SLEIPNER CARBON DIOXIDE STORAGE WORKSHOP

(25th-26th November 1997, Trondheim, Norway)

Report PH3/1

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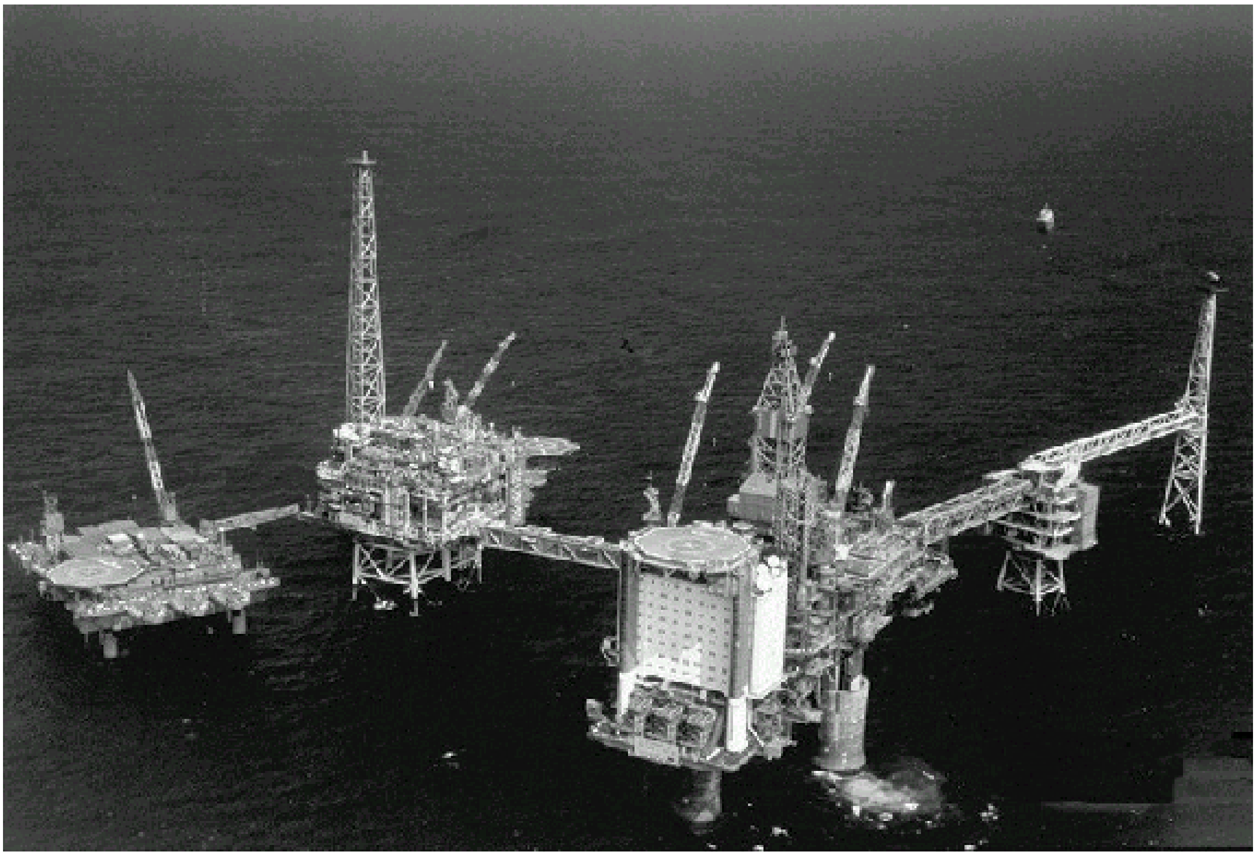

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1. Workshop Objective

The objective of this workshop was to identify monitoring requirements, prioritise research topics and outline plans for monitoring and research so that the underground storage of CO_2 from the Sleipner field in the Utsira formation can be fully understood.

2. Background

Large-scale storage of CO_2 underground is an unprecedented enterprise. It will therefore be a crucial and an exciting exercise to monitor the process carefully. The Sleipner project is the world's first commercial-scale CO_2 storage project; others are under discussion, such as the Natuna project offshore Indonesia. In both of these cases, the CO_2 is an unwanted by-product of natural gas production activities; both activities are positioned offshore and will inject the CO_2 into large, adjacent aquifers.

The major task of monitoring is to record the stability of the reservoir and to observe the development of the expanding CO_2 bubble. It will be important to follow the development of the expanding CO_2 bubble to check if the preliminary storage model corresponds with the real situation, to ensure that the CO_2 remains in the reservoir. Regular monitoring of a CO_2 storage operation would serve two purposes:

- to confirm that CO_2 storage in a deep saline reservoir is a safe and reliable CO_2 mitigation option
- to supply data to validate reservoir simulation models which will be essential in the planning operations of future CO_2 storage projects in other parts of the world.

An initial field scale CO_2 storage operation is an excellent opportunity to validate theory with practice and is of great interest for many organisations involved in this area of work.

For this reason, the IEA Greenhouse Gas R&D Programme and Statoil organised this workshop to make recommendations about priorities for monitoring and research on the Sleipner Aquifer Carbon dioxide Storage (SACS) operation and to stimulate the formation of an international collaborative programme to carry out this work. The workshop was held at the research centre of Statoil in Trondheim on 25^{th} and 26^{th} November 1997. It was attended by experts in the field and representatives of organisations interested in participating in the research/monitoring project .

3. SACS Workshop

Monitoring a field scale CO_2 storage operation will be a complex and costly project, especially in the case of an offshore storage field. Such a project is a unique and challenging enterprise. We hope, by this workshop, to mobilise the whole geo-industry to maximise both the technical output and the financial consequences of such a project.

This will be the first real opportunity to verify the performance of simulators of CO_2 behaviour in a reservoir with field data. Only a joint effort, involving a large international selection of specialists and companies could make such a project a success.

Seventy people from many disciplines attended the two day workshop. On the first morning the workshop opened with a plenary session, with presentations on the Sleipner storage project, its history and current status. The time was then devoted mainly to expert group sessions. Five expert groups were formed which identified monitoring requirements, prioritised research topics and outlined plans for implementation in the near term (0-1 years), the medium term (1-3 years) and the longer term (>3 years). The ultimate aim of this work is that the underground storage of CO_2 in the Sleipner Utsira formation would be fully understood, to establish the credibility of CO_2 storage in deep saline reservoirs as a mitigation option, and this learning applied to other projects.

4. Plenary Session

A welcome address was made by Stein Borre Torp, R&D Director of Statoil responsible for sub-surface research and by Paul Freund, Director of the IEA Greenhouse Gas R&D Programme. These were followed by a series of presentations on the Statoil project and on experience elsewhere with CO_2 storage underground. Allan Kalid from Statoil, presented the story so far; Kaare Horpestad from Statoil, described what is known about Utsira formation in the area; Ivar Brevik from Statoil, discussed what data is or could be available; Bill Gunter, from Alberta Research Council described monitoring experience from underground gas storage/enhanced oil recovery (UGS/EOR) projects; Sam Holloway of the British Geological Survey discussed relevant outcomes of the Joule II aquifer study. Brief summaries of these presentations are given below, with further details in the Appendices.

The Sleipner CO_2 facility - the story so far

Allan Baklid described the Sleipner field in the Norwegian sector of the North Sea. He explained that production from the Sleipner West gas and condensate field began in August 1996 (for full papers see Appendices A and B). Initiated in spring 1993, the Sleipner West development cost NOK 9.5 billion, about NOK 1.4 billion below the original budget; it was completed one month ahead of schedule. Savings on other work related to the project amounted to a further NOK 1.2 billion.

The Sleipner West project comprises two installations, the Sleipner B (SLB) wellhead platform on the field and the Sleipner T (SLT) treatment platform adjacent to the Sleipner East facilities. SLT is linked to the Sleipner A platform by a bridge. Other components in the development include a 12.5 kilometre flowline from SLB to SLT. The wellhead platform is remotely operated from the Sleipner A control room via an umbilical line.

A special feature of gas from Sleipner West is the high content of carbon dioxide. This will be reduced from about nine per cent to 2.5 per cent on SLT. Carbon dioxide stripped from the wellstream is being injected into a water-bearing structure in Utsira formation sands about 1 000 metres below the seabed. Treating carbon dioxide in this way, which almost entirely eliminates emissions to the atmosphere, marks a milestone in industrial history. This has never been done before on such a large scale (a million tonnes of carbon dioxide per year). Nor has carbon dioxide been compressed and injected underground on an offshore platform before.

The key to the treatment process is an amine compound. Added to the gas flow at SLT, this absorbs the carbon dioxide for collection. Equipment for such separation has been installed in one of the two modules on SLT, including heat exchangers, pressure/storage tanks, Pelton turbines and filters. Natural gas to be treated passes through two large absorption columns. A co-operation agreement has been concluded with Elf, which holds the patent for the system.

Energy freed by the amine process runs two generators (which have lower carbon dioxide emissions than traditional gas turbines), yielding a total of six megawatts of power for use on the platform. Weighing about 8 000 tonnes and standing 35 metres high, the carbon dioxide module cost about NOK 2 billion. The other SLT module is used for gas treatment. After the carbon dioxide has been separated the natural gas is transferred to Sleipner A for export to continental Europe The carbon dioxide is also transferred to Sleipner A, for injection into the Utsira aquifer. Some of the natural gas will also be reinjected into the Sleipner East reservoir to improve condensate production.

Licensees for the Sleipner West field are Statoil (operator) with 49.50%, including 32.37% as the government's direct financial interest, Esso Norge 32.24%, Norsk Hydro 8.85%, Elf Petroleum Norge 8.47% and Total Norge 0.94%.

The Utsira Formation in the Sleipner Area,

Kaare Horpestad explained that the Utsira Formation is a 200m massive sandstone formation located at a depth of 800 - 1000m, which was chosen as the reservoir for the CO_2 disposal from the Sleipner West Field. The CO_2 is injected into a small structural closure north-east of the Sleipner A platform. The CO_2 gas - not dissolved in formation water - is expected to be captured in this closure. When the closure is filled, the CO_2 is expected to spill towards the north and thereafter to the north-west. The CO_2 gas is not expected to reach the Sleipner A platform location which means that corrosion caused by injected CO_2 gas should be avoided.

The 3D seismic data covering the Sleipner East area has been used to map the Utsira Formation. The seismic response represents the impedance contrasts in the water-filled reservoir. The seismic impedance contrasts are likely to be changed when CO_2 is injected into the reservoir. This change in seismic impedance is expected to be seen on new seismic data. The presence of CO_2 and the movement of the CO_2 gas in the Utsira Formation reservoir could therefore be observed by acquiring new seismic data. A repeated seismic acquisition program (3 to 5 years interval) should therefore give the possibility to follow the movement of the CO_2 within the Utsira Formation as a function of time

The actual value of this change in seismic impedance needs to be calculated by use of seismic modelling.

What data is or could be available?

Ivar Brevik outlined the data that is already known about the Utsira formation (examples of structural data are given in Appendix C and Ivar Brevik's presentation is Appendix D). He described a base line survey (3D) carried out in 1994 before the CO_2 injection started. He also described seismic surveys, borehole logs and coresamples taken from the Utsira formation both at the Sleipner and neighbouring locations. He then went on to discuss the properties of CO_2 / brine mixtures and the modelling currently being carried out.

Monitoring experience from UGS/EOR projects

Bill Gunter presented a review of experience with underground gas storage and enhanced oil recovery, to compare the expertise gained with these techniques with that required for the Sleipner monitoring project (his overheads are attached as Appendix E). He discussed three main areas:

- the reservoir and movement of fluids,
- geotechnical expertise and movement of solids
- geochemical knowledge and the chemistry of the fluid-rock interactions.

He discussed the interaction of modelling experience with real data and the types of monitoring equipment that are available in situ and on the surface. A number of monitoring issues were described, including surface versus downhole, single well versus multiple well, one-point verses multi-point, and more advanced technologies, such as fibre optics. The use of tracers was also described, including radioisotopes, fluorescent dyes, alcohols, natural anions and cations.

He gave a review of seismic analysis covering, 2D, 3D and 4D monitoring and discussed some strategies that had been adopted for EOR covering short-term and long-term (10 years) monitoring strategies. Each of the methods had advantages and disadvantages which he summarised before concluding with some suggestions for monitoring the Sleipner aquifer storage. Measurement of the following was required:

- CO_2 bubble migration (leakage and sweep)
- CO_2 bubble dissolution (pressure drop)
- Gas hydrate formation
- Pore pressure and in-situ temperature
- Water-rock reactions
- Water-metal reaction and well corrosion

Joule II aquifer studies, directions to Sleipner

Sam Holloway gave a brief presentation about points which will have to be considered for any underground CO_2 storage scheme. The conclusions are contained in the final report of the Joule II project: 'The underground disposal of carbon dioxide'. This was a 2-year study 50% funded by the EU, which was conducted by the following organisations:

- Statoil
- IKU Petroleum Research
- British Geological Survey
- TNO Institute of Applied Geoscience
- CRE Group Ltd (formerly British Coal's Coal Research Establishment)
- University of Sunderland Renewable Energy Centre
- BRGM (France)
- RWE AG (Germany)

A summary of the Joule II study appears in Appendix F.

5. Results from the expert groups

The delegates at the workshop were divided into five expert groups covering the following areas:

- Monitoring and Well technology - Chairman, Allan Baklid, Statoil, Norway; spokesman David Cobb, British Petroleum, Norway
- Geochemistry - Chairman, Sam Holloway, British Geological Survey, UK
- Reservoir simulation & validation - Chairman, Paul Rutter, British Petroleum, UK
- Geophysical monitoring - Chairman, Colin Macbeth, British Geological Survey, UK
- SACS and the international scene - Chairman, Olav Kaarstad, Statoil, Norway

Each group was asked to put forward a set of tasks that they thought should be carried out within their subject area. These tasks were then prioritised by the group and a simple plan formulated covering the following:

The R&D needs and work required
The cost of the project(s)
The deliverables
The timescale required
Justification for the priority of each task
Potential partners to do the work

These recommendations are summarised below for each expert group.

Each group reported their findings to a plenary session. After discussion of these points, an outline plan of work was put forward and the groups reconvened to decide on priorities and timing of their recommended actions (see below: 'project formation').

Monitoring and Well technology expert group

This group based their discussion on the following questions.

1. Is the trap working, are there likely to be cap rock problems?
2. What is the lateral migration?
3. What is the near wellbore integrity, and the completion strategy?
4. What is the long term capacity of the reservoir to store carbon dioxide?
5. Can we validate the physics?

An important question underlying the discussion of this group (and many others) was: is there a requirement for an observation well?

The group then looked at each of the questions in turn evaluating the possible monitoring solutions to answer each question.

Is the trap working (cap rock problems)?

The concern would be if there was major failure of the cap; seepage of CO_2 was considered to be of much less importance. The main points were:

- Need base-line information; e.g. should measure the initial stresses; do not assume that the answers are known because this is unknown territory.
- Need to monitor the changes in in-situ stressing. e.g. temperature induced effects, especially on cap-rock; do not expect pressure induced effects will be as important as temperature induced effects but may need to address this later; look at the effects of cooling, local equilibrium effects, core studies.
- Monitor the presence of carbon dioxide in higher strata and/or the seabed; query need for observation well in the overlying shale.
- Measure regional pressure
- Time lapse seismic can be used to monitor the volume of the CO_2 bubble, as it increases with injected volume and as some dissolves in the formation water.

Many of these questions (except the last point on time lapse seismic) may be answerable with information which exists; the task is to find out what is known and who knows it. How to do this? Baseline data can be obtained from:

- Borehole breakout data (development wells)
- Obtain core data for cap rock
- Minifrac /leak off tests
- Full waveform sonic

Transient effects can be monitored by:

- Full waveform sonic (time lapse)
- 4-way calipers / tilt meters - this would be nice to have at some point to check the integrity of the well
- Monitor pressure fall-off when shut in the well (downhole gauges)

As to time lapse seismic - can this be used to monitor the size of the bubble? If so, this would confirm the integrity of the trap. This is essential for future progress.

What is the lateral migration?

- Regional migration/flow should be measured
- How much is there compartmentalisation of the aquifer? (need for structural geology)
- Where are the local pressure sinks (new oil/gas developments are using Utsira as a source of water; there is a need for a regional model to understand the implications)
- Definition of aquifer volume, plus carbon dioxide bubble
- Permeability distribution of Utsira (need better understanding/review of logs)

How to do it?

- Mapping of the structure needs regional geochemical study; may be able to measure regional pressures; there could be relevant messages here which should be communicated to other development programmes in the area.
- Regional mapping
- Time-lapse seismic of the bubble to define the aquifer volume and bubble

- Specialised coring would provide calibrated permeability log; there may be opportunity for interference test from others using Utsira (e.g. when they stop extracting).
- Observation well - this is the only way to look at saturation distribution in gas and dissolved water.

What is the near wellbore integrity; has the completion strategy succeeded?

- Pressure- impedance monitoring
- Fluid distribution in the horizontal well
- Corrosion, and the need for window cementation (when eventually abandon the well)
- Downhole pressure and temperature
- Horizontal seismic profile (HSP) and/or vertical seismic profile (VSP)
- Through-casing logs - these will be available in about 1 year's time - to understand saturation in the near well bore region.

Suggestions about how to do this were as follows:

- Injectivity index (well head pressure (WHP) plus rates)
- Downhole pressure and temperature gauges
- Callipers - thickness logs should be run all through this programme
- Horizontal well - permanent geophones, monitor bubble and cap rock
- Saturation changes - observation well required
- Supercritical flow - the current 2-phase flow regime is not helping to understand the system; go to 80 bar now to reduce the number of variables.

Validating the physics

This is essential for wider application of this technique. The main points to be addressed include:

- Long term geochemistry,
- Thermodynamics of free gas and dissolved gas
- Model the spatial distribution
- Mineral chemistry (long term), to measure the stabilisation of carbon dioxide
- Why has no pressure increase been observed?

This would be accomplished by:

- Obtaining core and fluid samples, both for the base case and long term monitoring
- Reservoir fluid modelling
- Change to supercritical injection regime
- Long term transient data - this requires an observation well.

Requirement for an observation well and long term capacity of the reservoir to store carbon dioxide

The need for an observation well, purpose made to monitor the aquifer, was discussed separately, as this would be an expensive component of the programme. Much data could be obtained from other development wells passing, through the Utsira aquifer, drilled by Statoil or other oil and gas companies. However, on present knowledge, some measurements could only be made from an observation well. It was recognised that the production from the natural gas field with minimal release of CO_2 is entirely dependent on one disposal well. On this basis, there is significant risk to production (probably worth several $million/month), unless of course production is maintained by venting CO_2 to atmosphere.

Information required	Could obtain from other development wells	Need purpose made observation well
Stress data	Yes - some	Transients
Reservoir description (permeability, cores etc.)	Yes - some	Some
Fluid data	Yes	-
Geochemistry baseline	Yes	-
Time-lapse data (VSP)	-	Yes
Risk management of CO_2 disposal	-	Yes
Transient data on saturation's	-	Yes

The priorities for action seen by this expert group were as follows:

- First priority is for baseline - to provide a solid foundation
- Decide which questions can be answered now
- Regional model
- Validation of assumption about flow in the reservoir
- Geochemistry
- Data acquisition by all operators using/passing through Utsira

Some activities were time critical (especially concerning the baseline) and these demanded priority.

It was pointed out that this project could give sufficient profile, to the need for co-operation amongst operators, that useful work could be done, for example a leak-off test.

This has just considered the Sleipner type of aquifer; there are many others.

Geochemistry expert group

The geochemistry group suggested 6 major tasks which covered the unknowns in their area:

1 Formation evaluation
2 Formation fluid evaluation
3 Experiments and modelling
4 Observations from monitoring well
5 Extension to modelling
6 Natural analogues

For each of these tasks they outlined the work that should be carried out.

Task 1 - Formation Evaluation

This is needed in order to define the reservoir, its properties and geometry. This information will be fed into future modelling. It is necessary to sort out the data requirements and evaluate what is currently missing. For this, core samples would have to characterised in detail. Detailed stratigraphy in the Sleipner area and regional stratigraphy of the Utsira area must be obtained. In particular the group felt that emphasis should be placed on the characterisation of the cap rock.

The deliverables of the task would be vertical and lateral geological structure, log-derived properties, mineralogical and petrographical characteristics and a representative sampling scheme.

The timescale required for core characterisation would be 3 months, stratigraphy in the Sleipner area, 3 months, and the stratigraphy in the regional area, 6 months. The cost of this task was estimated to be £100,000. Potential partners would be GEUS and BGS.

Task 2 Formation fluid evaluation

In order to establish baseline hydrogeology and geochemistry, it was important to record injected fluid (gas/water), pressure and temperature and the formation water mineralogy; initial equilibrium conditions must be characterised and natural flow in the aquifer established. It would also be useful to analyse the stable isotopes, which could serve as a tracer with later observation wells.

The deliverables from this work would be in-situ fluid composition of the injected and formation fluids, and the answer to whether or not there is any flow in aquifer.

Timescale for the work is 4 months from sample collection. The cost of analysis, modelling, sampling, geohydrology, will be about $50 000, not including collection of the samples. Potential partners, BGS, ARC, GEUS, BRGM.

Task 3 Experiments and modelling

Laboratory work is needed to provide better data to refine the models. Work required includes:

- measurement of carbon dioxide solubility and mineral dissolution rates,
- core flood experiments to estimate carbon dioxide transport properties,
- analysis of mineralogy before and after injection, including, φ, K, cap rock, acoustics and fines mobilisation.
- Fluid dynamic (eclipse) models,
- chemical modelling,
- cap rock susceptibility / integrity tests.

It was envisaged this would be a 3-year programme of work but some of this work needs longer duration laboratory tests in order to see how the minerals change over time. The deliverables would include: chemical impact assessment, measurement of reservoir property changes, predictions of distribution of minerals (blind prediction), prediction of chemical interaction in the reservoir, carbon dioxide formation fluid reactions and an estimate of the reliability of the reservoir/seal.

The group recognised that quite a large effort is required for this task; they expected this would take 6-10 man years over a three year period. Some experiments would benefit from a longer period of observation. The potential partners for this task would be, BRGM, Mobil, BGS, ARC, GEUS, Elf

Task 4 Observations from monitoring well

In order to validate the models of CO_2 behaviour in the reservoir, greater understanding is required of the influence of carbon dioxide on the formation rock and fluid. This would be achieved by regular monitoring from an observation well, to determine the migration of the CO_2 and fluids from the injector.

This requires periodic fluid sampling and analysis (for CO_2, Ca^{2+}, Mg^{2+}), pressure and temperature measurements (bottom hole), and regular core sampling for mineralogy changes. Deliverables would be improved calibration of reservoir models and calibration of the seismic analysis.

Timing for this work would be: periodically during the carbon dioxide storage lifetime. This was left open ended but could span a period >20 years. The group found the cost of the task difficult to predict; the main cost element would be for a dedicated observation well. Other costs would be several tens of thousands of $.

Potential partners for the work included Elf and Statoil.

Task 5 Extend modelling

In order to improve confidence in the prediction of the long term stability of the reservoir, and to estimate the time before equilibrium is established (in terms of pressure, temperature and chemical species), further work is needed to improve the models. Work to be carried out would include: coupling of chemical models with reservoir models, incorporate the results of core flood tests, allow the model to run to a predefined equilibrium state. A number of models would be evaluated as would a selection of modelling parameters. This work would need to be done irrespective of whether or not an observation well is sunk.

The deliverables would include a coupled model and end-state scenarios for the Sleipner store. The results should have broad applicability to other projects.

This is a longer term task, one which is predicated on the assumption that much of the data from previous tasks had been obtained. It does not demand urgent action but will have to be done sometime.

The timescale allowed for this task was estimated at14 months actual modelling work, once the data had been obtained. The cost of the task was estimated at around $600,000. Potential partners would be Mobil, BRGM, ARC

Task 6 Natural analogues - very long term fate

In order to demonstrate the long term stability of stored CO_2 after injection finishes, an investigation is proposed of a variety of natural analogues. A large number of natural CO_2 fields are known world-wide, and there are many other geological structures which could also offer useful information. For example, it was pointed out that gas fields offshore Vietnam have up to 80% CO_2 content, and it would be relatively inexpensive to obtain cores from such fields. The work required would be to identify CO_2 fields world wide, identify long-term fluid rock interactions, compare and contrast lithology and mineralogy, and then validate model predictions.

As a result, further evidence of the safety of this concept would be collected, other long-term sinks would be demonstrated and the models validated.

The cost of the task is estimated to be £200,000 for a two man year activity. Potential partners - BGS

General

In general, the group recommended early action on the formation evaluation and fluid evaluation tasks, in order to allow them a long time to run. They also emphasised the need for fluid samples close to Sleipner, in addition to the water samples which could be obtained by other operators passing through Utsira. Other wells to be drilled from Sleipner A for oil/gas production purposes could probably deliver most of the data required, except for the time lapse series. Perhaps a development well could be adjusted to provide much of this (if the requirement is not too demanding).

Reservoir simulation & validation expert group

It is very important to validate the models and this group suggested that, although an uncertainty about the fate of the CO_2 of, say, 2% might be acceptable in the short-term, in the longer-term much better precision would be required. They initially divided the data requirements for reservoir characterisation into two areas, looking at physical parameters and geochemical properties, as summarised in table 1, because of their different influence on the calculations.

Physical parameters	Geochemical parameters
topography	reservoir chemistry of CO_2 solution
boundary seals	reservoir chemistry of mineralisation
aquifer flow	reservoir chemistry of demineralisation
heterogeneity	long term changes in φ and K
injection temperature	reservoir and lab water chemistry
faults/fractures	

Table 1 - Listing of the required data for the reservoir simulation and validation models

There are a great number of unknowns amongst the physical parameters but at least they can be described, making a basis for discussing how to reduce the uncertainty in order to predict the short-term effects of injection. Amongst the geochemical parameters, there are also many unknowns, and these more affect our ability to predict the long-term performance. Pressure would be an important indicator as to whether the model is working properly.

As with the other expert groups, this one recommended pulling together as much data as possible from available sources to describe the shape/conformance of Utsira. Assuming that data will be made available, the group then decided on 5 tasks:

Task 1 - Reservoir model (including topography)

As a first step, the existing static model should be re-run. The purpose of this task is to provide a more complete structural model, drawing on natural analogues if they exist and also correlating the seismic impedance map to the petrophysical data. The estimate for the effort needed to complete this task was 1 man-year.

Task 2 - Construction of a simulator (from the results of task 1)

Initially the process to be simulated would have to be defined. Existing models would be evaluated and a number of sensitivity studies would have to be carried on some of the critical parameters, such as long and short term effects, including aquifer flow. The effort estimated for this task was 0.5 man-year.

Task 3 - Define what data is required to verify the numerical simulator.

This task would determine the minimum amount of data required to reduce significantly the uncertainty in the predictions; it would look at possible data from observation wells and seismic monitoring (would this indicate the real extent of the CO_2 bubble?). Estimated effort = 0.5 man-year.

Task 4- Verify and update the model using the best available data.

This task is essentially an iteration, using data from new production wells, from natural analogues and upscaling of data from the previous tasks. Effort required about 1 man-year.

Task 5 - Recognised unknowns

This task covered the gathering of data from the other expert groups in order to improve knowledge in the following areas:

- Rayleigh convection - density driven circulation
- geochemical effects
- natural CO_2 reservoirs database
- solubility behaviour at field scale
- boundary integrity of the reservoir

These can be run in parallel with the other tasks. In all of these tasks, it was recommended that the needs of the simulation should be used as an indicator of the priorities for measurement. Further discussion along these lines, using a small group of experts, could be used to flesh out the details.

Geophysical monitoring expert group

This group recognised a 3-step process: identify the problems, quantify and assess risk. Various geological/geophysical problems were recognised:

- Structural characterisation of cap rock, to evaluate cap rock leakage and possible faults
- Migration of carbon dioxide towards the platform, looking at spreading and movement.
- Formation collapse, geochemical implications, rock matrix and strength
- Structural characterisation of Utsira, initial results and internal boundary/barriers

This group highlighted their tasks by way of a flow diagram (Figure 1)

The later phases (Figure 1) require review of geophysical techniques which can be driven in time-lapsed mode. A diagram presenting a review of this "tool box" in terms of areal coverage and resolution is shown in Figure 2.

The tool box

The group's discussion in this area covered the types of equipment needed for measurements for local and long distance coverage, and is illustrated in Figure 2.

- For limited areal coverage with high resolution, logs provide a means of calibrating the rock physics model (provide α, β but not ρ). Some cores are available from 15-9/13.

- Use of an observation well for listening; this would need to be separate from the injector and preferably more than one would be used. Microseismic activity might be a means of monitoring the aquifer. For interpreting the depth of these events, 3 shallow observation wells would be needed. It is not known how much microseismic activity there is, whether there is sufficient to be useful.

Other techniques, especially seismic and gravimetrics, would provide wider areal coverage. These have the advantage that they do not need to penetrate the cap rock.

- Various sensors are available now for permanent mounting on the well casing. Another option would be to use 3-component receivers - this depends upon the level of detailed information that is needed.

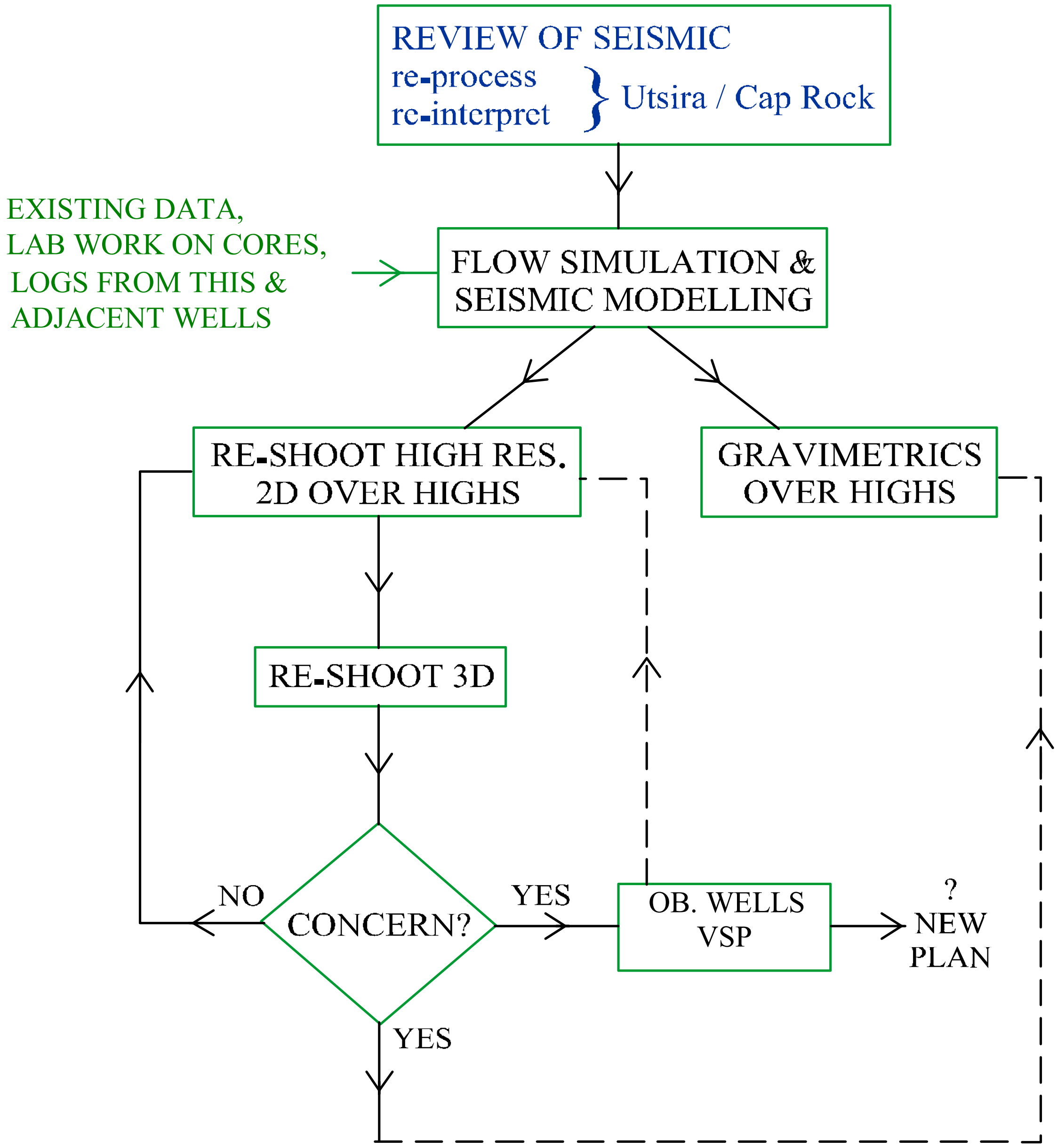

Figure 1 - Flow diagram illustrating the areas of work required in this area.

- Better areal coverage and similar resolution would be obtained from 3D-VSP, W/AVSP and others. Problem is the condition of the well; doubt was expressed whether a multilevel sensor could be put in the existing well and retrieved. With 3D-VSP, a mutilevel capability would be preferred; coupling is an issue; this would be limited by only one well being available at present. RSVP was mentioned as requiring a >4 inch vibrator.

- 2D seismic gives less resolution than 3D but changes in current practice might provide better focus on this shallow aquifer. Statoil's work on Troll suggests that it would be reasonably repeatable. It may be relatively cheap and it could give ongoing data, which could be used to provide indication of some feature/event which needs closer investigation.

- Ocean bottom cables (e.g. as used on Foinavon) were felt to be too new; there was uncertainty about what they could do; perhaps they could be used to monitor fracturing. It was thought that, because the cable becomes buried over time, this technique has not be too successful to date for monitoring.

- Another possibility is use of vertical seismic (hydrophone) cables.

- Gravimetrics - have low resolution (c. 1 km) but this could pick up the CO_2/water interface.

- 3D seismic - has the highest areal coverage; already have a baseline but has not been shot for the aquifer.

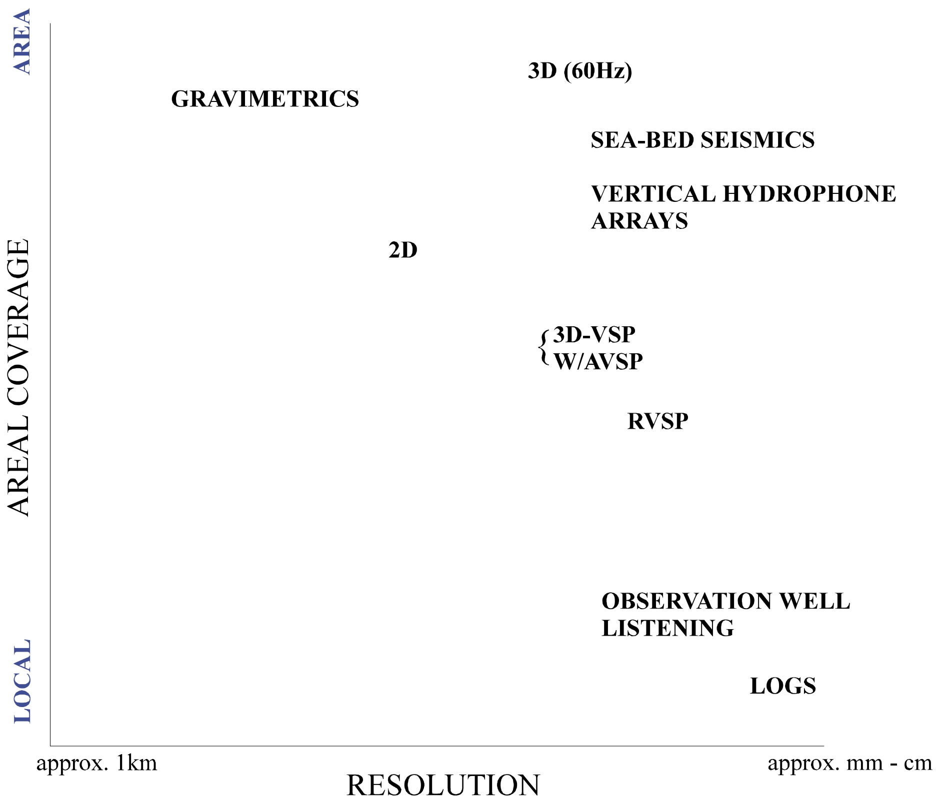

Figure 2 - The range and scope of potential geophysical monitoring equipment)

Benefits of data from other activities

Other fields containing CO_2 or other gases elsewhere in the world could help learn about CO_2 and how to monitor it using seismic techniques. Potential areas included natural carbon dioxide reservoirs, examples being Wyoming and Natuna, natural accumulation on shore of nitrogen, and EOR experiences from the United States. Also there would be data available from gas storage facilities where there is a known cycle of injection and completion.

Recommended actions

- In one year's time, re-shoot high resolution 2D seismic over higher parts of the aquifer and use gravimetrics over the highs too. Repeat this at about 1 year intervals.

- At some time after that, re-shoot 3D seismic

SACS and the international scene

Discussions within this group aimed to familiarise potential funders of the work with the many international programmes already underway or planned for the future. The group all introduced themselves and then listened to presentations by John Garnish and Massimo Lombardini describing the European Commission's Joule and Thermie Programmes. Perry Bergmann, from the USDOE then outlined the US Geosequestration Programme and his other activities within the IEA Greenhouse Gas R&D Programme. Paul Freund then outlined the work of the IEA Greenhouse Gas Programme and the International Energy Agency's Climate Technology Initiative (CTI) and explained the process for practical collaboration within the legal framework of the Greenhouse Gas Programme. Tore Torp and Olav Kaarstad then outlined Statoil's involvement with international research programmes.

Following on from this discussion the group put forward plans for a long term monitoring and research project covering SACS, which was presented to the expert groups.

6. Project formation

The results from the expert groups were presented by the chairman of each group (and in some cases other group members) to all the attendees. After discussion the groups re-formed to place their tasks and activities into an ordered programme of work based on the timetable outlined in Figure 3. The results for each group were then presented to all attendees and a programme of work was agreed. The overall programme of work will follow three distinct phases of work covering three time periods.

It was decided that initially, to get the project started, a Thermie proposal would be submitted this could then be followed up by additional international collaboration organised through the IEA Greenhouse Gas R&D Programme. The basic principle is outlined in Figure 3.

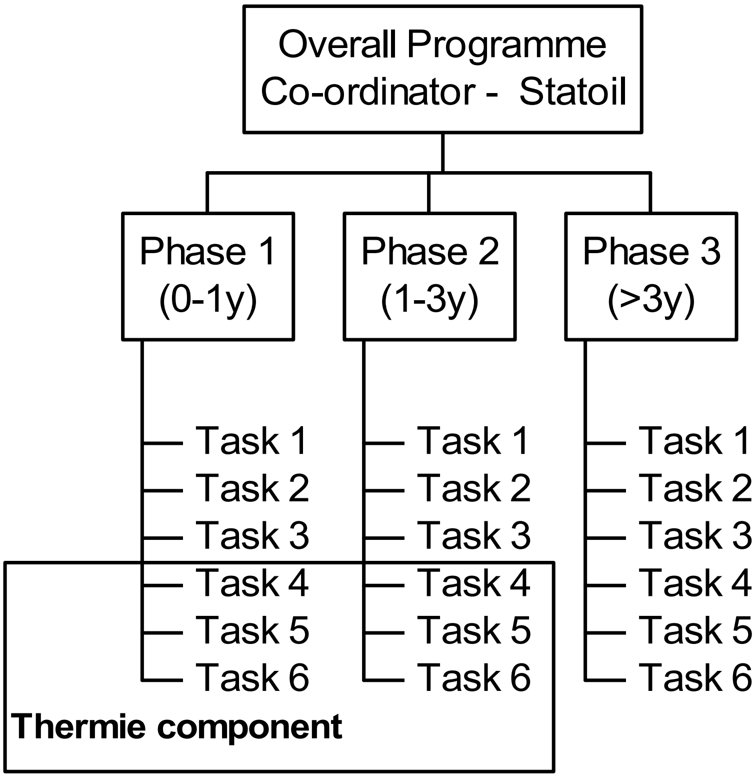

Figure 3 - The overall programme of work

Statoil is ready to share the data in a co-operative programme as long as the data is used for the benefit of science. It is quite happy to contribute to :

- European programmes
- National programmes of work
- International programmes of work

The only restriction would be on the publication of the results which Statoil must approve prior to publication.

The immediate requirement is to get as many partners together as possible and this workshop has already started that process. Many around the table expressed interest, including Statoil, Saga, BP, Norsk Hydro, Mobil, GdF, Vattenfall, ABB and Elsam. It was explained that the Netherlands Ministry of Environment were also broadly in support of this initiative.

It is hoped that the project will start with a Thermie application at the end of January 1998. Massimo Lambordini reported that the budget for the final call for the Thermie Programme is 25million ecu. He noted that Statoil is very good at getting applications although this was no guarantee of success. He pointed out that although the applications had to be presented by the end of January 1998, findings would not be available until September/October 1998. The only caution raised at the meeting was not to rush for the European money at the expense of wrecking the whole programme, and that effective management was required to make sure that anything initiated in the near future complemented the overall plans.

This European initiative would “kick-start” the project and allow time for other international programmes that are about to start to get involved at a later date. A good example of this was outlined by Perry Bergmann (USDOE) who has a major programme of work starting soon which could be directly applicable to this activity. Perry Bergmann and other international colleagues already have large practical initiatives being managed as projects established under the Implementing Agreement of the IEA Greenhouse Gas Programme. This is a useful route as the legal framework is already in place, the bureaucracy is reduced and support mechanisms are already in place. At the same time a number of additional tasks can be started with the help of industrial partners.

All this work needs to be carefully co-ordinated, a task that can be easily accomplished by co-operation between Statoil and the IEA Greenhouse Gas R&D Programme.

A major action for the group was to put together, before Christmas 1997, a list defining the tasks that can make up the major programme, suitably phased for the periods indicated in Figure 3.

These points were put to all the attendees. Considering the size of the group there was a surprising consensus on the activities that should be carried out. Not surprisingly, the initial thoughts were aimed at an overview to see exactly what data was available, fill in gaps, and collate it in a useful manner. This would avoid any repetition, with little effort (at low cost) and focus more accurately on the work to be carried out within later tasks. The next phase would look at extra measurements, improve the understanding and plan for future research. The third phase would look towards larger investment, in most groups requiring the drilling of a dedicated observation well. The output from each expert group and their categorisation into the different phases of work is listed below:

Phase One (0-1 year, period of work)

Monitoring and Well technology

- Overview of what data is available, database, structural model
- Compare existing data
- Contact other North Sea Operators for additional data
- Define monitoring requirements from this data
- Acquire baseline data (cores/fluid in offset wells) and define what is missing
- Evaluation of technology for further observation

Geochemistry

- Formation evaluation based on available data
- Fluid evaluation, based on available data

Reservoir simulation & validation

- Produce a more complete structural model, geology, hydrology
- Utilise analogue studies

- Start immediate data monitoring on the injection well, bottom hole, particularly temperature and pressure.
- Select best available simulator and begin sensitivity analysis.

Geophysical monitoring.

- Review available seismic data - detailed structural mapping (cap rock plus Utsira, assess initial leakage, integrity and geometry), look at existing VSP's.
- Review and improve physical properties data (input from analogues, well bore, core and fluid samples, also involve seismic mapping.
- Flow simulation and evaluate the feasibility of gravimetric measurement.
- Assess feasibility for worst case and best case scenarios and plan for future data acquisition.

Phase Two (1-3 year, period of work)

Monitoring and Well technology

- Data acquisition programme
- Define what observations are required and how this can be achieved
- Build model, and/or refine existing models (Statoil)
- Benchmark models
- Characterisation of fluids and cores

Geochemistry

- Modelling experiments
    - prediction of chemical interactions
    - change in reservoir properties
    - prediction of the distribution of the carbon dioxide
- Observations from monitoring well validation

Reservoir simulation & validation

- Build an updated numerical simulator based on the results of phase 1. This should incorporate a coupled geochemical model.
- Carry out a sensitivity analysis for short and long term predictions.
- Define the future monitoring programme.

Geophysical monitoring.

- First 2D surveying to take place over expected accumulation highs
- Gravimetric survey
- Assessment, processing and reinterpretation. Additional VSPs as required
- Carryout a second 2D surveying/ possible 3D
- Select a location for observation well

Phase Three (>3 year period of work)

Monitoring and Well technology

- Large investment will be required for a dedicated observation well(s)

Geochemistry

- Extend the modelling activities
- Compare data with natural analogues
- Continue monitoring (long term) with the use of an observation well

Reservoir simulation & validation

- Simulation validation through a long term monitoring programme
- Match the long term modelling capability to that required for hazardous waste disposal.

Geophysical monitoring.

- Continue 2D/3D seismic monitoring
- Drill an observation well(s) if required for long term data acquisition
- Continue to assess the situation

7. Progress since the workshop

The day after the workshop Perry Bergmann, from the US Department of Energy, held a short meeting with some of the delegates who were able to stay on in Trondheim. The minutes are attached as Appendix G.

Since the workshop, a number of meetings have taken place to "firm up" the THERMIE proposal. This was submitted to the European Commission on 29th January 1998. For the benefit of the THERMIE application the acronym has been changed from SACS to ACS (Aquifer carbon dioxide storage - offshore demonstration at Sleipner). The IEAGHG Programme is an associated proposer in the THERMIE application and is specifically mentioned in the proposal for its "umbrella project" role and its ability to co-ordinate international R&D co-operation. The IEAGHG also has a place on the THERMIE project steering committee. The initial work plan is outlined in Appendix H and I of this report. This shows the major tasks and the start of the planning for the additional international collaboration. The workshop had recommended some data collection and re-evaluation, which Statoil will carry out as "task zero" prior to the start of the full programme of work.

Other international interests can be involved in this activity through the IEA GHG in a similar way to the practical initiatives already being managed as projects under the IEA GHG Implementing Agreement (e.g. enhanced gas recovery with CO_2 storage in coal seams). Further, related geological storage projects are anticipated by Perry Bergman and colleagues, including disused oil and gas reservoirs, salt domes and hydrate deposits, and there is related work on acid gas disposal in Alberta, reservoir simulation using the STARS simulator, as well as investigation of CO_2 behaviour in reservoirs.

Through international co-operation, the experience from all of these projects can be shared and the work tasks co-ordinated for maximum co-operation and to minimise duplication of effort. A number of additional ACS tasks can be started with the help of industrial partners. The IEA GHG legal framework provides a means of minimising bureaucracy and establishing the necessary projects without delay. All of this work needs to be carefully co-ordinated, a task that can be accomplished by co-operation between Statoil and the IEA Greenhouse Gas R&D Programme.

We have already started to identify tasks which could be supported through an ACS research project under the IEA GHG Agreement. Some or all of the following topics are being considered:

- Natural analogues,
- Geochemical modelling,
- Drill a monitoring well
- Undertaking a sampling and measurement programme,
- Time-lapse 3D seismic monitoring,
- Input from regulators of other deep well disposal projects
- Investigation of CO_2 leakage along faults and fractures.

A proposal for a suitable project will be submitted to the IEAGHG Executive Committee for consideration as soon as possible. A draft of this report has been sent to Statoil and to the expert group chairmen for comment, prior to being issued.

8. Acknowledgements

We would like to take this opportunity to thank Statoil and its licence partners for allowing us to organise the workshop and for their continued co-operation. We would also like to thank the members of staff from Statoil in Trondheim who helped to make this event possible and, in particular, our thanks go to Tore Torp and Olav Kaarstad.

We are also indebted to all the experts who attended the workshop and gave their time and expertise freely. We would particularly like to thank the session chairman who helped make this event a great success.

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APPENDIX A

SLEIPNER VEST CO_2 DISPOSAL, CO_2 INJECTION INTO A SHALLOW AQUIFER

APPENDIX B

FACTS ABOUT THE SLEIPNER FIELDS

APPENDIX C

SLEIPNER STRUCTURAL DEPTH MAP

APPENDIX D

SLEIPNER CO2 STORAGE - SEISMIC MONITORING

APPENDIX E

MONITORING EXPERIENCE FROM UGS/EOR PROJECTS

APPENDIX H

ACS PROJECT WORK PLAN

APPENDIX I

ACS PROJECT TIMETABLE

APPENDIX G

POST-WORKSHOP MEETING MINUTES

APPENDIX F

JOULE II CO_2 STORAGE STUDY