dec.18	Shut in	Production

from PW-1. This is the first test of CO_2 sequestration in Japanese coal seams. Table 2 lists detailed schedule of the multi well test. Figure 3 shows CO_2 injection performance at IW-1 during the injection period. A total of 35.7 metric tons of CO_2 was injected at an average rate of roughly 2.3 metric tons per day. It should be noted that it was possible to inject CO_2 at a constant rate during the injection period. However, the CO_2 injection rate was much lower than expected. Well damage due to fine coal particles is strongly suspected. Figure 4 shows gas and water production performance at PW-1 during the multi well test. Gas production from PW-1 increased after the CO_2 injection at IW-1. This result may indicate the CO_2/CH_4 exchange mechanism actually happened in a real coal field.

2.3 Field Test in 2005

In 2005, a water injection fall off test was performed to investigate the CO_2 injectivity at IW-1 in May. Preliminary full wave tomography between IW-1 and PW-1 was conducted to investigate the possibility to monitor injected CO_2 in June. As the need to increase the CO_2 injectivity was suggested in the field test in 2004 and the water injection fall off test in May, additional holes were perforated at the injection zone of IW-1 in July.

A multi well test with IW-1 and PW-1 commenced in August. CO_2 was injected at IW-1 and coalbed methane gas was produced from PW-1. Table 3 lists detailed schedule of the multi well test. Figure 5 shows CO_2 injection performance at IW-1 during the injection period. CO_2 was injected by controlling the bottom hole pressure as 15.5 MPa, which was slightly lower than the fracture opening pressure.

A total of 115.4 metric tons of CO_2 was injected. The initial CO_2 injection rate was 1.6 metric tons per day, which was a little lower than that in the test in 2004. It should be noted that the injection rate increased constantly as the injection continued. The last injection rate was 3.5 metric tons per day, which was almost double the volume of the initial injection rate. This may be due to the decrease of effective stress around IW-1, which opened the cleats in coal. Figure 6 shows gas and water production

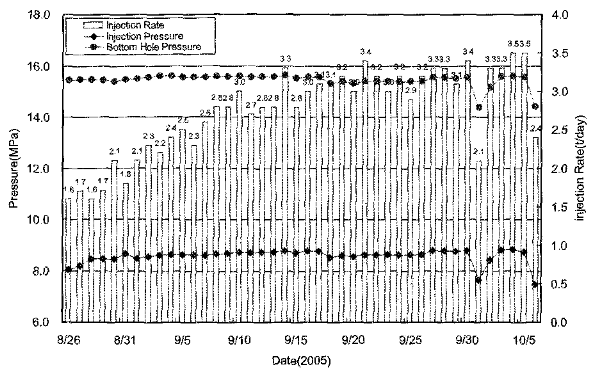

Figure 5 CO_2 injection performance at IW-1 performance at PW-1 during the multi well test. Gas production from PW-1 increased after the CO_2 injection started at IW-1, and began to decrease right after the end of CO_2 injection. This clearly shows that the CO_2 injection at IW-1 affected on the coalbed methane gas production at PW-1. This result may also indicate the CO_2/CH_4 exchange mechanism actually happened in a real coal field.

3. NUMERICAL MODELLING

3.1 Ishikari Model

The Ishikari model was constructed to perform numerical simulations for CO_2 sequestration field tests conducted in the Ishikari coal filed. The main purpose of the simulations is to help design the field tests. The model is also utilized to analyze field test results, and moreover the model may be used to estimate future CO_2 sequestration test performance as well as sequestrated CO_2 volume.

Figure 7 shows isopachs for the Y10 coal seam in relation to faults and the IW-1 and PW-1 wellhead locations. The test area is surrounded by faults, which are expected to act as barriers to the injected CO_2. Figure 8 shows the computational grid division used in the model. The shaded area denotes active cells surrounded by closed boundaries, which correspond to sealing faults. Tables 4 and 5 list the coal seam properties, which were estimated by laboratory experiments on coal samples, in situ measurement and analyses of water injection falloff test [2], [4].

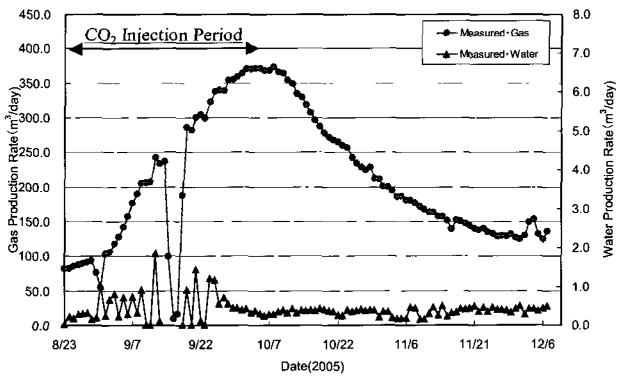

Figure 6 Gas and water production performance at PW-1

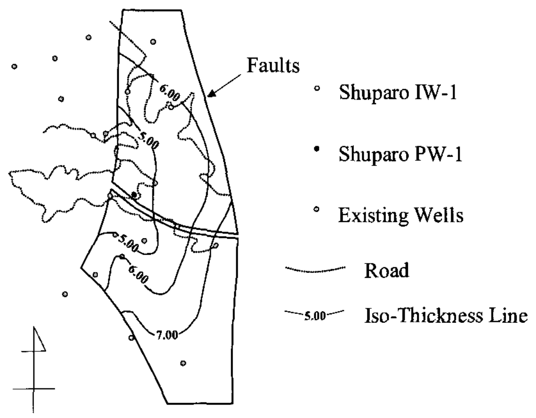

Figure 7 Isopach map of the Y10 coal seam of the test area

Table 4 Coal seam properties of the Ishikari model

Property	Value
Gross interval top depth, m	890.08
Gross interval bottom depth, m	896.30
Net coal thickness, m	5.55 (IW-1), 4.19 (PW-1)
Dip angle, degree	34.9 (PW-1)
Absolute permeability, md	1.0
Relative permeability	NA
Cleat spacing, mm	7.5
Dry, ash-free Langmuir CH_4 volume, m^3/t	28
CH_4 Langmuir pressure, kPa	1785
CH_4 sorption time, day	NA
Dry, ash-free Langmuir CO_2 volume, m^3/t	44
CO_2 Langmuir pressure, kPa	972
CO_2 sorption time, day	NA
Moisture and ash content, %	8.37
Porosity	NA
Coal seam compressibility, 1/kPa	NA
Original gas composition	See Table 5

Table 5 Measured original gas composition

Component	CH_4	C_2H_6	C_3H_8	C_4H_{10}	N_2	CO_2
%	98.15	0.03	0.04	0.0	0.19	1.59

3.2 History Matching of Field Test in 2004

Several coal seam properties were not obtained by laboratory experiments on coal samples, in situ measurement or analyses of water injection falloff test, as denoted by NA in Table 4. History matching studies on the multi well test conducted in 2004 were performed to estimate these missing properties and construct the Ishikari model.

As for initial conditions, coal seam cleats were estimated to be filled with water and coal was supposed to be saturated with coalbed methane gas from in situ measurements. Initial coal seam temperature and pressure were obtained by in situ measurement.

For the history matching studies, CO_2 injection rate at IW-1 and water production rate at PW-1 were used as input to match gas production rate at PW-1. Sensitivity studies for unknown coal seam properties were performed until obtaining good match between calculated and measured gas production at PW-1. Table 6 lists matching parameters.

A combination of matching parameters marked with asterisk in

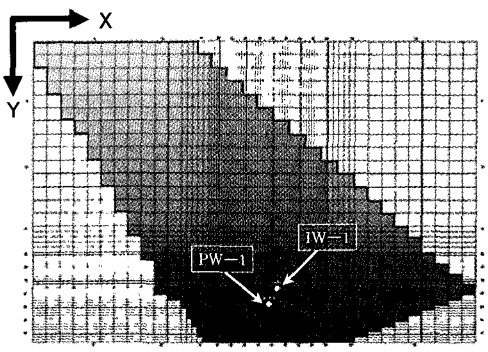

Figure 8 Grid division of the Ishikari model

Table 6 Matching parameters

Parameters	Value		
Relative permeability	Gash [5], Linear*		
CH_4 sorption time, day	0.5	5.0*	50.0
CO_2 sorption time, day	0.25	2.5*	25.0
Cleat porosity, %	1.0	0.8*	0.6
Pore volume compressibility, 1/kPa	0.0	0.001	0.0001*

Table 6 gave the best history matching result for gas production at PW-1, as presented in Figure 9. Through history matching studies, it was revealed that linear relative permeability curve was appropriate for gas and water multiphase flow through coal cleats. It was also clarified that the reduction tendency of gas production rate after reaching peak gas production depended on coal compaction. In this history matched case, the Ishikari model estimated that 98% of injected CO_2 was adsorbed to coal and sequestrated.

The history matched Ishikari model was used to investigate the CO_2 injection effect. Figure 10 compares gas production rate for CO_2 injection case and no injection case. This figure clearly shows the CO_2 injection effect. Gas production rate of CO_2 injection case increases rapidly after the CO_2 injection and is almost 5 or 6 times as much as the rate of no injection case. This figure also demonstrates the advantage of CO_2 sequestration in coal seams, that is, CO_2 is sequestrated and at the same time, the recovery of coalbed methane is enhanced.

3.3 History Matching of Field Test in 2005

As for the history matching studies of the multi well test in 2005, the same coal properties as those for 2004 field test history matching studies were used to validate the Ishikari model. The numerical simulations were continuous in time, covering all the stages of the field tests and shut-in periods in 2004 and 2005.

The strategy for the history matching was the same as that in 2004. That is, CO_2 injection rate at IW-1 and water production rate at PW-1 were used as input to match gas production rate at PW-1. Good history matching was obtained as shown in Figure 11, which validates the history matched Ishikari model. In this history matched case, the Ishikari model estimated that 96% of injected CO_2 was adsorbed to coal and sequestrated.

The history matched Ishikari model was used to investigate the CO_2 injection effect. Figure 12 compares gas production rate for CO_2 injection case and no injection case. This figure also clearly shows the CO_2 injection effect. Gas production rate of CO_2 injection case increases rapidly after the CO_2 injection and is almost 10 times as much as the rate of no injection case. Because a larger volume of CO_2 was injected in 2005, the CO_2 injection effect was strongly observed. This figure again demonstrates the advantage of CO_2 sequestration in coal seams, that is, CO_2 is sequestrated and at the same time, the recovery of coalbed methane is enhanced.

4. CONCLUSIONS

The CO_2 sequestration project entitled "Japan CO_2 Geosequestration in Coal Seams Project (JCOP)" commenced in 2002 as one part of the "Carbon Dioxide Sequestration and

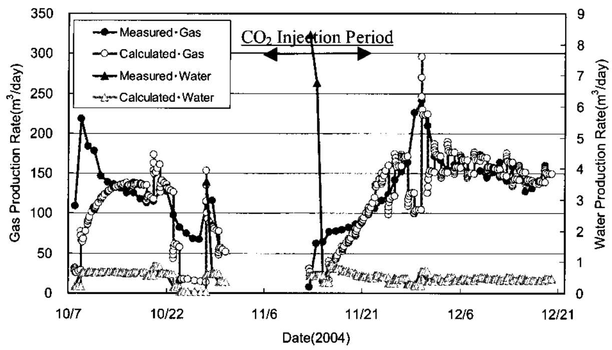

Figure 9 History matching for gas production at PW-1

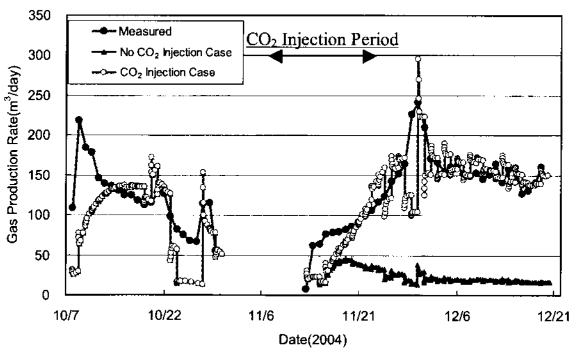

Figure 10 Comparison of gas production rate for CO_2 injection case and no injection case

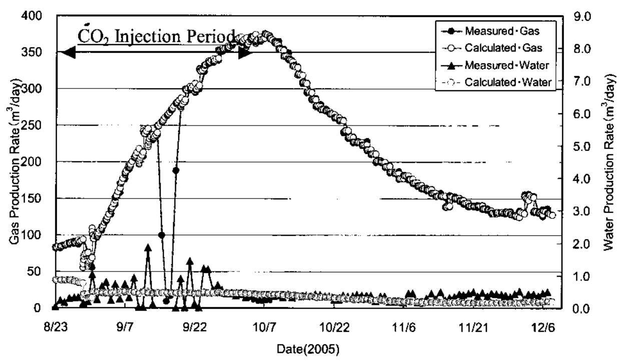

Figure 11 History matching for gas production at PW-1

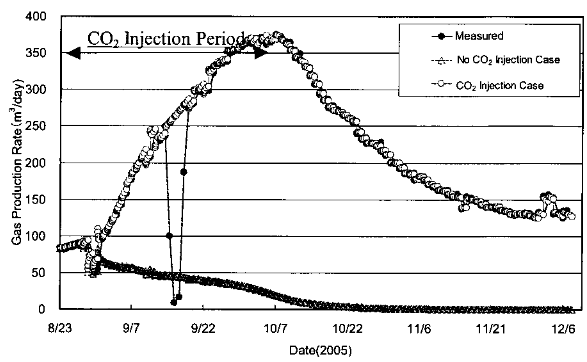

Figure 12 Comparison of gas production rate for CO_2 injection case and no injection case

Effective Use Program", promoted by the Japanese Ministry of Economy, Trade and Industry (METI).

The purpose of this project is to develop a series of processes that can 1) extract the CO_2 discharged from thermal power plants and other large-scale emitters, 2) fix it within coal seams in a stable state, and 3) in the process, recover methane as a clean energy source.

In 2004, CO_2 was actually injected and sequestrated in coal seams for the first time in Japan. A larger volume of CO_2 was injected in 2005. By analyzing these multi well field test results, it is indicated that the CO_2/CH_4 exchange mechanism actually happened in a real coal field. The Ishikari model was constructed through history matching studies of the multi well tests in 2004 and 2005. By history matching studies, unknown coal seam properties such as relative permeability, CH_4 and CO_2 sorption time, cleat porosity of coal seam, and pore volume compressibility were estimated. The history matched Ishikari model estimated that 98% and 96% of injected CO_2 was adsorbed to coal and sequestrated for the multi well field tests in 2004 and 2005, respectively. The Ishikari model also demonstrated the advantage of CO_2 sequestration in coal seams, that is, CO_2 was sequestrated and at the same time, the recovery of coalbed methane was enhanced.

Acknowledgment

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