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# The Altmark Natural Gas Field is prepared for the Enhanced Gas Recovery Pilot Test with $CO_2$

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**Abstract**

The joint project CLEAN was a Research & Development (R&D) action accompanying a pilot Enhanced Gas Recovery (EGR) project designed by GDF SUEZ E&P Deutschland GmbH (GDF SUEZ) in cooperation with Vattenfall Europe. Within the framework of this project a total of 16 German research and industry partners participated.
The project was set up as pilot to investigate the processes relevant to EGR by the injection of $CO_2$ into a subfield of the almost depleted Altmark natural gas field (Germany). Despite the setback that permission for active injection was not granted by the mining authority during the period of the project, important results fostering the understanding of processes linked with EGR were achieved.
The CLEAN results provide the technological, logistic and conceptual prerequisites for implementing a $CO_2$-based EGR project in the Altmark and provide a benchmark for similar projects in the world.



*Keywords*: CLEAN, enhanced gas recovery, EGR, Altmark, gas field, $CO_2$ storage

## 1. Introduction

CLEAN was a scientific program in support of a pilot Enhanced Gas Recovery (EGR) project which was designed to be carried out in cooperation with GDF SUEZ E&P Deutschland GmbH (GDF SUEZ)

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and Vattenfall Europe [1]-[3]. Within the framework of this R&D project a total of 16 German research and industry partners participated.

The Altensalzwedel block, a separate geological section of the Altmark natural gas field, which is hydraulically isolated due to its structure and is almost completely exploited, had been selected by the field operator for this purpose. The operator also developed and provided the infrastructure required for the implementation of the pilot project above and below ground. The aim of the project CLEAN was to develop and test technologies, which enable to store for a long time significant amounts of $CO_2$ economically, ecologically and safe in a natural gas reservoir. Hence the main objectives of the joint research project were:

- to test whether it is possible to mobilize gas quantities which cannot be recovered by conventional means in order to enhance gas production and
- to study the natural gas field in view to its general suitability for the injection and storage of $CO_2$ and whether the $CO_2$ injection is generally possible.

Research in the framework of CLEAN mainly focused on the development and optimization of suitable techniques and methods: (1) for an optimum $CO_2$ injection with the purpose to exploit the gas reservoir to its maximum extent; (2) to determine and assess the integrity of existing wells, including test of a long-term well closure; (3) to study, describe and evaluate all processes relevant to $CO_2$ injection and the displacement of natural gas in the reservoir; (4) to monitor the entire geological complex from the surface down to the reservoir, with regard to $CO_2$ propagation as well as focus on environmentally relevant processes; and (5) to provide extensive information to the public and other stakeholder.

The joint research project was coordinated by the Helmholtz Centre Potsdam, GFZ - German Research Centre for Geosciences in close cooperation with all research partners and the field operator GDF SUEZ. The focus of the joint research project was on the topics (i) technical aspects, (ii) well integrity, (iii) evaluation of geo-processes, (iv) reservoir and cap rock monitoring and (v) environmental and process monitoring. An additional topic dealt with public acceptance to provide factual and technically sound information especially to the regional public. Activities within this area were conducted by GFZ and implemented in close cooperation with GDF SUEZ and the German Ministry of Education and Research (BMBF).

Under the pilot project, it had been planned to inject nearly 100,000 tons of $CO_2$ into the Altensalzwedel block. However, the permitting procedure required under mining law was delayed by significant political influence as well as the delays in transposing the Directive of the European Parliament and Council on geological storage of carbon dioxide (DIRECTIVE 2009/31/EC) into German federal law. Therefore the responsible mining authority (State Office for Geology and Mining of Saxony Anhalt) did not issue a permit for $CO_2$ injection during the period of the project.

Despite this setback for the CLEAN project, it was possible to complete most of the scientific work. This was made possible by adjustments to the implementation and the objectives. Many fields of research within the project (e.g. well integrity and evaluation of geo-processes) were hardly affected and were thus able to reach their targets. Major results are presented in the following. However, for further details the reader is referred the final publication of the project [4].

In the light of the general political conditions, which were still not clear in the second quarter of 2010, GDF SUEZ had to postpone the awarding of any further services to subcontractors. The opening of the information centre at Salzwedel which was ready for work and fully equipped is still lacking. Public relations were adapted to this situation and continued. As an alternative, the information material that had been developed is presented to the public at the GFZ and the Ketzin visitor centre [5] (http://www.co2ketzin.de).

## 2. Fields of Research and Major Results

### *2.1. Technical Aspects of $CO_2$ Injection*

The almost depleted Altmark gas field was chosen by the owner and operator GDF SUEZ E&P Deutschland GmbH (GDF SUEZ) for an Enhanced Gas Recovery (EGR) project. GDF SUEZ took part in the joint research project CLEAN providing this site as a basis for the scientific work of the partners from academia and industry. In November 2007, GDF SUEZ filed the application for injection of up to 100,000 t of $CO_2$ with the State Office for Geology and Mining of Saxony Anhalt. The permitting process came to a halt towards the end of 2008, because the responsible mining authority considered a national CCS (Carbon Capture and Storage) law to be the only legal basis for approval. In January 2009, the erection of the interim $CO_2$ storage and conditioning unit in Maxdorf was completed. New flow lines between the Maxdorf surface installations and the potential injection wells were fully planned but never build. Corrosion resistant re-completion of the injection wells did not take place either. Within the funding period of the CLEAN project (2008–2011), there was no injection of $CO_2$.

### *2.2. Well Integrity*

The implementation of an underground $CO_2$ storage requires evidence that the storage is and will remain tight in the future. This refers to the cap rock and the wells penetrating it. Assessment and verification of well integrity of accessible wells is technically possible. The available methods, allowing a direct assessment, were evaluated and a measurement and testing strategy is proposed. Unlike accessible wells, already plugged ones require predictive methods for their assessment. These are based on well information and a comprehensive understanding of the coupled thermal, hydraulic, mechanical and chemical processes during well construction, operation and after abandonment. The methods have been applied to a well zone characterised by conditions typical for the subsurface in the area of interest and with regard to the potential injection site in the Altmark. The calculated safety margins emphasize that technical well integrity of the 12 examined boreholes is given for enhanced gas recovery injecting 100,000 t of $CO_2$ in the Altensalzwedel subfield without a need for any further intervention.

Self-healing of defects was investigated in full-scale experiments under in-situ conditions. In addition to the expected self-healing as a result of salt creep, healing was also observed resulting from the interaction of salt, cement and casing with dry or wet $CO_2$.

Methods and technologies for $CO_2$ well monitoring and intervention presented here are sufficient for the mining safety of $CO_2$ storage wells under high pressure. The system contains technologies proven under field conditions as well as procedures in which $CO_2$ was applied.

An innovative well abandonment concept was developed and tested in the field for the long-term containment of $CO_2$ in depleted Rotliegend gas reservoirs [6]. It aims at amending the conventional standard well abandonment procedure, takes advantage of the natural creeping ability of the thick, homogeneous Zechstein salt formation located at around 3,000 m depth in the Altmark area and consists of four main sealing units: (1) a standard sealing element with cement from the reservoir to the impermeable cap rock, (2) a salt plug created in the formerly reamed section of casing within the plastic Zechstein (Upper Permian) rock salt formation, (3) two bridge plugs at the bottom and top of the salt plug and (4) standard cement sealing elements from the top bridge plug to the ground surface. Comprehensive numerical simulations conducted prior to and during the field test in 2010 and 2011 successfully predicted the evolution of the now proven convergence using downhole measurement data [7]. This new long-term sealing concept has been successfully tested at the Altmark natural gas field.

### 2.3. Evaluation of Geo-Processes

A holistic understanding of the physicochemical processes induced by $CO_2$ injection and storage in a reservoir is based on a geoscientific characterisation of the overall geological system consisting of reservoir rocks and cap rocks. It requires in a first step a comprehensive baseline characterisation (sedimentological, mineralogical, geochemical, mechanical, etc.) of pertinent parameters and conditions. To properly handle the large amount of different geoscientific information a Data Management System (DMS) was developed, which proved indispensable to conduct such a multi-disciplinary project. The DMS provides a tool for scientific process management, data analysis, integration and visualisation, data transfer and scheduling through specialised database systems and retrieval techniques, storage technology, and efficient data access [8].

Sedimentological (facies), mineralogical and petrophysical data classify the Altmark Rotliegend sandstones of high quality with best porosity and permeability in altered/bleached aeolian sandstones [9]. Those properties are strongly controlled by sediment deposition (facies-type) and by early and late diagenesis, namely by early pore-filling cementation and late fluid-rock interaction. The fluids involved probably originated from Carboniferous formations and ascended along (re-) activated faults through the Rotliegend volcanic rocks during Triassic-Jurassic times. Major features controlling the extent of fluid-rock reactions are grain size and grain sorting, respectively pore size, pore shape and pore connectivity. Especially grain coating chlorite and pore-filling carbonate and anhydrite will most probably affect reactivity during $CO_2$ injection. Laboratory batch experiments with core samples reveal that $CO_2$ saturated brines cause dissolution of (pore-filling) minerals and alteration of fluid and flow properties of the reservoir rocks [10]. This also was emphasised by a parameter study based on numerical modelling [11]-[12], which indicate a tendency of increasing anhydrite dissolution and calcite precipitation with increasing $CO_2$ partial pressure. Increasing temperature and salinity counteracts this effect. Changes of rock properties observed comprise an increase in porosity, permeability, water binding capacity, rock wettability and a slight decrease in residual gas saturation.

The recent stress field was determined by direct measurement of the effective primary principal stresses [13]. The total primary stresses were calculated from the effective primary stresses, pore pressure effectiveness and pore pressure. The orientations of the primary horizontal stresses coincide with the directions of the fault zones in the Salzwedel area. Stress ratios for the anhydrite and claystone strata, calculated from the obtained effective primary stresses, are expected to be modified with a pilot injection into the reservoir.

Methods and numerical tools were developed, which are dedicated to the numerical characterisation of the nearly depleted gas reservoir as well as to the simulation of the processes during $CO_2$ injection and migration storage [14]-[16]. The only practical option for predicting the long-term behaviour of $CO_2$ in reservoirs is numerical analysis, supported by the understanding gained from the relatively short-term laboratory and field-scale experiments. Corresponding to the real site conditions, compositional gas flow has to be considered including mutual interactions with thermal, mechanical and geochemical (reactive) processes taking into account high pressures and temperatures. Process- as well as site-related benchmarks were jointly developed and implemented. It was observed that the high accuracy of complex equations of state (EoS) do not justify the higher computing costs compared to simple, cubic equations of state [17]. The Peng-Robinson equation of state is the most suitable EoS with regard to pure $CO_2$. At no stage of the process there is any evidence of plastic deformation. Both reservoir and cap rock behave elastically. In general, $CO_2$-EGR operation might cause only local changes in the pore pressure of the reservoir, while $CO_2$ storage will increase the reservoir pressure dependent on the injection rate if no gas is produced at the same time. Simulations revealed that an initial tensile stress regime is the safest precondition while the compressive stress state is problematic with regard to the reservoir integrity. The calculated, virtual tracer test, applying krypton, indicates that concentrations at the monitoring wells would be too low to be detected [18]. Hence a test under the considered constraints is not feasible.

### *2.4. Reservoir and Cap Rock Monitoring*

One aim of the CLEAN project was to develop and test monitoring methods for the reservoir cap rock and the reservoir itself. It is shown here that advanced injection and production profile evaluation can be achieved using a combination of pressure, temperature and spinner flow meter data. Using distributed temperature sensing, temperature profiles in gas-filled wells can be acquired, as the sensor cable can be stationary during the measurement allowing for simultaneous thermal equilibration along the entire logged profile. A first field test of the developed hybrid wireline logging system was successfully performed under static conditions and the feasibility of warm-back monitoring was shown based on the results of numerical simulations for a possible $CO_2$ injection scenario. A combined approach using the developed hybrid system for enhanced production logging (PL) during injection followed by warm-back monitoring within a subsequent shut-in period would allow for accurate determination of the spatial extent and injectivity of individual $CO_2$ injection intervals (Baumann and Henninges 2012).

Application of the pulsed neutron gamma (PNG) method for estimation of saturation changes is hampered under the considered conditions because of the low contrast between $CO_2$ and natural gas. However, considering the effect of drying-out of the bound water with associated salt precipitation, which is expected to occur close to injection wells, could be monitored with PNG logs depending on the volume of bound brine [19].

In preparation to seismic MSP/VSP experiments numerical models were calculated, which helped to find boundary conditions for the survey design. In this framework it was possible to identify the receiver depths with largest amplitude changes (more than 5 %) depending on the offset, the dimension of density and velocity changes and the expansion radius of the $CO_2$ front. As expected, the amplitude changes during the replacement of the reservoir gas by $CO_2$ are very small. For a direct detection of the $CO_2$ front using the seismic wave field, large pressure and/or temperature changes would be required. The concentration of an active seismic monitoring in the Altmark must be focused on the appearance of possible leakages, which cause larger velocity changes. Tests with synthetic datasets showed that seismicity location with the diffraction summation method is possible. For this purpose four stations or rather four boreholes are necessary.

For $CO_2$ injection projects, stable isotopes and isotope mass balance calculations are new and promising tools to monitor migration of $CO_2$ plumes and to accurately quantify the amount of $CO_2$ dissolved in water respectively [20]. The baseline monitoring of the Altmark site yielded a good overview of baseline variations of the DIC (dissolved inorganic carbon) and isotope values, which are clearly distinguishable from the $CO_2$ to be injected. Laboratory results revealed theoretical trends. They indicate that with high $pCO_2$, $\delta^{13}C_{DIC}$ and $\delta^{18}O_{H2O}$ add up as valuable monitoring tools for different respective intervals of DIC concentrations. In these applications of isotope monitoring, fractionation plays a major role as they influence the isotope ratios resulting from dissolution and speciation processes. Thus, the determination of their temperature and pressure dependence as well as the influence of salinity are important to hone isotope techniques to serve as accurate tools for the assessment of CCS reservoirs before and after injection.

The microbial community of the 3.5 km deep nearly depleted gas reservoir was analysed by molecular genetic techniques. Comparative analysis of the fluid samples from three different wells, which differ in their temperature profiles and operative history are presented. DNA fingerprinting indicated the presence of microorganisms similar to previously identified microbes from thermophilic and anaerobic environments in deep hypersaline and hot reservoir environments. Phylogenetic analyses revealed a high microbial diversity including different $H_2$-oxidising bacteria (hydrogenophaga, acidovorax, ralstonia and pseudomonas), thiosulfate-oxidising bacteria (diaphorobacter), dissimilatory metal reducers (pantoea), aromatic-degrading deep sediment inhabitants, (sphingomonas), extremophiles (bacillus), and biocorrosive thermophilic microorganisms. Additionally several sequences of microorganisms similar to representatives from different saline, hot, anoxic, deep environments were detected, which had not been cultivated previously. Cell numbers of SYBR Green total cell counts were less than 102 cells/ml and the cells were usually attached to particles.

### *2.5. Environmental and Process Monitoring*

The development and application of methods to monitor groundwater, vadose zone and atmosphere during the intended EGR measure at the Altmark site and to control the injection process was a major aim. If a $CO_2$ leakage should occur and $CO_2$ migrates upwards, shallow freshwater aquifers are the first protected good that might be affected. All current laws and regulations demand an “adequate monitoring”, but it will be an iterative discussion in the future between public authorities and scientists to define what should be measured, how often and where is the place of assessment. The CLEAN project contributes to this discussion by providing a compilation of measurement methods with sensitivities, applicability and costs. However, an unsolved issue is the large area which has to be monitored. Currently no techniques to monitor large areas are available and the application of observation wells would be expensive. Perhaps the air borne electromagnetic measurements, which were tested at the site, can provide a comprehensive detection method for $CO_2$ leakage in the future.

The recent groundwater and sediment composition at the site was documented in terms of a baseline monitoring. It was an important result that the temporal fluctuations of groundwater composition are generally small, but spatial variations are large. At least at this site not much time is required in advance to the $CO_2$ injection to determine a baseline, but many observation wells are recommended.

A geological structure model for the upper aquifers was compiled from literature and borehole data. The structure model was the basis for a numerical flow model and for multiphase flow simulations. The numerical simulation of a $CO_2$ gas phase spreading in a shallow aquifer demonstrate that $CO_2$ gas and dissolved inorganic carbon should be expected and measured in the upper part of a confined aquifer. They also show that $CO_2$ gas will follow the steepest gradient of the overlying aquitard and accumulate in anticlinal structures, while the dissolved inorganic carbon migrates in groundwater flow direction. The aquifer volume, where geochemical shifts due to $CO_2$ intrusion are possible, is defined by the sum of gas phase body and the plume of dissolved $CO_2$ spreading in flow direction.

If the $CO_2$ leakage rate is sufficiently large to penetrate the overlying aquifer structures, it migrates into the vadose zone. Here the $CO_2$ can be measured before it discharges into the atmosphere. Within the CLEAN project a technique was developed and applied to measure the $CO_2$ concentration in the soil and to transfer the measured data wireless to the receiving scientists. The $CO_2$ concentrations in the soil are temporarily variable due to microbial degradation of organic carbon. Continuous measurements below the microbially active zone for at least two years in advance to a $CO_2$ injection are recommended to determine a baseline. The $CO_2$ concentrations also vary spatially. Currently it is not known how many soil measurements are required for reliable leakage detection at the site.

$CO_2$ can leak through the geological formation into the atmosphere, but it can also be released due to accidents at the surface facilities. Only very few investigations exist how $CO_2$ might spread in the atmosphere and where hazardous concentrations are reached. Several simulations have been performed for different release scenarios to support the risk assessment at the site. The simulations demonstrate that very simple recommendations can improve safety, like turning the exhaust of the safety valves vertically upwards to enhance mixing in the atmosphere. Additionally a method was developed to colour $CO_2$ in the atmosphere. This is an innovative method to investigate $CO_2$ spreading in the atmosphere, but a large scale application e.g. colouring the $CO_2$ injected at an EGR or CCS site is questionable.

The CLEAN projects of the thematic network investigated many different single aspects for monitoring of atmosphere, vadose zone and groundwater. The next stage should be a coherent monitoring concept for a whole site. An intensive discussion between legal authorities and scientists will be required to harmonize what is technically possible and what is socially and legally expected.

## 3. Summary and conclusion

Work carried out under the joint research project CLEAN led to a comprehensive evaluation of the EGR potential of the Altmark field [4]. Digital databases and models were developed and the well integrity, potential production as well as consequences and risks of the EGR technology at the Altmark site were compiled. It was also possible to document, summarize and assess the major in-situ processes occurring in connection with $CO_2$ injection in the depleted gas reservoir. The development and testing of different monitoring techniques facilitates improved surveys of $CO_2$ storage sites. This not only increased the knowledge about EGR and $CO_2$ storage but as well of the deep underground in general (e.g. geothermal reservoirs, exploration of hydrocarbons). In addition to that, the results of the joint research project provide the technological, logistic and conceptual preconditions for implementing an EGR pilot project with $CO_2$ injection at the Altmark site [3]. This conclusion is underlined as well by the "Theoretical test case of the injection of 100 kt of $CO_2$ into the Altmark depleted gas field" [4]. Feasibility of such pilot injection is further emphasized by results from [21] who state that safe storage and effective monitoring of $CO_2$ in depleted gas fields is possible based on their results from the Otway site in Australia.

The optimized use of the potential subsurface storage capacity and the reduction of risks during future EGR and $CO_2$ storage projects are the main economic benefits of the work carried out. However, the economic success of the accomplished work will largely depend on the political developments over the next few years and decades.

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