The CO_2SINK Boreholes for Geological Storage Testing

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Introduction

Europe's first onshore scientific carbon dioxide storage testing project CO_2SINK (CO_2 Storage by Injection into a Natural saline aquifer at Ketzin) is performed in a saline aquifer in NE Germany. The major objectives of CO_2SINK are the advancement of the science and practical processes for underground storage of carbon dioxide, and the provision of operational field results to aid in the development of standards for CO_2 geological storage. Three boreholes (one injection well and two observation wells) have been drilled in 2007, each to a depth of about 800 m. The wells are completed as "smart" wells containing a variety of permanent downhole sensing equipment, which has proven its functionality during its baseline surveys. The injection of CO_2 is scheduled for spring 2008 and is intended to last up to two years to allow for monitoring of migration and fate of the injected gas through a combination of downhole monitoring with surface geophysical surveys. This report summarizes well design, drilling, coring, and completion operations.

Since the publication of the Intergovernmental Panel on Climate Change Report (IPCC, 2005), carbon dioxide capture and storage, including the underground injection of CO_2 through boreholes, became a viable option to mitigate atmospheric CO_2 release. One of the major goals for the immediate future is to investigate the operational aspects of CO_2 storage and whether the risks of storage can be successfully managed.

CO_2SINK is the first European research and development project on *in situ* testing of geological storage of CO_2 in an onshore saline aquifer (Förster et al., 2006). Key objectives of the project are to advance understanding of and develop practical processes for underground storage of CO_2, gain operational field experience to aid in developing a harmonized regulatory framework and standards for CO_2 geological storage, and build confidence towards future set in "projects of that kind".

The CO_2SINK site is located near the town Ketzin to the west of Berlin, Germany (Fig. 1). The plan is to inject into a saline aquifer over a period of two years a volume of approximately 60,000 t of CO_2. For this purpose, one vertical injection well (Ktzi-201) and two vertical observation wells (Ktzi-200 and Ktzi-202) were drilled at a distance of 50 m to 100 m from each other (Fig. 1). All three wells are equipped with downhole instrumentation to monitor the migration of the injected CO_2 and to complement the planned surface geophysical surveys. The injection of CO_2 will be interrupted at times for repeated downhole seismics (VSP, MSP), cross-hole seismic experiments, and downhole geoelectrics.

The preparatory phase for CO_2 injection started in April 2004 with a comprehensive geological site characterization and a baseline fluid monitoring (Förster et al., 2006). This was followed by a baseline 3-D seismic survey (Juhlin et al., 2007) and the development of a drilling and completion concept (Fig. 2) allowing for monitoring during CO_2 injection and storage observation.

Geological Background

The CO_2SINK site is located in the Northeast German Basin (NEGB), a subbasin of the Central European Basin System. The sedimentary succession in the NEGB is several kilometers thick containing geological formations of Permian to Quaternary age, comprising abundant deep saline aquifers. The CO_2 will be injected into the Stuttgart Formation (lower portion, Fig. 3) of Triassic (Middle Keuper) age, into the southern flank of a gently dipping double anticline.

The 80-m-thick target formation rests at about 630–710 m depth at a temperature of about 38°C. The formation is made up of siltstones and sandstones interbedded by mudstones deposited in a fluvial environment. The reservoir is in sandstone channels as well as levee and crevasse splay deposits. These channel-(string)-facies rocks alternate with muddy

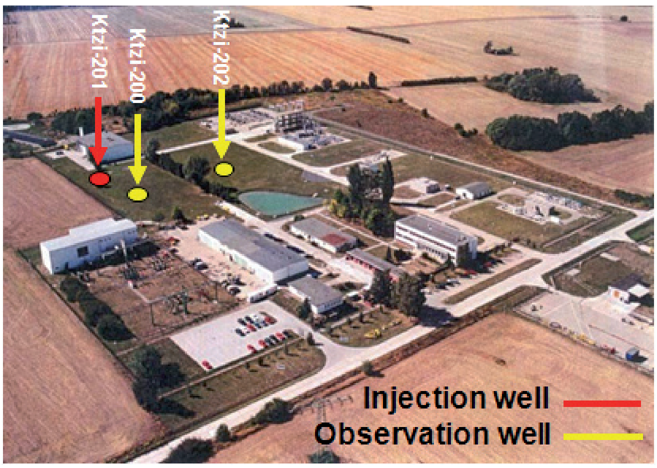

Figure 1. Location of boreholes at Ketzin industrial park.

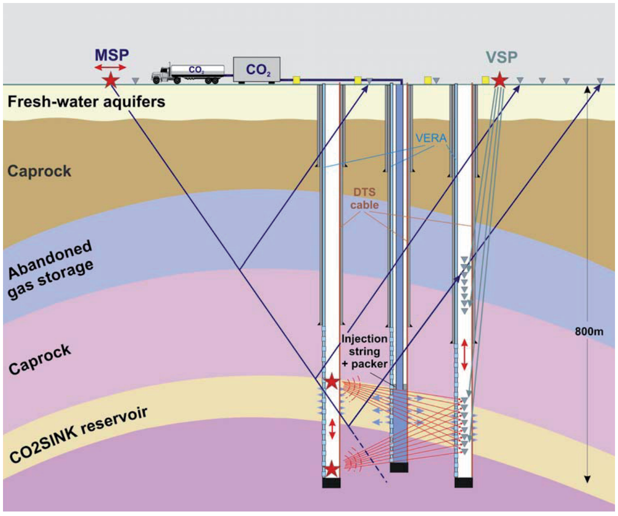

Figure 2. Schematic concept of Ketzin geology, drilling, and geophysical monitoring including moving source seismic profiling (MSP), vertical seismic profiling (VSP), cross-hole seismics, surface 3-D seismics, and surface and cross-hole geoelectrics using a permanently installed Vertical Electrical Resistivity Array (VERA), and Distributed Temperature Sensing (DTS) (from Förster et al., 2006).

flood-plain-facies rocks of poor reservoir quality. A geostatistical approach applied to the reservoir architecture (Frykman et al., 2006) pointed towards variable dimensions of the sandstone bodies and was supported by continuous wavelet transforms on 3-D seismic data (Kazemeini et al., 2008).

The Stuttgart Formation is underlain by the Grabfeld Formation (Middle Keuper), which is a thin-bedded mudstone succession with interbedded marlstone, marly dolomite and thin anhydrite or gypsum beds deposited in a clay/mud-sulfate playa depositional environment (Fig. 3; Beutler and Nitsch, 2005). The immediate caprock of the Stuttgart Formation, the Weser Formation (Middle Keuper), also is of continental playa type, consisting mainly of fine-grained clastics such as clayey and sandy siltstone that alternate with thin-bedded lacustrine sediments, like carbonates, and evaporites (Beutler and Nitsch, 2005). The high clay-mineral content and the observed pore-space geometry of these rocks attest sealing properties appropriate for CO_2 capture (Förster et al., 2007). The Weser Formation is overlain by the Arnstadt Formation (Middle Keuper), again of lacustrine character (mud/clay-carbonate playa; Beutler and Nitsch, 2005) with similar sealing properties. The two caprock formations immediately overlying the Stuttgart Formation are about 210 m thick (Fig. 3).

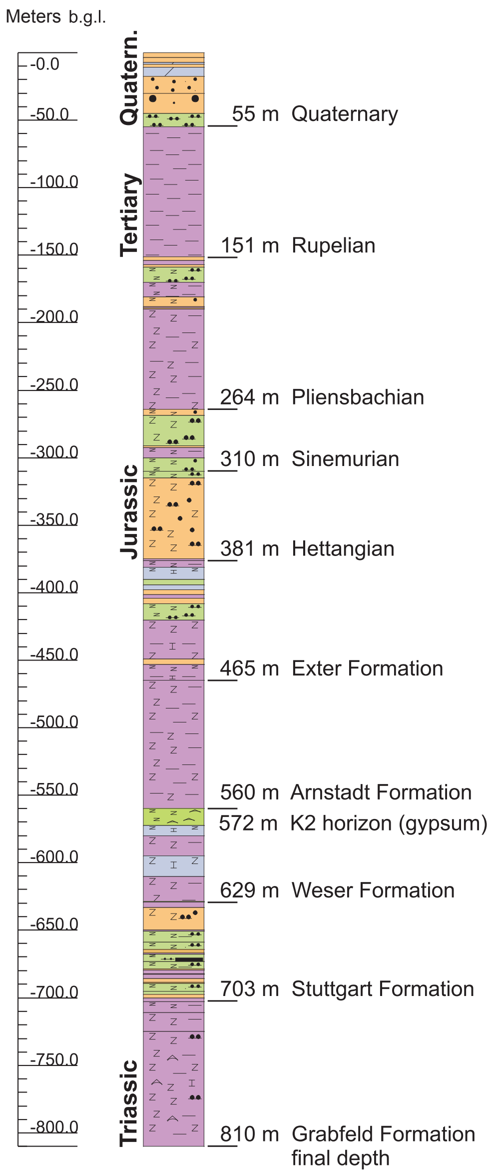

Figure 3. Condensed geological profile of the Ktzi 200/2007 borehole. Lithological color code: mudstone (magenta), siltstone (green), sandstone (yellow), anhydrite (light blue).

Borehole Design

All three wells were designed with the same casing layout, including stainless production casings equipped with pre-perforated sand filters in the reservoir section and wired on the outside with a fiber-optical cable, a multi-conductor copper cable, and a PU-heating cable to surface (Table 1). The reservoir casing section is externally coated with a fiber-

Table 1. Casing Schemes

	Depth [m]	Diameter [inch]	[mm]	[lb/ft]	Quality	Connection
Stand pipe	30	24	610	125.5	4140	welded
Conductor	150	18 5/8	473	87.5	X56	Buttress-BTC
Reserve Casing	ca.340	13 3/8	340	54.5	K-55	Buttress-BTC
Intermediate	590	9 5/8	244	36	K-55	Buttress-BTC
Production String	800	5 1/2	140	20	13Cr80 (outside coating)	VAM Top
Injection String	680	3 1/2	89	9.3	C-95 (inside coating)	TS-8

glass resin wrap for electrical insulation. A staged cementation program was planned around the application of newly developed swellable elastomer packer and stage cementation downhole tools. This technology was preferred over perforation work that would have caused unmanageable risks of potential damage of the outside casing cables.

The 200-m core sections for detailed reservoir and sealing property investigations were recovered with a 6" x 4" wire-line coring system using polycrystalline diamond compact (PDC) core bits. The 6 1/4" core hole sections were enlarged to 8 1/2", and the wells finally deepened below the reservoir zone to accommodate sufficient sensor spacing for installation of behind-casing sensor arrays.

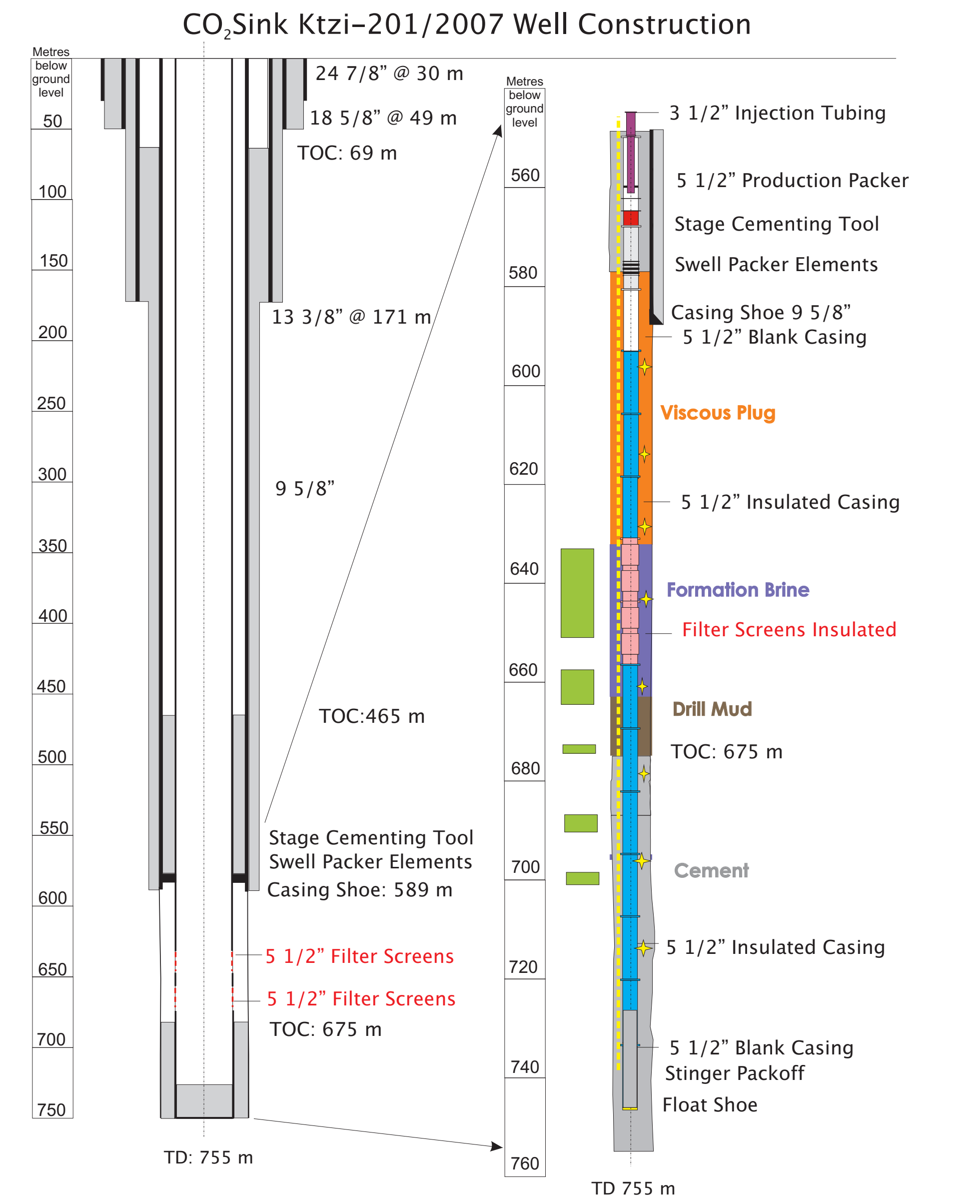

Figure 4. Drilling design and well completion of the Ktzi 201/2007 borehole. Yellow line indicates DTS and ERT cables with location of ERT electrodes (yellow pluses). Sandstone reservoir intervals are shown in green.

Drilling and Completion Operations

Constructing three wells close to each other and with such a dense sensor and cable population requires detailed planning. For this purpose, high-end oilfield QHSE (Quality, Health, Safety, Environment) management tools were applied, such as “drill well on paper” (DWOP), hazardous operation identification, repeated incident reporting, post job analysis, and risk management.

Drill site construction started in December 2006, and the drilling operation commenced on 13 March 2007 with the mobilization of a truck-mounted and top-drive equipped rotary drill rig. All the Ketzin wells were drilled with a shale inhibited KCl-water-based mud system, with the exception of the top-hole section in the fresh-water aquifers, where a K_2CO_3-water-based system was required by the authorities. Both drill muds were conditioned at 1.05–1.16 gcm^{-3} density. In order to avoid potential risks from environmental hazards, the project further implemented a “shallow gas” procedure in this well section to avoid spills when the wells would encounter high pressurized shallow gas from the past gas storage activity. For this purpose, the top-hole section of the first borehole was pre-drilled with a blow-out preventer/diverter/gas-flare installation on the rig to capture and control unexpected and sudden shallow gas influxes. As no stranded shallow gas was encountered during drilling (as also confirmed by reconnaissance wire-line logging and surface seismic processing), this pilot drilling was consequently skipped for the second and third well. Casing (18 5/8") running and cementation with stinger to surface were performed in all three wells without problems.

In the following 12 1/4" sections, the wells penetrated the Jurassic aquifer systems in which under-balanced pressure regimes were supposed. All wells encountered a minimum of three loss circulation zones between 366 m and 591 m with cumulative mud losses of 550 m^3. The addition of medium- to coarse-grained shell grit to the mud cured the loss of circulation and brought the wells safe to the 9 5/8" casing depth between 588 m and 600 m.

The lower part of Weser Formation and the entire Stuttgart reservoir section were cored with a specially designed $CaCO_3$-water/polymer drilling mud (1.1 g cm^{-3}). In the first well, a total of 100 m core was drilled in thirty-nine core runs, and an average recovery of 97% was achieved. In the second well 80 meters of core was retrieved in thirty-one runs (100% recovery). In the third well only the top 18 m of the Stuttgart Formation was cored with the same excellent performance. The 6 1/4" core hole section was then enlarged to 8 1/2", and the wells finally deepened below the reservoir into the Grabfeld Formation.

Stainless steel 5 1/2" production casings (Fig. 4) were installed and cemented in all wells with sensors and cables on the outside. The cables were terminated and fed pressure tight at the wellhead to the outside through the drilling spool below the casing slips. The cement selected in all casing cementations was standard class-G with fresh water and no additives (SG = 1.98 kg L^{-1}), with the exception of the plug cementation, for which a specially designed CO_2-resistant class-G salt cement was selected.

The CO_2 injection well was completed with a gas-tight and internally coated production tubing, including a permanent production packer above the injection horizon, a fiber-optic pressure and temperature mandrel/gauge arrangement above the packer and a wire-line-retrievable subsurface safety valve at 50 m depth below the well head. The optical cables and hydraulic safety valve actuation lines were clamped to the outside of the production tubing and fed pressure tight to the outside at the tubing hanger adaptor below the Christmas tree gate valves.

Permanent Downhole Sensors for Monitoring of CO_2

Geophysical monitoring techniques are applied in CO_2SINK to delineate the migration and saturation of injected CO_2 (Fig. 2). The injection well and the two observation wells are equipped with state-of-the-art as well as newly developed geophysical sensors. The data from this permanent downhole monitoring will be interpreted in combination with data from periodic seismic monitoring (VSP, MSP, and cross-hole seismics) and periodic fluid sampling and well logging (Reservoir Saturation Tool).

The following permanent components were installed in the boreholes for scientific monitoring:

- a fiber-optic-sensor cable loop for Distributed Temperature Sensing (DTS; all wells)
- a two-line electrical heater cable (Ktzi 201/2007, Ktzi 202/2007)
- a Vertical Electrical Resistivity Array (VERA) consisting of fifteen toroidal steel electrodes, 15-line surface connection cable (all wells)
- fiber-optic pressure/temperature (P/T) sensor, fiber-optic surface connection cable (at injection string only).

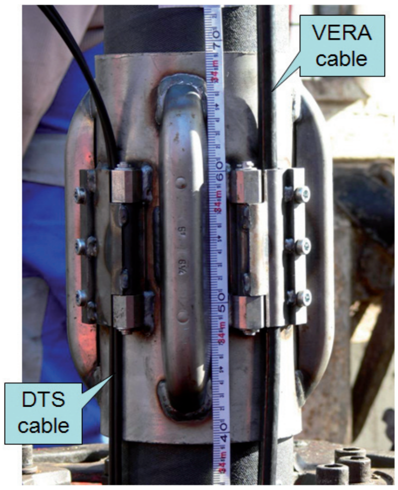

Figure 5. Centralizer attached to casing string with DTS (left) and VERA cables (right).

Using the DTS technology, quasi-continuous temperature profiles can be measured on-line along the entire length of the wells with high temporal and spatial resolution (Förster et al., 1997; Büttner and Huenges, 2003). The permanent installation of DTS sensors behind the casing (Hancock et al., 2005; Henninges et al., 2005) offers the advantage of full access to the well during technical operations, which, for example, allows control of the process of casing cementation (Henninges and Brandt, 2007). The borehole temperature data will primarily serve in the delineation of physical properties and of the state of the injected CO_2. To enhance the thermal signal and improve the monitoring of brine and CO_2 transport, successive thermal perturbation experiments (Freifeld et al., 2006) will be performed, using the electrical heater cable installed adjacent to the DTS cables. VERA provides data on the CO_2 saturation employing the Electrical Resistivity Tomography (ERT) method. Each of the VERA arrays covers an interval of about 140 m centered in the injection horizon and consisting of fifteen electrodes spaced at about 10-m intervals. The P/T-sensor installed at the bottom of the injection string above the packer system will continuously monitor the downhole pressure and temperature changes during injection. Data will be transferred via optical fiber attached to the injection string.

The inclusion of the permanent downhole sensors into the well completion required a selection of suitable completion components and procedures. Custom-made casing centralizers were used for outside-casing installation of sensor cables, for centralization of the casing inside the borehole, and for protection of cables from mechanical damage during installation (Fig. 5). The 8 1/2" borehole diameter in the lower reservoir sections allowed for sufficient clearance within the annular space between casing and borehole wall and thus for a safe installation of the downhole sensors. Within the 140-m zone, where the VERA electrodes are placed, the steel casing was electrically insulated outside using a fiberglass coating.

After an on-site installation test had been conducted, the installation of the DTS and VERA cables (Fig. 5) and electrodes in the Ktzi 200, 201, and 202 wells was performed on 5 May, 5 July, and 18 August 2007. After careful installation operations of up to 18–24 h duration, the cables were guided into the substructure of the drill rig, and the casing was cemented.

The DTS monitoring allowed online monitoring and control of the cementing operations and provided valuable information about the positions of the cemented sections during the setting of the cement. This information was verified by subsequent industry-standard cement-bond logs. The installation of monitoring tools was finished by feeding the cables into the casing spool at the wellhead, which was subsequently pressure-sealed using a stuffing box. Preliminary tests of VERA have shown that all electrodes and cables are fully functional.

Field Laboratory

The CO_2SINK field laboratory comprised core-cleaning and core-sealing facilities, a full core imager, and a Geotek gamma-ray density core logger. The field lab was designed to record and describe a high core-run volume within a short handling time to quickly generate the litholog for the drilled boreholes and to identify the reservoir section. This procedure was necessary in order to proceed rapidly with decision making on the selection of the borehole intervals completed with filter casings through which the CO_2 would be injected into the formation or monitored.

In the preparation for unconsolidated sandstone in the Stuttgart Formation, coring was performed with PVC liners in 3-m liner intervals. At the drill rig, liners were cut after orientation marking into 1-m sections, and the cut surface geologically described was sealed before being transferred to the field lab for analyses. Sections containing sandstone were shipped preserved in liners to a commercial laboratory for "hot-shot" poro-perm analysis. Reservoir sandstone intervals (Fig. 6) with porosities on the order of 20%–25%, together with requirements for permanent ERT sensor arrangement on the casing, guided the depths at which the wells were completed with filter screens for CO_2 injection and monitoring.

Figure 6. Core image of reservoir sandstone showing cross-bedding.

The geological description of core started with the sections of well-cemented mudstone after its cleaning with synthetic formation water, reorientation, and scanning unrolled using an optical core scanner. Later, the "hot-shot" reservoir sections were included. From the geological core and cutting descriptions and interpreted petrophysical well logs, stratigraphic-lithologic logs (Fig. 3) were finally generated for all three CO_2SINK wells to refine the geological model. For example, the stratigraphic-lithologic logs were used to calibrate the 3-D seismic time sections (Juhlin et al., 2007). Petrographical and mineralogical studies and geochemical analyses from reservoir and caprock were performed to characterize the Ketzin site on micro-scale as a basis for fluid-rock-alteration modeling.

Outlook

CO_2SINK is the first project that extensively uses behind-casing installations for a study of the CO_2 injection and storage process in a geological medium. In this regard, CO_2SINK differs from other scientific projects of CO_2 test storage, such as the Frio experiment in Texas (Hovorka et al., 2006), the Nagaoka experiment in Japan (Kikuta et al., 2004), the field test in the West Pearl Queen Reservoir in New Mexico (Pawar et al., 2006), and the Otway Basin pilot project in Australia (Dodds et al., 2006).

It is envisaged that the extensive set of data generated by cross-correlation of seismic surface monitoring, well-logging and monitoring, and simulations, will allow for verification of *a priori* scenarios of storage/migration of fluids. Emphasis, for example, will be given to the observation of non-isothermal effects in the storage formation during injection as described by Kopp et al. (2006). This type of effect also can occur during leakage from a storage reservoir along a fracture zone as numerically investigated by Pruess (2005). Thus, the observations in progress will contribute to a sound understanding of the thermodynamic processes of CO_2 injection at well-scale as well as in the short and longer term the processes during CO_2 storage at larger scale.

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