Operational Reservoir Monitoring at the CO_2 Pilot Storage Site Ketzin, Germany

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Abstract. In June 2008, a continuous injection of CO_2 into the subsurface of Ketzin (approx. 25 km West of Berlin, Germany) was commenced for research purposes. By May 20112 A total of 61,396 t CO_2 had been injected into the deep underground in a sandstone aquifer without any safety-related disturbances and abiding by the Federal Mining Law regulations. The initial project layout using 1 injection well and 2 observation wells was further developed in 2011 by drilling a shallow well for monitoring in the upper groundwater horizon and in 2012 by drilling another observation well for additional monitoring and the extraction of CO_2 flooded samples from the reservoir. The monitoring concept developed consisted of continuous measurements of surface and underground pressure and temperature (P/T), wellbore logging campaigns including reservoir saturation and wellbore integrity measurements, gas-, hydro-, and geochemical sampling, as well as differently scaled geoelectric and seismic measurements. Besides its scientific benefits, the monitoring concept provided all the data needed for a safe and reliable operation. Furthermore, the data provided important insights into the reservoir behaviour, which can be transferred to other locations. Compared to the operational engineering of underground storage of natural gas, which has been an established secure technology for decades, differences were found in the detection of the gas distribution and the installation design of the P/T tools. The long-term experiences in natural gas storage of the operator VGS and the subcontractors UGS and ESK turned out to be essential for the effective and secure integration of best practise operational reservoir monitoring at the CO_2 storage pilot site Ketzin. Based on this the next step should be to transfer the experiences gained within the scope of this project to an industrial scale, on-shore CO_2 storage project as soon as possible.

Keywords: CO_2 storage, reservoir monitoring, reservoir simulation, continuous measurements.

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1 Introduction

Successful geological storage of CO_2 in deep saline formations is crucial for the industrial scale implementation of this climate friendly technology (Bachu 2000, Zemke et al. 2003, Bradshaw et al. 2007). Pilot sites for the geological storage of CO_2 in saline aquifers thus form a central part of most technology roadmaps. Natural gas storage in saline aquifers has been a well proven technology for many decades and a lot of the operational and technological experiences gained there may be transferred to the storage of CO_2. However, different physicochemical properties of CO_2 and natural gas together with the potential of chemical reactivity of injected CO_2 within the storage complexes prevent direct transfer from one to the other. There is, therefore, every indication that a general need exists for first-hand operational and technological experiences which can be gained at active CO_2 injection sites. The paper in hand presents a brief overview of the operational and reservoir engineering experiences from the Ketzin pilot site in Germany, which is the first European on-shore pilot site for CO_2 storage in saline aquifers and is still the only active German storage project (Würdemann et al. 2010, Martens et al. 2011, 2012). It is focussing on the injection related monitoring applied at Ketzin and its applicability for future CO_2 storage operations.

2 Project and Site Description

Under the entrepreneurship of the German Research Centre for Geosciences (GFZ) the pilot site Ketzin is operated by the VNG Gasspeicher GmbH (VGS), the owner of the mineral rights at the Ketzin site. The subcontractors Untergrundspeicher- und Geotechnologie-Systeme GmbH (UGS) and ESK GmbH (ESK) are responsible for the operational and reservoir engineering. Additionally, UGS is responsible for the regulatory reporting to the Federal Mining Authority (Landesamt für Bergbau, Geologie und Rohstoffe Brandenburg, LBGR). With their long-term experience in natural gas storage the operator VGS and the subcontractors UGS and ESK guarantee a successful integration of the operational reservoir monitoring at the CO_2 storage pilot site.

In June 2008, a continuous injection of CO_2 was commenced, for research purposes, into the subsurface at the pilot site for geological CO_2 storage near the town Ketzin in Brandenburg, Germany (approx. 25 km West of Berlin). The pilot site is located at the south-east flank of a roughly west-south-west to east-north-east elongated double anticline ("Roskow-Ketzin anticline"), which was formed above a salt pillow at 1,500 to 2,000 m depth (for details of the site geology see Förster et al. 2010, Norden et al. 2010). The reservoir was formed by sandstone layers in the upper parts of the Upper Triassic Stuttgart formation at a depth of about 630 to 650 m. The reservoir is overlain by more than 165 m of clay- and mudstones of the Upper Triassic Weser and Arnstadt formations, which form the first seal of the multibarrier system at the Ketzin site. The Arnstadt formation is overlain by a succession of permeable and impermeable lithologies of the Upper

Triassic Exter formation and Lower Jurassic formations up to the base of the Tertiary at depth of about 150 m. The base of the Tertiary is formed by Rupelian Clay, which separates the shallow freshwater horizons from the deep saline formations and therefore forms the ultimate seal at the Ketzin site.

3 Technical Facilities

Prior to the injection, three wells (Ktzi 200, Ktzi 201 and Ktzi 202) -were drilled in 2007 to depths of approx. 800 m and were completed with permanently installed monitoring devices ("smart casing" concept, Prevedel et al. 2008, 2009, Schmidt-Hattenberger et al. 2011). The well Ktzi 201 serves as a combined injection and observation well whereas the wells Ktzi 200 and Ktzi 202, which are located at distances of 50 and 112 m from the well Ktzi 201 serve as observation wells (Figure 1). All wells have a 5 ½" production casing and are connected to the reservoir via slotted liners with filter screens. In the injection and observation well, Ktzi 201, a 3 ½" injection tubing is installed at a depth of 560 m. In 2012, a third observation well Ktzi 203, which is located at a distance of ~ 25 m from the well Ktzi 201, was drilled to allow additional monitoring and to recover core samples from the reservoir and cap rocks exposed to CO_2. Above zone monitoring is done with a shallow observation well P300, which reaches the first aquifer above the main seal within the Exter formation at a depth of 446 m.

The CO_2 at the Ketzin pilot site is delivered by trucks at ~ 18 bar/-18 °C, stored in surface tanks, and then pre-conditioned in the injection facility to the desired injection conditions using plunger pumps and ambient air and electrical heaters. The injection facility allows maximum injection rates of 3,250 kg/h (set point value). Typical injection rates during continuous operation are either ~ 1,600 kg/h or ~ 3,200 kg/h.

4 Injection History

During the commissioning phase of the pilot site prior to the onset of continuous injection, the injection facility was intensely tested and the first operational experience was gained by the injection of small amounts of CO_2. These operational tests included several start, shut-in and re-start runs as well as the test of N_2 admission during the shut-in time. The commissioning phase was completed on June 30th, 2008, when the pilot site entered the test run phase with continuous injection of CO_2 (Figure 1).

The test run phase ended on September 24th, 2008 and since then the facility works under normal operation on a 24 hours/7 days basis. Due to the drilling of the well Ktzi 203, the injection was stopped in May 2012 and will be re-started at the beginning of 2013. Since the start of injection a total of 61,396 tons of CO_2 have been injected. Until March 2010, the mean injection rate was ~ 1,500 t CO_2/month (= total of ~ 32,000 t CO_2) and from March 2010 to May 2012, the overall injection rate was lowered to ~ 1,100 t CO_2/month (= total of ~ 30,000 t CO_2).

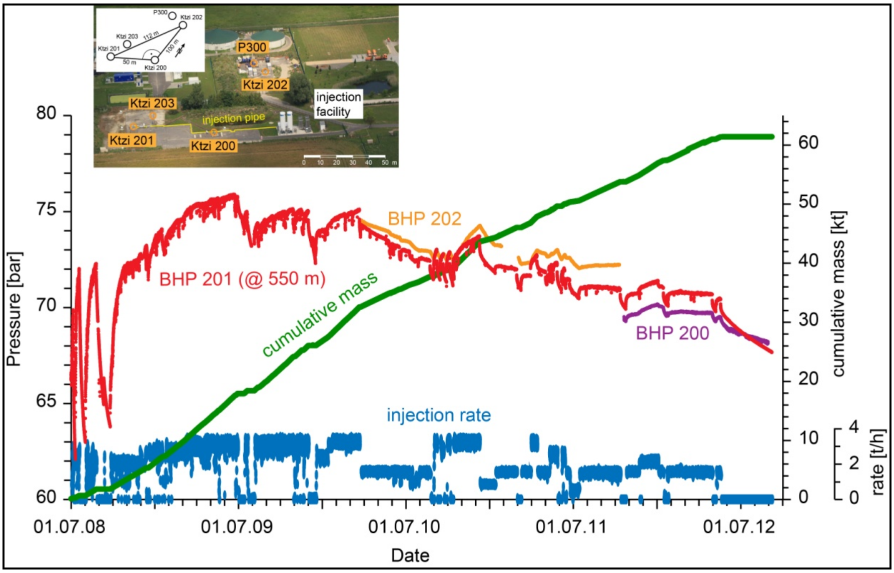

Fig. 1 Recorded development of downhole pressures in the wells Ktzi 200, Ktzi 201 and Ktzi 202, injection rates and cumulative mass of injected CO_2 since the start of continuous injection in June 2008. The small inlet shows site infrastructure and outlay of the four deep wells and one shallow well.

5 Operational CO_2 Storage Monitoring

5.1 General Approach

The monitoring methods applied to underground storage of natural gas and those applied to CO_2 storage show overall similarities but also significant differences in certain aspects. The experiences gained from the operational reservoir monitoring on natural gas storage as well as on CO_2 storage clearly confirm that the choice of monitoring activities has to depend on the local geological and technical conditions. The standard monitoring methods applied to underground storage of natural gas establish a basis for the development of suitable monitoring systems for CO_2 storage at the Ketzin pilot site. Comparable to the underground storage of natural gas, pressure and temperature monitoring of the injection facility, the wells and the reservoir together with the control of the injection rate form an integral part of the monitoring for CO_2 projects.

However, based on the non-cyclic operation and the different chemical and physical properties of CO_2 compared to natural gas, the monitoring systems have to be adjusted. The detection of the distribution of the CO_2 in the reservoir, especially, requires the application of other procedures and methods. Test development and verification of these methods are fundamental objectives of the R&D work done at the Ketzin pilot site (Liebscher et al. 2012, Martens et al. 2012).

5.2 Well Monitoring

For the purposes of the operational and reservoir engineering the following operational data are monitored and recorded (Möller et al. 2012): pressure and temperature conditions, and flow rate at the injection facility, wellhead pressure (WHP) at all three wells, bottom hole pressure (BHP) and bottom hole temperature (BHT) in the well Ktzi 201 via a permanently installed P-T sensor at the end of the injection tubing at a depth of 550 m, and BHP in the wells Ktzi 202 (March 2010 to October 2011) and Ktzi 200 (since October 2011) via a wireline pressure sensor.

In order to optimize the data base within the scope of the reservoir monitoring on the Ketzin site, it has been necessary to install additional pressure sensors in the observation wells Ktzi 200 and 202 at top-reservoir-depth. Pressure-temperature logging and distributed temperature sensing show complicated 2-phase fluid conditions within the observation wells that preclude extrapolation of recorded wellhead pressures to reservoir pressure (Henninges et al. 2011). The in-well pressure sensors then allow for direct recording of the reservoir pressure and thereby also for investigation of the pressure interferences between the different wells. The 2-phase fluid conditions within the observation wells are not only observed by P-T measurements and theoretically deduced, but are also visualized by spectacular borehole video inspections in the observation wells Ktzi 200 and Ktzi 202. These video inspections show the transition from the 2-phase gas-dominated CO_2 conditions in the upper part of the well to the 2-phase liquid-dominated CO_2 conditions in the lower part, to occur at depths of ~ 290 m (Ktzi 200) and ~ 270 m (Ktzi 202), consistent with the P-T measurements.

5.3 Reservoir Simulation

As a responsible operational manager for the CO_2 injection, UGS is obliged by the Federal Mining Authority to report half-yearly on the analysis of the overall storage performance and after every 20 kt of injected CO_2 to provide a storage forecast for the next 20 kt. Performing this task of data sampling and integration from the different monitoring methods and operational experiences, GFZ provides UGS with a static and dynamic reservoir model that is continuously adjusted and updated by GFZ according to the information available for the Ketzin pilot site (Martens et al. 2012). This model forms the basis for the dynamic 3D simulations with ECLIPSE 100 (Mark of Schlumberger) for storage analyses and storage forecasts, evaluation of potential gas leaks and adhering to limiting parameters for the injection operation. Prior to the start of the injection, a first reservoir model was used to determine the feasibility of injecting CO_2 at the pre-selected site and of recording the arrival times of the CO_2 plume at the two observation wells (Kempka et al. 2010). In addition, hydraulic test data from pre injection tests (Wiese et al. 2010) as well as results from a modified isochronal test during CO_2 injection are incorporated into the models.

A revised simulation model for the CO_2 migration within the Stuttgart formation was set up by the modelling group at GFZ in 2012. For the geological model which is in use for reservoir monitoring, the following points have been substantially revised:

- facies within the Stuttgart formation
- integration of the faults
- geometry of the grid (vertical / horizontal)

History matching was carried out on the basis of the updated geological model with a dynamic flow simulation of the past injection period. Therefore the data base up to the end of June 2012 (61,369 tonnes of CO_2 injected) was taken into account in terms of the following outcomes:

- reservoir pressure at Ktzi 201
- CO_2 arrival times at the observation wells Ktzi 200 and Ktzi 202.

Regardless of some details in the comparison of the modelled and the measured pressure data, the simulation results show a very representative picture of the pressure development within the injection horizon.

Another important match parameter for the verification of the dynamic model is the arrival time of CO_2 at the observation wells Ktzi 200 and Ktzi 202 (Zimmer et al. 2011). For this purpose the following values are available for history matching:

- observation well Ktzi 200 - 21 days after the start of injection
- observation well Ktzi 202 - 271 days after the start of injection.

The reservoir simulation performed, based on the current geologic model, resulted in the following arrival times at the observation wells:

Ktzi 200: 21 days simulated vs. 21 days detected
Ktzi 202: 254 days simulated vs. 271 days detected.

Thus, in Ktzi 200, the CO_2 arrival time can be simulated accurately. At Ktzi 202, an early arrival by 17 days (after 254 days) occurs during the simulation. The final results of the history matching and the simulated horizontal and vertical distribution of the CO_2 plume in the Stuttgart formation for the current amount of 61,396 t CO_2 injected until the end of June 2012 is shown graphically in Figures 2 and 3.

During the geological modelling adjustment, zones with higher porosities and permeabilities were located east of the injection point and at the top of the Stuttgart formation which lead to increased concentrations of gas in these area. The migration of carbon dioxide within the Stuttgart formation in a north-western direction (top of the structure Ketzin) is reflected in the vertical profiles (Figures 3a and 3b).

Advanced geologic modelling and flow simulation techniques are used to develop the model for the target interval of CO_2 injection. Intensive simulation studies are carried out to gather information about the areal pressure and CO_2 plume distribution in the structure for the period in time when the forecasted volume will be injected.

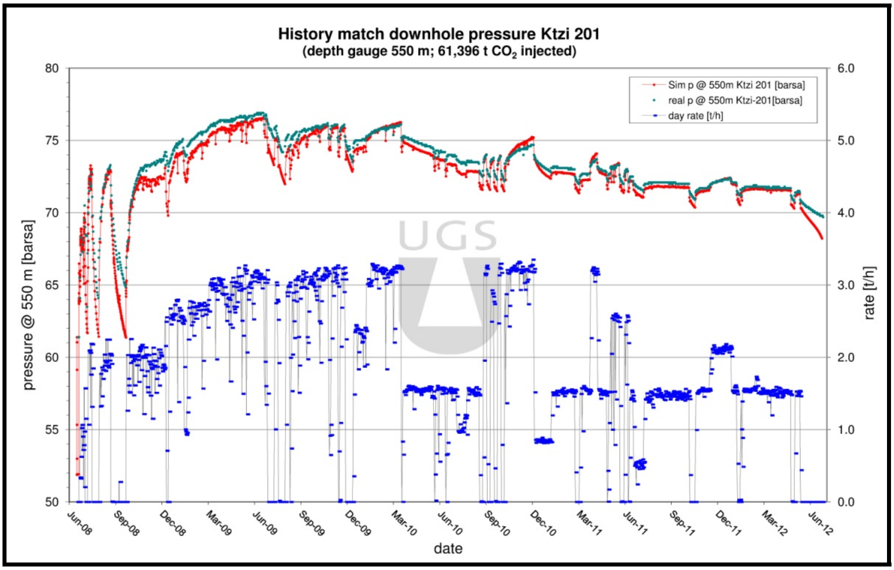

Fig. 2 Injection rate (blue curve) and measured downhole pressure in the injection well, Ktzi 201, at 550 m depth (green curve). The red curve is the simulated downhole pressure in the injection well, Ktzi 201, at 550 m depth. History matching was performed on June 30th, 2012 after the injection of 61.396 t CO_2.

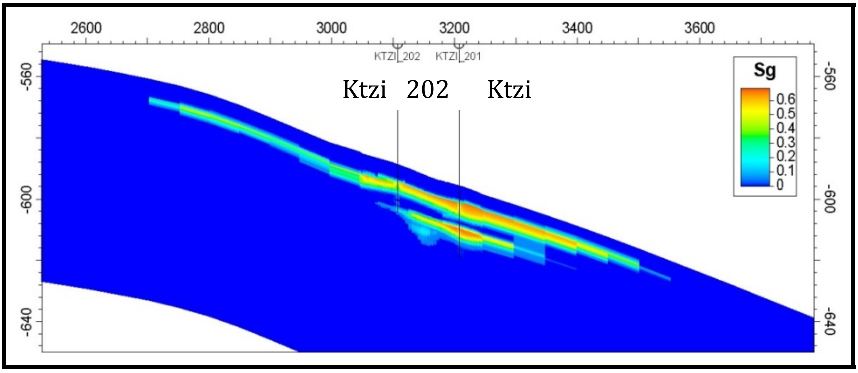

Fig. 3a CO_2 saturation in the Stuttgart Formation after 61,396 t CO_2 injected @ 30.06.2012 - North / South cross section 5x exaggerated (Units: x-axis [m]; z-axis [MASL]; Sg [%])

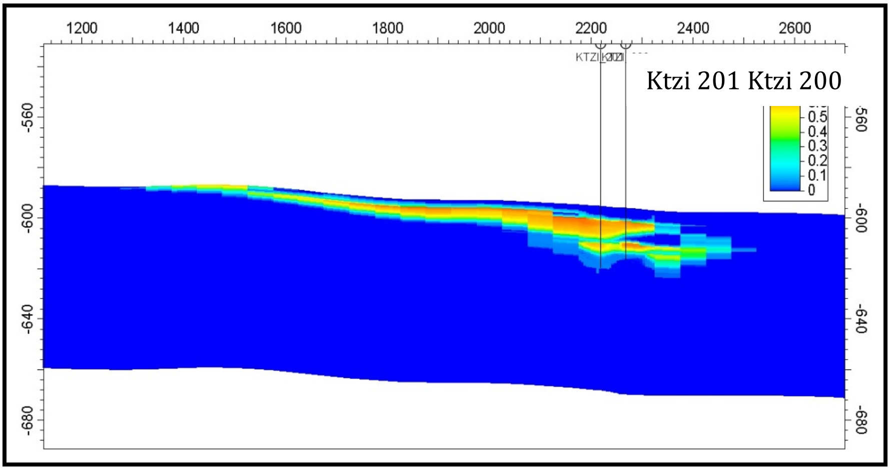

Fig. 3b CO_2 saturation in the Stuttgart Formation after 61,396 t CO_2 injected @ 30.06.2012 - West / East cross section 5x exaggerated (Units: x-axis [m]; z-axis [MASL]; Sg [%])

The modelling**,** after more than four years of operation**,** shows a very good history matching between the forecasted pressure development and the recorded data and indicates the amount of CO_2 that could be injected in the target interval without violating regulatory constraints. Modelling itself proved to be a valuable and accepted tool for controlling the injection and, furthermore, for all permitting procedures and regulatory issues. In addition it can be stated that intensive operational reservoir monitoring and high level data integration together with advanced reservoir simulation methods are the key preconditions for a secure operation on every future CCS site, even if the actual results reflect the current project status and accordingly an optimization of the reservoir model still continues.

5.4 State of the Project – Ready for the Industrial Scale

Using 1 injection and 2 observation wells, a total of 61,396 t CO_2 was injected deep underground until May 2012 without safety-related disturbances and abiding by the Federal Mining Law regulations.

In autumn2012, a third observation well (Ktzi 203) was installed at a distance of ~ 25 m from the injection well Ktzi 201. The injection pipeline had to be partially removed partially for the drilling work. At this time, the CO_2 injection was interrupted. After Ktzi 203 is finished, it is intended to carry on the injection with a rate of ~ 1,000 tons per month.

After more than 4 years of CO_2 injection experiences in operational reservoir monitoring at the pilot site Ketzin, the consortium of engineers and scientists engaged in the different projects (e.g., CO_2MAN and the precursor project CO_2SINK) are prepared for the next step. The combination of different monitoring procedures, such as:

- continuous underground P/T measuring,
- sequential gas-, hydro, microbiological and geochemical sampling,
- soil gas sampling
- different geophysical methods of measurement, i.e.
  - geoelectric,
  - seismic and
  - gas saturation

takes place at the storage site. Comparing these measures with the standards applied for natural gas storage (Table 1) it becomes clear that at the Ketzin site many more methodologies are used.

Table 1 Monitoring methods at the Ketzin site compared to the standard methods of natural gas storage in aquifers

Methodology	Ketzin	Natural gas storage
Bottom hole pressure	X	rarely
Wellhead pressure	X	x
Flow rate	X	x
Temperature	X	only wellhead
Reservoir saturation	X	x
Repeated 3D seismic	X	-
Reservoir modelling	X	x
Well integrity	X	x
Gas sampling	X	x
Geochemical sampling	X	-
Soil gas sampling	X	-
Microbiological sampling	X	only exceptional
Geoelectric monitoring	X	-
Elevation monitoring (terrestic or InSar)	X	x

As there will be an evaluation of the effectiveness of each single method regarding cost/benefit relation and, even more important, the impact on the local community it is expected that the complete programme of Ketzin will not be transferred to industrial projects. It seems likely that some methods will be used only once for site characterisation or documenting the base line and others will become standard, independent of the size or location of the project.

The pilot site for CO_2 storage at Ketzin is the only on-shore laboratory in Europe that addresses the main issues of CO_2 injection and storage at a scientific scale, forming the basis for CCS implementation on an industrial scale.

Despite the current discussions in central Europe about the feasibility of large scale CCS projects in terms of economics and political framework, it has to be stated that the project at Ketzin delivered valuable experiences. All three main parties involved in future projects (authorities, general public and companies/institutions) will benefit strongly from these experiences and therefore any future project should be based on the reliable results gained at the Ketzin pilot site. The next step should be transferring the experiences gained to an industrial scale on-shore CO_2 storage project as soon as possible.

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