Thematic Report

CO_2 Transport Session May 2014

A report from the European CCS Demonstration Project Network

Public version

Proceedings from the knowledge sharing event of the 8th and 9th May 2014

Introduction

This report summarises the topics raised at the Thematic Workshop on CO_2 Transport. The workshop formed one of three parallel tracks of the Network Knowledge Sharing Event in Ponferrada (Spain) on 8-9 May 2014, hosted by CIUDEN (Compostilla Project). The other tracks addressed storage of CO_2 and the regulatory development for CCS.

1. Contents

List of figures

Participants

In the Transport Group, three Network projects were represented: ROAD (NL), Compostilla (ES), and Sleipner (NO) with apologies for absence from Don Valley Project (UK).

Agenda

Prior to the Knowledge Sharing Event, members of the Transport Group had agreed on the items to be specifically addressed in the technical sessions on Friday 9 May 2014. The following presentations took place along with discussions within the group:

CO_2 transport: update on progress and planning
ROAD Project
Compostilla Project
Presentation of CO_2 pipeline & corrosion at esCO_2 (CIUDEN)
Compostilla Project
CO_2 storage characterization with flow assurance tools
Sleipner Project
Planning and preferences for the next KS event in October 2014

1. Status reporting

From the previous workshop the following key conclusion was drawn:

Except for Sleipner, the demonstration projects were placed in limbo, awaiting further financial agreements. They had planned to build pipelines that are largely oversized for the demonstration phase, with the intention to extend the use of these pipelines within a possible larger CCS chain to emerge in the future.

Against this backdrop, updates on the latest progress were delivered by ROAD and Compostilla, summarising the status and main experiences gained since the previous knowledge sharing event in October 2013.

ROAD project

The ROAD project was initiated in 2009, aiming to become operational by 2015. The plan was first amended in 2012 due to funding issues that are still unresolved. The following de-facto events and indicative milestones summarising the ROAD project time line so far were presented:

14 July 2009:	EU project proposal submission
September 2009:	Project selection by EU
May 2010:	Grant decision by the Government of the Netherlands
Q2 2012:	Project placed in “slow mode” due to funding gap
End 2013:	Hot commissioning of power plant (MPP3) started (without CCS)

2014: MPP3 Commercial Operation to start (with provisions for retrofitting with CCS later)

For the ROAD project everything is ready except for the financing. The implication is that the detail engineering of the transport system is suspended. Engineering will need to be refreshed once the project restarts.

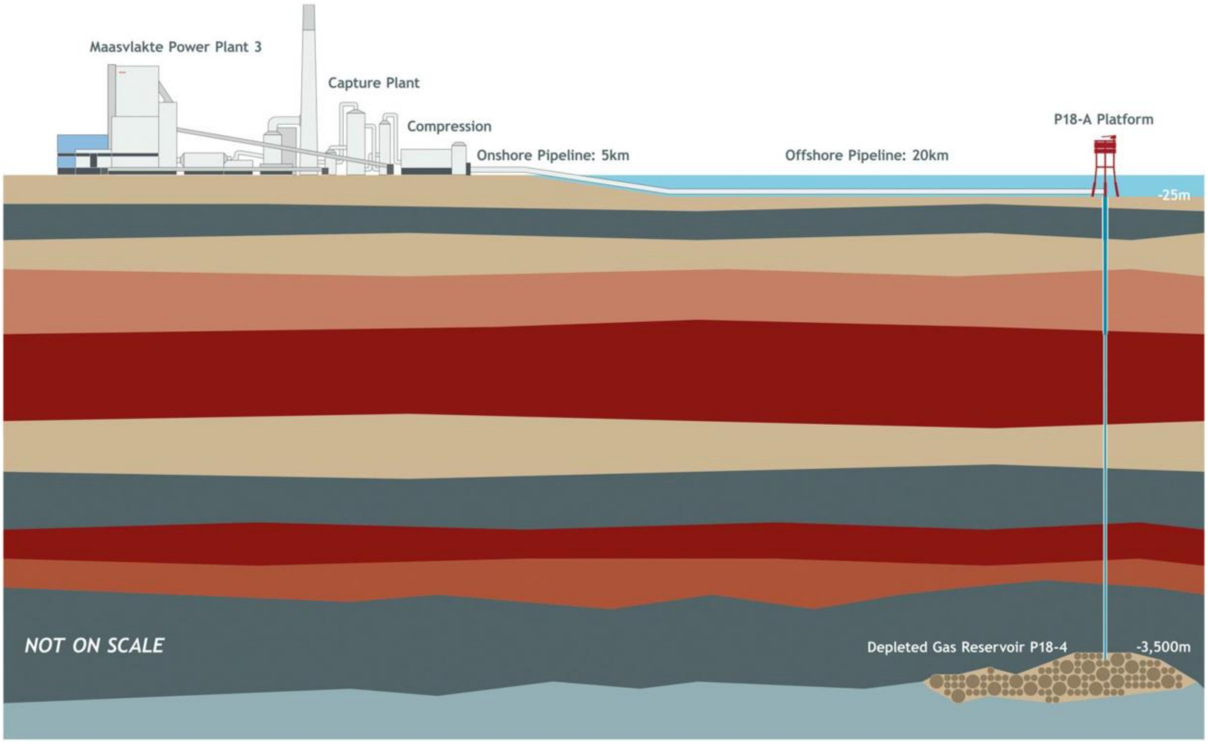

Figure 1: The integrated CCS chain for ROAD project

The CCS Chain

The overall status is:

Engineering:

- Detailed engineering of capture plant is underway.
- Some long lead suppliers are chosen and components engineered.
- Pipeline route engineered and 'flow assurance' study completed.
- 'Tie-ins' (i.a. flue gas, steam) with power plant are installed (ready for integration).
- Storage design completed, detailed FEED ready to start.

Permits:

- Permitting procedures are finalised (beginning of 2012).
- Capture permits are definitive and irrevocable.
- Storage permits are definitive and irrevocable from September 2013.
- Transport permits are agreed, with publication imminent.

Contracts:

- Capture supplier are selected and EPC[1] contract is ready to be signed.
- Contracts with power plant (utilities etc.) are ready for signature.
- Commercial contracts for transport and storage are agreed, and will be signed at final investment decision (FID).
- But, all price validity has expired, so reconfirmation is necessary once the funding gap is closed.

Finance:

- Very low CO_2 prices have caused a financing gap compared to plan.
- Delay in CCS roll-out and loss of confidence in EU low carbon energy policy has also weakened the strategic case for the demo.
- ROAD is still negotiating with potential funders, but currently without agreement.

The main power station started hot commissioning in late 2013. As the required permits have been granted, commercial operations may start during the summer (2014).

The plant is running on hard bituminous coal commercially available in the Rotterdam harbour. According to ROAD, the power cycle is designed for all qualities of international coals. Firing with any coal, including co-firing with biomass, will only have a marginal impact on the flue gas composition at the capture plant. This is due to the effect of the upstream flue gas clean up equipment. Only lignite may cause some difference but it has not been assessed. The content of sulphur affects however the performance of the flue-gas desulphurisation unit (FGD) and is expected to be typically around 1%.

As the main power plant is still in the hot testing mode, it is running at part-load. The purpose is to optimise the control system and to make sure that the settings are aligned with the correct operating window.

The plant is designed to be able to divert a stream of flue gas, corresponding to 250 MW_e, for the purpose of demonstrating the full CCS chain. The capture system differs from the ones already used in industry, but the unit is not considered to be the first of a kind. Reference plants handling natural gas exist, and the design is considered to be robust.

With the capture unit in place, the plant will capture 169 t/h of CO_2. This corresponds to 1.1 Mt/y to be stored, assuming 70% availability of the entire CCS system.

The CO_2 Transport System

Since the ROAD project has been kept on a slow mode since 2012, progress on the CO_2 transport system is rather limited. Some actions have been made, mainly to refine the flow-

[1] Engineering, procurement and construction (EPC).

assurance work. A detailed Flow Assurance study is now available on the Global CCS Institute's website[2].

Flow assurance

Typical of the ROAD project is that the pressure of the depleted gas field is very low, despite the depth of 3.5 km underneath the seabed. Prior to the onset of the gas exploration, the pressure used to be 350 bar. Currently the pressure is less than 20 bar, and it is still decreasing as the reservoir continues to produce gas. One problem is that if CO_2 is brought to the platform in dense phase and injected through the well head, the immediate pressure relief will result in freezing temperature due to Joule-Thomson cooling.

The down-hole temperature is considered to constitute a severe bottleneck mainly due to the risk of hydrates formation. In order to eliminate this risk, the temperature should be kept above 15°C. Combining this requirement with Joule-Thomson cooling, a fairly hot CO_2 must be dispatched from the compression train. Hence, the warm pipeline operation appears to be a unique feature of the ROAD project.

In order to handle this situation, a flow control philosophy at steady state has been established. The idea is to adjust the temperature in the pipeline, whereby the density of the CO_2 is controlled according to the required hydrostatic head. This head must gradually increase as the reservoir pressure builds up. In this way, the pipeline pressure can be kept constant and choking can be avoided. Hence:

- Initially, at very low reservoir pressures, the pipeline is operated with warm CO_2 (above critical temperature). Thereby single phase is ensured in the pipeline and the well. This will also limit the hydrostatic head in the well.
- Later, as the reservoir pressure exceeds a certain threshold, colder CO_2 is used with higher density, thus increasing the gravity head in the well. The use of a choke valve at the platform is probable, ensuring pipeline pressure above the critical pressure of CO_2.

The intention is to empty the pipeline into the well on shutdown, to the extent allowed by the reservoir pressure. This minimises the CO_2 remaining in the pipeline, and therefore minimises the condensation of liquid CO_2 as the pipeline cools when off-load. At low reservoir pressures, the pipeline can be kept in the gas phase, but at high reservoir pressures and long shutdown periods, some CO_2 will condense into the liquid form. This will cause some slugging at restart. The possibility to use slug catchers has been investigated, but was deemed rather impractical and therefore rejected. The current position of ROAD is that although slugs will occur, they are not expected to have a detrimental impact neither on the platform nor on the injection well. Slugs will, at any rate, not reach the bottom of the well.

[2] http://www.globalccsinstitute.com/publications/road-project-flow-assurance-and-control-philosophy

The procedures for shutdown/start-up are still being optimised, but they will include the following actions:

- On shutdown: empty the pipeline into the well.
- On start-up: start the flow into the well as soon as the pipeline pressure is high enough.
- Accept that CO_2 may turn into liquid phase in the pipeline during shutdown, and that slugs may flow through the wellhead on start-up.
- Design the platform to withstand/accommodate slugs.

Further modelling work on the shut-down and restart procedures is underway.

Pipeline

The current pipeline design does not follow a straight line (Figure 2). It is designed to follow existing pipelines, thus omitting the shipping lane and areas associated with wind turbines. Directional drilling is required twice for the crossing of shipping lanes.

As already explained, rather than operating above the critical pressure, the pipeline will operate at a temperature well above the critical temperature of CO_2 (i.e. 31.1°C). This is obtained by keeping the compressed CO_2 leaving the compression train essentially uncooled. Moreover, the pipeline must be insulated.

Figure 2: ROAD project pipeline route[3]

CO_2 Storage

The available storage capacity is:

- For the demonstration phase: 7-8 Mt (reservoir P18-4), enough space of about 7 years of operations.
- For the subsequent phase: 28-32 Mt (reservoir P18-2).

The injection of the 1.1 Mtpa CO_2 will require only one well. Although the reservoir pressure is already very low, it may become even lower before CCS operations are due to start, as natural gas is still being produced. For this reason, the initial injection pressure remains unknown.

Technical Progress: Connection to OCAP

An additional study has been carried out to assess the potential linking of the ROAD pipeline to the existing OCAP CO_2 transport system supplying low pressure CO_2 to greenhouses around Rotterdam.

So far, CO_2 is fed into the OCAP CO_2 transport system via a low pressure CO_2 pipeline from a hydrogen facility and a bioethanol plant. Most greenhouses in the Netherlands are kept operational throughout the year. The demand for CO_2 needed by these greenhouses shows a huge seasonal variation. In the winter, lighting and heating are mostly provided by local

[3] http://www.globalccsinstitute.com/publications/road-project-flow-assurance-and-control-philosophy

combined heat and power units (CHP) leaving surplus amounts of CO_2 available for the adjacent greenhouses. Towards the summer season, however, the CO_2 demand increases, partly because sunlight requires more CO_2 for the photo synthesis. The local CHPs also become inefficient as heat is (usually) not needed in the summer. Thus, the locally produced CO_2 becomes deficient.

The peak demand of the OCAP CO_2 transport system is in June-July, with at significant variation between day and night. So far, there is a maximum demand that can be met reliably by the existing supply (taking into account day/night and weather variations). However, there is more demand for CO_2 from greenhouses that cannot currently be met. The proposal is to connect the OCAP and ROAD systems so that OCAP uses CO_2 from ROAD to provide CO_2 to additional greenhouses. This would also allow ROAD to store surplus CO_2 from OCAP in the winter months. The challenge is, however, to connect the two pipelines: OCAP operates at low pressure whereas ROAD operates at high pressure.

Figure 3: The Rotterdam CO_2 Hub – Existing OCAP System[4]

The study involves several technical issues, such as "second life possibilities". These include the opportunity for the reuse of a pipeline (for chemicals etc.). However, the larger the pipe,

[4] http://www.ocap.nl/index.php?option=com_content&view=article&id=11&Itemid=28

the more difficult it is to reuse it. Several options have been explored combining the geological storage.

OCAP would need to make capital investments to extend the local infrastructure connecting more greenhouses with its CO_2 pipeline system. This is a relatively low cost carbon reduction opportunity for the greenhouses that can be combined with district heating for the greenhouses (removing CHP units altogether), and it would create a fully functioning CO_2 hub (with capture, transport, utilisation and storage) in Rotterdam.

Summarising the ROAD project

- The ROAD project is comfortable in terms of engineering and technical aspects. The only problem is funding.
- ROAD will have to make the decision to go ahead or stop before the end of the year.

Compostilla project

Since the Compostilla project has been abandoned, the report on further development is rather limited. In retrospect:

a) The OxyCFB300 FEED study was accomplished during last autumn (2013).
b) The CO_2 transport system and the flow assurance study of Compostilla were presented at the previous workshop in Stavanger (October 2013).
c) Few days later, Endesa made a negative final investment decision (FID) (early November 2013).

Knowledge development activities

The following updates were reported:

- A new partner will join in to bring more knowledge on CO_2 dispersion. The dispersion release study, conducted for a group of companies, will be shared.
- The crack arrest tests, are still to be conducted. These tests will be performed later this year and shared at the next knowledge sharing event.
- The remaining items of the knowledge development matrix have been terminated.

Permitting status

The environmental authorisation process is managed by the Ministry of Environment and the Ministry of Industry. The process followed is presented in Figure 4.

The Environmental Initial Document which provides the identification of the project and main environmental issues was completed in 2011. The public consultation is documented in the Environmental Impact Study and the Environmental Impact Declaration was delivered to the Spanish authorities in 2012.

The environmental authorisation has been placed on hold and the project authorisation has been refused. The reason is that a regulatory framework has not been enacted in Spain. The only feedback received is that authorisation cannot be granted without a regulatory framework. This position has blocked any further progress.

The only probable way to resume the process is that the Spanish authorities implement a relevant transport regulation, as for CO_2 storage. The latter has been in existence in Spain since 2010. Since 11 November 2012, Compostilla has obtained no further feedback from the Spanish Government.

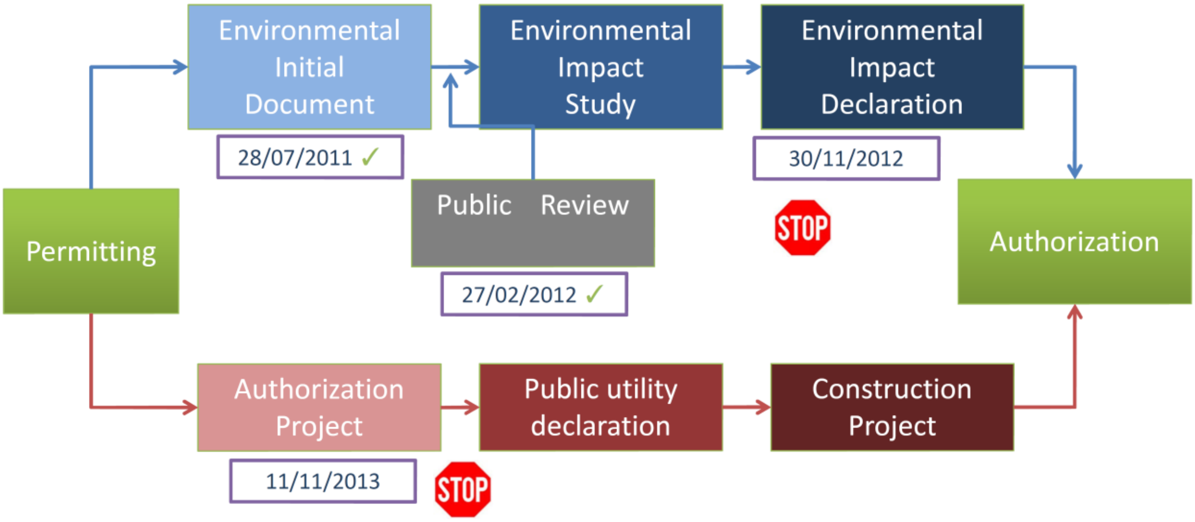

Figure 4: Permitting process scheme for OxyCFB300 project

2. CO_2 transport facility at CIUDEN

The CO_2 transport test facility of CIUDEN is entirely new and opened in 2013. It can be seen in Figure 5, within the overall esCO_2 facilities. It is specifically designed at a scale representative of a 150 km long buried pipeline. Still, the experience of CO_2 pipeline corrosion is limited at CIUDEN. The advantage of this test facility is that it may replicate real life operations. It is useful in emulating realistic operating conditions. The test facility is designed not only for corrosion studies, but for depressurisation, pressure losses, instrumentation testing, leakages, etc. Experiments are also made in support of the storage programme (cavitation investigation).

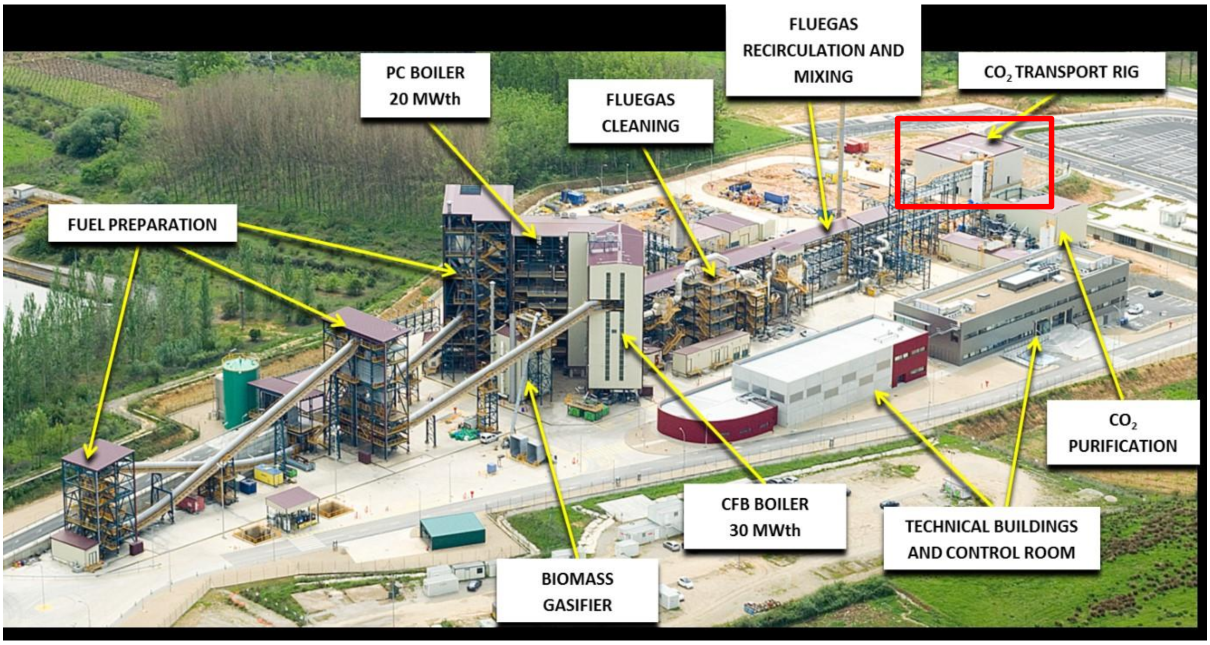

Figure 5: esCO_2 - aerial view[5]

As CIUDEN expects corrosion to take place throughout the full length of the carbon steel pipes, they are designed with an additional thickness. This additional thickness will enable CIUDEN to carry out a number of corrosion tests until the test rigs starts failing. The tests can be carried out by using a length of pipe from 300 m up to 3,000 m (in multiples of 300 m).

Test facility characteristics:

- The test rig is planned for various purposes, not just for corrosion studies (both metallic and elastomeric materials). Other important issues, for which experiments have already been made or are planned, are cavitation under choke conditions and instrumentation testing.
- Although the rig is quite tight, no leaks of CO_2 that may affect the bulk flow have occurred. So far, some minor non-intentional leaks have been detected at several locations, mostly due to ice around the leak which is formed from the ambient moisture.
- Rupture tests, originally part of the plan, have been left out of the current agenda. The reason is that these tests are considered difficult to design.
- A further ambition is to introduce see-glasses to the pipeline to observe the flow and detect bubbles appearing during depressurisation.
- It is possible to expand the range of fluids to include natural gas and even oil, but this will require further investigation.
- The test rig is also envisioned to be used as a training ground. All normal piping issues can be encountered, at a manageable scale.

[5] http://www.compostillaproject.es/resources/pdf/KSF_OXYCFB300_Compostilla_CCS_Project.pdf

- Specific corrosion samples may be fit in barrels, separated with seals.

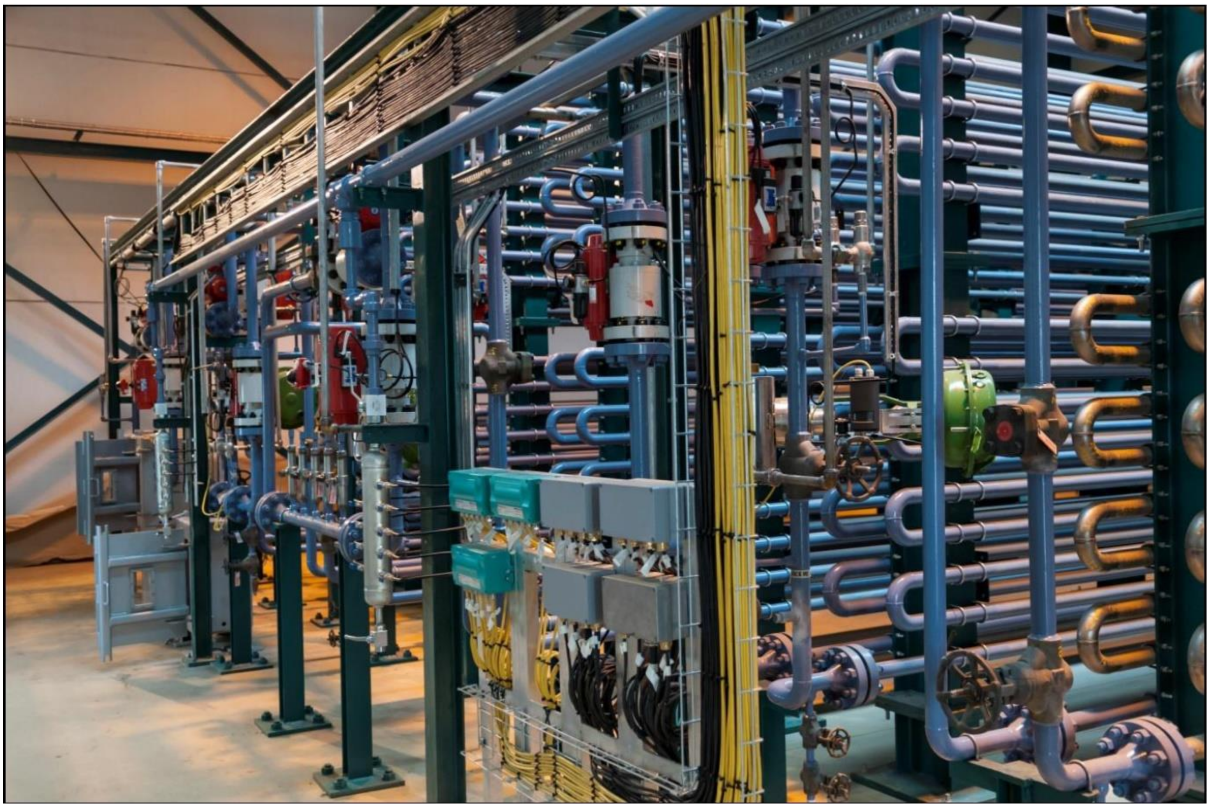

Figure 6: CO_2 Partial view transport experimental facility at CIUDEN esCO_2 test centre[6]

- The test samples are designed in order to simplify the replacement (separately) and avoid any disturbance of the flow. The plan is to change selected samples while keeping the remaining ones unchanged. Intentionally, this will keep track of the history of the samples and their aggregated exposure to different concentrations of impurities.
- A number of corrosion transmitters are installed, measuring general corrosion, using linear polarisation resistance (LPR) as well as pitting corrosion, using electrochemical noise (ECN) and conductance.
- The corrosion transmitters are made from a material compatible with the test sample. The transmitters include software converting measurements to corrosion in mm/year. Different materials can be simulated simply by adjusting a characteristic parameter.
- Conductance measurements are used to observe the general corrosion, determined via transmitters that also record the conductance of the material.
- Different stream compositions of CO_2 with water as well as impurities, additives and materials can be used in the rig.

[6] http://www.compostillaproject.es/resources/pdf/KSF_OXYCFB300_Compostilla_CCS_Project.pdf

Further areas of interest include:

- Behaviour of materials in terms of corrosion.
- Behaviour of equipment or instrumentation used in real installations to different CO_2 flows.
- Depressurisation tests.
- Behaviour as to how the installation responds to transitions in the flow system.
- Experimentation with the pump (temperature changes etc.).
- Procedure setting for the industry, in terms of transients and continuous operation, as well as for operations such as venting the pipe, etc.

3. CO_2 storage characterisation with flow assurance tools

The purpose of flow assurance is to ensure successful and economical flow of the CO_2 stream from source to storage. From the insights on operational experiences of CO_2 transport, injection and storage behaviour provided, numerous key points can be highlighted.

Injection of CO_2 into the Utsira Formation at Sleipner has been operational since 1996, at a rate of approximately 1 Mtpa per year. Apart from a minor disruption in the beginning of injection, operations have been running smoothly over the years.

From the control room, normal fluctuations in flow rate and CO_2 concentrations from the Sleipner West production stream can be observed.

A similar multi-disciplinary set of tools to that of hydrocarbon operations applies for CO_2, but logically in the opposite direction to oil and gas production, as the CO_2 is injected into the ground. A main difference, however, is the thermodynamic behaviour of the CO_2:

- The critical point of CO_2 appears in the centre of the operating window for the well as the reservoir conditions are supercritical. As a result, multi-phase flow occurs in the well, which is simulated within reasonable uncertainty constraints. Pressure, flow rate and composition are monitored at the well head, but there is no down-hole pressure-volume-temperature instrumentation (PVT). It is quite likely that a liquid phase transition occurs prior to the deeper supercritical conditions at the injection interval. The initial conditions in the reservoir are reasonably well constrained, and well path simulations provide insights into the subsurface transport conditions.

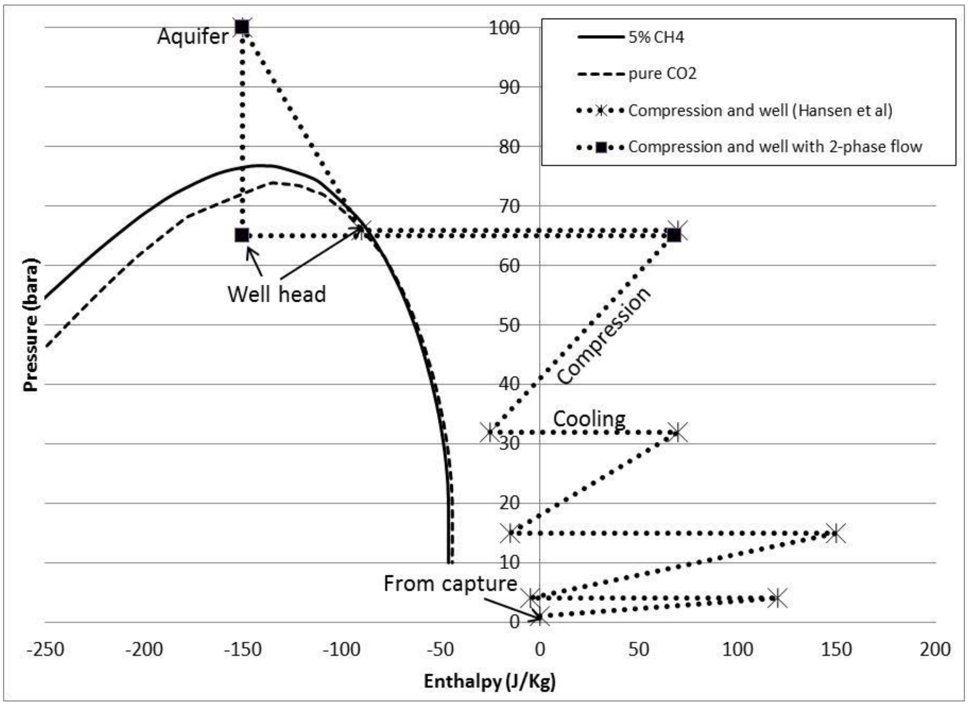

Figure 7 Pressure enthalpy diagram for pure CO_2 and CO_2 with 5% CH_4 showing two compression and well paths at Sleipner[7]

- CO_2 is a heavy, non-combustible gas but asphyxiation is a risk.
- The triple point may be reached during depressurisation.
- Hydrate formation is not an issue at Sleipner. Hydrate formation is prevented by keeping the CO_2 stream sufficiently dry. It should be kept in mind that CO_2 can potentially become too dry. There is an optimal operation window.
- The operating window must be balanced against the risk of hydrates formation. The Sleipner CO_2 stream is less complex than the CO_2 stream typical of a power plant capture. SOx, NOx and O_2 are not typical of natural gas clean-up.
- Sleipner involves standard amine capture issues similar to those associated with power generation.
- Corrosion with water, O_2 and/or NOx may occur if these components are present.
- A strong Joule-Thomson effect within the reservoir may take place depending on pressure conditions.

The wellhead pressure at Sleipner is around 60 bar[8] (i.e. gaseous phase). The phase management in the well is based on simulations and several scenarios have been considered for two phase flow in the mid-part of the well.

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[7] Munkejord et al/ **Energy Procedia** 37 (2013) 2904 – 2913.
[8] Eiken et al. / **Energy Procedia** 4 (2011) 5541–5548.

So far, no indication has been obtained regarding any hydrate incident in the well, mainly due to careful engineering. Sleipner is however, at a reasonably high risk in terms of humidity content and temperature.

The CO_2 is dehumidified in the processing plant. While the right PVT conditions exist along the transport line for clathrate formation (CO_2 and CH_4), there is not enough water vapour for an ice bond to form. This is an effective way to assure flow.

At Sleipner, the CO_2 is not fully dried, as bone dry streams are expensive and sub-optimal from an engineering perspective. Moreover, at Sleipner, there is a fairly normal temperature profile in the ground from the point where the CO_2 is injected to the top of the natural gas reservoir.

A strong Joule-Thomson effect may occur when CO_2 enters the reservoir. In such a scenario, the expansion of CO_2 has a significant cooling effect on the surrounding reservoir. The reservoir PVT characterisation at Sleipner is fairly straightforward. The CO_2 stream enters the well in a single phase, potentially becomes two phases along the well path, and then turns into a dense phase as it approaches the reservoir. This transition has not caused issues in terms of flow assurance, but may alter the PVT conditions of fluid entering the reservoir.

The more progressive loss in injectivity can be a result of injecting into a fairly restricted space. The gradual injectivity decline and pressure build-up can be due to a restricted fault-bounded compartment. The response to pressure build-up experience of Statoil, was to switch to the planned alternative storage formation, i.e. to move the injection interval to the better quality reservoir of the Stø formation. The injection has continued successfully in the Stø formation since the well was reperforated. Given the proximity of the new storage location to the gas asset, the gas reservoir is carefully monitored for signs of breakthrough and CO_2 contamination of the natural gas. Well placement options are being considered, to ensure that CO_2 injection and storage can continue for the lifetime of the field. Seemingly, no seasonal variation occurs, although notable flow fluctuations in the compression train are observed related to routine shut-down and maintenance of the gas capture and compression facility. The supply of CO_2 to the well depends on the supply from the onshore facility. As the supply may vary over time, the bottom-hole pressure (BHP) is affected accordingly.

From a transport point of view, a wet stream characterised by free water must be avoided. In North America, significant funds have been spent on water wells which have been converted to CO_2 injectors. The combination of old water wells and subsequent corrosion issues associated with CO_2, results in wells that are in reasonably bad condition. Although water well conversion is often assumed to be a cheap option, projects have opted for more expensive horizontal CO_2 wells[9].

[9] note that this largely reflects an optimal flood strategy for CO_2 EOR

The effect of methane on hydrate formation

The effect of methane on hydrate formation differs by site. InSalah, located in the desert of Algeria, was the warmest CCS plant, and also the plant with the highest surface compression pressure. The transport lengths are moderate at a few kilometres. In contrast, Sleipner has the shortest path for transport from the separation unit, at less than a kilometre. Snøhvit has the longest pipeline, situated subsea in the Artic and hence the coldest CO_2 (4°C). This implies that the CO_2 at Snøhvit is more exposed to hydrates formation. Despite this fact, no additive is used for the injected CO_2.

Latest development

- A new flow assessment modelling is conducted, using the CO_2 VIP module of OLGA.
- Dispersion experiments:
  - available for CO_2PipeTrans,
  - investigating what would happen if the pipe blew out due to catastrophic failure,
  - model improvement is ongoing.
- More and more equilibrium and corrosion experiments have been performed.
- SINTEF's COTT code has been verified in the EU-based CO_2 Dynamics project.
- Heat transfer and CO_2/N_2 depressurisation experiments from Statoil/SINTEF to be presented at GHGT-12 in Austin, Texas, later this year.
- New project DeFACTO (2 years) on transient flow in wells.

DeFACTO project

Vertical flow test facility will be made as an extension of the existing horizontal flow test facility.
The characteristics of the project are:

- Main objective: to investigate vertical flow behaviour emphasising transient scenarios such as shut-in and blow-out.
- Fully equipped with pressure and temperature sensors along the test pipe.
- Design and quality assurance of critical elements are part of the current CO_2 IT IS project.
- Final design and building are planned to be executed in a subsequent project.

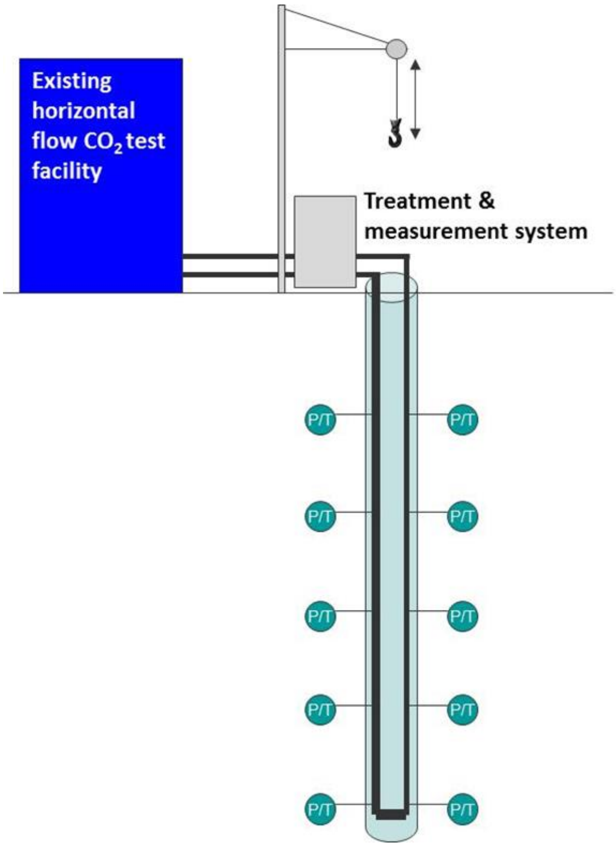

Figure 8 Schematic of the vertical CO_2 test loop to be built within DeFACTO project[10]

[10] http://www.sintef.no/home/SINTEF-Energy-Research/Project-work/DeFACTO/

ccsnetwork.eu
*connect *construct *share

The European CCS Demonstration Project Network was established in 2009 by the European Commission to accelerate the deployment of safe, large-scale and commercially viable CCS projects. The Network that has been formed is a community of leading demonstration projects which is committed to sharing knowledge and experiences, and is united towards the goal of achieving safe and CCS. The learnings that are gained will be disseminated to other projects, stakeholders and public to help gain acceptance of the technology –and support CCS to achieve its full potential as a vital technique in our fight against climate change.

Network support provided by: