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CO_2 storage development: status of the large European CCS projects with EEPR funding

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Abstract

This paper presents an overview of the CO_2 storage element of the projects that are part of the European CCS Demonstration Project Network, an FP7 funded project to support the knowledge exchange among the CCS projects that have received funding under the EEPR framework. These projects include the ROAD project (The Netherlands) and the Don Valley project (UK). The Hontomín project (Spain) can be regarded as the third project, as it was developed as the research site for the Compostilla project in Spain; the Compostilla project, also a beneficiary of EEPR funds, was discontinued in 2013 after completing FEED studies. The Sleipner project joined the Network in 2011 and provided its experience and expertise to the EEPR funded projects. Together, the projects in the Network cover a wide range of storage options, from a depleted gas field to saline sandstone and carbonate formations. The ROAD project uses a compartment of an offshore depleted gas field, and the Don Valley project is developing an offshore saline aquifer. The Hontomín site, dedicated to research, uses an onshore carbonate reservoir. This paper gives an overview of the storage solutions developed or under development by these projects.

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1. Introduction

The European CCS Demonstration Project Network was established in 2009 by the European Commission with the objective of accelerating the deployment of safe, large-scale and commercially viable CCS projects. The Network facilitates knowledge sharing amongst the demonstration projects and leverages experience from the projects in order to gain public confidence in the potential of CCS. The successful operation of these demonstration projects is seen as crucial for enabling the widespread commercial application of near zero emission power plants or industrial installations by 2020 to allow Europe to reach its environmental objectives, stimulate job creation, and generate a sustainable economic and industrial base.

The Network currently consists of 3 large-scale integrated projects: ROAD (The Netherlands), Don Valley (UK) and Sleipner (Norway). The fourth Network member is the Hontomín project (Spain), which is a research-oriented site. The Network is composed of one post-combustion power project, one IGCC power project and a gas processing, amine capture project, all capturing or planning to capture over 1 $MtCO_2$/yr. Sleipner is the only project currently in operation.

The power plant projects received European Energy Programme for Recovery (EEPR) funding and were founding members of the Network. The Sleipner oil and gas project joined the Network in 2011. Four other power plant projects: Janschwalde (Germany), Bełchatów (Poland), Compostilla (Spain) and Porto Tolle (Italy) have left the network since 2012 because they were discontinued.

The knowledge sharing is facilitated by a secretariat led by the Global CCS Institute and supported by IFPEN, SINTEF and TNO.

The activities of the network mainly consist of semi-annual knowledge sharing events focusing on themes such as CO_2 transport, CO_2 storage and CCS policy, legal and regulatory issues. Specific workshops have also been organized on selected topics such as communication and public engagement. Detailed reports are compiled by the secretariat for the benefit of the Network members. A public version of these reports is made available to the general public on a portal from the EU Commission (www.ccsnetwork.eu).

This paper discusses in detail recent activities at the sites, briefly outlined above. The lessons learnt that are relevant to other CO_2 storage projects will be highlighted, such as the cost savings in drilling the wells at the Hontomín site. Special attention is given to the design of the injection and monitoring facilities. The different types of storage location used by these projects renders the results relevant to most other CO_2 storage projects.

2. ROAD project

2.1. Project overview

ROAD is one of the largest integrated Carbon Capture and Storage (CCS) demonstration projects in the world. It is widely recognized as the most promising CCS project in Europe. ROAD applies post combustion technology to capture the CO_2 from the flue gases of a new 1,100 MWe coal-fired power plant (Maasvlakte Power Plant 3) in the port and industrial area of Rotterdam. The capture unit has a capacity of 250 MWe equivalent and aims to capture 1.1 Mt of CO_2 per year. The capture installation is planned to be operational in 2017.

From the capture unit the CO_2 will be transported through a new insulated pipeline: 5 kilometers over land and 20 kilometers across the seabed to the P18-A platform in the North Sea (Fig. 1). The pipeline has a transport capacity of around 5 Mt/yr.

2.2. Storage reservoir

ROAD plans to store the captured CO_2 in one of the depleted pressure gas reservoirs under the North Sea. The gas reservoir is located in block P18 of the Dutch continental shelf, approximately 20 kilometers off the coast. The depleted gas reservoir is at a depth of around 3,500 meters under the seabed of the North Sea. The CO_2 will be injected from the platform into the depleted gas reservoir. The estimated storage capacity in the three P18 reservoirs (P18-6,-4 and -2) is approximately 35 million tonnes. ROAD will use the P18-4 reservoir for CO_2 storage. The P18-4 reservoir has an estimated storage capacity between 7 - 8 Mt.

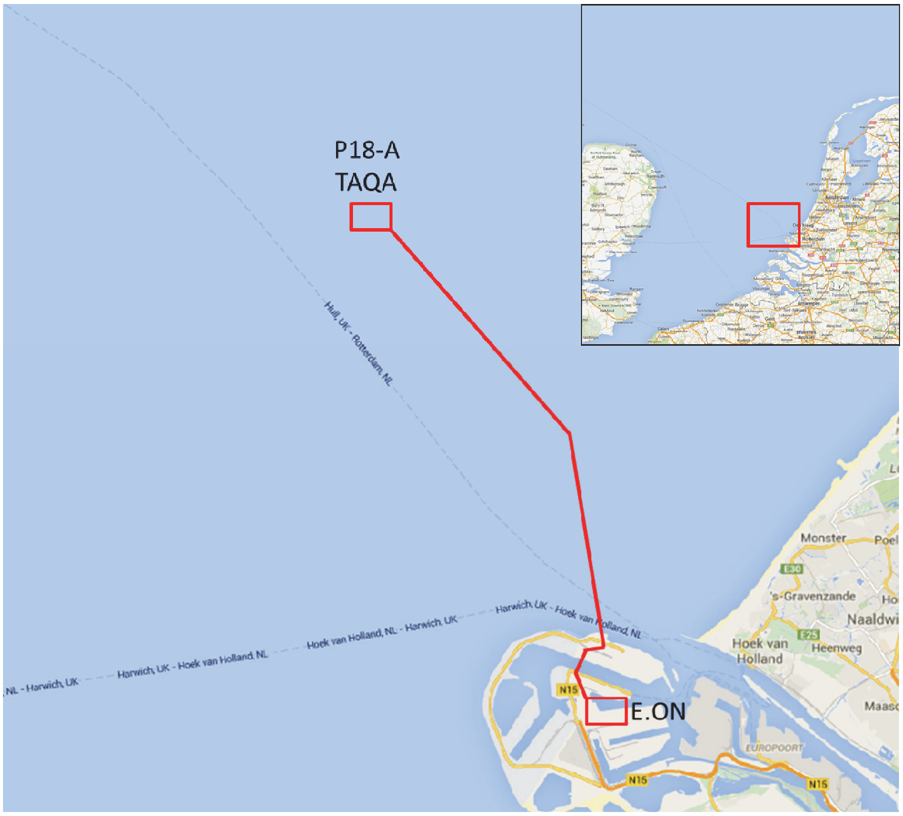

Fig. 1. Approximate lay-out of the ROAD CCS project. The EON power plant is located in the Rotterdam harbor area ('E.ON'); the transport pipeline is indicated in red; the storage location is the P18-4 depleted gas field; the platform is located in the red box labelled 'P18-A'.

At the start of operation the reservoir pressure will be low (10-20 bar). With limited space available to install a heater on the platform, the ROAD project will build an insulated pipeline to transport the CO_2 warm (40-80 °C) to avoid hydrate formation. Various studies (e.g., [1]) identified the range of CO_2 transport and injection conditions at which two-phase flow could occur. The operating philosophy is to minimise the period of time during which two-phase CO_2 will be flowing across the platform and into the well. Injection of liquid CO_2 slugs may occur under system start-up conditions, but the forces that these might exert will be taken into proper account through the design, construction and operation of the pipeline and platform and well facilities.

The injection facility is the P18/A platform. The well protector platform dates from the early 1990s and is a six-slot, four leg jacket, normally unattended installation (NUI). The platform is controlled from the nearby P15 platform and/or from shore. The six wells are currently producing natural gas from three reservoirs. The wet gas is transported to the P15 platform for further processing and transport to shore. The P18-4A2 well is the only well producing natural gas from the P18-4 reservoir; it will become available for workover to adapt to CO_2 injection in approximately 2016. The P18-4A2 well was drilled in 1991; it came on-stream in 1993 and has a total drilled depth of 4,352 m (true vertical depth 3,303 m). Based on completion data when the well was installed as well as subsequent inspections and production data over the last decades, there are no reasons to suspect significant well degradation over time.

In the P18 block, the reservoir is formed by sandstone layers from the Triassic period (Bunter sandstone). The reservoir sandstones were deposited in a semi-arid continental basin by rivers and wind. The total reservoir interval is about 200 metres thick. The storage site consists of the P18-4 reservoir (see Table 1). Within this Bunter reservoir, four units can be distinguished (see Table 2): the Hardegsen, Upper Detfurth, Lower Detfurth, and Volpriehausen layers. The P18-4A2 well is part of the storage site as well, up to the control valve on the platform.

Table 1. Reservoir characteristics of the P18-4 reservoir

Characteristic	Value	Unit
Initial reservoir pressure	348.5	bar
Reservoir pressure at end of production	approx. 20	bar
Reservoir temperature	117	°C
Depth (top of reservoir)	3,220	m TVDss (True Vertical Depth subsea)
Thickness of Bunter reservoir	approx. 200	m
Condensation proportion	70	m^3 per million m^3 natural gas
Average porosity	10	%
Produced volume of gas	2.9	bcm
Total volume of gas initially present	3.2	bcm

Table 2. Reservoir units in the P18-4 reservoir

Reservoir unit	Thickness (m)	Permeability (mD)	Porosity	Remarks
Hardegsen	24	207.0	0.131	Most permeable zone
Upper Detfurth	53	0.8	0.092	
Lower Detfurth	19	0.1	0.065	
Volpriehausen	101	< 0.1	0.049	Least permeable zone

2.3. Storage complex

The storage complex is related to the reservoir and all areas that could possibly come into contact with CO_2 as a consequence of the injection of CO_2 into reservoir P18-4 (the storage site). The storage complex comprises the following areas:

- the storage site or storage reservoir P18-4.
- all geological layers above the storage reservoir up to the base of the Chalk Group, consisting of the Upper Germanic Triassic Group, Altena Group, Schieland Group, Rijnland Group, and aquifer intervals Rijn/Rijswijk sandstone, Holland Greensand, and Texel Greensand.
- the formations below the storage reservoir, consisting of Rogenstein and Main Claystone.
- the fault zones around reservoir P18-4.
- the P15-9 reservoir, from which the P18-4 storage reservoir is separated by a fault zone.

The P18-4 reservoir is entirely surrounded by faults (Fig. 2). The faults that form the eastern, southern and western borders of reservoir P18-4 are sealing, because these faults have a significant vertical movement. Due to this, reservoir rock is present on the one side of the fault and on the other side of the fault there is non-permeable claystone from the Triassic or Jurassic periods.

2.4. Fault zone between P18-4 and P15-9

The fault north of the P18-4 reservoir forms the border with the gas reservoir P15-9. The vertical movement of this fault is not as large. The P18-4 Bunter reservoir sandstone possibly partially borders here on similar Triassic reservoir rock of reservoir P15-9 (reservoir juxtaposition). On the seismic cross-section, the thickness of the reservoir (approx. 200 m) is approximately equal to the fault displacement (approx. 170 – 230 m). On the basis of the seismic research, there is a maximum juxtaposition of around 30 m on the northwest end of the fault between P18-4 and P15-9, while on the southeast end of this fault there is no juxtaposition. Juxtaposition would bring the top reservoir zone of P18-4 (Hardegsen, with high permeability, 207 mD) into possible connection with the lowest reservoir zone (Lower Volpriehausen, with extremely low permeability, <0.1 mD) of P15-9. The possible presence of reservoir juxtaposition means that connectivity is possible between reservoirs P18-4 and P15-9 if the fault zone itself is not gas tight and the low permeability allows flow of gas. CO_2 migration from reservoir P18-4 to P15-9 can only occur if there is reservoir juxtaposition in combination with a non-gas tight fault zone and adequate permeability to allow gas flow.

There are good arguments for believing the fault to be gas tight. On the basis of the pressure measurements during the production phase, there is no reason to doubt the gas tightness of the fault zone between reservoirs P18-4 and P15-9, because the pressure development in both reservoirs behaved differently over time. The fact that this pressure difference is maintained during production indicates that the fault between reservoir P18-4 and P15-9 is gas tight. Then there is also a difference in composition of the gas in each reservoir. Based on these facts, there is no indication that there is any communication between the two reservoirs (at any rate, not during the production phase). Substantial research has been conducted into the nature of the rock in the fault zone. The fault zone is a gouge and the forces involved during its formation will have reduced the constituent grains to an extremely fine size. Such material is expected to act as a complete and permanent seal.

When CO_2 is injected into reservoir P18-4, a new situation will arise. The injection of CO_2 under ROAD will make the pressure in reservoir P18-4 rise again, with a maximum reservoir pressure of 250 bar (well below the original reservoir pressure of 348.5 bar). As is now anticipated, no CO_2 will be injected into reservoir P15-9. This reservoir will reach the end of its production phase in the coming years, after which the pressure in this reservoir will remain relatively low (approx. 20 bar). Based on these facts, no communication between the two reservoirs is expected.

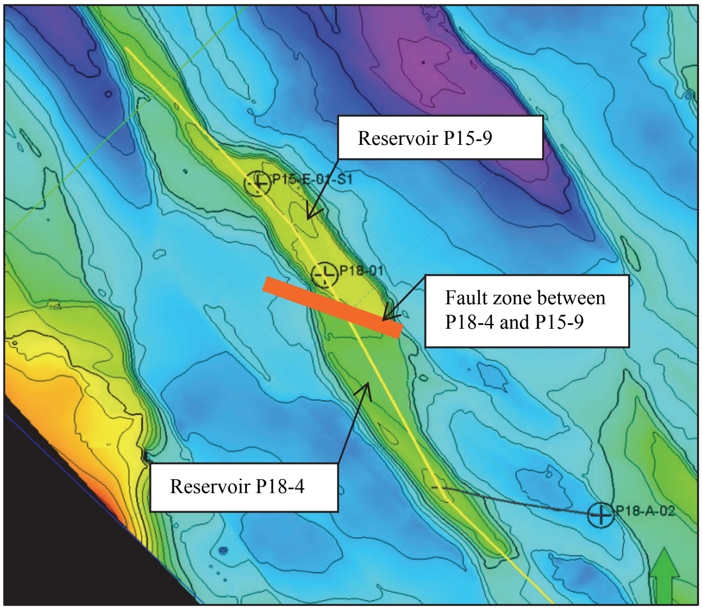

Fig. 2. Detailed representation of the P18 reservoirs, showing the fault zone between reservoir P18-4 and P15-9 (source: TNO).

When CO_2 is injected into reservoir P18-4, a pressure difference will be created across the fault zone that can increase to a maximum of 230 bar. In the pre-production situation (before commencement of the gas extraction) and during the production phase, this kind of pressure difference has not yet occurred. Based on the pressure measurements and gas compositions during the production phase, there is no reason to doubt the gas tightness of the fault zone between reservoirs P18-4 and P15-9. However, a supplementary study has been carried out, the most important findings of which are:

- Seismic research into possible juxtaposition of the reservoirs resulted in the finding that there is no juxtaposition in the southeast, but that it cannot be excluded in the northwest. In the northwest, the juxtaposition could reach a maximum of 30 m.
- Geomechanical research has shown that the fault at the location of possible reservoir-reservoir juxtaposition (northwest section) has been reactivated (hundreds of millions of years ago). The fault zone started as a normal fault and then reactivated as a thrust fault. Due to this, a cataclastic gouge (paste) was formed in this fault zone.
- The presence of this gouge at the location of the possible reservoir-reservoir juxtaposition (northwest section) means it is very likely that when the reservoir is filled to a pressure difference of around 300 bar, no migration of CO_2 will occur.
- In the southeast part of the fault no CO_2 migration can take place, because of absence of reservoir juxtaposition.

In the extremely unlikely situation where CO_2 would flow between the reservoirs and eventually equalize over millions of years, the final reservoir pressure in both reservoirs would be approximately half of the 230 bar referred to above. The overall conclusion is that the P15-9 reservoir has good potential as a CO_2 storage site.

3. The Don Valley project

The Don Valley project is developing an offshore saline formation (5/42) in the Southern North Sea (SNS), in combination with a CO_2 EOR project in the Central North Sea. While the Don Valley EOR project is to utilize the CO_2 for enhanced oil production, the saline formation is envisaged to provide anchor storage capacity, storing CO_2 when there is no demand from the oil field. The volume to be stored is close to 5 Mt/yr. Approximately half of that volume will be captured in the first phase of development, with 100% of the CO_2 intended for storage in the 5/42 saline formation. This paper discusses the saline formation project; the EOR project is currently put on hold and not discussed here.

3.1. Don Valley saline formation project

National Grid is playing a leading role in the development of the CCS industry in the UK through its 100% owned subsidiary National Grid Carbon Ltd (NGCL). Its primary focus is on the development of shared infrastructure in the Yorkshire and Humber area, which has the potential to bring together a large concentration of emitters and connect them to large subsurface saline formations in the Southern North Sea (SNS). This region has the highest concentration of CO_2 emitters in the UK, equal to around 10% of the UK's total emissions, and analysis shows there could be a reduction of around 40% in the transport and storage costs per tonne of CO_2 for two commercial scale capture projects sharing that infrastructure, compared to separate solutions.

NGCL assessed all potential offshore storage sites in the SNS (both saline formations and hydrocarbon fields), using extensive 3rd party 2/3D seismic data and well data. This led to the identification of 5/42 as the best anchor store for a CCS cluster development in the region against five criteria: capacity, integrity, injectivity, proximity and data availability. An appraisal well was drilled to confirm formation characteristics and to provide direct measurements of reservoir and caprock quality. The saline formation has a capacity greatly in excess of that required for the Don Valley project and is expected to receive CO_2 from multiple emitters via a high capacity CO_2 trunkline. It is envisaged that 5/42 will act as an offshore hub to supply CO_2 to other locations, including acting as an enabler for CO_2 EOR. The Energy Technologies Institute partnered with NGCL in the appraisal programme and incorporated the learnings into the UK CO_2 Storage Evaluation Database (CO2 Stored) which they have developed with the British Geological Survey and The Crown Estate (TCE).

NGCL created a subsidiary (National Grid Twenty Nine Ltd - NG29) to act as the storage operator. NG29 was granted the first UK Carbon Dioxide Appraisal and Storage Licence the UK government in 2012 for the 5/42 storage site. This was necessary to drill an appraisal well and sets the framework for obtaining a Storage Permit for the full operation of the site. The term of the Licence is 8 years. TCE awarded an Agreement for Lease (AfL) in 2013. The work programme for this Licence consists of one firm appraisal well, which was fulfilled through the drilling of well 42/25d-3. The term of the AfL is 8 years to match the Storage Licence.

3.1.1. 5/42 modelling

A geological model (static model) and dynamic reservoir simulation model were built using 3rd party seismic and well data that were subjected to a full petrophysical analysis. The overall results indicate that a thick, relatively good quality Bunter Sandstone reservoir and Rotliegend Clay caprock is widely developed across the area of interest.

A key requirement of any CO_2 storage site is the ability of the top seal to retain the captured CO_2 through time. A coupled model, combining the dynamic simulation model with a geomechanical/thermal model, was built to calculate stress within the caprock and reservoir layers and to identify acceptable injection scenarios. This modelling addresses the possibility of thermal fracturing due to the injection of cold fluid. The original coupled model input data derived from 3rd party log data. A new phase of geomechanical modelling is now underway using the mini-frac and leak-off test data from the appraisal well and core analysis from the reservoir and caprock sections. Seismic and log data from the structure and surrounding wells have been analysed and confirm the extent of the Rotliegend Clay cap rock over the structure and its ability to provide a competent seal, with no evidence of fracturing or faulting seen in 3D seismic.

A comprehensive stratigraphic and structural framework was created from Top Rotliegend to seabed using available 3rd party data. Facies derived from a petrophysical study of offset well and seismic data include 4 types of cemented sand facies and two un-cemented facies. The Bunter Sandstone formation is difficult to subdivide due to a lack of fossil material and an absence of readily correlative shale intervals. Chemostratigraphy, using ratios of different elements within the rock, has established a clear reservoir zonation.

A geomodelling workflow (using Petrel) has been created to estimate gross rock volume (GRV) while varying top structure, spill level and isochore thickness. The workflow generated an estimated GRV range which was input into statistical simulation software, combining it with Net to Gross (N:G) and porosity distributions to create the net pore volume (NPV) distribution. The Monte Carlo simulation was run 10,000 times and showed that N:G has the greatest impact on volumetric uncertainty, varying the NPV range by -23% to +10%, with top reservoir structure as the next most significant uncertainty parameter, (varying the range by -16% to +11%). Porosity also has a large impact (-13% to +7%) while isochore thickness had a minor impact on the range. The NPV range will be updated to reflect changes to reservoir parameter distributions that fall out from the appraisal well core analysis.

Geophysical studies noted a seismic phase reversal proximal to the flanks of the structure; this has been interpreted as a boundary between good quality un-cemented sands on the crest of the structure and cemented poorer quality sands down-dip. Three alternative cementation models were created to test the sensitivity to different assumptions and to establish hypotheses to test with the appraisal well. Understanding of the cementation is not critical for the volumes planned for injection by the Don Valley project given the size of the store. However, it introduces an uncertainty into plans to fully exploit the pore volume in the store in future.

Results prior to incorporating the appraisal well data indicate that the prospective storage site capacity is sufficiently large to be permit injection of up to 10 Mt/yr of CO_2 for 20 years, so long as formation pressure can be managed.

3.1.2. Appraisal well (42/25d-3)

An appraisal well (42/25d-3) was drilled in mid 2013 to gain the remaining data required to characterise the saline formation and confirm its suitability as a CO_2 geological store. An extensive wireline logging and coring programme took place to gather information from the Bunter sandstone, the caprock and the overlying rock. The well programme also recovered water samples and pressure drawdown, build-up and interference test data. The drilling and testing activities were completed safely with no lost time injuries and the well was successful in delivering more than the minimum data required to complete the understanding of the storage site and surrounding geology. The quality of the recovered samples and data is excellent.

The logs were analysed to calculate reservoir property correlations and the results are consistent with results from offset wells on the structure and nearby. The core samples collected from the well (both the reservoir section and the caprock) have been subjected to conventional core analysis. The storage site has good reservoir porosity and permeability throughout the section, with no evidence that the pore space has been occluded by halite and/or other mineral cements. The petrophysical evaluation of the appraisal well data is being integrated to refine the rock properties interpretation, which will be used to update the assumptions in the static and dynamic models.

The analysis of multiple water samples obtained by the appraisal drilling programme showed the formation fluid is highly saline, sodium chloride dominated, brine with concentrations of common rock constituents, calcium, magnesium and sulphate. Isotopic analysis indicated the fluid was Triassic in origin and no evidence of hydrocarbons was detected. The logs indicate that the pore space is filled by saline water. The volume of gas associated with all the samples was insufficient to afford meaningful analysis and the abundance of all selected groups of bacteria was found to be below the detection limits.

Three Vertical Interference Tests (VIT's) were undertaken to determine formation permeability, identify barriers to vertical flow and quantify vertical to horizontal permeability ratio. The interpretation of the VIT's showed that there were no barriers to vertical flow over the intervals tested. The pressure drawdown test had a radius of investigation of 1.3km and detected no barriers or reservoir discontinuities.

Core samples are also undergoing special core analysis (SCAL) to determine CO_2-brine relative permeability properties at reservoir conditions and study the propensity for halite precipitation under scenarios of formation brine migration/replenishment. Geomechanical testing will establish the strength of the reservoir rock and the suitability of the caprock for long term containment of CO_2. A study to investigate the impact of particulate fines on well injectivity was also conducted.

The initial results from the appraisal well confirmed that the 5/42 storage site is suitable for the safe and permanent storage of CO_2. The data from this analysis and the ongoing core analysis feeds into the next design phase for the storage development and will be used as a critical part of the Storage Permit application.

3.1.3. Development Concept

It was identified that up to three deviated wells could be grouped from a single drill location while meeting the CO_2 injection requirements for the first phase of the storage development. The choice of drill location for the initial development has taken into account considerations of numbers of wells and well trajectory, sea bed conditions, spatial conflicts with other users, operational issues and other regulatory/ commercial considerations.

The capital cost of dry- and wet- tree solutions was found to be similar but a dry tree solution (wellhead platform) was adopted because of the need for operating flexibility in this first of a kind development, particularly to accommodate the need for well interventions. There is a possibility that halite precipitation will occur in the near wellbore region, which may require occasional water washing. The potential need for filtering of CO_2 to remove pipeline corrosion products prior to injection is also a significant technical uncertainty. A wellhead platform provides greater latitude for filtration, well water wash operations and offshore CO_2 venting, amongst other things.

A study was undertaken into materials issues downhole. In the upper part of a CO_2 injection well (above the packer), normal operating conditions are expected to be dry (apart from short-term water wash treatments where corrosion inhibitor and oxygen scavenger will be used) and non-corrosive so that carbon and relatively low alloy stainless steels can be used. In the lower part of the well, the potential combination of the injection CO_2 stream and the highly saline formation water could be extremely severe for metallic materials. A low oxygen specification (10 ppmv) has been set. This allows the use of 25Cr super-duplex stainless steel rather than more exotic material.

3.1.4. Monitoring Plan

A key component of the CO_2 storage scheme will be the ability to monitor the distribution of injected CO_2 over the life of the project and NGCL is considering various seismic acquisition technologies. Repeat surface-towed streamer acquisition appears the most economic proposition. However, sea bottom acquisition can provide higher data quality and potential future wind farm infrastructure could have a bearing on the feasibility of surface towed streamer acquisition. Sea bottom data acquisition appears very expensive upfront because of the effort involved in installing sea bed cables or nodes and the high cost of cabling but the cost of repeat surveys is much lower than with towed-streamer data acquisition. However the sea-bed seismic costs are more sensitive to the survey parameters than for corresponding surface-towed streamer estimates and it may be that data quality requirements only require a sparse grid over a restricted survey area. A preliminary rock physics evaluation has been undertaken to determine the expected change in elastic seismic properties that could be expected – and hence inform the survey parameters. Future studies will account for effective stress changes and potentially long term geochemical alteration of the rock frame, using geomechanical data from the appraisal well core.

The storage site may have a wind farm located nearby. As well as the potential physical obstacle to seismic acquisition this could create, the concern was raised of frequencies generated during wind farm operations interfering with seismic signals. NGCL commissioned a study to model the frequency spectra for a range of wind turbine scenarios. The study showed that a range of frequencies of significant amplitude occurred between 0 and ~ 50Hz. These frequencies and amplitudes are not thought to be a problem in reducing the coherence of towed streamer 3D data acquisition. However, signals of this magnitude may be an issue for long-term seabed based acquisition or borehole passive micro-seismic monitoring.

While undertaking the site survey for the appraisal well rig location, the offshore survey vessel also conducted a survey of the Bunter seabed outcrop at which is approximately 20 km from the edge of the storage site) and a magnetometer survey of the two abandoned wells on the structure. These data are being considered as part of the development of an MMC programme.

4. The Hontomín project

The Compostilla-Hontomin site is dedicated to research. Two wells were drilled and completed there in 2013: a monitor (H-A) and an injection well (H-I). Significant cost savings were achieved in the drilling process. At the end of 2013, the site was ready for the planned further work in 2014, which includes test injection of CO_2, continued monitoring and baseline monitoring.

4.1. Site description

This site was chosen after a careful site selection process, then leading to a precise geological characterization in order to acquire the baseline parameters and confirm the suitability to host the Technology Development Plant for CO_2 storage. It is currently starting operations, once site construction and characterization are finished.

A wide set of techniques for site characterization were applied: geological mapping, petrophysics, hydrogeology, hydrogeochemistry, surface deformation and several geophysical techniques, including a 3D seismic survey, gravimetry and electromagnetic methods.

The characterization of reservoir and seal formations of the storage complex of Hontomín was carried out in two phases: the first phase was the study of analogue samples from surface outcrops and the second was the analysis of core samples recovered from the HI and HA wells.

In 2013, during the drilling of the injection and monitoring wells of Hontomín, HI and HA, respectively, altogether 64.14 m core of 79 mm of diameter was recovered. The coring focused on the principal target formations of the site including the following four units:

- Marly Lias unit, which comprises the sequence of seal formations of the storage complex.
- Pozazal Formation. This formation is a transition between the seal and the reservoir and also has the role of secondary seal.
- Sopeña Limestone Unit, which is the upper part of the reservoir.
- Sopeña Dolomite Unit, which is the lower part of the reservoir.

The values acquired in lab studies indicated a low permeability and a wide variation in porosity values, and after the first hydraulic characterization tests, fractured-dominated permeability was identified. Current efforts are dedicated to better define the precise parameters of the reservoir hydraulic response in order to define the best CO_2 injection strategies.

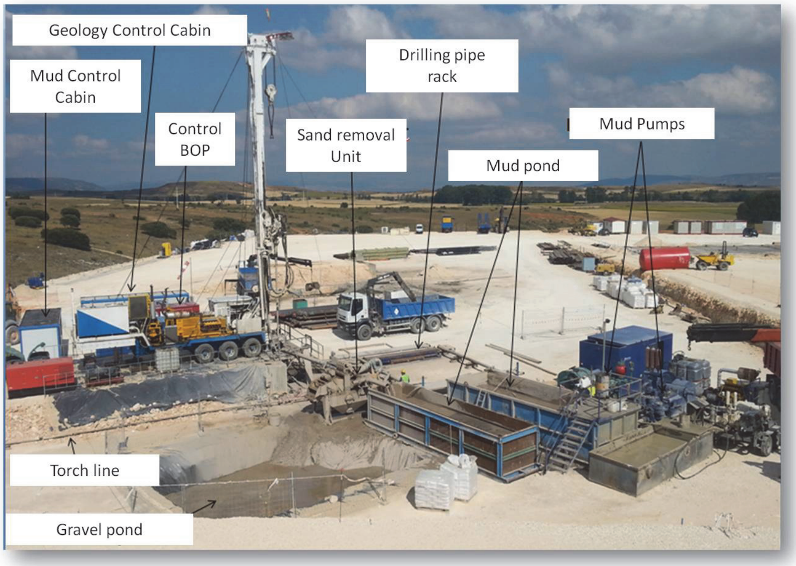

Fig. 3. Drilling rig and auxiliary equipment lay out at the Compostilla-Hontomín site.

4.2. Description of the facility

The Technology Development Plant (TDP) for CO_2 Storage mainly consists of an injection well (H-I) and monitoring well (H-A), a CO_2 injection facility, a water conditioning facility and a technical building where the control room is located. Two vertical wells (1,570 and 1,580 m depth) have been drilled and completed, one of them (H-I) for the injection of CO_2 and a second (H-A), for observation and test monitoring. The wells are 50 m apart at the surface. The H-A and H-I wells have been drilled with a light rig, normally used in water, mining, geological and geothermal wells, instead of a classical oil drilling rig. The main reason for using this rig was to develop a versatile drilling technology for geological CO_2 storage reservoirs at an acceptable cost. The rig was also equipped with auxiliary equipment as seen in Fig. 3.

The CO_2 injection facility consists of a storage stage, with a capacity of 150,000 l of CO_2, in 3 cryogenic tanks; a pumping stage formed by 3 cryogenic pumps; and gasification stage to adjust the CO_2 temperature to the different injection conditions. The facility is also formed by piping to the injection wellhead, instrumentation, valves and the rest of the required elements for operating the system. The facility is ready for CO_2 injection in the liquid, gas and supercritical phases. The injection condition ranges are 10 to 45ºC, 10 to 120 bar and up to 2kg/s flow rate. Fig. 4 shows a view of the current situation at the Hontomín site.

With these facilities, the setting of Hontomín technology development programme is as follows:

- Two wells that at near 1,600 m depth, one for injection (equipped with ERT electrodes, DTS system for temperature measurements within the tubing, U-tube system for fluid sampling, reservoir fluid pressure and temperature sensors), and one for monitoring (equipped with a retrievable array of hydrophones, ERT electrodes, reservoir and seal pressure and temperature sensors).
- A set of characterization and monitoring devices used in shallow aquifers as part of a hydrogeological monitoring network, consisting of 8 wells, including 3 located in the surroundings of the TDP, that allow acquiring continuous data on the shallow aquifers.
- A set of characterization and monitoring devices on the surface, including microseismic, microgravity and electromagnetic networks and a set of reflectors to develop InSAR campaigns.

Fig. 4. (a) Current view of Hontomín CO_2 injection plant. (b) Injection Well (H-I).

The wells and surrounding area in surface are densely equipped with monitoring tools, in order to track progress during the operation, as can be seen in Fig. 5.

4.3. Current status and plans

The current activities at Hontomín are mainly related to hydraulic characterization tests and the commissioning of the different parts of the facility, including the CO_2 injection plant, which is essential to test different CO_2 injection strategies in the coming months. The works at Hontomín will aim to improve storage monitoring techniques and methodologies. Key issues will be tested such as:

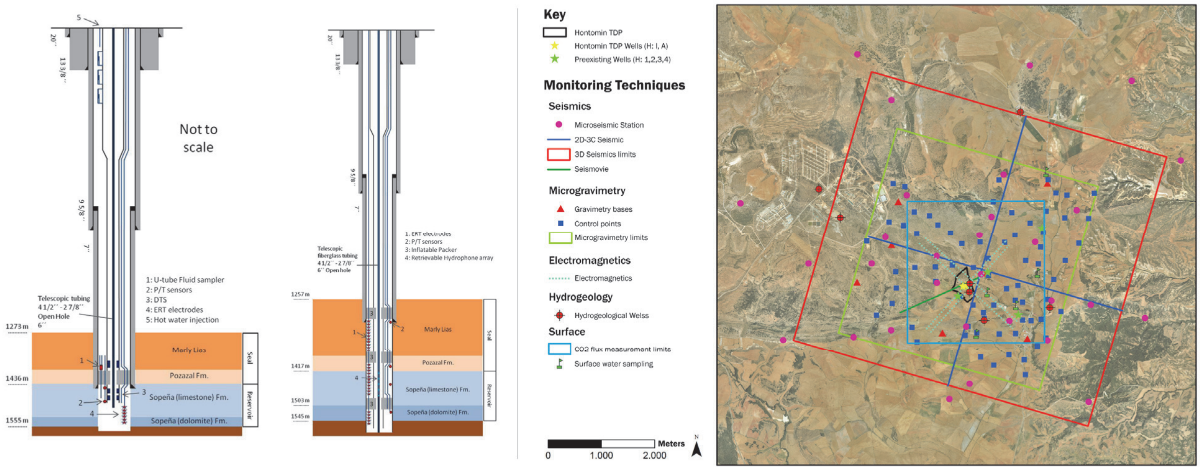

Fig. 5. (a) Well settings. (b) Surface monitoring at Hontomín.

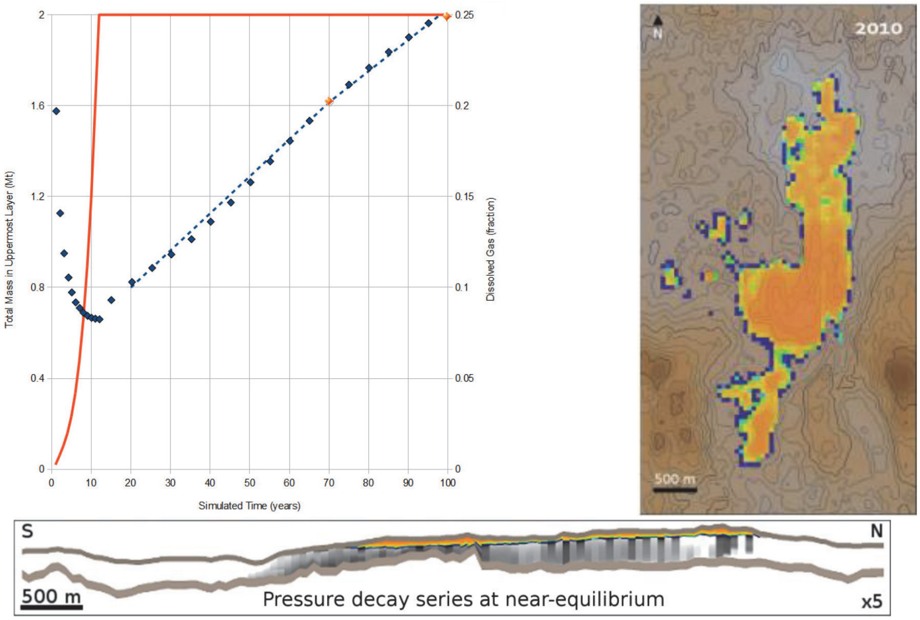

Fig. 6. Example of results from modelling the development of the plume of CO_2 in the Utsira reservoir (Sleipner project). The monitoring efforts at the Sleipner project have significantly increased the understanding of the behaviour (migration, dissolution) of CO_2 injected in saline formations. After [3].

- characterizing the permeability of the site at the scales relevant for CO_2 storage,
- evaluating different CO_2 injection strategies,
- determining the reliability of monitoring techniques at surface and at depth,
- establishing monitoring protocols to assist the operator in preparing the proper monitoring plan, and
- assisting the regulator in identifying appropriate criteria for the approval of such plans.

These activities are expected to allow CO_2 storage technologies to become a more cost-effective option for scaling up into commercial projects.

5. The Sleipner project

The Sleipner Project [2] is based in the North Sea, about 250 kilometres west of Stavanger, Norway. The project operator is Statoil in partnership with Total and Exxon Mobil. It is a gas processing project, the only non-power project in the Network. The natural gas produced at the Sleipner Vest field is stripped of its high (~9%) CO_2 content via a conventional amine capture. The CO_2 stream is then injected into a deep saline aquifer, the Utsira Formation, via a 2 km deviated well. The project commenced in 1996 and has captured and injected 15 Mt of CO_2 to date.

The Sleipner project has been covered extensively in the literature, with over 200 research papers to date. There has been a strong emphasis on monitoring and modelling of the plume since the start of injection in October 1996, as well as extensive reservoir characterisation and caprock analysis. Additional areas of research include amine capture on offshore installations, with the Sleipner experience directly influencing the aims of the Technology Centre Mongstad (TCM) capture research facility.

Repeated seismic and gravity monitoring in Sleipner has allowed for significant improvements in understanding CO_2 flow dynamics, as well as the rate of dissolution of CO_2 in saline formation. The latter is key to understanding and predicting the long-term fate of injected CO_2 and security of containment. Fig. 6 gives an example of results obtained for the Utsira CO_2 plume. The simulation results clearly indicate that the plume is percolating through the reservoir, and that the distribution beneath the caprock is gravity-dominated capillary flow; the plume is apparently close to equilibrium at every observation point. A recent result of these efforts is the publication of a benchmark case for reservoir modelling of the CO_2 in the Utsira Formation [3]. An updated Sleipner Benchmark is expected to be released to the CO_2 storage modelling community in 2015.

The current status of the Sleipner project is as follows:

- Some 1 Mt/y of additional CO_2 will be injected following the tie-in of the Gudrun field in 2014. Oil and gas from Gudrun will be piped to the Sleipner site and CO_2 separation will continue to take place at the Sleipner T platform.
- The injection rate peaked at just over 1 Mt per year in 2004, and is currently around 0.8 Mt per year, with minor fluctuations in rate related to operational maintenance on the well; the main reason for the slight decrease in injection rate is the gradually declining CO_2 content of the produced gas.
- A continuous monitoring programme is in place. To date eight repeat seismic surveys have taken place, as well as several gravity surveys, seafloor surveying, wellhead pressure and temperature monitoring.

It is expected that CO_2 capture at Sleipner and injection in the Utsira Formation will gradually decrease over the decade. The capture and injection phase of the project is currently expected to have ceased by 2020.

6. Conclusion

The European CCS Demonstration Project Network currently has four members: three full-chain CCS projects and one research oriented pilot project. Two of the three full-chain projects are the remaining Flagship projects under the European Energy Programme for Recovery (EEPR): the ROAD project (The Netherlands) and the Don Valley project (United Kingdom). The Sleipner project (Norway), the third full-chain project, is the only operational, commercial CCS project in the Network. The Hontomin project (Spain), is a research oriented, pilot-scale site, that was developed as part of the Compostilla project, a former EEPR Flagship project.

Together, the four Network members cover a wide range of storage types, ranging from a extremely large offshore saline sandstone formation, through offshore depleted gas (sandstone) fields to an onshore carbonate resevoir. In addition, the four projects are at various stages in the lifetime of a CO_2 storage project.

The Network members have already provided key data on the storage technology, the permitting process and cost of CCS. As the ROAD project is preparing for a decision to start construction, the Don Valley project is developing its FEED study, preparations are made at the Hontomín site for first injection and the Sleipner project continues to inject CO_2 at a commercial scale, these four project will continue to provide knowledge, experience and data that will prove to be highly valuable for the development of CCS in Europe.

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[3] Cavanagh A. Benchmark calibration and prediction of the Sleipner CO_2 plume from 2006 to 2012. Energy Procedia; 2013; 37; 3259-3545.