Final Technical Report

"SACS" – Saline Aquifer CO2 Storage

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Contract Number: OG / 306 / 98 / NO
Contractor: Den norske stats oljeselskap a.s. - Statoil
Person to be contacted: Tore A. Torp
Tel. +47 7358 4181
Fax. +47 7358 4630
E-mail: tat@statoil.com

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1. Executive Summary

1.1. PROJECT ADMINISTRATION

Steering Committee met for "kick-off" on 29 October 1998 and the project has been run from 1.November 1998 until 31.December 1999. It will be followed up by a SACS2 project.
Work Meetings of the Geological, Reservoir, Geo-chemical & Geophysical Groups, separately and in combinations, has been arranged to co-ordinate flow of data and test material, as well as the scientific work in subtasks.
Technical Seminar has been arranged to present work, questions and results to all involved. The aim was to develop a consensus for the scientific basis of the concept; SACS overall goal.

1.2. DISSEMINATION

INTERNET: IEA Greenhouse Gas R&D Programme is presenting the SACS project (public parts) on their homepage: www.ieagreen.org.uk
PUBLICITY: A large number of periodicals and daily press articles have presented the concept of aquifer underground storage of CO_2, the Sleipner case and the SACS project. This has also been presented at a couple of conferences concerning energy and environment.
PUBLICATIONS: Concrete plans to present general results and more specific scientific findings in conferences etc, will be decided in January 2000. Publications in scientific, reviewed periodicals are under planning for publication in 2000. This work is co-ordinated with other European CO_2 relevant projects under EU 5.Framework Programme, Accompanying Measures in activity "CO2Net".

1.3. NATIONAL, EUROPEAN & INTER-CONTINENTAL CO-OPERATION

Co-operation and co-ordination with analogue work in Australia, Canada and USA will continue and is now being organised through the IEA Greenhouse Gas R&D Programme as an "Umbrella". Important steps were taken under the BP Amoco/IEA/US DoE sponsored CO_2 sequestration workshop in Houston, Texas in September 1999. Concrete partners and topics for co-operation have been identified, plans drafted and co-operation documents under the IEA "Implementing Agreement" are being prepared.

1.4. WORK AREAS

MAIN RESULTS: The CO_2 "bubble" around the Sleipner injection well in the Utsira formation at 1000 m below sea bottom, was by September 1999 large enough, and in such concentrations, that it was clearly possible to monitor by a 4D "time lapse" seismic survey. This was the expected result after the first geological analysis, reservoir simulations and seismic modelling during spring 1999. Injection had been ongoing since October 1996 with around 1 Mt CO_2 pr year. The Steering Committee in May decided a major shift in the budget, reducing the volume of scientific work, and approved to bring forward the seismic survey to the summer 1999. The data from the seismic contractor Geco-Prakla is still under processing, so final interpretation results can not be presented, but "the bubble" is evident.

Geo-chemical laboratory work was started late due to difficulties in getting samples and data, hence in selecting parameters. Preliminary results are reported, but works continue in SACS2.

The delayed work in the areas Geology, Reservoir, Geochemistry and “Monitoring well?” has been included in the SACS2 to be run under the EU “5.Framework Programme” in 2000-2001.

The overall goal is still to learn the maximum from the Sleipner case and to produce a draft “Best-Practice-Manual”.

MAIN DIFFICULTIES MET has been to bring the available data and sample material to the institutes needing them, and in a workable form.
Availability of formation water and material from the cap rock over the “Utsira” formation has shown to be poor. Water analysis had to be taken from Oseberg field, far away but still representative? Cap rock material is in form of drill cuttings only; no core sample is known to be anywhere around the North Sea?
In SACS2 further efforts are needed to find or produce a cap rock core sample and/or better formation water.

PLANS FOR CONTINUATION of the SACS project for the last two of the three years originally planned for, has been prepared. After the summer 1999 application round, the EU 5.Framework Programme/Energy granted 35% support for a two year continuation; plans are according to the originals from 1998. Extended contracts has been negotiated, but as of 1.January 2000 not yet signed. Necessary industry and national support for the two years has been promised.

ACKNOWLEDGEMENTS
This project was built on contributions of several types and from many sources. Without the resulting pool of resources this project would not have been executed. Data were contributed from too many to allow all to be mentioned here. Never the less, without the permission to use data from the Sleipner field operations and to collect seismic data from their area, the project had become a pure theoretical study. We thank:
Partners in the Sleipner license for their permissions:
- Den norske stats oljeselskap as (Statoil)
- Esso Norge as
- Norsk Hydro Produksjon AS
- Elf Petroleum Norge AS

Financial support:
- Commission of the European Union – Directorate-General Energy (Thermie)

- BP AmocoBP Exploration Operating Company Ltd – BP Amoco, UK
- Den norske stats oljeselskap as – Statoil, NO
- Mobil Exploration Norway Inc – Mobil, NO
- Norsk Hydro ASA – Norsk Hydro, NO
- Vattenfall AB – Vattenfall, SE

National authorities with financial and/or data support:
- Norwegian Petroleum Directorate – NPD, NO
- Ministry of Environment and Energy, Energy Board, DK
- Ministry of Housing, Spatial planning and Environment – VROM, NL
- Department of Trade and Industry – DTI, UK
- Research Council of Norway – NFR/”KLIMATEK”, NO

Geo-science experience and in-house tools, and, for some, own funds:
- Natural Environment Research Council, British Geological Survey – BGS, UK
- Bureau de Recherches Geologiques et Minieres – BRGM, FR
- Geological Survey of Denmark and Greenland – GEUS, DK
- Institut Francais du Petrole – IFP, FR
- SINTEF Petroleum Research – SINTEF, NO
- Netherlands Institute of Applied Geoscience - NITG-TNO, NL

Inter-continental co-ordination and facilitator:
- IEA GreenHouse Gas R&D Programme – IEA GHG, EU

2. Work carried out during the project period

2.1. PROJECT MANAGEMENT

”Kick-off” Steering Committee Meeting, Trondheim, NO, 29 October 1998.
Work Meeting, Geological Group, Copenhagen, DK, 9 December. Participants: GEUS, BGS & SINTEF.
Steering Committee Meeting, Sunbury, UK, 17 February 1999.
Work Meeting, Geological Group, Haarlem, NL, 10 March. Participants: NITG-TNO, GEUS, BGS & SINTEF.
Work Meeting, Geochemical Group, Copenhagen, DK, 30 March. Participants: BRGM, BGS & GEUS
Work Meeting, Geological & Geophysical Groups, Copenhagen, DK, 26-28 April. Participants: GEUS, BGS, NITG-TNO & SINTEF
Steering Committee Meeting, Hoofdorp, NL, 7 May.
Steering Committee Meeting, Stavanger, NO, 8 June.
Steering Committee Meeting, Stockholm, SE, 23 September
Technical Seminar, Participants: all SACS partners, Nottingham, UK, 8-9 November
Steering Committee Meeting, Nottingham, UK, 9 November
”Closing SACS, Kick off SACS2” Steering Committee Meeting, Paris, FR, 25 January 2000.

2.2. DISSEMINATION

An international symposium entitled “TOWARDS ZERO EMISSIONS - The challenge for Hydrocarbons”, was organised by Eni Tecnologie in Rome, 11 – 13 March 1999. N.P.Christensen of GEUS was invited to present the paper “Subsurface Storage of CO2 - current initiatives and future potential”. A poster “Aquifer CO2 Storage – The Sleipner Case” was presented by T.A.Torp at EUROGAS 99, Bochum, DE, 25-27 May 1999.

Primarily resulting from presentations previously given by Torp and Christensen to MEP's and the European Commission, the concept of geological CO2 storage became one of the issues of debate in Denmark during the electoral campaign for the European Parliament in the early summer of 1999. Mr. Christian Rovsing, who raised this debate, was re-elected. Several newspapers ran extensive popular and technical articles about the concept in Norway and Denmark.

INTERNET: IEA Greenhouse Gas R&D Programme is presenting the SACS project (public parts) on their homepage: www.ieagreen.org.uk

PUBLICITY: A large number of periodicals and daily press articles have presented the concept of aquifer underground storage of CO2, the Sleipner case and the SACS project. This resulted in many fair and good presentations of the underground CO2 storage concept to the public. Several students in many countries have been given background information for their work with CO2 sequestration. The general interest is felt as steadily growing.

PUBLICATIONS: Concrete plans to publish general results and more specific scientific findings will be decided in January 2000. Publications in scientific, reviewed periodicals are under planning for publication in 2000. This work is co-ordinated with other European CO2 relevant projects under EU 5.Framework Programme, Accompanying Measures in activity “CO2Net”.

2.3. NATIONAL, EUROPEAN & INTER-CONTINENTAL CO-OPERATION

a) National

Close contacts with national authorities in NO, DK, NL and UK have been maintained; basically through the research institutes, but also through industry partners.
Contact with French national authorities has also been sought, so as to inform them about Sleipner CO_2 injection and SACS project, and invite them to a dialogue with the SACS project partners. Not yet succeeded.
The Norwegian Research Foundation (NFR) / KLIMATEK granted support for a 3 years complementary project in addition to the shared national support for SACS proper. The complementary projects are run by SINTEF Petroleum and Nansen Remote Sensing Centre, both Norway and are dealing with tectonics and methods to estimate geological interpretations respectively. These projects will support general understanding of the "Utsira" formation, but the topics were given lower priority during the original planning of SACS. They use much of the same underground data, and the work is closely co-ordinated with the SACS project.

b) EU 5th Framework Programme

- SACS2 : Application for remaining years (2000-2001) and for postponed part of SACS-Thermie work filed 15 June 1999. Funding grant and contract was offered.
- Cluster project with EuroGeoSurveys on CO_2 subsurface opportunities in Europe for application GESTCO. Also this received a funding grant and contract.
- In parallel with the SACS2 application, another consortium filed an application called MSCO2. EU evaluators proposed to merge essential parts of this project into SACS2 as an "assistant contractor". As part of the contracts such co-operation is now under preparation. By sharing data and scientific evaluation in the area of seismic monitoring methods, the basis for scientific consensus will be broadened.

c) Inter-continental / IEA "Umbrella" Programme

IEA GreenHouse Gas R&D programme (IEA GHG), Cheltenham, UK was together with Statoil involved in the shaping the idea of the SACS project. IEA took on the task of using their established network to support and co-ordinate inter-continental co-operation around underground aquifer storage of CO2, named an "Umbrella" project.
Contacts and talks has been held, based on concrete proposals for close co-operation and co-ordination of scientific work from from 1)Lawrence Livermore National Laboratories, US, 2) GEODISC project, Australia, 3) Weyburn project, Canada, 4) the NEDO organisation, Japan and 5) Battelle Columbus as well as University of Texas (Austin), USA.
Proposals of geochemical elements for the "Umbrella" were sent by BRGM and IFP to IEA GHG in March 1999. Contacts for work in the geochemical area have been established with the Weyburn project, Canada, and the Battelle Columbus Institute, US.

Important steps were taken under the BP Amoco/IEA/US DoE sponsored CO2 sequestration workshop in Houston, Texas in September 1999. Concrete partners and topics for co-operation have been identified, plans drafted and co-operation documents under the IEA "Implementing Agreement" are being prepared.

These co-operations are expected to give access to data and geological samples from other geological theatres. One example is natural analogues as natural CO2 reservoirs. By this the scientific basis for consensus about safe and reliable CO2 sequestration will be even wider.

2.4. WORK AREAS

WORK AREA 1: GEOLOGY

This chapter comprises a summary of the work carried out in SACS under Work Area 1. More detailed accounts of the work done are to be found in supporting technical reports: Lothe & Zweigel (1999), Pearce et al. (1999) and Holloway et al. (2000).

The objective of Work Area 1 is to characterise the 3-D stratigraphy, structure, rock mass properties and natural fluid flow of the Utsira Sand and adjacent sand bodies, together with the stratigraphy, structure and sealing capacity of their caprocks. The Work Area incorporates a wide range of activities, from detailed characterisation of the reservoir around the Sleipner injection site, to a much more regional evaluation of the ultimate CO_2 storage potential of the Utsira Sand and similar, adjacent sandy reservoirs. Data sources include rock core, well cuttings, geophysical logs, fluid pressure information and seismic reflection data, ranging from localised 3-D surveys to regional 2-D data sets.

Work has been carried out by BGS, GEUS, NITG-TNO and SINTEF Petroleum.

Subtask 1.1 Characterise Core and Cuttings From The Utsira Sand (SINTEF/BGS)

Near the start of the SACS project, Statoil cut a 9m (905.4-910.8 m TVDSS) core from the Utsira Sand in Sleipner field development well 15/9-A23. Sections of core were sent to SINTEF Petroleum Research, BGS and GEUS. Drill cuttings from 3 Statoil-owned wells in the Norwegian sector and 39 wells in the UK sector were sampled.

Macroscopic and microscopic analysis of core and cuttings samples show that the Utsira Sand consists mainly of a very poorly-cemented, friable, fine to medium grained sand, moderately to well sorted, with occasional coarse grains. The grains are predominantly angular to sub-angular and consist primarily of quartz with some feldspar and shell fragments. Small amounts of sheet silicates occur, commonly as a thin coating on the sand grains. XRD indicates these are mainly smectite with minor illite and chlorite. Limited SEM evidence suggests that some smectite morphologies are indicative of authigenic development. The core material shows no visible layering or preferred orientation of minerals. This may signify a high energy depositional environment (e.g. turbiditic) or alternatively, may be due to bioturbation.

Estimated porosity of the Utsira Sand is quite high. Microscopic modal analysis of thin sections indicates porosities generally ranging from $\Phi = 0.27 – 0.31$; geophysical logs give results in the range $\Phi = 0.30 – 0.40$. Porosities are highest in the Sleipner area and decrease somewhat away from there.

Subtask 1.2 Reinterpret existing Sleipner 3d survey (NITG-TNO/SINTEF)

The existing 3D seismic dataset ST98M11 covers a rectangular area of about 400 km^2, over the Sleipner gasfields, close to the UK/Norway median line. Four seismic reflectors were interpreted: Top Pliocene Prograding Unit, Intra-Pliocene Prograding Unit, Top Utsira Sand and Base Utsira Sand. These were linked to corresponding reflectors interpreted on the regional 2D seismic datasets (Subtask 1.3). Two-way travel-time, isopach and seismic attribute maps were generated (e.g. Figure 1.1). The Top Utsira Sand horizon was also depth-converted to establish potential spill points more accurately.

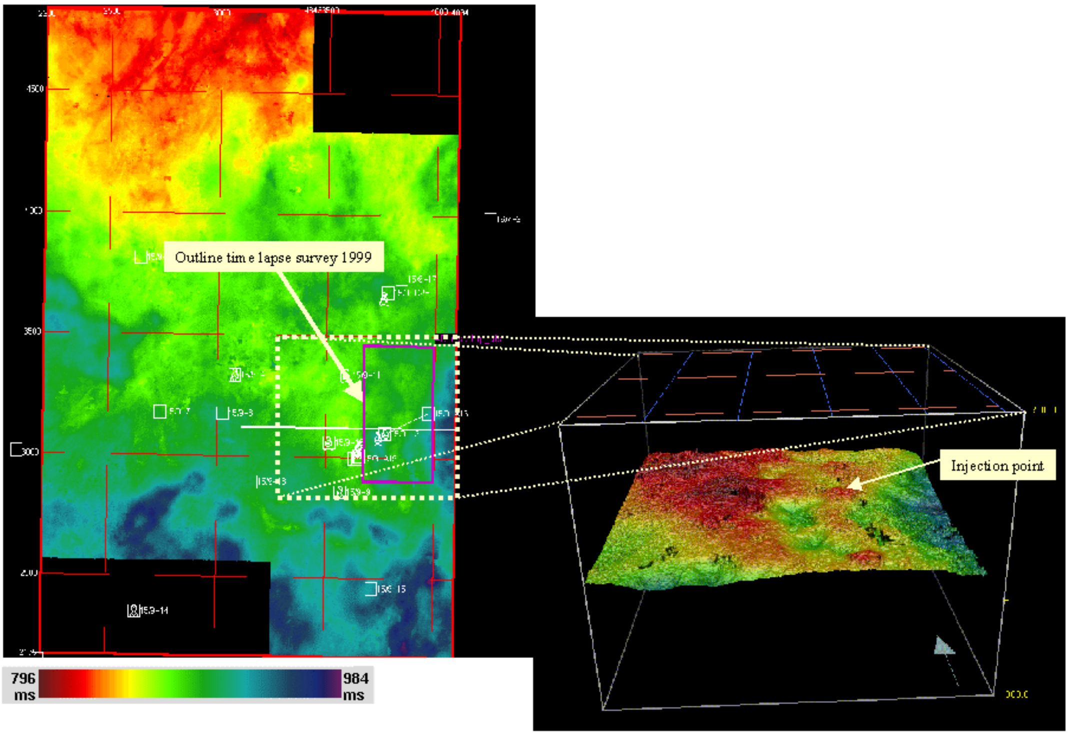

Figure 1.1 Structure map in two-way travel-time (ms) of the Top Utsira Sand around Sleipner. Note the general southerly dip and a more detailed 3D image of the Top Utsira horizon around the injection well, showing local domal and anticlinal structures. [The purple square indicates the boundaries of the 1999 time-lapse seismic survey].

The 3D dataset has provided detailed information on the Utsira Sand around the injection site. The base of the reservoir is cut locally by small, predominantly reverse faults, but those identified so far do not penetrate significantly into the Utsira Sand itself or its caprock. Mounds at the base of the Utsira Sand have also been identified and mapped. They are thought to signify syn-depositional mud volcanism and diapirism. The shale mounds are marked by corresponding depressions at the top of the Utsira Sand, interpreted to be a consequence of differential compaction. These local modifications to the general southward structural dip include local domal and anticlinal features which may act as traps and/or channels during CO_2 migration (Figure 1.1).

Subtask 1.3 Stratigraphy and structure of the Greater Sleipner area (BGS/GEUS/SINTEF)

Seismic data from three North Sea regional surveys have been utilised, together with more detailed infill data in the vicinity of Sleipner. In the early stages of the work, incomplete or corrupted digital seismic datasets caused severe problems with data loading. These have now been mostly overcome. A large number of wells have also been loaded onto the workstations, most with interpreted stratigraphy, geophysical logs and time-depth information. Current data holdings are summarised in Table 1.1

Table 1.1 Current data holdings

SEISMIC DATA		
survey	UK	Norway
CNST82 (original and reprocessed versions)	yes	yes
NNST84	yes	yes
NVGT88	yes	yes
VGST89	Yes	Yes

WELL DATA		
UK	Norway	
137	240	number of wells loaded onto workstations
101	138	interpreted stratigraphy
87	103	geophysical logs
81	89	time-depth information

Regional interpretation so far has concentrated on the CNST82 and VGST89 surveys. Five main reflectors define the Utsira geotechnical system: Top Pliocene Prograding Unit, Base Pliocene Prograding Unit, Top Utsira Sand, Base Utsira Sand and Mid-Miocene Onlap Surface (Figure 1.2).

The Utsira Sand forms a basinally restricted unit, overlain by argillaceous caprocks. Provisional two-way travel-time maps have been made of Top Utsira Sand (Figure 1.3), Utsira Sand Isochore, Base Utsira Sand and the Mid-Miocene Onlap surface.

The top of the Utsira Sand lies at about 1300 ms twtt (~1250 m) in the south, shallowing to less than 700 ms (~650 m) in the north. It reaches a maximum thickness of more than 280 ms twtt (~ 300 metres) in the Sleipner area, but thins away from this depocentre in all directions with updip pinchout limits established to the west and east. Well logs from released wells penetrating the Utsira Sand have been compiled and regional scale correlation diagrams made. Porosity was determined from geophysical logs in all released wells in the UK and from in several wells in the Norwegian sector. Provisional estimates of net sand and total pore volume have been made.

In the immediate vicinity of Sleipner, several thin (<1m thick) shale layers have been identified within the Utsira Sand, these are expected to influence migration of CO_2 on the local scale. More regionally, and neglecting the effects of natural fluid flow, the general migration trend appears to be northwards from Sleipner.

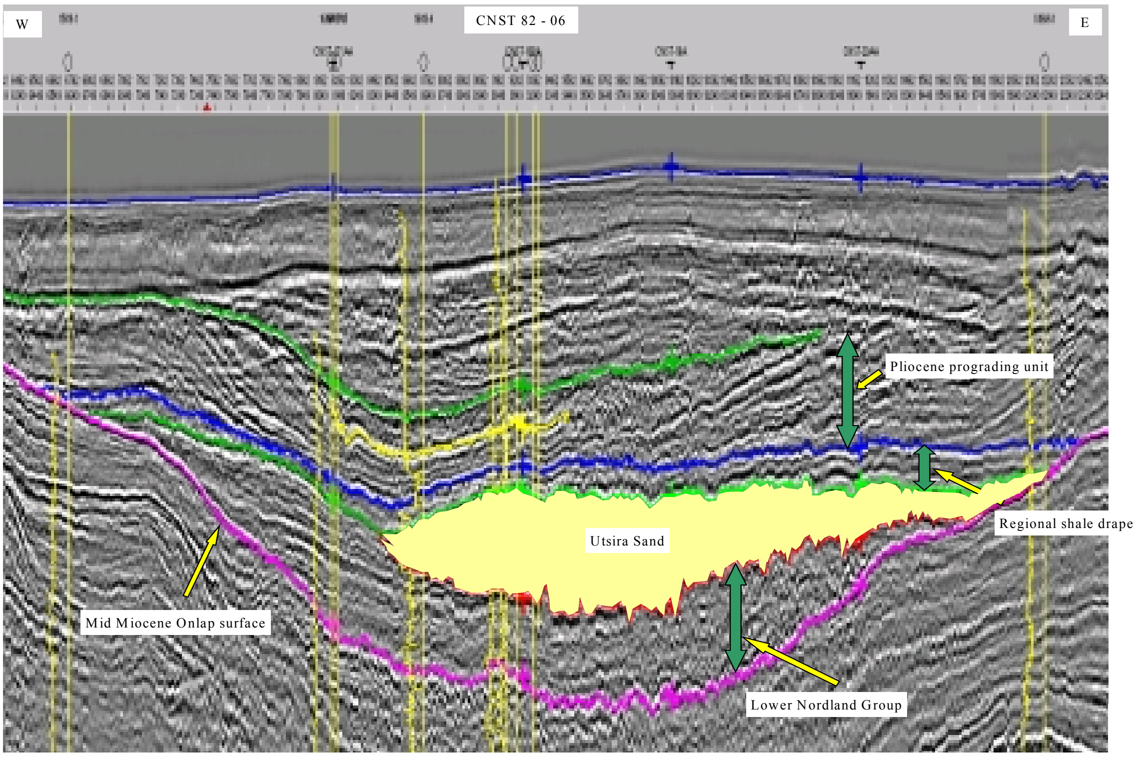

Figure 1.2 Regional seismic line through the Utsira geotechnical system

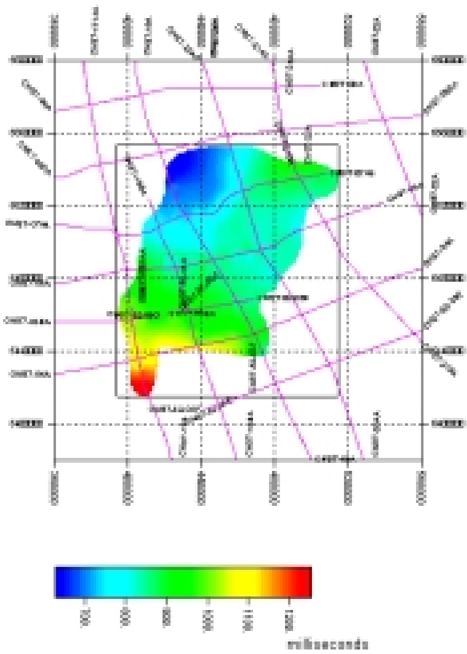

Figure 1.3 Two-way travel time map to Top Utsira Sand, Greater Sleipner area. Note general shallowing of the reservoir top to the north and northwest.

Subtask 1.4 Characterise caprock (SINTEF/GEUS/BGS)

No core material is currently available from the caprock. However, drill cuttings, mudlogs and wireline log data from the caprock were compiled and interpreted.

Wet cuttings samples from 3 wells around Sleipner were obtained and described and a representative selection from 2 of the wells was analysed by X-ray diffraction. Search for further cap rock samples (preferably wet samples and/or cores) from close to the injection site will be continued in SACS2.

Cuttings samples from 39 wells in the UK sector were inspected, and selected samples were collected for analysis. Initial results indicate that the caprock consists of medium grey to dark grey mudstone. Further work will be carried out in SACS2.

Petrophysical analysis of the caprock was carried out using wireline log data. Shale volume has been estimated, but ideally needs to be calibrated to the shale volume determined from other methods (e.g. measurements on core).

Subtask 1.5 Evaluate formation fluids (GEUS)

No fluid samples from the Utsira Formation were available for analysis. Both GEUS and BGS extracted pore fluid from their core segments. However the recovered fluid samples were found to be heavily contaminated by drilling mud (see Work Area 3).

Subtask 1.6 Determine natural fluid flow in the Utsira Sand (GEUS)

Only three pressure measurements are currently available from the Utsira Sand so it was not possible to determine the natural fluid flow in the Utsira Sand with any confidence. A preliminary flow calculation, using Darcy's Law indicates very slow regional flow (about 3 km per thousand years) in a general northward direction. It is stressed however that serious doubts about the accuracy of the pressure data in the Utsira Sand render such conclusions speculative. Work planned for SACS2 includes basin-modelling of the Utsira reservoir system to establish the importance of regional compaction-driven fluid flow.

Supporting Confidential Technical Reports:

Pearce, J.M., Kemp, S.J. and Wetton, P.D. 1999. Mineralogical and petrographical characterisation of a 1m core from the Utsira Formation, Central North Sea. British Geological Survey Report WG/99/24C.

Lothe, A.E. & Zweigel, P. 1999. Saline Aquifer CO2 Storage (SACS). Informal annual report of SINTEF Petroleum Research's results in work area 1 'Reservoir Geology'. SINTEF Petroleum Research Report No. 23.4300.00/03/99 (Restricted).

Holloway, S., Arts, R., Chadwick, R.A., Gregersen, U., Johannessen, P.N., Kirby, G.A., Kristensen, L., Lothe, A.E., Pearce, J.M. & Zweigel, P. 2000. Saline Aquifer CO2 Storage (SACS). Final Report. Work Area 1 – Geology. British Geological Survey Report WH/2000/21C (Confidential).

WORK AREA 2: RESERVOIR SIMULATION

The objective of this part of the project is to simulate the effects of injecting CO_2 into the Utsira Formation, during and following the injection period. This is a critical part of the project because it is the most important method of demonstrating the migration, distribution and predicting the ultimate fate of the injected CO_2. During the project, simulation of the present history can provide information on when, where and how to perform the most optimal seismic survey.

Subtask 2.1: Fluid properties of the CO_2/brine system

The work of this subtask has been supplied by SINTEF Petroleum Research.

Important input parameters for reservoir simulations are densities and viscosities of the fluid involved, and their temperature and pressure dependence. Also solubility and vapour pressure can have significant effects besides the parameters that are related to the interaction between fluids and the porous rock (absolute and relative permeability and capillary pressure). This task is however limited to the pure fluid properties. The surface tension between gas and water is actually also a pure fluid property, but this parameter is also treated in an other task because it is used for estimation of capillary pressure, which is a due to interaction between rock and fluid.

It was realised already in the pre-project (“Task Zero”) that the contamination of CO_2 with 2 – 3 % methane could have a pronounced effect on the fluid properties. This task does therefore also include studies of the ternary system CO_2-methane-brine as well as pure CO_2 properties.

Experimental data for pure CO_2 densities have been reviewed and a lot of data were found in the most interesting temperature and pressure range. For the CO_2/methane system experimental data are scarcer and unfortunately, in the important range between 15°C and 37.8°C there is a lack of experimental data. It was therefor decided to measure some more data in this range for CO_2/methane mixtures with low methane content. This work was, however, interrupted and postponed to next phase of the project due to the budget cut. In the reservoir simulations performed this year, we had to relay on fluid models for CO_2/methane mixtures that were based on a less optimal data set (Duan et al.)

For viscosity we have the same situation as for density, there exists a a lot of data for pure CO_2 while data for the CO_2 and methane are lacking. These data most therefor be estimated by methods with some uncertainty.

For brine, however, there exists a lot of reliable data for both density and viscosity and these data sets provide sufficient material for simulation input.

A computer program that can process the best fluid data available and produce fluid data input files for a reservoir simulation, has been developed. This was used for the some of the simulation in Task 2.5

Task 2.2: Relative permeability measurements of water/CO_2

The work in this task is supplied by SINTEF Petroleum Research.

This task, which is also most based on experimental work, was the task that suffered most of the budget cut as it was reduced with 37%. This was, however, partially compensated by reducing somewhat on the SINTEF contribution in Task 2.1 and 2.7, work that most compensated and completed in the next phase of the project.

A method to take core samples for laboratory experiments for the totally unconsolidated Utsira sand has been developed. Permeability for both horizontal and vertical samples has been measured and also a capillary curve has been obtained by centrifuge experiments. The simulation this year had to rely on relative permeabilities for CO_2 and brine that had been measured in the SINTEF laboratory on a less permeable core (Bentheimer). The relative permeability measurement has to be completed in the next phase of the project and a core is already prepared for this purpose.

Task 2.3: Selection of a simulation tools.

The work in this task has been supplied by NITG-TNO.

For proper simulation it's essential to have extensive knowledge about the following four subjects:
Full understanding of all physical processes involved;
Available tools to simulated these processes;
Full knowledge of the shortcoming of the simulation principle used and assumptions made;
Type, volume and measuring method of reservoir and fluid data available
Tasks 2.3 been executed in such a matter that both the goals of this tasks are met as well as that discrepancy between results from historical simulation work and actual reservoir behaviour are being resolved.

All available data has been collected and analysed. A relative large amount of time has been devoted on an attempt to find and collect data from the CO_2 injection location in the Utsira formation. Information requests addressed to Statoil, the operator of the field, have been redirected to SINTEF. SINTEF has made available to NITG-TNO general Utsira data, of the public available type. Statoil has not measured any data from the Utsira reservoir in the vicinity of the CO_2 injection well. CO_2 injection practice and operations constrains have been deducted from the available injection data and from papers published by the Statoil production operations personnel.

A limited literature study has been performed to gather as much as possible information and data on all processes involved if CO_2 is injected in the sub-surface. It was concluded that a total of five processes, or storage mechanisms would be crucially important in case CO_2 is injected in a saline aquifer formation. These five are:
- CO_2 as a free fluid at super critical conditions;
- CO_2 dissolved in formation water;
- CO_2 trapped in carbonate form in minerals;
- As residual gas; and
- CO_2 containment by gravity instability.

The physics of the individual processes have been studied including the monitoring possibility of these processes. Special attention has been paid at the ability to obtain laboratory or field measured data concerning the effects of these processes. Furthermore, three commercial available simulators have been evaluated in their capability to simulate the above mentioned

processes. A model comparison study has been performed in order to research their capability to model the listed processes. The general conclusion from this work can be summarised as follow:
All three simulator-approaches give similar results, for the limited simulation period. This period is within the active stage of the storage. The absolute results of long term simulations, far into the passive storage period, must be treated with the utmost care.
The simulator approach of the CO_2 solubility in water process needs refinement. In order to simulate pressure equilibrium diffusion a time/concentration dependent approach is needed.
The simulation technology of fluid rock interaction in combination with fluid transport is still not in a practical state. None of the investigated simulators takes care of this phenomena
The compositional and GOR approach simulations overestimate CO_2 solubility at the front of the displacement.
In the areas with low residual water saturation the prediction of CO_2 saturation is nearly the same for all three methods.
All three simulators predict the same well performance.
Sound engineering judgement is needed to interpret the calculated simulation results in case of all present simulation work related to CO_2 injection.

Task 2.4 and 2.5 Preliminary simulation model and simulation of the present history of CO_2 injection

The work is task has been supplied by SINTEF Petroleum Research and NITG-TNO and is here reported as one task because for such a short project they are highly integrated.

Nine different models for simulation of CO_2 density has been tested in the most relevant temperature and pressure region and the best of these give a satisfactory consistence with experimental data for pure CO_2. For CO_2/methane mixtures the models are less satisfactory.

The reservoir simulations has been performed along two different approaches:

One set of simulations has been carried out on a models where the only heterogeneities are horizontal impermeable shales with varying extension as shales can be seen on the well logs from the area, but their size and integrity are uncertain. These simulations were carried out on a radial grid consisting of between 20 000 and 120 000 grid points.
The other sets of simulation were carried out on a Cartesian type coarse grid and the sensitivity of the extension of the CO_2 bubble with respect to the permeability was studied. These simulation were carried out on both a regional and local scale.

In the first set simulations of the CO_2 injection history corresponding to the injection in Utsira formation from September 1996 to 15. August 1999 were performed . A homogeneous and a heterogeneous reservoir model were tested based on the shallow anticline structural trap near the injection point. In both cases significantly accumulations of CO_2 with up to 20 m thickness will be present either under the cap rock or under the impermeable shales deeper in the formation. In the homogeneous case CO_2 will start to accumulate under the cap rock three weeks after the injection started. The CO_2 bubble will then gradually increase in radius until it reaches the spill point 1. December 1998 at 800 m radius. The CO_2 will then start to migrate to one of the three traps north, west or south of the injection trap. In the heterogeneous model the accumulation under the cap rock will be delayed with 34 months. However, large accumulations with a thickness up to 12 m will be present deeper in the reservoir. An example of the results of the heterogeneous grid is given in Figure 2.1

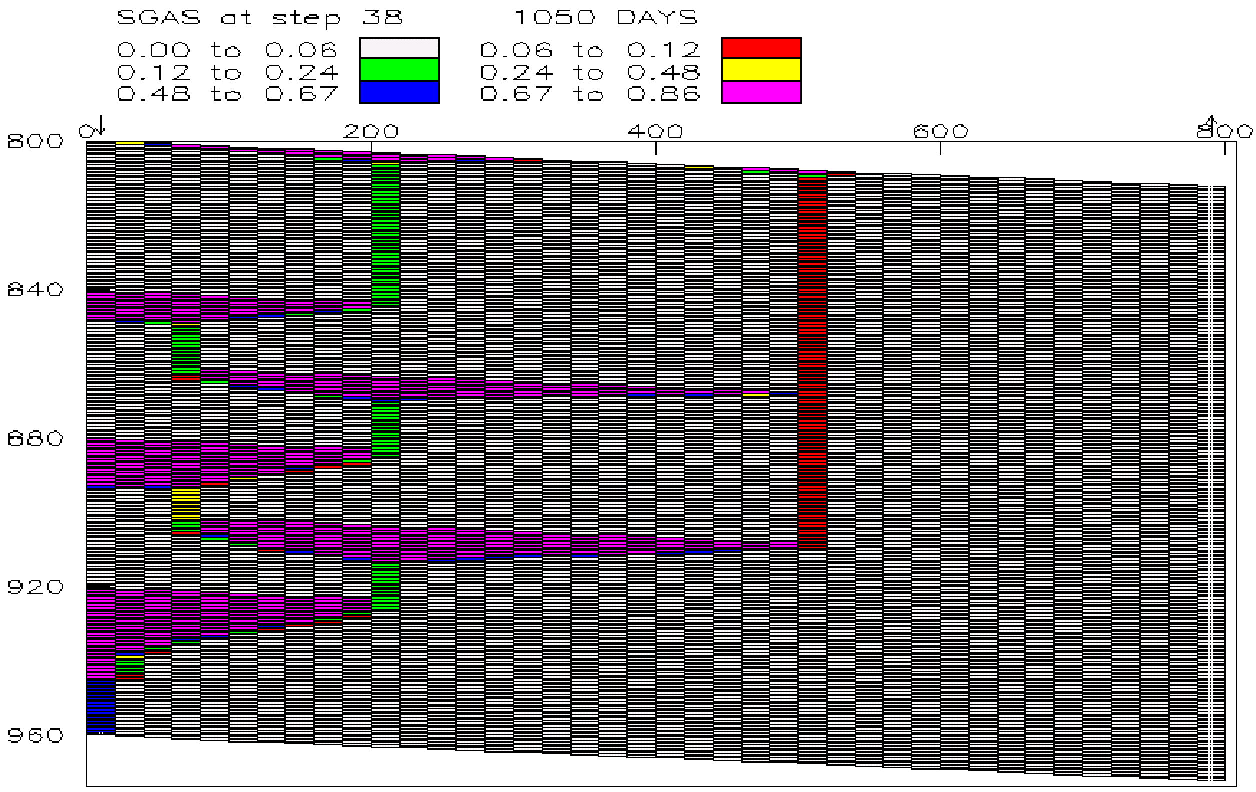

Figure 2.1 Saturation profile of the heterogeneous reservoir model at 15. August 1999. The CO_2 has recently reached the cap seal but large CO_2 bubbles have accumulated under impermeable shales.

<u>This result was used to justify the rescheduling of the seismic survey.</u>

The well injection bore plays an important role in the Sleipner CO2 injection activity. The field operator controls the Bottom Hole Flowing Pressure (BHFP) by varying the flowing well head temperature at a nearly constant injection pressure of 6100 kPa. Effectively, changing the fluid from gas into a liquid or a mixture of these phases which results in a varying CO_2 column weigh in the well bore. In this manner the CO_2 density at the wellhead can vary from around 150 kg/m^3 to 700 kg/m^3. As pressure increases, by increasing depth and temperature, the injection fluid density will gradual change to the one of a critical fluid. It is easily understandable that this process is complex and dependable of many operational conditions. Consequently, the prediction of this behaviour is difficult, especially in the case in which not all operational conditions are known. In the case of the Sleipner operations, we have to conclude from vertical flow sensitivity calculations, that the CO2 well head fluid condition is of the liquid type for nearly the whole historical injection period. The calculated result show flowing bottom hole pressures from around 10500 kPa for a gas type injection fluid to 11800 kPa for a liquid type of injection fluid. From this simulation exercise it became clear that more research is needed. This especially in the field of fluid phase behaviour around the critical conditions of CO_2 and the multi phase fluid behaviour in vertical conducts.

For fluid simulation in the reservoir we have made use of a downscaled version of the model used in the regional simulation study. The historical injection data has been converted to simulator input data. For the following simulation runs a uniform permeability of 3500 mD has been used. The calculated result are shown in the figures 2.2 and 2.3

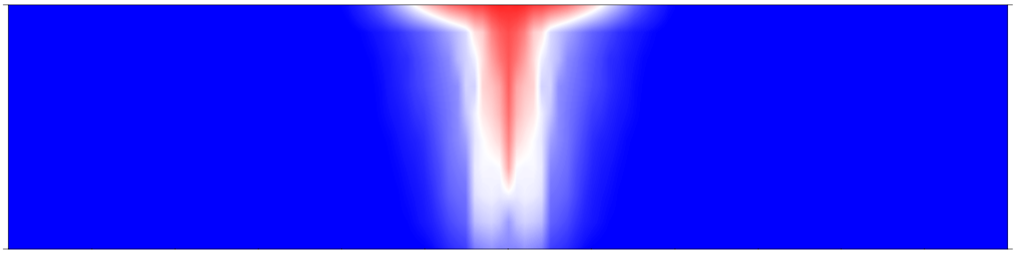

Figure 2.2 CO_2 Saturation cross section map at end of History Match period (861 days)

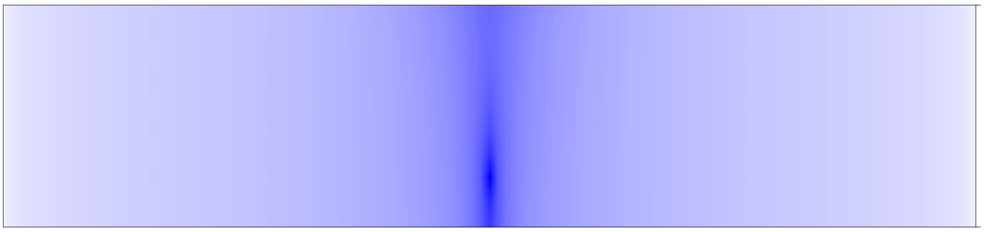

Figure 2.3 Pressure cross section map at end of History Match period (861 days)

The saturation map is showing a for CO_2 familiar picture, of a rising CO_2 column and CO2 spreading pattern under the caprock. The horizontal CO_2 movement is mainly dictated by the relative large permeability. The pressure distribution is showing only small increments around, and directly above, the injection point.Preliminary 4D seismic data show a promising result.

Task 2.7: Rayleigh convection

This work in this task has been supplied by SINTEF Petroleum Research.

If circular convection in the reservoir is present due to thermal gradients (Rayleigh convection), or if convection can be induced by compositional gradients due to diffusion of CO_2 into the water column, this could significantly increase the fraction of CO_2 that will be dissolved in the water on a long term scale. A simple analytic analysis of these phenomena, indicated that it could be an important parameter in reservoirs with a high water column and high vertical permeability. In a more thorough analysis, a numerical simulation of the transport equations should be performed to include the transient character of diffusion. If convection is significant, the results from these simulations should be taken into consideration in the ordinary reservoir simulation.

The physical model and basic equations have been established and a fully implicit numerical model has been built The final testing and optimising of the code has been deferred to next phase.

WORK AREA 3: GEOCHEMISTRY

The overall objective of this work area is to determine the potential for chemical reactions between the reservoir rock (Utsira sand) and caprock, and injected CO_2. It aims to assess :

- how much CO_2 can be trapped by geochemical reactions (as dissolved CO_2, bicarbonate or carbonate minerals),
- the chemical behaviour of caprock and its susceptibility to damage by the injected CO_2,
- the effect of the chemical changes on the porosity and permeability of the reservoir, which constrain fluid flow within the reservoir,
- the ability of geochemical codes and coupled reaction/transport codes to reproduce experimental observations and make accurate predictions.

The methodologies used within the SACS project lie on laboratory experiments (Task 3.2) and numerical modelling for the interpretation of these experiments (Task 3.3) and for the assessment of the geochemical state of the Utsira formation prior to CO_2 injection (Task 3.1).

The geochemical partners involved are two experimental groups (BGS and GEUS) and two modelling groups (BRGM and IFP). BRGM has been the co-ordinator of the geochemical work area since the beginning of the project. Regular discussions took place between the four partners, through e-mails, informal geochemical meetings just before or after steering committee meetings, and a geochemical meeting on March 30 in Copenhagen.

Preliminary work consisted in requesting and searching for geochemical data and rock samples relative to the Utsira formation and caprock, which were necessary to start the geochemical programme. Unfortunately, it turned out that only the following data and samples were available:

* *Samples of Utsira rock*: two frozen cores from the Sleipner field, coming from well 15/9-A-23 and corresponding to depths 1084.1-1085.0m (GEUS sample) and 1085.1-1086.0m (BGS sample). Dimensions about 1m long and 4 inches diameter.
* *Samples of Utsira caprock*: there exists no core from the Sleipner field or other fields, only cuttings.
* *Fluid data for the Utsira formation*: One detailed fluid chemical analysis is available in the Oseberg area (surface sample, see p. 19 of the SACS Phase Zero report). Two other chemical analyses were carried out on the porewaters of the two core samples from the Sleipner field; however there were highly contaminated by drilling mud (probably KCl + SO4 + organic polymers…). More details are given in the Task 1.5 report below, as it has been thought more relevant to include it in the Geochemical report.
* *Fluid data for the caprock formation*: no data are available on the Sleipner field as only cuttings exist.

Work achieved over the reporting period has been:

(i) the assessment of the initial fluid/rock geochemical state prior to CO_2 injection (Task 3.1),

(ii) the initiation of laboratory experiments (Task 3.2), and in particular the initiation and initial sampling of long-term batch experiments running under in-situ conditions, development work on flow experiments and analytical methodologies,

(iii) the development and running tests of geochemical and coupled reaction-transport numerical codes (Task 3.3).

The three tasks of the geochemical programme will continue into SACS II. Work is still underway and the results so far may change.

Part of the originally planned geochemical work within SACS has been shifted to SACS II, due to the opportunity to acquire seismic data in 1999.

The main problem encountered during the reporting period was that of difficulties in obtaining rock and fluid samples, fluid chemical data and mineralogical data. This introduced some delay on the beginning of all tasks of the geochemical work programme, which was partly alleviated by the postponement of part of the work on the SACS II project.

TASK 1.5 EVALUATION OF FORMATION FLUIDS (GEUS)

The objective of this task has been to collect available information on the water composition of the Utsira Formation and to carry out supplementary formation water analyses. GEUS role has been to analyse fluid samples or extract pore water from preserved core if available.

Unfortunately, no fluid samples were available from the Utsira Formation. However, GEUS received 5 pieces of frozen 4” diameter core, in total 0.9 meter core covering the interval 1084.1 – 1085.0 meter MD from the 15/9-A23 well. The core pieces were preserved in ordinary plastic bags but appeared in a good condition. Pore water was extracted for analysis. Results were compared to the analyses carried out by BGS on their core sample and to the analysis from the Oseberg fluid.

As seen from the very high potassium concentration (~30000 ppm), the core material was heavily contaminated by drilling mud. Water analyses from the nearby Oseberg field typically have potassium concentrations ~200 ppm. An attempt to correct the analyses would require data on the chemical composition of the drilling mud, and even then it is questionable if a precise correction could be obtained considering the massive contamination. It has not been possible to obtain any information on the mud composition. Therefore the best estimate of the Utsira Formation water composition is the analysis from the Oseberg field given in the SACS Phase 0 report.

TASK 3.1. INITIAL FLUID/ROCK EQUILIBRIUM STATE OF THE UTSIRA FORMATION (BRGM)

The objective of this task is to describe the initial thermodynamic equilibrium state within the Utsira formation before CO_2 injection started. This baseline information will allow changes to the initial chemical conditions resulting from the CO_2 injection to be recognised and monitored.

The only data presently available and considered for this task are:
- a surface water analysis from the Oseberg field, 200 km north from the Sleipner field (see task zero report),
- the mineralogical description of 2m core in the Sleipner field (well 15/9-A-23, 1084 to 1086 depth), as well as cuttings mineralogical description (see task 1.1 report).

The scarcity of the data and the fact that the water analysis and mineralogical description do not refer to the same location prevent from being able to do a precise and reliable assessment of the baseline geochemistry. The Oseberg analysis may not be fully representative of the Sleipner area, for instance regarding gas content, and do not report Al and Si contents which are crucial in studying aluminosilicate reactions. However, as the aqueous Na concentrations of the extracted porewaters (8-9 g/l), which were not affected by drilling mud contamination, are close to that of the Oseberg fluid (10 g/l), the decision of using the Oseberg analysis as representative of the Utsira formation is presently an acceptable compromise. Direct measurements of Utsira fluid salinity are in agreement with this choice (33-43 g/l in the Oseberg field and 35-40 g/l in the Sleipner field, see SACS Task Zero report).

Work achieved during the reporting period has been:
- comments on the chemical analysis of the Oseberg fluid (surface sample)
- assessment of in situ fluid composition in the Oseberg field (23 °C, 7-8 MPa)
- assessment of in situ fluid composition in the Sleipner field (37 °C, 8-11 MPa)

For this, two geochemical codes were used: (i) the EQ3/6 software package, a reference code for geochemical modelling of water-rock interactions, developed at Lawrence Livermore National Laboratory (Wolery, 1995); (ii) SCALESIM, a geochemical code built at BRGM (Azaroual *et al.*,1999), which takes into account the effect of pressure (assumed to be 10 Mpa) on thermodynamic constants and uses the Pitzer formalism for the calculation of activity coefficients (Al is not considered in SCALESIM).

Further calculations will be carried out within SACS II and refinements will be achieved working on thermodynamic data, mineralogical observations and results of the blank batch experiments. The latter will be of great interest for studying the baseline geochemistry before CO_2 injection.

TASK 3.2. GEOCHEMICAL LABORATORY EXPERIMENTS
(BGS and GEUS)

The objective of this task is to determine the potential for reaction of the reservoir rock (Utsira sand) and caprock with injected CO_2, identify the key geochemical reactions (direction, magnitude and rate) and provide test cases to improve the ability of geochemical modelling packages to make accurate predictions. The four partners of the geochemical programme decided to use a 'synthetic Oseberg fluid' in the experiments, as representative of the Utsira formation fluid (compromise).

BGS EXPERIMENTS

Long term batch experiments under in-situ conditions (involving Utsira sand, synthetic Oseberg porewater and CO_2)

A series of these experiments were initiated in early August 1999, and by the end of the reporting period will have been running for approximately 5 months. The aim of these experiments, carried out at reservoir conditions (37 °C, 10 MPa), is to investigate the reactions caused by adding CO_2 to Utsira sand and synthetic Oseberg porewater. The experiments are being done in pairs, with each pair set up identically to one another. The only difference is of the timescale of reaction, which varies from 1 month to 24 months. When the results of the experiments are plotted over increasing time it should be possible to get information on the rates and magnitude of the geochemical changes.

Each pair of experiments consists of one pressurised with CO_2 and an 'experimental blank' pressurised with nitrogen. The experiment pressurised with nitrogen is useful for finding out just how close the Oseberg porewater is to equilibrium with the Utsira sand. In other words, the data from these experiments will help to compensate for the lack of information on baseline geochemistry at Sleipner. The experiment pressurised with CO_2 will allow observation of changes over and above those occurring in the experiments pressurised with nitrogen.

Long term batch experiments at a temperature above in-situ conditions (involving Utsira sand, synthetic Oseberg porewater and CO_2)

These experiments have not started yet, though they are due to do so early in SACS II. They will be very similar to those described above, except for their higher temperature (70 °C). The elevated temperature was chosen so as to increase the possibility of achieving an observable reaction over a laboratory time scale whilst not encouraging the formation of unrepresentative secondary phases.

CO_2 solubility measurements under conditions relevant to (i) and (ii) above

The first few of these experiments have already started. They are aimed at providing data on exactly how much CO_2 can dissolve into the synthetic Oseberg formation water over a range of conditions.The conditions chosen vary between 8-12 MPa and 37-70 °C.

Long term, long pathlength flow experiments (involving Utsira sand, synthetic Oseberg porewater and CO_2)

These experiments have not started yet, though they are due to do so early in SACS II. They are aimed at providing the geochemical modelling groups with 'test cases' with which to 'benchmark' the various modelling packages being employed in SACS. Work undertaken on them during the reporting period has concentrated on devising a suitable experimental approach and obtaining the necessary equipment.

Development of in-situ pH measuring technique

In order to be able to measure pH under high pressure conditions, we have found that an interesting possibility exists of transferring a technique developed to aid the understanding of uranium processing (Toews *et al.*, 1995). In order for the above to be used in the current experimental programme, a high pressure optical cell was manufactured at BGS. It is envisaged that use of this optical cell to determine in-situ pH in the experiments will become a standard technique in SACS II.

GEUS EXPERIMENTS

GEUS role has been to characterize the mineralogy of the sand, to supply standard core analysis data, to undertake dynamic flooding experiments at reservoir conditions and take fluid samples for chemical analysis. Delays have occurred due to lacking information on the Utsira Sand formation water composition and running in problems with new analytical instrumentation. CO_2 flooding experiments lagging behind will be carried out during SACS II.

Porosity, grain density and liquid permeability were measured at room conditions for several Utsira sand plugs. Some of them were then transferred to a reservoir condition rig, and the confining pressure slowly increased to a net overburden (NOB) of 100 bar (equal to 62 bar hydrostatic confinement used in the experiments). The porosity reduction was calculated from the amount of liquid produced during pressure increase from 10 to 100 bars NOB.

The next step will be to increase the temperature to 37 °C (reservoir temperature) and conduct a series of blind tests before the CO_2 saturated Synthetic Oseberg porewater is injected. A tracer study will also be conducted.

TASK 3.3. INTERPRET THE GEOCHEMICAL EXPERIMENTS (BRGM and IFP)

The objective of this task is to interpret the results of the laboratory experiments by numerical modelling, and test through the various experimental test cases the ability of geochemical codes and coupled reaction-transport codes to make accurate predictions.

Work achieved within the reported period consisted in code development and running tests under conditions close to the experimental conditions, to ensure accurate and robust calculations. Confrontation of modelling calculations and experimental results will only begin within SACS II, as very few experimental results were available at the end of SACS.

BRGM MODELLING ACTIVITIES

Selection of a rock composition representative of the Utsira Sand for geochemical modelling

Considering the results of the petrographical and mineralogical studies carried out by SINTEF, GEUS and BGS, it seems that the whole-rock mineralogy and the modal mineralogical composition given by BGS (from 1085 to 1086 m in well 15/9-A23) can be considered as representative of the Utsira Formation. For the purpose of geochemical modelling, the resulting composition has been simplified and slightly modified.

Modelling codes used by BRGM for the interpretation of the experiments

Batch experiments will be interpreted using geochemical codes, mainly EQ3/6 and SCALESIM (see Task 3.1), as well as a specific chemical simulator named 'UTSIRA simulator' developed by BRGM for the SACS project. Core flooded experiments will be interpreted using a coupled geochemical and tranport code, specially developed for the SACS project by coupling the UTSIRA chemical simulator to the flow and transport code MARTHE. Conceived and developed by BRGM group for the hydrodynamic and hydrodispersive modelling of groundwater flow in porous media, the MARTHE software package (Thiéry, 1994) is designed to resolve underground hydrodynamic problems in various contexts.

Construction of the geochemical UTSIRA simulator

The geochemical modelling strategy adopted in BRGM is based on the concept of Specific Chemical Simulator (SCS). For each new study a SCS is developed. The construction is facilitated thanks to the use of the modelling software ALLAN and NEPTUNIX, which automatically generate a FORTRAN code (Kervévan and Baranger, 1998).

The Utsira simulator was constructed under the ALLAN environment to calculate the evolutions with time of water solute speciation and water-rock-CO_2 interactions. It is designed (especially appropriate management of input/output data) to be further coupled to the Hydrogeological and Transport Code MARTHE (Kervévan *et al.*, 1998). The Utsira simulator presently takes into account 9 minerals (calcite, quartz, dis-dolomite, albite, K-feldspar, kaolinite, muscovite, anorthite, illite), 32 aqueous reactions involving 42 relevant dissolved species (and 11 chemical elements: O, H, Na, K, Ca, Mg, Al, Si, S, C, Cl), and CO_2 as a gas phase. All thermodynamic data come from the data0.com.R2 database of the EQ3/6 v7.2b software package (Wolery, 1995). Dissolution-precipitation reaction of minerals are described according to a kinetic law derived from the Transition State Theory.

A validation stage of the UTSIRA simulator is necessary before coupling the SCS with a hydrogeological code. For that purpose, code-to-code verifications were carried out with the EQ3/6 code. Simulations were performed to compare the results generated by EQ6 and UTSIRA simulator, respecting to aqueous speciation.

Construction of the coupled reaction-transport Utsira simulator
The coupling of the geochemical UTSIRA simulator with the MARTHE flow and transport model is carried out according to a sequential non-iterative approach. It means that at each time step, for each cell, first hydrodynamics, then transport of each chemical component and finally chemistry (call of the geochemical UTSIRA simulator as an embedded subroutine) are calculated.

IFP MODELLING ACTIVITIES

In the framework of the SACS project, IFP is using the reaction-transport code DIAPHORE developped for the modelling of water-rock interactions, particularly those active during diagenesis of reservoirs. DIAPHORE can be used with a “box-system”, closed or open. Alternatively, it can be used with a dimensional system. For modelling the lab experiments, the two options are used : the box system is adapted to the BGS batch experiments, and a 1-dimensional system was designed for simulating the GEUS coreflood experiments.

The simulations carried out up to now are preliminary tests to a significant comparison with the experiments, because at the date where this report is written only the batch experiments, launched three months ago, provided first results (water analyses).

During the reporting period, work was focused on:
- water composition, speciation and dissolved C calculations, in order to address CO2 solubility issues;
- selection of the mineralogical system to be used in the modelling: nature of the minerals, thermodynamic and kinetic data;
- simulation tests in closed system (to be compared to batch experiments);
- simulation tests in open, 1-dimensional system (for future comparison to coreflood experiments).

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WORK AREA 4: MONITORING WELL?

According to revised plan this work has been delayed to SACS2 (year 2000-2001).

WORK AREA 5: GEOPHYSICAL MONITORING

TASK 5.3 Sensitivity study on possible changes in seismic data due to CO_2 injection (SINTEF)

We have investigated the possibility of monitoring the injection of CO_2 in the Utsira formation at Sleipner from seismic data. For this, we calculated the expected seismic response of the earth before and after the injection of gas was started.

An earth model was constructed, using geological and petrophysical information about the area of interest. A structural 2-D model was obtained using interpreted horizons from a seismic line which passes close to the injection point. The depth of the top Utsira horizon was slightly adjusted to reproduce the shape of the 12 m high anticline just above the injection point. We used a combination of information from well log data in wells around the injection point and from petrophysical empirical laws to estimate the seismic parameters between the different horizons. This allowed building a 2-D elastic model for finite-difference modelling of data from the base survey.

From reservoir modelling, we obtained a description of the geometrical and physical properties of the gas accumulations. We considered CO_2 bubbles of different thickness stored in the anticline, and CO_2 accumulations created by thin shale barriers in the Utsira formation. The density and compressibility of the CO_2 were calculated using state equations. The porosity of the Utsira formation being known, the changes of the density, and compressional- and shear-wave velocities caused by a change of pore fluid were calculated using the

Gassmann equation. This allowed building several elastic models representing different possible situations for the gas accumulations.
Using these different models, the seismic response after the CO_2 injection, and the change in seismic response caused by the injection were calculated, first using a very simple convolutional model, then by a high-order 2-D finite-difference modeling.

Major results of task 5.3

In the Utsira formation, the gas has an extremely high compressibility because the temperature is just above the critical temperature. Because the rock matrix in the Utsira formation is very weak, the compressional velocity is also unusually sensitive to the compressibility of the fluid. Therefore, the presence of gas induces a dramatic drop of the compressional wave velocity even for moderate gas saturations. The Gassmann equation predicts a 34% to 37% decrease of the P-wave velocity, a 6% to 12% decrease of the density, and a 3% to 6% increase of the shear wave velocity, depending on the composition of the gas. Moreover, the transition between full-water and full-gas saturation zones is very sharp.
Hence, the top and bottom of gas accumulations are very good seismic reflectors, with negative and positive impedance contrasts, respectively. Since the thickness of gas is smaller than the dominant wavelength in the seismic signal, the reflections from the top and bottom of the gas accumulations interfere. The resulting signal is clearly detectable on seismic prestack data or on a zero-offset section, both for gas stored in the anticline and accumulated below shale barriers, even for thin gas accumulations (e.g. 3 m thick). Comparison of the data modeled with and without gas helps tracking the extension of the gas buble. Due to the excellent contrast in velocity and density between water saturated and gas saturated sands in the Utsira formation, our modeling predicts that gas accumulations thicker than 1 m cause changes in the data that are as strong as reflections from important horizons like the top Utsira. The presence of gas accumulations also causes a slight increase of the traveltime down to the base Utsira. The change induced by this push-down effect on the seismic data is also detectable, although about five times smaller than the direct effect previously mentioned. These results suggest that a new seismic survey with the same data quality as the existing base survey would allow to locate even very thin gas accumulations (about 1 m or more) in the anticline or below shale barriers above the injection point.

TASK 5.4 Acquire and interpret time-lapse seismic

Task 5.4 was carried out by Statoil with a contractor, Geco-Prakla doing the actual seismic survey and processing of acquired data.
Parameters for the seismic were chosen after a decision process involving the relevant departments in several of the participating energy companies as well as the institutes. The basic problem was to take maximum advantage of the pre-injection 1994 survey, and to optimise the parameters towards this year's target, CO2 containing water at 1000 meter depth below sea bottom.

After a bidding round coupled with other seismic survey jobs in the North Sea for the season of 1999, a fixed price bid for acquisition and processing from Geco-Prakla was chosen. The target area being relatively small, the actual survey was done during a couple of days around 1.October 1999. That was exactly 3 years after CO2 injection commenced, 1.October 1996.

The survey and following processing went absolutely normal and was finished by end of 1999. The time schedule did not, however, permit interpretation of the data, except for a few very preliminary lines. These lines alone showed excitingly encouraging results.

The full interpretation and reporting of this seismic, compared with the pre-injection seismic shot in 1994, will be done during the SACS2 project. There it will be a major and important part of the project development work.

TASK 5.8 Feasibility study of microseismic monitoring (BRGM)

Objective

Evaluate cost, practicality and benefits of microseismic monitoring, as a tool to detect distribution of CO_2 in the storage reservoir.

Summary of subtasks:

1. State of the art of literature
2. State of the art of data acquisition and processing
3. Evaluation of what could be expected at Sleipner
4. Proposition of a monitoring experiment (Sleipner or Alberta?)

State of the art

- Mapping of induced microseismicity is widely used to map fractures stimulated by hydraulic fracturing in Hot Dry Rocks geothermal projects (Soultz, France, Kakkonda, Japan)
- Some examples in US show that fractures stimulated by hydraulic fracturing for EOR purpose can be mapped by microseismicity monitoring
- There are several examples of microseismicity induced by oil-production (US and North sea), gas production (Lac, France) and gas storage (France)
- One advantage of microseismicity monitoring is that it is continuous !!

Data acquisition and processing

- Observation wells are compulsory for use of microseismicity! Distance of observation must be less than few hundreds of m (magnitudes < 0!)
- Downhole 3-component geophones (single or arrays of up to 48 levels) are currently used
- Clamped to casing or cemented behind the casing
- Benefits of a 2d or more observation wells
- Methods of location of hypocenters are now well developed: relative mapping (Joint Hypocenter Determination), doublets, hodograms...
- Focal mechanisms and stress tensor determination are available
- Panel of downhole seismic companies (CGG, CSMA, etc.)

What could be expected at Sleipner

- Due to high permeability of Utsira formation: low magnitudes
- Depends on initial stress state of the formation (close to rupture?)
- Stress changes as low as 0.01 MPa have promoted seismic activity in oil reservoirs or triggered earthquakes after main shocks
- Microseismicity induced by production/injection was observed elsewhere in North Sea oil fields

Propositions for a field experiment

- Check 1st if induced microseismicity can be observed at Sleipner: an observation well is necessary
- Evaluate the cost of 3-month recording experiment with a single 3-component geophone, circa 0.15 MEuro
- If positive, plan a continuous recording with a vertical array of geophones, cost ??
- If the project is not considered at Sleipner, plan the same experiment at Alberta (IEA umbrella)?

3. Problems and difficulties encountered

WORK AREA 1: GEOLOGY

During the course of SACS, the time-lapse 3-D seismic acquisition was brought forward (Work Area 5). This was financed by deferring the budget from several tasks to the forthcoming SACS2 project. The effect of this was to reduce the Work Area 1 budget by about 25 percent, with a significant impact on the amount of interpretation work possible.

WORK AREA 2: RESERVOIR SIMULATION

This task was performed by two partners, NITG-TNO and SINTEF Petroleum Research with an original budget of respectively 65 000 Euro and 170 000 Euro. During the course of the project it was decided to advance one of the seismic surveys and perform it on this part of the project. The survey was financed by reducing the budget on other tasks and as far Task 2 was concerned, SINTEF's budget was reduced from 170 000 Euro to 130 000 Euro in the middle of the work. This had substantial effect on the execution of the tasks where SINTEF was involved. The deferred work has been included in the plans for the continuation, SACS2.

WORK AREA 3: GEOCHEMISTRY

The main problem encountered during the reporting period was that of difficulties in obtaining rock and fluid samples, fluid chemical data and mineralogical data. This introduced some delay on the beginning of all tasks of the geochemical work programme, which was partly alleviated by the postponement of part of the work on the SACS II project.

In particular, Utsira formation fluid chemistry was very poorly constrained. Formation water was extracted from the frozen core and analytical results proved the core was heavily contaminated with drilling mud filtrate (Task 1.5). No mud sample was available to correct the formation brine data, and it is questionable if a correction was at all possible due to the substantial contamination.

The only available analysis was from the Oseberg field some 200 km from Sleipner (Gregersen *et al.*, 1998). In the absence of any other data, the Oseberg porewater composition had to be used as the starting point for the fluids used in the geochemical experiments. Synthetic equivalents were then made up. However, the reported Oseberg analysis contains no data for Al and Si, both of which are vital in order to establish the degree of saturation state of aluminosilicate minerals. Such minerals are very important as they have a major control on buffering solution pH (Czernichowski-Lauriol *et al.*, 1996; Gunter et al, 1993; Hitchon, 1996; Hutcheon, 1993), and as a consequence, the ability of the porewater to dissolve CO_2.

The lack of firm data regarding baseline geochemistry is of broader importance than just for setting up the geochemical experiments. The uncertainties arising from the absence of such data may result in it being harder to defend the approaches taken in SACS when it comes to presenting the results of SACS to the public, regulatory bodies, and the scientific community.

A note has been written about the need to get at least a water sample and a caprock core sample in the Sleipner area, taking advantage of possible future exploratory wells.

At a more technical level, GEUS encountered difficulties with its new ICP-MS instrument which should be used in the project because it is considered as an advantage to run all elements (except Na) on the same instrument. However, a number of technical problems occurred with this instrument in the beginning, and it was early October before we had the first usable results. Finally in late November Si could also be analysed, but the analytical programme for the project was delayed for some months.

IFP reported some difficulties for calculating fCO_2, due to the DIAPHORE version used. The gas version will be used in SACS II.

WORK AREA 4: MONITORING WELL?

According to revised plan this work has been delayed to SACS2 (year 2000-2001).

WORK AREA 5: GEOPHYSICAL MONITORING

Compared to the other work areas, this work area met no major problems and difficulties. However, the seismic survey was run over the Sleipner CO2 injection area as late as 1 Octobre 1999. According to the fixed price bid from the contractor, the processing of data was done before end of 1999. This did not permit interpretation of the data, except for a few very preliminary lines. These lines alone showed excitingly encouraging results.

The full interpretation of this seismic – compared with the pre-injection seismic shot in 1994 – will be done during the SACS2 project.

4. Changes or modifications from the original project

In May the Steering Committee decided, and the EU Commission later approved, a major shift in the budget, reducing the volume of scientific work, and approved to bring forward the seismic survey to the summer 1999. The seismic contractor Geco-Prakla was after a biding round, hired to make the survey and the primary data processing at unexpected low costs and under a fixed price contract. The survey was done in September 1999. The acquired data are still under processing, so final interpretation results can not be presented, but "the bubble" is evident on the preliminary graphs – A World First!

This major change reduced studies, modelling and laboratory work in several tasks; see below. Work area 4 – "Monitoring well? was delayed completely. The other tasks suffered part reductions, which are now fully included in the continuation project, SACS2 during years 2000-2001.

WORK AREA 1: GEOLOGY

Generally fewer well logs, etc could be dealt with because of the delayed availability of data and samples. However, since the budget was reduced, the revised work plan was completed. Still both the resulting local and the regional interpretation are regarded as good. When 1999 3D seismic will become available, the SACS2 work will iterate and improve the findings.

WORK AREA 2: RESERVOIR SIMULATION

As in Work Area 1: Geology the reservoir simulation volume was reduced. The first round of simulations during spring 1999 never the less established a basis for the decision of bringing the 3D seismic survey forward. Also as for geology, reservoir simulations will work under far less uncertainty when the 1999 3D seismic data becomes available. The big question now was: "Are the clay minerals found in the cuttings and the unconsolidated sand core, coming from more or less continuous shale layers, or are the clay minerals randomly distributed?"

WORK AREA 3: GEOCHEMISTRY

This work area had the largest difficulties in getting essential material, samples and data. It turned out that there is probably not anywhere around the North Sea any core material from the "Utsira" sand, even though there has been drilled more than 200 wells through it. Drill cuttings had to be relied on. For pre-injection formation water – a central factor in setting the baseline for all geochemistry – one had, after several ways showed futile, to settle for taking the chemical composition from "Utsira" formation water sampled at Oseberg field, 200 km away.
To get samples and/or core from the cap rock and strata above "Utsira", and more reliable formation water data, is a major challenge for the geochemical work area in the SACS2.

WORK AREA 4: MONITORING WELL?

According to revised plan this work has been delayed to SACS2 (year 2000-2001).

WORK AREA 5: GEOPHYSICAL MONITORING

The greatest change in the 1999 SACS project was bringing the “time lapse” 3D seismic survey forward to the summer 1999. It was done at the expense of high priority work in all other work areas; bitterly regretted by many scientists, but all the same all participants supported the decision. The cost – in double meaning – was reduced when the biding round showed the seismic survey and processing could be acquired at unexpected low cost during the 1999 summer season. This was partly because of a “low activity” period, and partly because of the time flexibility SACS could accept from the seismic contractor, Geco-Prakla.

Seeing the (preliminary) results, all involved participants are still happy with the decision.

5. Results, comments and conclusions

MAIN RESULTS: The CO_2 "bubble" around the Sleipner injection well in the Utsira formation at 1000 m below sea bottom, was by September 1999 large enough, and in such concentrations, that it was clearly possible to monitor by a 4D "time lapse" seismic survey.

Before the SACS project started it had for years been a heated debate among geophysicists, whether it was at all *possible* to "see" the injected CO_2 in the aquifer. "The density difference between water and liquid CO_2 would be too small to be detectable?!" Now that is settled.

The result we have now, was the expected result after the first geological analysis, reservoir simulations and seismic modelling during spring 1999. Injection had been ongoing since October 1996 with around 1 Mt CO_2 pr year. In May the Steering Committee decided a major shift in the budget, reducing the volume of scientific work, and approved to bring forward the seismic survey to the summer 1999. The data from the seismic contractor Geco-Prakla is still under processing, so final interpretation results can not be presented, but "the bubble" is evident. A WORLD FIRST.

OTHER IMPORTANT ACHIEVEMENTS
Data background:
Available data for the Miocene strata of a major part of the North Sea has been catalogued. "Task Zero", a pre-project run in 1998, put effort into collecting data from all available sources, quality checking it and issued a report. Since these data today are not regarded as commercially sensitive, the only constraint for the work was finding the sources.

1. Geology:
The "Utsira" formation – potentially capable of storing 600 to 700 000 million tonnes of CO_2 – has been investigated, both locally and in regional context. Previous work (Holloway 1996) estimating this figure, can now be reiterated with far better scientific basis. The general understanding of these strata has increased enormously. Earlier now one cared much to spend efforts to investigate them. The commercial and national interests were far deeper down.

2. Reservoir simulation:
First rounds of reservoir simulations, including an evaluation of available simulator codes, has highlighted special features of the "Utsira": Are the shale and clay minerals randomly distributed or are the traces found in the unconsolidated samples coming from more or less continuous shale layers. These layers can influence both the CO_2 flow, the distribution patterns, and – ultimately – the total CO_2 storage capacity in the "Utsira" sand formation. Probably the 1999 seismic survey, and the next round of simulations in SACS2 can give the answer.

3. Geo-chemistry:
Laboratory work was started late due to difficulties in getting samples and data, hence in selecting parameters. Only preliminary results are reported, but works continue in SACS2.

4. "Monitoring well ?"
The aim of this activity is to establish the potential use of a future monitoring well. Collecting samples, check flow, detect micro-seismicity ? The cost/benefit has to be documented. Expected costs are in the range of 10 million Euro (80 million NOK).

5. Geo-physics:
Based on the encouraging results from the geological and reservoir simulation work done during spring 1999, combined with favourable economic terms, a 3D seismic survey could be conducted during September 1999. It created a first "time lapse" sequence together with the equivalent 3D seismic done in 1994 by the Sleipner license group, operated by Statoil, before CO2 injection started (in October 1996). The survey was conducted by the well recognised seismic contractor Geco-Prakla. The very preliminary results indicate the data to be good and the images shown to be clear and strong: ***The CO2 distribution can be monitored!***

6. "Best-Practice-Manual":
The original plans for a 3 year project had to be divided in two parts, the SACS / Thermie part in 1998-99 and SACS2 /5FP in 2000-2001. It was caused by limited EU funding available in Thermie only could cover the 1999 work. Clearly the "Best-Practice-Manual" can not be drafted when only one third of the work has been completed.
On the other hand, the strongly growing interest in co-operation from many inter-continental research groups, is widening the base for creating a widest possible scientific consensus about the scientific questions connected with aquifer CO2 storage.

The overall goal is still to learn the maximum from the Sleipner case and to produce a draft "Best-Practice-Manual".

6. Commercial potential of this demonstrated technology

The commercial potential of this work is long term; possibly 10 – 20 years for full scale applications? For niche applications, it can come earlier?

However, this project work ***had*** to be done now, when the Sleipner field is running their production and CO2 injection of around 1 million tonne of CO2 annually. To monitor the development in the injection reservoir, the “Utsira” sand, the seismic surveys and other sampling had to be done before and from the start. Statoil, as field operator, had prepared the baseline by the 3D seismic survey done in 1994, well logs run during drilling etc.

The goal for the SACS project work, when it is finished in year 2001, is to catch the “time window” when Sleipner is injecting CO2 in an industrial scale and establish a sound scientific basis.

The concept of aquifer storage of CO2 is now regarded to become generally commercial ***if, and only if*** a Kyoto II protocol demands deep cuts in the CO2 emissions. Kyoto I can be regarded as a stabilising action, and its goals can be expected to be reached mainly by lower cost sequestration actions. Niche applications can be possible even under today’s Kyoto regime. It can be places with very special circumstances: a petrochemical plant, a LNG plant as planned in Northern Norway fed by natural gas from the Snøhvit field, or similar. There aquifer CO2 storage can be a realistic alternative to emitting pure CO2 under a tax threat; as was the case with Sleipner.

If climate concerns about CO2 emissions should increase significantly and Europe decides to make the deeper cuts, the concept can become “commercial” under changing tax and/or regulation regimes. IEA GHG studies indicate that North European power stations could capture, transport and inject their CO2 under the North Sea at an increase of gross electricity prices around 50-100% above today’s levels? Of the extra costs, a three quarter share would be related to catching the CO2 (extra investment and loss of efficacy) and one quarter related to pipeline transport and underground injection (extra investment and compression energy used).

A broad consensus about how this should be done in a predictable and safe way needs time to develop. It will demand the involvement of science, industry and authorities. SACS has created the first basis, and SACS2 will greatly improve the scientific knowledge. To start that process in the larger society, the follow-up in SACS2 will produce as its main result, a draft “Best-Practice-Manual”.

7. Dissemination plans

As before and under the project period the concept of abating CO2 emissions and its possible climate effect will continue through available channels. International symposium, conferences and workshops has shown to be effective towards the research community, both in industry and research institutes and universities in Europe and inter-continentally.

Concrete plans have been prepared for 2000; to present results so far for European and inter-continental geo-scientific audiences, and for CO2-emission-climate-concerned audiences. When more final results are ready this will be repeated. Then also the longer perspective (Kyoto I and II?) will have to be presented for the whole energy industry and national and European policymakers involved with energy and environment.

One example primarily resulting from presentations previously given by Torp and Christensen to MEP's and the European Commission at a seminar, the concept of geological CO2 storage became one the issues of debate in Denmark during the electoral campaigns for the European Parliament in the early summer of 1999. Mr. Christian Rovsing, who raised this debate, was re-elected. Several newspapers ran extensive popular and technical articles about the concept in Norway and Denmark.

INTERNET: IEA Greenhouse Gas R&D Programme is presenting the SACS project (public parts) on their homepage: www.ieagreen.org.uk
Already the response is evident from interested people in science and media.

PUBLICITY: A large number of periodicals and daily press articles have presented the concept of aquifer underground storage of CO2, the Sleipner case and the SACS project. This resulted in many fair and good presentations of the underground CO2 storage concept to the public. Several students in many countries have been given background information for their work with CO2 sequestration. The general interest is felt as steadily growing.

PUBLICATIONS: Concrete plans to publish general results and more specific scientific findings will be decided in January 2000. Publications in scientific, reviewed periodicals are under planning for publication in 2000.

CO-ORDINATION: The concept of aquifer CO2 storage is closely related to other CO2 sequestering technologies; as Co2 injection for EOR – enhanced oil recovery, CO2 injection in unminable coal bed seams and to storage in the deep oceans. All of these are again related to CO2 capture from large CO2 sources as fossil fuelled power stations, to CO2 transport (pipelines?) and to mapping of possible storage sites. All of this is on the agenda at the IEA Greenhouse Gas R&D Programme.
This work is co-ordinated with other European CO2 relevant projects under EU 5.Framework Programme, Accompanying Measures in activity “CO2Net”.

8. Patents, if any, applied for or issued during the reporting period

None, as expected.