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Development of a monitoring plan for the Vedsted structure in Denmark

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Abstract

Vattenfall is considering a Carbon Capture and Storage (CCS) project in the North Jutland region of mainland Denmark. The project would involve the post-combustion capture of CO_2 from the Nordjyllandsværket coal fired power plant at Aalborg followed by geological storage of the CO_2 in a nearby, onshore, saline aquifer within the Vedsted structure. A thorough monitoring plan is considered to be an essential element of the start-up phase of the project based on risk evaluation. This paper describes the first design of such a monitoring plan that was developed for Vattenfall by a team from CO2GeoNet in discussions involving the company and the Danish Geological Survey (GEUS). The monitoring methodologies to be deployed include downhole tools via a monitoring well, 2D and 3D surface seismic for subsurface imaging of the plume, shallow geophysics for the fresh-saline water interface and surface, atmospheric and remote sensing tools for leakage integrity.

Keywords: CO_2 storage; saline aquifer; onshore; monitoring;

Introduction

This paper describes an initial concise monitoring plan for the proposed CO_2 storage in the Gassum Formation, a saline aquifer at Vedsted, North Jutland, in Denmark. The Vedsted structure was identified by the Danish Geological Survey (GEUS) as a possible candidate for geological storage of CO_2 [1]. It is an anticlinal closure within a fault block. The closure includes several sandstone reservoirs of good quality at depths of 1100-1900 m. A number of thick claystone intervals, hundreds of metres thick, provide an excellent caprock above the reservoirs. Additionally, several hundred metres of chalk provide a secondary seal. The storage capacity of the Vedsted structure has been provisionally estimated by GEUS at 161 Mt of CO_2 based on an analysis of existing data. Based

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on the current state of knowledge of the site, an initial risk and performance assessment was carried out by Det Norske Veritas [2]. The three main critical risks identified at this storage site are related to:

1. The abandoned Vedsted-1 well
2. Uncertainties due to limited reservoir characterization (requiring more detailed characterisation of the Gassum Formation).
3. Uncertainties and lack of understanding of the properties of the bounding fault zones (requiring a thorough investigation of the faults and their properties).

Investigations are ongoing on safety measures for the Vedsted-1 well, as part of the CO2WELLS joint industry project. Regarding the other two issues, one of the main concerns is the potential (local) pressure build-up in the reservoir and the spreading of the pressure field. Although the amounts of CO_2 planned to be injected (1.8 Mt y^{-1} , [3]) are in the range of other proposed projects, they are larger than current demonstrations such as Sleipner and In Salah (e.g. [4] & [5]), and there could be consequences from this upscaling; potential risks related to pressure build-up are caprock integrity and reactivation of faults, which require the serious consideration of a wide range of health, safety and environmental aspects. An additional risk, which is related to ongoing efforts on defining CO_2 storage capacity standards, is the actual CO_2 storage capacity of the Vedsted storage structure.

Injection into the Vedsted structure has been simulated for a 30 year period [6]. These simulations are an important basis for the development of a detailed monitoring plan. Different scenarios have been developed corresponding to different monitoring aims and to various options such as the availability of a monitoring well. A time-schedule for the application of the various monitoring tools is provided over the full period of injection and for a short period before and after. Specific locations for the monitoring tools have been proposed. This monitoring plan is a first version (referred to as version 0) based on the current state of knowledge and is expected to be updated as site characterisation and predictive modeling improves.

1. Aims of monitoring and scenario development

The simulations performed by [6] are the basis for the development of a detailed monitoring plan. The following aims for monitoring have been considered in this plan based on risk evaluation: Spreading of the plume (1), sealing behaviour of the caprock (2), fault integrity (3), spreading across spill points (4), shallow variations in CO_2 content (natural or indicative of leakage)(5), groundwater quality (6), ground movement (7) terrestrial and marine ecosystem quality (8).

For the first four aims, in particular, the link with predictive flow simulations will play an essential role, both in calibrating and providing confidence in the models. Well integrity has not been considered as part of the monitoring plan in this paper, since well design will be done at a later stage of the project development.

For each of the specific targets, different monitoring scenarios have been developed. This has led to five main scenarios, most of which have been subdivided into different sub-scenarios dependent on either choices to be made (e.g. whether there is a monitoring well) or on the spatial coverage (e.g. locally vs. globally). The first set of scenarios addresses plume tracking and demonstrates the integrity of the caprock. The second set of scenarios deals with fault integrity. For shallow monitoring, recommendations have been made for near surface gas monitoring, shallow groundwater monitoring, remote sensing and marine monitoring in the remaining set of scenarios. The following sections describe the different monitoring options per category of monitoring techniques.

1.1. Geophysical measurements in the injection area

The first three scenarios (figure 1) address plume tracking and caprock integrity. The optimal way of achieving these aims is by time-lapse seismic data. In any case a full baseline 3D seismic survey will be acquired covering an area of approximately 60 km^2. Several options for geophysical monitoring are available. A rather detailed image of the subsurface could be acquired through a 3D offset-Vertical Seismic Profile (VSP). Typically an image with a radius of about 500-800 m around the well could be obtained. The VSP would be acquired preferably from the injection well, or from a monitoring well placed near the injection well (typically < 500 m away) in order to cover the whole plume development in the early years. Besides the 3D offset-VSP a limited 3D seismic survey is recommended. This survey could cover the initial plume development over a period of about 2 years. For this initial period, one could potentially choose between a limited repeated 3D survey and repeated 3D offset VSP. However, it is recommended to acquire both. The overlapping area between the two methods will be of great help in characterizing the seismic signal, which would be very useful in later years, when plume tracking can no longer be covered by the 3D offset VSP.

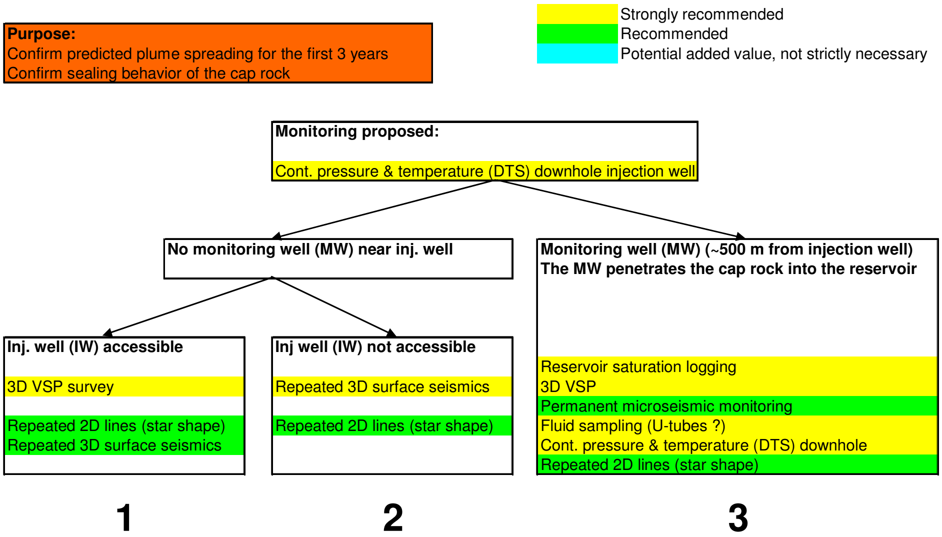

Figure 1: Monitoring scenario near the injection point to confirm plume spreading in the reservoir and to confirm sealing behaviour of the cap rock. Three options have been considered: The first option has no monitoring well, but the injection well is accessible for monitoring, the second option has no well access at all for monitoring and the third option includes a dedicated monitoring well close to the injection well (<500 m).

A final alternative would be 2D seismic lines instead of 3D acquisition. This is not recommended at the early stage, where the accurate detection of plume spreading is crucial for initial calibration of the predictive models. 2D lines do not provide the full spatial coverage and suffer from imaging effects such as side-swipe. However, in view of the difficult acquisition conditions in the area, 2D lines in combination with 3D offset VSP data from the injection well might be considered for the first 4 years and baseline 2D data is therefore recommended to keep this option open.

In general the same arguments used above for plume tracking hold for demonstrating the integrity of the cap rock. This will be demonstrated by absence of time-lapse changes in signal in the overburden.

In addition to the 3D offset VSP, microseismic monitoring is recommended if a monitoring well is available. The aim of the microseismic monitoring would be to pick up signs of induced geomechanical effects in the reservoir and caprock which may ultimately compromise containment integrity. This requires permanent geophones in the borehole. Microseismic monitoring from the surface to detect plume spreading or cap rock breaching is not expected to give useful results, however a more detailed analysis might be carried out to investigate this further.

1.2. Monitoring well

Besides geophysical methods, like VSP and microseismic monitoring, a purpose-designed monitoring well penetrating the caprock into the reservoir would allow more direct measurements of CO_2 in the form of saturation logging (e.g. RST) and fluid sampling to detect CO_2 and to understand the vertical distribution of the plume and dissolution effects [7]. Moreover, the well would allow direct pressure and temperature measurement in the reservoir at a distance from the injection point [e.g. 8]. Such measurements would be very useful, both for calibration purposes and for assessing caprock integrity. Measurements in a monitoring well would also provide insights into the long-term behavior of CO_2 (dissolution, convection, mineralization, etc), supporting the best abandonment strategy.

In the case of detailed geophysical imaging during the initial 2-4 years, through either limited repeated 3D seismics or via 2D / 3D offset VSP surveys, it is recommended that the monitoring well is placed outside the "imaged" area in the direction where flow is expected (updip). The optimal location in our view is the crest of the structure, since this is where the CO_2 will likely accumulate and where the maximum vertical column of CO_2 is expected. By repeated logging/sampling measurements, dissolution effects relevant for assuring long term containment could be followed closely.

1.3. Monitoring faults and spillpoints

The primary measure of fault integrity, other than by very detailed core-based characterization, is by geophysical seismic methods (figure 2). Again, if no monitoring well is available near the fault, either repeated 2D lines are recommended or, preferably, a limited repeated 3D survey. By the time fault integrity needs to be evaluated, the detectability of CO_2 on seismic data will have been assessed in the area near the injection point. Based on those results it should be possible to judge, whether repeated seismics are sufficient to identify potential leakage at the fault zone or not. In the latter case a second monitoring well would be recommended. As for the first monitoring well, this well could be used for direct measurements near the fault zone, for offset-VSP imaging and for microseismic monitoring. Microseismic monitoring from the surface to detect potential movement along the fault plane is recommended if no monitoring well is drilled.

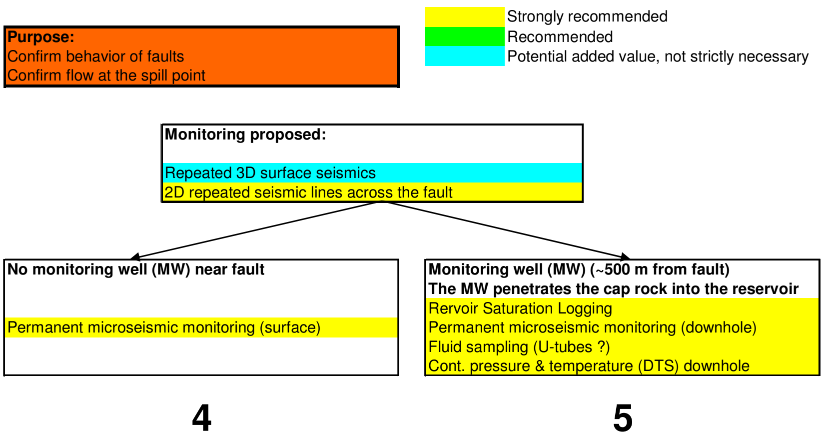

Figure 2: Monitoring scenario near fault zone to confirm sealing behaviour of the faults and flow across spill points. Two options have been considered: The first option has no monitoring well, the second option includes a dedicated monitoring well close to the fault zone (<500 m).

1.4. Surface gas

Surface gas measurements [e.g. 9] are proposed at three different spatial scale (figure 3) s. This is described in more detail below considering the most likely plume spreading as indicated in the last section of this paper.

1.4.1. Monitoring of large area

This is recommended essentially for the area of the baseline 3-D seismic survey with regional gas concentration and flux measurements over the whole of the accessible area at a spatial sampling density of about 2-5 samples per km^2. Lower density observations would occur beyond the 3-D area to the bounds of the defined storage site. Baseline surveys would be followed by repeat surveys every 5 years during injection. Continuous monitoring of concentrations and flux would be made at selected background sites chosen on the basis of survey results and taking account of other factors such as security, access, power supplies etc. The 3-D seismic area is approximately 60 km^2, this would mean 120-300 soil gas sampling points within this area. The wider site boundary is about 160 km^2 or an additional 100 km^2, at a lower sample density this means another 50 -100 sampling points.

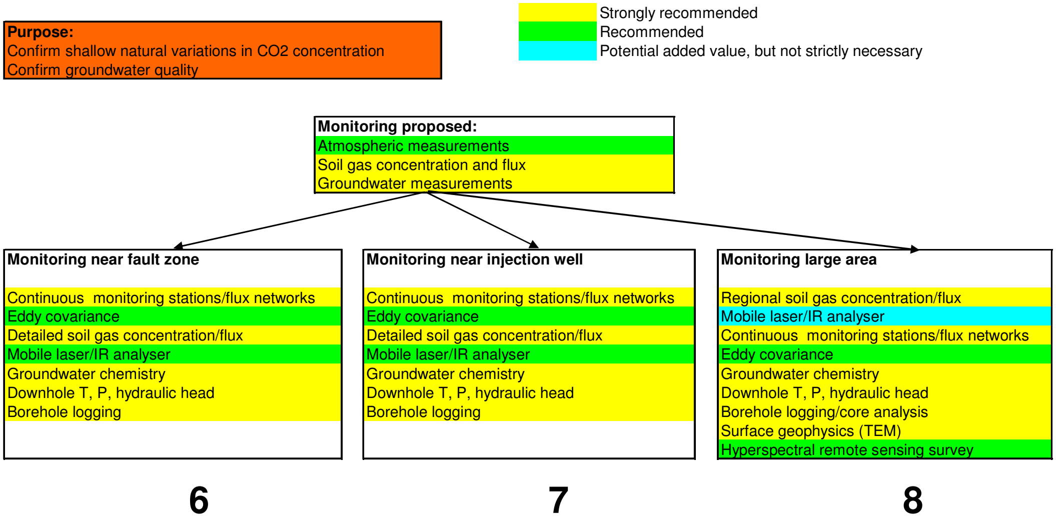

Figure 3: Monitoring scenario to confirm natural variations in CO2 concentration and to confirm groundwater quality. The monitoring approach has been split into three different areas, i.e. a detailed survey near the fault zone, a detailed survey near the injection well and a more sparse survey over the entire area of Vedsted.

1.4.2. Site specific investigations

Baseline surface gas studies are also recommended at the proposed injection and monitoring wells at an increased sample density using grids and horizontal traverses with sampling spacing between 20-50 m. Similar density sampling would also be made over the major faults concentrating in particular above those areas that modelling suggests will be impacted by the CO_2 plume, i.e. the northern part of the easterly fault, the central fault (as the plume gets close to this after 40 years) and those parts of the westerly fault closest to the modelled plume development (in case migration rates are more rapid than predicted). These areas would also be covered by more detailed measurements made with mobile open-path lasers and/or IR analysers [10]. All these surveys would continue into the first year of injection and at regular intervals of 5 years thereafter. Additional surveys could be undertaken if other monitoring indicated the possibility of leakage. Concentrations and fluxes would also be measured continuously at the well sites using autonomous stations and/or eddy covariance methods, and at selected points on the faults, both before and throughout injection. Some background sites, away from the predicted plume would also continue to be monitored.

1.5. Groundwater

This would also cover essentially the 3-D seismic survey area. TEM (Transient Electromagnetic Method) surveys are proposed over this area at a density of 15-20 per km^2 to delineate the fresh-saltwater interface. This survey could be repeated later if necessary. Four new boreholes would be drilled to 150-200 m depth into the Chalk in this area. One of these should be sited on the northern section of the easterly fault. All four would have the full suite of monitoring of T, P, hydraulic head, water chemistry and borehole logging. Baseline results might indicate a need for additional boreholes. Continuous logging of T, P and hydraulic head would continue in the wells during injection.

Borehole logging and water chemistry would be repeated on a 5 year cycle, although this could be increased if other monitoring indicated leakage.

1.6. Remote sensing

The 3-D seismic survey area would essentially be the area studied with these methods, although coverage could be easily extended over the entire storage site. Effectively the whole area would be covered at the resolution of the methods used. Point Scatterer Satellite Interferometry is proposed to examine possible ground movement arising from CO_2 storage [e.g. 5]. For this it would be important to ensure that there are sufficient point scatterers across the whole area (whether already present or by installing artificial corner reflectors, figure 4). In particular there will need to be enough located above the modelled CO_2 plume over the full course of its development, and across the major fault zones.

Hyperspectral imagery is suggested over the whole area at high resolution (1-2 m pixel size) but particular attention would be paid to vegetation stress above the developing plume and in the vicinity of faults, especially where these are intersected by the plume. Changes occurring in these area, which are not observed elsewhere, could be indicative of leakage. Ground measurements, including surface gas measurements, would be needed to support interpretation of the hyperspectral data and establish whether or not leakage was occurring. Further ecological monitoring is not considered in this study. Sensitive areas (such as Natura 2000 sites) would be a focus of more detailed investigations.

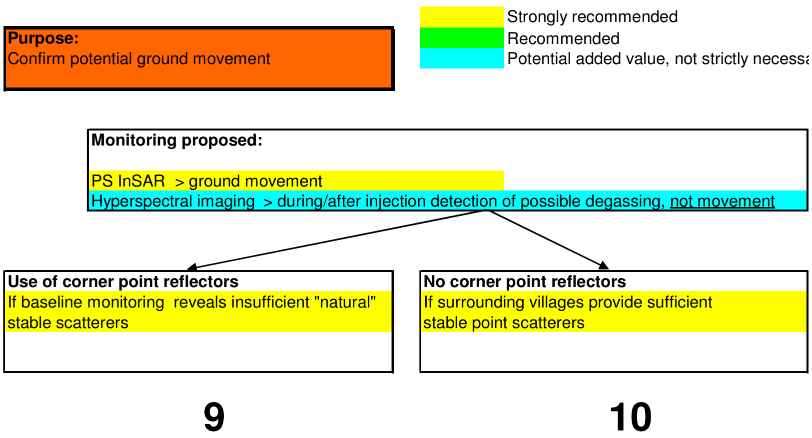

Figure 4: Monitoring scenario to confirm potential ground movement. The monitoring approach has been split into two separate cases. The first case requires the placement of corner point reflectors, whereas the second case does not require any active placement of corner point reflectors.

1.7. Marine

In principle the modelled development of the CO_2 plume, and the extent of the known faults, does not extend to the offshore area. The offshore monitoring proposed includes: direct gas detection, examining changes in seabed morphology, pH measurements in seawater and an assessment of impacts on vertebrate, invertebrate and microbial communities. Baseline surveys would describe the fauna/flora and identify sensitive or rare species that would be a focus of subsequent monitoring. Changes in biodiversity and the behavior or mortality of organisms would be assessed. Shipboard, ROV and fixed mooring observations are suggested, with the use of video cameras, CTDs, sampling of water, sediment and biota and continuous gas monitoring stations. For the first 3 years seasonally repeated surveys are recommended. The survey frequency is then likely to decline with time, perhaps to a 3-5 year repeat cycle.

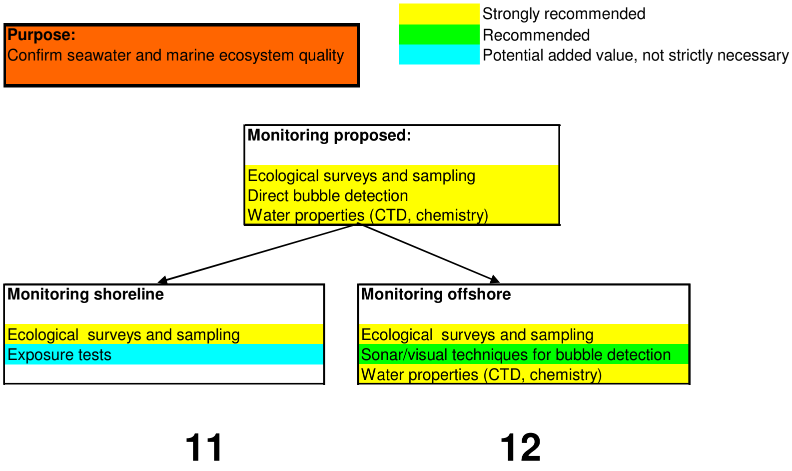

Figure 5: Monitoring scenario to confirm seawater and marine ecosystem quality. The monitoring approach has been split into two different areas, i.e. the shoreline and offshore.

2. Monitoring locations based on the expected plume spreading

Based on the expected plume spreading, a more detailed analysis of the locations for monitoring has been made, especially for the geophysical monitoring, where a brief additional description is given below. This section considers a scenario where there is a monitoring well close to a fault and relatively near the injection point. The monitoring well has been placed at the crest of the structure about 2.5 km from the injection well. This would give insight into the migration velocity of the CO_2 to the top of the structure, the pressure development at that location and the vertical saturation distribution of the CO_2 over the entire column. Furthermore this location is not too far away from a fault allowing both for time-lapse imaging and microseismic monitoring. Baseline data is strongly recommended for 2D seismic, 3D seismic and 3D offset VSP from the injection well and from the monitoring well (the latter referred to in the figures as 3D Walk-away VSP or 3D WVSP). After 2 years of injection a repeat 3D WVSP from the injection well is recommended. This should be accompanied by at least a 2D seismic repeat survey, but preferably by a limited 3D repeated survey. For the 2D seismics a star-shaped layout over the injection well is proposed to fully cover any preferential directional flow from the injection well. A number of parallel 2 D lines are also recommended covering the area most affected by the CO_2. A similar layout has been successfully deployed at Sleipner using 2D high resolution lines. After 5 years, a similar repeat 3D WVSP from the injection well is suggested, accompanied by at least a 2D seismic survey, but preferably by a limited 3D repeated survey. After 10 years the plume is expected to have reached the monitoring well. A 3D WVSP from the monitoring well is recommended. To cover the imaging of the entire plume, this should be accompanied either by a 3D WVSP from the injection well combined with 2D seismic lines or by a limited 3D seismic survey. After 20 years the plume will cover an extensive area. A repeat 3D seismic survey is proposed as a major 'mid-term' check. Potentially 3D WVSPs could be acquired from the monitoring well and from the injection well at the same time. When combined with 2D seismic lines, these could be an alternative to the 3D seismic data, though not covering the entire plume. Finally, a repeated 3D seismic survey is recommended at and/or after the end of injection (here assumed after 30 years). The exact requirements will depend on the actual and predicted configuration of the plume, and how the safety case for site closure is argued. Near the monitoring well a fault has been identified. Continuous microseismic monitoring from the monitoring well combined with one or two surface stations is recommended. For the shallow monitoring, note that the satellite monitoring would cover the entire area. Furthermore, in this particular case, no offshore monitoring would be required.

3. Choice of monitoring tools and priority

This section describes briefly the background to why a few techniques have not been proposed for the monitoring plan. Tracers have proved extremely useful elsewhere, for example in the K12-B reservoir [11], where resident CO_2 could not be distinguished from injected CO_2. In Vedsted however, injection would take place in a virgin aquifer, so the CO_2 can be considered as a tracer itself. In the case of more than one injection well tracers should definitely be considered to identify where any CO_2 seen in monitoring wells has come from. Repeated surface EM for deep characterization is not considered in this study because of its low resolution compared to repeated seismic data and its difficult application onshore. 4D gravity has been applied with some success at Sleipner [12], but its resolution is much lower than for seismics and severe constraints are required on the acquisition for repeatibility. The technique is definitely interesting for demonstration purposes, but could not replace repeated seismic data. Crosswell EM is not considered suitable, since it requires two accessible wells within an acceptable distance (<1000 m apart).

4. Conclusions

This paper describes an initial design of a monitoring plan for the Danish Vedsted saline aquifer site. The recommendations have been split into deep (geophysical) and more shallow monitoring. The strategy developed is based on current predictive models of plume spreading and will be adapted as more data becomes available and models are refined.

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