# External Review of the Storage Plan for the Peterhead Carbon Capture and Storage Project

Energy Programme

Confidential Report

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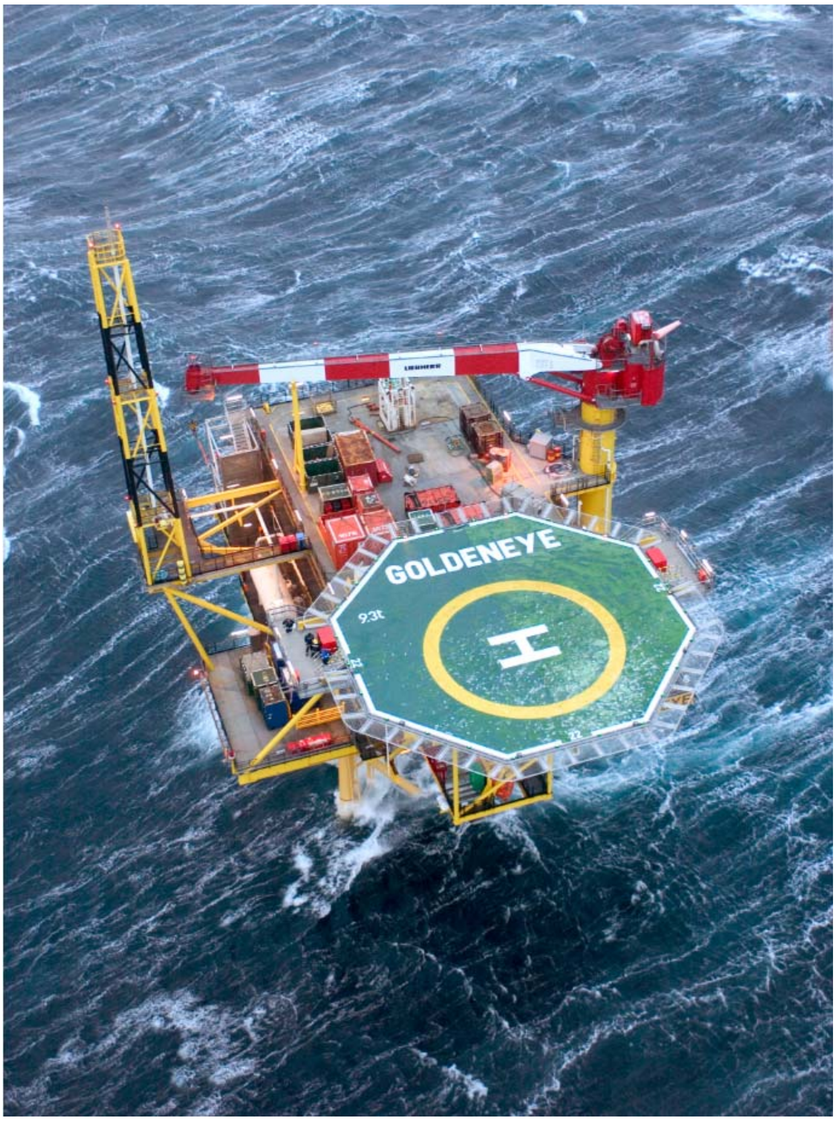

BRITISH GEOLOGICAL SURVEY

ENERGY PROGRAMME
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# External Review of the Storage Plan for the Peterhead Carbon Capture and Storage Project

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Keyworth, Nottingham British Geological Survey 2014

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# Foreword

This document summarises the findings of the external independent review of the storage plan for the proposed Peterhead Carbon Capture and Storage project.

As the Peterhead CCS project is part of the UK CCS Commercialisation Competition, which has not yet reached its conclusion, some of the material referred to in this report is not publicly accessible. However many of these documents have been made publicly available online at https://www.gov.uk/government/collections/carbon-capture-and-storage-knowledge-sharing as part of the Knowledge Transfer element of the CCS programme. More will become available over the next year.

While the external review process concluded in July 2014, some of the text of the report has since been updated to reflect changes made to the draft content of Shell's Storage Permit Application.

# Acknowledgements

The review team comprised experts from the British Geological Survey (BGS) and Heriot-Watt University (HWU):

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# Contents

# Executive Summary

This document summarises the findings of an external independent review of the storage plan for the proposed Peterhead Carbon Capture and Storage project which aims to store up to 20 million tonnes (Mt) of $CO_2$ within the framework of the European Directive on the geological storage of $CO_2$.

The Peterhead Carbon Capture and Storage Project proposes to capture carbon dioxide ($CO_2$) from an existing gas-fired power-station at Peterhead and to store this in geological strata at a depth of around 2600 m beneath the outer Moray Firth. The plan is to store 10 - 15 Mt of $CO_2$ over a ten to fifteen-year period commencing around 2020, but the site is being qualified for 20 Mt to allow for potential extension of the injection period. Storage will utilise the depleted Goldeneye gas condensate field with the Captain Sandstone reservoir as the primary storage container. The Storage Site covers some 70 $km^2$, and comprises the Captain Sandstone and underlying strata of the Cromer Knoll Group, bounded by a polygon some 2 to 3 km outside of the original Goldeneye oil-water contact. The Storage Complex is larger, around 154 $km^2$, bounded some 2 to 7 km outside of the original oil-water contact, and extending upwards to the top of the Dornoch Mudstone at a depth of more than 800 m. The top-seal of the primary container is a proven caprock for natural gas and is formed by the mudstones of the Upper Cromer Knoll Group, the overlying Rødby and Hidra formations and the Plenus Marl. A number of additional seals are present in the overburden within the Storage Complex, as are a number of potential secondary containers which could also serve as monitoring horizons.

The geological interpretation of the storage site is based on the comprehensive datasets acquired during the discovery, appraisal and development of the Goldeneye field, and also data from other wells, fields and seismic surveys in the surrounding area. The static geological model of the storage site and adjacent aquifer has been stress tested for the key uncertainties, and it is considered to be robust. The storage capacity of the Goldeneye structure has been calculated using both static (volumetric) methods and dynamic flow modelling together with uncertainty analysis. Total estimated capacity of the structural closure is in the range 25 to 47 Mt and so robustly exceeds the proposed injected amount.

A large number of $CO_2$ injection scenarios have been assessed using different well configurations and testing uncertainties in the static model, including possible worst-case scenarios. The injection plan is extremely robust in terms of plume migration and pressure development, and significant irregularities are considered to be very unlikely. A key aspect of the storage is the ‘pressure sink’ effect of the depleted field. Reservoir pressure at the start of injection will be less than 70 % of hydrostatic and will remain substantially below ambient pressure for the duration of the injection operation. The tendency therefore will be for fluids to flow into the storage reservoir rather than out of it, which is a major positive safety factor.

A comprehensive risk assessment has been carried out based on the bow-tie method, linking threats to consequences via a range of preventative and corrective measures. Potential risks include short and long-term releases of $CO_2$ to seabed, sub-sea and platform, lateral migration to adjacent fields and wellbores, and lateral migration of dissolved $CO_2$. Wellbores within and around the Goldeneye field are identified as the main potential leakage risk. All have an effective primary sealing barrier at top reservoir, and some have a secondary sealing barrier higher in the Storage Complex. In addition, a detailed analysis has been carried out of the specific risk profile at each well and this is considered to be robust.

The measurement, monitoring and verification (MMV) plan aims to demonstrate containment and conformance and is closely linked to the risk assessment. The main surveillance element

focusses on the reservoir and overburden and utilises a limited number of proven technologies: time-lapse 3D seismics, together with down-hole pressure, temperature, geophysical logging and fluid sampling – the latter to be deployed both in the injection wells and in a dedicated monitoring well. A comprehensive shallow environmental monitoring programme is also planned, employing seabed imaging, seabed sampling and seawater sampling technologies. Robust baseline datasets will be acquired for both the deep-focussed and shallow monitoring elements, and we consider the overall plan to be fit for purpose.

The corrective measures plan is based on the risk assessment and focusses on addressing significant irregularities, with the ultimate aim of preventing or repairing leakage or emissions of $CO_2$. Leakage scenarios have been assessed, prioritising various possibilities for wellbore leakage, but also addressing leakage via the geological pathways. A comprehensive portfolio of corrective measures has been designed ranging from additional contingency monitoring, through adaptation of the injection programme, to wellbore interventions, and if necessary, a full well kill by the drilling of a new relief well.

The provisional post-closure plan is designed to meet the requirements of the European Directive in a pragmatic and cost-effective way and aims to transfer responsibility for the site within ten years after cessation of injection. Platforms and wells will be closed within three years of ceasing injection, with down-hole monitoring maintained for as long as practicable. Additional post-closure monitoring will comprise two 3D seismic surveys and two seabed / environmental surveys. The former is to demonstrate no leakage and long term gravitational-stabilisation, the latter to demonstrate no leakage or emissions. Resources will also be made available for the UK authority to carry out two post-transfer seabed emissions surveys. Overall we consider the plan to be very satisfactory.

It is clear that the technical studies carried out by Shell are founded on a comprehensive suite of modern high-quality datasets and are very robust. We conclude therefore that the Goldeneye storage site is characterised and understood to a high level of detail and is suitable for the purpose of storing up to 20 million tonnes of $CO_2$ injected according to the specified plan. The British Geological Survey has prepared a signed statement to this effect.

# 1 Introduction

This document summarises the findings of an external independent review of the storage plan for the proposed Peterhead Carbon Capture and Storage project.

The review took place between January and June 2014 via an iterative process of document review, response and discussion. The initial stage involved review of 20 technical documents (Appendix 1). Issues arising from this initial review were transmitted to Shell and addressed in a two-day Engagement Session between Shell and the review team in Aberdeen on 5-6 March 2014. The Engagement Session comprised 14 technical presentations (Appendix 2) from Shell and detailed discussions on the points of issue. A set of remaining issues were then transmitted to Shell for response and actions. Actions included additional modelling, clarifications and text re-drafting. A second, one-day Engagement Session was held in Aberdeen on 20 May 2014. This comprised 13 presentations (Appendix 3) from Shell addressing the points of issue and further detailed discussions. A draft review report was produced and, after provision of further documents (Appendix 4), remaining minor residual issues were addressed. The review was finalised on 31 July 2014.

It is noteworthy that all the contributors from the Shell team participated fully and openly at both Engagement Sessions, that the responses from the various members of the team were consistent with one another, and that issues raised and discussed at and after the first Engagement Session had been studied in detail, with additional results presented and discussed at the second Engagement Session.

Our conclusion is that the proposed Goldeneye storage site is suitable for the purpose of storing up to 20 million tonnes of $CO_2$ injected according to the specified plan. BGS have signed a statement to this effect (Annex 1).

The outcome of the Review is outlined below, under headers corresponding to the main scientific and operational topics.

# 2 Selection and characterisation of the storage site and storage complex

## 2.1 DEFINITIONS

Key definitions cited in the draft Storage Permit Application conform to those in Directive 2009/31/EC of the European Union, on the geological storage of carbon dioxide (henceforth the Directive).

The *storage site* essentially comprises the depleted Goldeneye gas condensate field, the reservoir of which comprises the Captain Sandstone of the Cromer Knoll Group, being bounded by a polygon that lies a short distance (~2 to ~3 km) beyond the original oil-water contact and of area ~70 $km^2$. It comprises all the geological formations from the top of the Kimmeridge Clay (base Cromer Knoll Group) to the top of the Captain Sandstone, the latter at a depth of about 2500 m at the top of the structure. The storage site is overlain by the storage seal which is a proven seal for natural gas and comprises the Upper Valhall Member of the Cromer Knoll Group, the Rodby and Hidra formations and the Plenus Marl.

The *storage complex* is bounded by a larger polygon, ranging from ~2 to ~7 km beyond the original oil-water contact and of area ~154 $km^2$. It comprises all strata from the top of the Kimmeridge Clay to the top of the regionally persistent Dornoch Mudstone at a depth of more than 800 m.

The storage site and storage complex are both logically defined and likely to prove effective in operation. The storage complex definition is particularly robust. Its outer boundary lies well beyond any plausible $CO_2$ migration pathway and its upper boundary comprises two regionally extensive sealing units, the Lista and Dornoch mudstones. In addition it contains a number of additional seals and secondary containment units, the latter potentially suitable as monitoring horizons.

## 2.2 GEOLOGICAL INTERPRETATION AND STRUCTURAL CONFIGURATION

The geological interpretation of the storage site is based on the comprehensive set of data acquired during the discovery, appraisal and development of the Goldeneye gas condensate field, but it also utilises a wide spread of data from other wells, fields and seismic surveys in the region around the field. In our view this dataset is sufficient to adequately characterise the storage site and storage complex.

The geological and geophysical characterisation of the storage site and storage complex is described in a range of technical reports and the draft Storage Permit Application (Appendix 1). The studies are all highly detailed and meet the requirements for site characterisation described in Annex 1 of the Directive. It describes the reservoir, seal and other rock properties of the geological formations comprising the storage site and storage complex, and their three-dimensional stratigraphy and structure, including an interpretation of the stress field, faults and fractures in these rock volumes and the seismicity of the region around the site. It also describes *inter alia* the pressure and temperature regime and the fluids initially and residually in place in the reservoir, including the charge history of the hydrocarbon field. It demonstrates the secure nature of the natural trap for buoyant fluids that is the Goldeneye reservoir and its sealing units (the Rodby, Hidra and Plenus Marl formations). It also describes the potential for secondary containment in the rocks above the reservoir topseal, principally in the Palaeocene Mey Sandstone Member of the Lista Formation.

The main site characterisation issues resulting from the review and explored with Shell were:

- Imaging and resolution limitations of the 3D seismic surveys and consequent uncertainties in the interpretation of the three-dimensional stratigraphy and geometry of the storage site and fault patterns and linkages within it.
- Structural and stratigraphical continuity or compartmentalisation within the Captain Sandstone and significance of uncertainty in these properties.
- Faults in the reservoir and potential links to faults in the overburden.
- The significance of uncertainty in the depth conversion and the extent to which resulting errors in three-dimensional reservoir geometry were significant.
- Lateral continuity and thickness of the primary container topseal.

Based on the initial review, the response from Shell (further static and dynamic modelling to address the points raised) and subsequent re-review, we conclude that the storage site and complex have been characterised to a suitable level of detail and accuracy.

## 2.3 STATIC MODELS

A range of three-dimensional static geological models of the storage site have been built specifically for the storage project using Petrel$^{TM}$ software. These comprise a range of Static Reservoir Models, the Overburden Model and a model of the wider Captain fairway (the Aquifer Model). They have been used by Shell to calculate the storage capacity of the site and have formed the basis for a comprehensive dynamic modelling study (Section 4).

The main static modelling issues resulting from the review and explored with Shell were:

- Whether the full range of potentially adverse geological characteristics (*inter alia* reservoir and spill-point geometry, reservoir fluid flow properties, fault distributions and linkages) that might occur had been properly captured in the range of static models.
- The statistical procedures used to obtain the reservoir properties for the static reservoir model.

Based on the initial review, the response from Shell (including further static and dynamic modelling) and subsequent re-review, we conclude that the static geological modelling is sufficiently accurate and includes a robust range of uncertainties such as to fully meet the requirements of the project [Note: a specific ‘stress test’ was carried out involving the inclusion of an arbitrary high permeability thief zone from one of the injection wells to the spill-point of the structure. This was subsequently dynamically modelled with no adverse consequences (Section 4)].

# 3 Rock and fluid properties and interactions

A number of detailed ancillary studies, including laboratory measurements and a range of modelling studies, were carried out to assess rock and fluid properties and interactions within the storage complex (Appendix 1).

## 3.1 SPECIAL CORE ANALYSIS (SCAL)

Interpretation of the rock and fluid properties of the storage site is based on the comprehensive set of legacy core and geophysical log data acquired during the discovery, appraisal and development wells of the Goldeneye gas condensate field, and other wells in the region.

Extensive steady-state imbibition and drainage core-flood experiments had previously been carried out to characterise the hydrocarbon / brine system during the primary depletion phase. These data had been validated by virtue of a good match between the dynamic model and observed data during the hydrocarbon production phase of field life. Additional unsteady-state tests involving $CO_2$ were then carried out, with the objective of assessing factors that would influence $CO_2$ mobility, a key to determining $CO_2$ injectivity and potential migration. To avoid likely capillary end effects, up to 20 cm long cores were used in this latter phase of experimental work. Gas phase relative permeabilites were shown to be little changed by the introduction of $CO_2$. Brine $CO_2$ interfacial tensions were also measured, with values consistent with those reported in the literature. There is some uncertainty as to the extent of capillary trapping when $CO_2$ is displaced through rock initially at 100% water saturation, but as the dynamic modelling shows that $CO_2$ will not migrate beyond the spill point, this is not a critical issue.

The main issues resulting from the review and explored with Shell were:

- Clarification and justification of laboratory procedures, their limitations and consequent uncertainty range in the properties assigned to the static and dynamic models.
- Extent to which relative permeability and capillary pressures are the same for hydrocarbon gas / brine and $CO_2$ / brine systems.

In our view this dataset is sufficient to adequately characterise the storage site and storage complex. The reservoir and overburden properties derived from these data underpin the attribution of the static and dynamic models (Sections 2 and 4 respectively).

## 3.2 PVT

As with SCAL data, the originally developed Equation of State had been validated by virtue of the match between the dynamic model and observed flow data. A Peng Robinson Equation of State was tuned with pure $CO_2$ based on a six component system. National Institute of Standards and Technology (NIST) measured properties were used in calculating the Equation of State - the NIST data being widely accepted as the most reliable to use for such calculations. Pure $CO_2$ was assumed, a reasonable assumption given the $CO_2$ source will be gas fired power generation equipment, typically a source of $CO_2$ relatively free of impurities. The PVT calculations have been reproduced (assuming pure $CO_2$). Restriction on well diameter to maintain tubing head pressure and avoid excessive Joule-Thomson cooling during steady state injection and during start-up and shut-in, is conservative but nonetheless appropriate.

## 3.3 GEOCHEMICAL INTERACTIONS

The geochemical issues at Goldeneye appear to be quite generic and the assessment is in line with previous research findings at storage sites elsewhere. Shell has run a number of model simulations with 'worst case' scenarios in a number of attempts to 'break the system'. These ranged from short-term effects such as the development of dry-out zones and salt precipitation around the wellbore and much longer term effects related to reservoir, topseal and wellbore chemical integrity. The studies all showed that geochemical and chemical effects are likely to be minor. It was usually the case that not enough new water/$CO_2$ was available in the reactive system to overcome buffering and allow reactions to continue long-term. In particular it was always the case that insufficient mobile $CO_2$ and water were available to produce significant adverse effects in the vicinity of wellbores.

The main geochemical issues resulting from the review and explored with Shell were:

- Integrity of faults (in the presence of $CO_2$ and water)
- Integrity of reservoir rock (in the presence of $CO_2$ and water)
- Integrity of topseal (in the presence of $CO_2$ and water)
- Integrity of wellbores (in the presence of $CO_2$ and water)
- Near-wellbore effects (injectivity, porosity/permeability and formation strength modification)

Based on the initial review, additional information and clarifications from Shell and subsequent re-review, we conclude that geochemical interactions are sufficiently well understood to pose no significant threat to project operation.

## 3.4 GEOMECHANICAL INTERACTIONS

The programme of rock mechanics testing reported is appropriate. Although the number of samples tested was low, this is commonplace, and the sequence of testing was suitable for the application (depletion and then inflation), and the measured values are consistent with what would be expected from a weak/friable formation. Comparisons with other measurements conducted for the same field are valid and the results are consistent.

The geomechanical modelling is consistent in its use of laboratory derived data, assumptions, and relative to corresponding data in the dynamic simulation model. Where required, data values obtained from the literature have been used. A significant conclusion is that tensile failure will not occur. In all the sensitivities, the calculations indicate that there will be stability in the reservoir and the caprock, even in the worst case of very weak, unconsolidated rock with maximum depletion pressure.

The main threat to instability in the reservoir and the over/underburden is identified as the compressive shear stresses that might be produced from the depletion/injection process. For the stresses calculated, the values of shear stress will not affect the stability. Extending the range of values that could represent the mechanical parameters of the reservoir / overburden / underburden the material still does not fail, and this gives assurance that shear failure is unlikely. A related issue is the possibility of induced strains in the overburden due to the depletion / injection cycle causing the formation of new micro-annuli along the casing / cement / rock interfaces. This was tested by additional geomechanical modelling.

Two issues in particular were reviewed and explored with Shell:

- Given the uncertainty in the interpreted fault distribution and fault orientations, in order to maintain a conservative approach it was recommended that the fault stability analysis include a hypothetical optimally-oriented, cohesionless fault with a low friction co-efficient, in order to show that faults in the reservoir or overburden would not be reactivated by pressure changes.

- Near wellbore geomechanical interactions between the wellbores (compaction/expansion and displacement) and the overburden, the possible development of micro-annuli, and how this might affect wellbore integrity.

Based on the initial review, Shell undertook additional dynamic modelling studies to test the issues raised. These included the requested fully conservative fault stability analysis and also geomechanical modelling of the wellbore- rock interfaces (see also Section 6). In the light of this we conclude that a comprehensive geomechanical analysis has been carried out, based on an experimental programme and associated geomechanical modelling. This thorough analysis leads to the conclusion that the risk of geomechanical failure affecting storage security is very low.

# 4 Reservoir engineering

A comprehensive dynamic fluid flow modelling effort has been carried out, including detailed history matching with the hydrocarbon production phase, and a range of predictive injection models, on a range of time-scales, to assess uncertainty. The models have been used to:

a) Model the injection and long-term storage of $CO_2$ in the storage site including the distribution of $CO_2$ and pressure through time.

b) Help demonstrate the robustness of the long-term security of storage within the site.

c) Model the potential long-term fate of any $CO_2$ in the unlikely event that it somehow breaches the natural and man-made barriers and leaks out of the storage complex.

A wide range of sensitivities were evaluated, and Shell has explored the uncertainty limits and consequences by credible attempts to try and 'break the storage system'.

## 4.1 DYNAMIC STORAGE MODELLING

Four distinct simulation models have been developed: two homogeneous box models for Goldeneye and the overburden (to assess the risk of leakage through wellbores), and two heterogeneous full field models (FFM) for the Goldeneye Field and the overburden. Numerous sensitivity calculations were performed to test the impact of various assumptions, the results giving confidence that the conclusions drawn from the modelling study are robust. Of particular significance are that the simulation grid resolution and plume mobility issues were explored satisfactorily.

### 4.1.1 Box model for Goldeneye

This model was successfully used to test the PVT data and the sensitivity of migration patterns to relative permeability. From this it was established that the relative permeability end-points have only a minor impact on plume displacement. This is an important conclusion, since relative permeability functions are amongst the most sensitive and poorly-constrained of inputs in a reservoir simulator, and the ability to model $CO_2$ migration pathways is an important component of the mitigation strategy to address the risk of leakage.

### 4.1.2 Field model for Goldeneye

A good history match of the hydrocarbon production period had been achieved, and the model alterations to include $CO_2$ injection, discussed above, all seem relevant and appropriate. As noted above, the same relative permeability curve was used for both hydrocarbon gas and $CO_2$ by assuming $CO_2$/brine system is similar to gas/brine. This assumption is of importance, since, as already noted, relative permeability functions are generally sensitive inputs, and most simulators do not allow for a change in relative permeability as a function of change in gas composition. The work undertaken with the box model significantly increases confidence that predictions of $CO_2$ migration pathways using the FFM model are accurate.

### 4.1.3 Box model for overburden

Consideration should be given to the impact of tilting the model in *both* X and Y directions to identify the impact on distance that $CO_2$ would migrate. The field model for the overburden, however, did explore the impact of structure on the flow paths.

#### 4.1.4 Field model for overburden

A good effort was made to model the migration of $CO_2$ through the overburden should any migration out of the reservoir take place. In the event that $CO_2$ were to escape from the storage site (the Captain Sandstone reservoir in the Goldeneye field and its seal comprising the Rødby, Hidra and Plenus Marl formations) it might reach the overlying Chalk. The Chalk is likely to comprise a significant regional physical and chemical barrier to $CO_2$ migration but there is a hypothetical scenario in which $CO_2$ might eventually reach the thick Palaeocene sandstones (principally the Mey Sandstone Member). To address this Shell have modelled the migration of $CO_2$ within the Mey Sandstone to determine whether a feasible $CO_2$ plume could encounter any existing wellbores. The results suggest this is extremely unlikely, and indeed a large proportion of the injected $CO_2$ would have to escape from the storage site for there to be a possibility of this occurring. There is moreover significant uncertainty in the characterisation of this zone. For instance, the extent of small-scale sedimentary rugosity under any impermeable barriers which would trap $CO_2$ locally and retard its advance was not considered, leading to probable pessimistic (over) prediction of $CO_2$ migration.

It is noted that a large pore volume multiplier was used in the overburden field model at the edges to ensure a constant pressure boundary. This was reviewed with Shell and discussed in the context of a comparison with the Regional Aquifer modelling (see below).

### 4.2 REGIONAL AQUIFER MODELLING

While the Full Field Model was well matched during the hydrocarbon production period, an alteration to some of the aquifer permeability values (increasing these by a factor of 1.9) was required to match the observed pressure rise due to aquifer recharge after the field was shut-in. The shut-in period between cessation of production and the start of $CO_2$ injection has thus been beneficial in terms of further constraining the Full Field Model. Changes in the aquifer permeability did not alter the validity of the history match during the hydrocarbon production phase of field life.

The main issues resulting from the review and explored with Shell were:

- Radically different fault patterns, linkage and fault permeability are incompatible with the excellent production history-match of the field and surrounding aquifer, which takes into account adjacent field operations, and therefore it can be concluded that the features of the geological model that will determine the migration pathways for $CO_2$ are well constrained.

- There is a possibility of Shell continuing to receive updated pressure information from other fields in the Captain Fairway to better calibrate predictive dynamic models etc.; this is to be encouraged to further improve the predictive capacity of the models, and the support of the Department of Energy and Climate Change (DECC) in obtaining these data should be sought.

# 5 Storage capacity

A range of estimates of $CO_2$ storage capacity for the site were produced using both static (analytical) and numerical dynamic methods. The static methods are based on the voidage created by the volume of hydrocarbons and water extracted from the field, modified by a range of factors that reduce the volume available for storage (such as recharge of the depleted field by brine migrating from the Captain aquifer that is in lateral continuity with the field) and another set of factors that increase it (such as dissolution of $CO_2$ into the formation brine). The static estimates take into account the uncertainty in the pore volume of the field and the volume of hydrocarbons initially in place. They indicate a "most likely" storage capacity of 34 Mt of $CO_2$, with a range of possible storage capacity between about 25 Mt and 47 Mt of $CO_2$. Even the low end estimate provides a very substantial margin above the ~10 to 15 Mt of $CO_2$ to be stored as part of the DECC Commercialisation Programme. Shell did a robust assessment of multiple injection cases ranging from 10 to 20Mt – we consider the storage capacity to be adequate for all injection cases.

The dynamic estimates confirmed that there is a substantial margin of $CO_2$ storage capacity above the 20 Mt scenario. The dynamic simulations investigated a range of injection scenarios utilising different sets of injection wells. 20 Mt of $CO_2$ could be stored in all scenarios except injecting the entire amount through well GYA01 – where it was not possible to inject the whole quantity. In all scenarios a Dietz Tongue of $CO_2$ occurred, in which $CO_2$ moved below the original hydrocarbon-water contact in the west of the field, but at the end of $CO_2$ injection any mobile $CO_2$ in this tongue retreated into the field closure. None of the $CO_2$ in the Dietz Tongue reached beyond the spill point between the aquifer and the field. Although the presence of an undiscovered high permeability thief zone connecting the $CO_2$ saturated zones to the spill-point was tested in the modelling and found to be incompatible with the history matches, it nonetheless did not lead to $CO_2$ migration beyond the spill point.

Other than the risk of migration beyond the spill point due to a thief zone, the main issues discussed were:

- Whether Shell would run 10 Mt injection models as part of a revised capacity test.
- Whether Shell would run 10 + 10 Mt injection models to check that the full 20 Mt could be injected sequentially at 1 Mt per year. The previous simulations had injected 20Mt at 2 Mt per year.

In response Shell confirmed that a full suite of 10 Mt dynamic models (including 10 + 10 Mt) would be run to further test storage capacity. This has now been carried out and we conclude that the storage capacity estimates for the Goldeneye structural closure are robust.

# 6 Wellbore containment

The construction and, where appropriate, the abandonment, of the wells penetrating the storage site and storage complex are described in detail. A total of ten wellbores are identified as having the potential to be contacted by the predicted $CO_2$ plume: five production wells, and five more widely scattered exploration and appraisal wells (the E&A wells are now plugged and abandoned). All of these have an effective primary sealing barrier at top reservoir, and some have a secondary sealing barrier higher in the Storage Complex (at the Lista Formation). In addition, a comprehensive 'decision-tree' type of analysis of the leakage risks at every well in the storage complex (18 in total) has been carried out to assess specific risks pertinent to each well.

The main wellbore integrity issues resulting from the review and explored with Shell were:

- Integrity of the abandoned E&A wells.
- Contingency planning if cement bond and caliper logs suggest integrity of well is compromised.
- Possibility of induced micro-annuli associated with stress changes and strains in the overburden due to the depletion / injection cycle. Additional modelling to assess this.
- Hydrate risk if water saturated with $CO_2$ rises up the wellbore.
- Pressure relief options with current well stock.

Based on the initial review, the response from Shell (including additional DIANA modelling of wellbore / overburden mechanical interactions) and subsequent re-review, we conclude that the wellbore containment case is robust. It was noted during the discussion that the level of well-related problems during the Goldeneye production phase was extremely low, and that the field production history had gone according to plan with no relevant wellbore issues during the operations, all of which bodes well for integrity of $CO_2$ storage.

# 7 Transportation and injection

A detailed plan for injection, covering the key engineering aspects, was presented.

It is noted that elastomer seals in wells will be replaced prior to $CO_2$ injection. At start-up, some $CO_2$ will be vented at the platform, and, to avoid damaging the storage reservoir, only once a stable and clean flow of $CO_2$ is achieved will $CO_2$ be injected downhole. A four-inch methanol line will be used during the start-up period only. No other fluids will be used in this line to reduce the risk of damage to the line due to incompatibilities between fluids.

All injection wells have a (greater than 200 feet) cement barrier at the primary seal. Cementation reports showed no losses, and there were no significant pressure losses during production. Additionally, there were no major incidents reported for the wells during the production phase of field life. The most significant issues were repairs to one of the Christmas-trees, and to a control line for a sub-surface safety valve, both of which will be replaced prior to $CO_2$ injection. Cement bond logs and caliper logs will be run before the start of $CO_2$ injection. While a risk of loss of integrity of the completion due to interactions with $CO_2$ at reservoir intervals was identified and discussed with Shell, the reviewers are satisfied that the cement barrier at the primary seal provides a more than adequate barrier to prevent loss of $CO_2$ above the target injection horizon.

Injection capacity is assured by the fact that there is redundancy in the system. Of the five wells available for injection, only three will be required for injection, and then only one at any one time. This will leave one to be used for monitoring and one to be abandoned at reservoir level. If there is loss of injection capacity and these two wells are also used for injection, and if there is still insufficient capacity, there is an option to side-track one or more of the accessible wells.

# 8 Risk assessment

The risk assessment for Goldeneye is based upon an extremely comprehensive 'bow-tie' analysis whereby unwanted Events are treated in terms of causative Threats and arising Consequences. To reduce the risk of an Event occurring, a range of preventative safeguards (e.g. geological barriers, monitoring sensors) are placed between the Threat and the Event. Should the Event occur, to reduce the impact, a suite of corrective safeguards (e.g. well intervention) are placed between the Event and the Consequence.

Potential Consequences considered in the analysis include short *inter alia* and long-term releases of $CO_2$ to seabed, sub-sea and platform blowouts, lateral migration to adjacent fields and wellbores, lateral migration of dissolved $CO_2$ etc.

From this a Risk Assessment Matrix (RAM) was developed prioritising Threats in terms of the likelihood and severity of their Consequence.

A number of issues were explored:

- In terms of RAM likelihoods, previous operational experience in industry is not robust for CCS and the extent to which other analogous industry experiences should be included.

- Most relevant analogous industries e.g. water injection vs. natural gas storage vs acid gas injection vs $CO_2$-EOR.

- Treatment of Threats with very high Consequence in the RAM, and the desirability of assigning ALL top severity matrix cells a red colour, irrespective of likelihood.

- Revised assessment for the 10 Mt injection case, where risks would potentially be different (and lower) due to smaller $CO_2$ source, potentially fewer injection wells, lower pressures etc.

The issues were discussed at length. Shell confirmed that more suitable analogous industries would be considered for assessing event likelihoods and risks for the 10 Mt injection case would be addressed specifically. The latest risk assessment now includes a very comprehensive literature review.

# 9 Monitoring plan

The MMV plan is robust utilising a limited suite of mature and proven technologies, based on a comprehensive technology feasibility review. It focusses on proving containment and conformance and is linked closely to the risk assessment and the dynamic predictive flow modelling. A base-case monitoring programme is defined together with a contingency monitoring programme in case of significant deviations from expected behaviour.

Reservoir pressure and temperatures will be monitored continuously in the injection wells and in one or more dedicated monitoring wells. Wireline logging and down-hole fluid sampling is also planned to further characterise reservoir processes. Time-lapse 3D seismics will provide full spatial coverage of the Storage Complex, with robust 3D spatial coverage of the overburden for out-of-reservoir $CO_2$ migration and leakage detection. It also provides some opportunity to image $CO_2$ in the reservoir (particularly any $CO_2$ that migrates outside of the original oil-water contact). A new purpose-designed baseline 3D seismic survey is to be acquired which is commendable. A repeat survey will be acquired after five years, with a second repeat survey about one year after cessation of injection. A final 3D survey will be acquired six years after closure (see below). Alternative configurations of the 3D seismics, including permanent seabed sensors, will be considered. In addition, deployment of possible complementary technologies such as downhole optic fibre acoustic cables giving potential for time-lapse 3D vertical seismic profiles (VSP) will also be investigated.

A comprehensive shallow monitoring programme is planned, employing seabed imaging, seabed sampling and seawater sampling technologies, with the option to update the plan if new technologies become available.

The MMV issues resulting from the review and explored with Shell were:

- Possibility of integrating legacy seismic data for outer parts of Storage Complex 3D seismic baseline.
- The extent to which repeat 3D seismic surveys of more limited area could be utilised to reduce costs and environmental impact balanced against risk of having to re-mobilise if small survey does reveal non-conformance.
- The extent to which 4D VSP might replace the 3D mid-term repeat seismic survey.
- The need to plan the extent of the repeat survey very carefully to make sure that specific risks are fully addressed and conformance verification objectives are maintained. Full surveillance of the original oil-water contact perimeter would likely be required.
- Timing of the mid-term (5-year) survey in terms of predictive models and also with respect to 5-year DECC review.
- Seismic sensitivity analysis including modelling for time-shifts as well as reflectivity changes and the relative effects of pressure and fluid saturation on seismic response.
- Suitability or otherwise of well breakthrough times as a conformance criterion.

- Selected monitoring tools need to be robust against false positives (e.g environmental baseline survey).

- The desirability of carrying out explicit modelling and risk assessment of the 10 Mt injection case because of different $CO_2$ volumes, pressures mass of $CO_2$ below the various wells, may well have different conformance criteria.

In response, Shell carried out additional rock physics analysis to test sensitivity to time-shifts and improved their pressure sensitivity calculation. They also confirmed that revised 10 Mt injection models would be used to check conformance criteria. We are therefore satisfied that the proposed monitoring plan, both base-case and contingency elements, is fit-for-purpose.

# 10 Corrective measures plan

A corrective measures plan has been developed, based on the risk assessment and focussing on addressing significant irregularities, with the ultimate aim of preventing or repairing leakage or emissions of $CO_2$.

A full range of leakage scenarios has been assessed, prioritising the various possibilities for wellbore leakage, but also addressing leakage via the geological seals.

A comprehensive portfolio of corrective measures has been designed ranging from additional contingency monitoring, through adaptation of the injection programme, to wellbore interventions, and if necessary, a full well kill by the drilling of a new relief well.

Two hypothetical remediation scenarios have been developed, showing workflows for correcting leakage through a platform injection well and through an abandoned E&A well.

An assessment of the likelihood of remedial work being successful was undertaken. This concluded that chances of successful remediation were highest with a platform well leak and lowest for leakage through the geological seals. This is in line with the expectations of the Directive guidance documents (GD2).

The main corrective measures issues resulting from the review and explored with Shell were:

- If there is an unexpected increase in pressure in any of the planned injection wells, which could lead to a loss of containment, an additional well previously used for production could be used as a replacement $CO_2$ injection well.

- Any evidence of leakage from one of the platform wells would be addressed by a workover.

We conclude that the corrective measures plan is fully in line with regulatory and operational considerations.

# 11 Provisional post-closure plan

A provisional post-closure plan has been developed, which would be subject to revision during the course of the project. It is designed to meet the requirements of the Directive in a pragmatic and cost-effective way and aiming to transfer responsibility for the site six years after cessation of injection.

Platforms and wells will be closed within three years of ceasing injection, with down-hole monitoring maintained for as long as practicable (up to three years). Additional post-closure monitoring will comprise two 3D seismic surveys the first one year after closure and a final one, at least five years after the first post-closure survey. These will be augmented by seabed / environmental surveys, with emphasis on detecting leakage at the wellheads. Resources will also be made available for the UK authority to carry out two post-transfer seabed leakage surveys (multi-beam echosounding or similar technology).

Shell will use the comprehensive post-closure monitoring programme to demonstrate that at the point of transfer, the $CO_2$ will not be leaking, it will be behaving as predicted in terms of pressure and plume conformance and it will be progressively approaching gravitationally-stable equilibrium. The latter will initially be via buoyant trapping within the structural closure and subsequently, on much longer time-scales, by dissolution into the formation water.

The main issues arising from the review and discussed with Shell include:

- Validity of reducing the indicative 20-year default post-closure period, as required by the Directive, to less than ten years.
- Long-term stabilisation criteria, including down-dip migration of dissolved $CO_2$.
- Post-transfer monitoring.

From the discussions and clarifications we conclude that the provisional post-closure is scientifically sound and likely to be effective, with the proviso that it might be subject to revision as the project proceeds and more information becomes available.

# 12 Concluding remarks

It is clear that the technical studies carried out by Shell are founded on a remarkably comprehensive suite of modern high-quality datasets and are in line with the current state-of-the art. All of the elements of the project technical study meet or exceed the necessary level of detail. Uncertainties are constrained and understood, and linked to a monitoring and remediation strategy. The probability therefore of unexpected irregularities leading to adverse outcomes sufficient to threaten the project is exceedingly small.

We conclude therefore that the Goldeneye storage site is characterised and understood to the degree required by the regulations and is suitable for the purpose of storing 10 –20 million tonnes of $CO_2$ injected according to the specified plan. The British Geological Survey has prepared a signed statement to this effect.

# Annex 1: BGS letter

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7th August 2014

To whom it may concern

The British Geological Survey (BGS), assisted by specialists from Heriot-Watt University, have carried out a comprehensive technical review of the plan for the proposed carbon dioxide ($CO_2$) storage project (known as the Peterhead Carbon Capture and Storage project) at the Goldeneye depleted field beneath the North Sea.

The review has assessed the key elements of the project plan which include inter alia, geological site characterisation, predictive dynamic models of storage performance, risk assessment, monitoring and corrective measures planning, handover criteria, and post-closure actions.

Based on this review, it is the conclusion of BGS that the plan for the Goldeneye storage project is robust and will provide for the secure long-term underground storage of $CO_2$.

Our conclusion is based upon the comprehensive information and access made available to us for the purposes of the review and on our professional judgement according to the current prevailing understanding of $CO_2$ storage science.

Yours sincerely

Robert Gatliff
Director, Energy & Marine Geoscience

INVESTOR IN PEOPLE

# Appendix 1: Review of documents provided by Shell for initial review

Static Model Overburden.pdf
Static Model Aquifer.pdf
Static Model Field.pdf
Geochemical Reactivity Report.pdf
IIP Volumes Estimate.pdf
Report on Results of Lab Experiments Geo-mechanical Investigation - Chemo-mechanical response of Captain Sandstone to CO2 injection.pdf
SCAL report.pdf
Seismic Interpretation Report.pdf
Bow-tie risk assessment for 20Mt.pdf
Conceptual_Well_Completion_Design_Proposal.pdf
Corrective_Measures_Plan_provisional29.pdf
Dynamic_modelling_report_Longannet_update_will_be_given_at_workshop.pdf
Measurement_Monitoring_and_Verification_Plan_provisional.pdf
Petrophysical_Modelling_Report_ZP-9032-00001_A01.pdf
PVT_Report.pdf
Well_Functional_Specification.pdf
PCCS-05-PT-ZP-9025-00003 - Monitoring Technology Feasibility Report provisional.pdf
PCCS-05-PT-ZP-9025-00004 - Geomechanics Summary Report.pdf

Draft (work in progress) Storage Permit Application

# Appendix 2: Technical presentations at 1st Engagement Session

03 - BGS External Review engineering overview 5Mar14 version 2.pptx
04 - Goldeneye External Review Geoscience Feb 2014.pptx
05 - Geochemical_Reactivity_2014_03_05.ppt
06 - Well Integrity and Containment assessment - 5 March 2014.pptx
07 - Goldeneye_Geomechanics_Review_5Mar2014.pptx
08a - RE_slides_March2014_v1.pptx
08b - Goldeneye SCAL Summary.pptx
08c - RE_slides_March2014_stress_tests.pptx
09 - Injection Wells.pptx
10 - Site and risk assessment v2.pptx
11 - Monitoring Technology Selection External Review 2014.pptx
12 - Goldeneye MMV Plan External Review 2014.pptx
13 - Corrective Measures.pptx
14 - Handover Criteria and Provisional Post Closure Plan - for BGS - LT OT.pptx

# Appendix 3: Technical presentations at 2nd Engagement Session

Goldeneye_BGSReview_Geomech_May2014.pptx
External_Review_of_Goldeneye_Store_II-Well_Integrity&Containment_20May_2014.pptx
2014_05_External_Review_-_Wells_-_Ajay.pptx
Goldeneye_MMV_Plan_External_Review_May20_2014.pptx
Bowtie_Analysis_-_Presentation_to_BGS_-_Sheryl_Hurst.pptx
External_Review_-_Presence_of_high_perm_streak_May20_2014.pptx
Goldeneye_External_Review_Geoscience_input_May_2014.pptx
Goldeneye_Por_Perm_Transforms_19_May_2014.pptx
Injection_Wells_depths_vs_Top_of_Cemen.pdf
Goldeneye_External_Review_Part_II_Geochemical_Reactivity_2014_05_20.ppt
PCCS_External_Review_2_Reservoir_Engineering_CT.pptx
E&A_Wells_comparison_to_UKOA_12.pdf

# Appendix 4: Further documentation provided subsequent to 2nd Engagement Session

Petrophysical Modelling Report ZP-9032-00001-A02.pdf
Static Model Aquifer ZG-0580-00003-A02a.pdf
Static Model Field ZG-0580-00004-A03.pdf
Static Model Overburden_ZG-0580-00005-A02.pdf
Dynamic_modelling_report_FEED_2014_update.docx
Risk Assessment A0.docx