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Assessing interactions between multiple geological CO_2 storage sites: generic learning from the CO_2MultiStore project

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Foreword

This report is the technical output from Work Package 4, Knowledge Capture and Reporting, from the CO_2MultiStore project. Work Package 1 of the project identified possible issues and potential concerns to the secure containment of CO_2 by the interaction between two or more geological storage sites within a deeply buried sandstone of regional extent. Reduction of possible issues and mitigation of perceived concerns were investigated in Work Package 2 by static geological, dynamic flow and geomechanical modelling of two reasonable and realistic sites within a northern North Sea case study of storage in the Captain Sandstone. Work Package 3 developed recommendations for a monitoring plan that specifically addresses the uncertainties and threats arising from storage at multiple sites. The report captures knowledge gained from the process, progress and findings of the research that is applicable to the development of any multi-user storage resource.

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Contents

TABLES

Executive summary

The CO_2MultiStore project (SCCS, 2015) investigated a case study of two injection sites within a multi-user store anticipating the need to inform a second phase of CCS developments following-on from initial commercialisation projects. The CO_2MultiStore study investigated the operation of a multi-user store using a North Sea case study, the Captain Sandstone. The Captain Sandstone contains the Goldeneye Gas Condensate Field which is the planned storage site for the Peterhead CCS project. Previous research (SCCS, 2011) was augmented by data from offshore hydrocarbon exploration and detailed investigation of the Goldeneye Field for CO_2 storage by Shell (2011a-i). The research was targeted to increase understanding and confidence in the operation of two or more sites within the Captain Sandstone. Methods were implemented to reduce the effort and resources needed to characterise the sandstone, increase understanding of its stability and performance during operation of more than one injection site.

Generic learning was captured throughout the CO_2MultiStore project relevant to the characterisation of the extensive storage sandstones, management of the planned injection operations and monitoring of CO_2 injection at two (or more) sites within any sandstone formation.

This report describes the generic learning gained from the CO_2MultiStore project investigations that are relevant to any multi-user store; learning from the process and the technical knowledge gained.

Capture of generic knowledge from the case study applicable to all UK storage sites was undertaken by:

- Facilitated study workshops with project members and invited industry participants with experience in Carbon Capture and Storage (CCS)
- Knowledge capture sheets from meetings, discussions and activities during the progress of the project.
- One-to-one discussions
- Consideration of the process
- Elucidation of key questions
- Recording of technical knowledge gained

Generic learning is presented by stage of investigation of a multi-user store. The investigations undertaken within CO_2MultiStore were the development of a consistent 'static' geological model (Section 2.4), increasing confidence in storage site performance by 'dynamic' flow modelling (Section 3.4), increasing certainty in the geomechanical stability (Section 4.4) and conclusions on the design of a plan for monitoring a multi-user store (Section 5.4). For each stage of investigation generic learning that would apply to any multi-user store was elucidated by the knowledge capture activity described above. The report outlines the context of each of the points raised and the generic learning from the case study investigations is presented and discussed. The points raised are presented in Table 1.

Key findings obtained from across the research, or those that have a regional perspective, are:

1. Integration of existing models should be considered for assessment of a multi-user carbon dioxide (CO_2) store. The models capture understanding of the formations, the rock types, the fluids contained within them, and subsurface conditions which are

all appropriate for re-use to inform assessment for CO_2 storage:

- Three-dimensional ‘static’ geological models of the sites may be merged and integrated to construct a regional-scale model suitable for multi-user store assessment provided they are consistent and well documented.
- Fluid property data from a hydrocarbon field box model, either within or adjacent to a storage site, can be used to validate the representation of contained fluids in the multi-user store model.
- Rock property and initial fluid pressure data can inform prediction of geomechanical stability of the prospective storage sites and pressure history information can be used to validate that the predictions are correct.

2. Where hydrocarbon fields are present within or adjacent to a multi-user store, access to field production data is essential to validate the predictive site performance models and to inform monitoring planning. The initial reservoir pressure at the start of hydrocarbon production can be difficult to obtain and the pressure history and well flow data during production is regarded as confidential to the operator. Access to such data by participation of the field operator in the storage project or via an independent third party might be arranged. Ideally, a field history database across all fields in a hydrocarbon province would inform the appraisal of fields for re-use as CO_2 stores.
3. Integrated working is essential when appraising a multi-user store. This is not solely best practice (initial fluid property modelling provides input data for geomechanical modelling that determines the maximum acceptable pressure which, in turn, is a constraint for flow modelling), but supports the consideration of the interaction of one site on another and the implications of the results of one predictive modelling discipline on another. The effect of the ‘footprint’ of increased pressure from a later injection prospect on an existing injection site with the interaction and cumulative effect of two (or more) sites must remain within the maximum acceptable pressure at both.
4. In the scenarios investigated in this case study, accurate prediction and active monitoring of the pressure response from multiple injections was identified as being the single most important tool for indicating site performance. A regional, basin-scale approach must be taken if a multi-user store is being assessed. All strata that have connected pore space, i.e. where the contained fluids are in hydraulic communication, must be considered. It is an obligation to monitor and manage pressure to ensure interactions are not detrimental to other users including where there is more than one CO_2 injection site in a multi-user store. The connection and transmission of changes in pressure due to CO_2 storage site operations, must be considered both in their extent and over time. In terms of a multi-user store the maximum acceptable pressure is defined by the lowest value for the two (or more) sites; the storage capacity and containment in a regional store (the parts in hydraulic communication) will be limited by the maximum allowable pressure at any given point in the store. The duration and timing of the components of a multi-user store must be assessed, as interactions from a later site may be potentially detrimental to an existing site. Extended baseline monitoring observations for a later-implemented site will be needed to define appropriate pressure thresholds which determine the storage capacity for follow-on injection sites in a multi-user store.
5. It seems sensible to plan to optimise the CO_2 storage capacity of a regional storage resource as a multi-user site. Additional monitoring infrastructure may be cost effective to optimise storage capacity if a regional approach is taken. Multiple iterations of storage scenarios should be modelled to optimise capacity by different

injection scenarios (relative timing of development of sites, and varying injection rates, volume of CO_2 stored and well positions etc.). Resource-effective assessment of the predicted pressure effect for a multi-user store can be achieved using simplified basin-scale models. Comparison of predictions using a simplified and a complex model for the same prospective storage site illustrates that a simplified model is acceptable for a regional-scale assessment of pressure change. Pressure prediction using a simplified regional-scale model would inform a prospective storage site operator and the permitting authorities of the overall performance of a formation for CO_2 injection before undertaking more detailed site characterisation modelling.

1 Introduction

1.1 CONTEXT OF THE CO_2MULTISTORE PROJECT

Demonstrator projects to reduce emissions of greenhouse gases from power and industrial plant by capture, transport and geological storage of CO_2 have mostly proposed to contain the captured gas in depleted hydrocarbon fields. Estimates of offshore CO_2 storage capacity for many nations around the North Sea hydrocarbon province include storage in suitable depleted oil and gas fields and also within sandstones that contain brine (Norwegian Petroleum Directorate, 2011; Bentham et al., 2014). The brine-saturated (saline aquifer) sandstones are very extensive and their potential storage capacity is estimated to be of much greater magnitude (thousands of million tonnes CO_2) than in depleted oil and gas fields (tens to hundreds million tonnes CO_2) (SCCS, 2009; Bentham et al., 2014).

Exploitation of the potential storage resource within regional formations will be required to provide sites of sufficient capacity to accommodate commercial-scale storage of CO_2 in order to reduce greenhouse gas emissions. To maximise use of this resource multiple injection sites will be required within any given storage formation. The large extent of individual sandstones, the hydrocarbon fields and the multiple store sites anticipated within each, present challenges to and implications for the licensing, operation and integrity of the storage asset.

The CO_2MultiStore project investigates a case study of two storage sites within a single multi-user storage asset. The study investigated the operation of a multi-user store using a North Sea case study, the Captain Sandstone, within the mature oil and gas province offshore Scotland. The Captain Sandstone contains the Goldeneye Gas Condensate Field which is the planned storage site for the Peterhead CCS project. Previous research (SCCS, 2011) was augmented by data from offshore hydrocarbon exploration and detailed investigation of the Goldeneye Field for CO_2 storage by Shell (2011a-i).

This report identifies generic learning relevant to any multi-user store from the process and technical knowledge gained. The investigations undertaken by the CO_2MultiStore project, from which the generic learning presented here is drawn, are summarised in SCCS (2015).

1.2 RATIONALE FOR CO_2MULTISTORE PROJECT

The objectives of the CO_2MultiStore project are to reduce uncertainties and increase confidence for the economic and business case for the development of multi-user CO_2 store. The project investigates the interaction and cumulative effect of two CO_2 injection sites and their effect on existing hydrocarbon fields in the vicinity. This approach assumes a first injection site within a depleted hydrocarbon field and surrounding aquifer sandstone and the subsequent introduction of a second (or more) injection site within the same sandstone at a later date.

The definition of the two case study injection sites is intended to be both technically reasonable and realistic. The investigations of the North Sea exemplar case study addresses issues raised by the perceived effect of one injection site on another, as opposed to seeking to identify all best practice associated with storage appraisal.

Technical activities were focused to increase understanding of the character of the multi-user store and reduce uncertainties arising from the interaction of the injection site(s) with other users of the pore space. The predictive model investigations were sufficiently detailed to address technical issues of greatest potential concern to the industry technical experts and researchers. No attempt was made to present predictive models that are comprehensive or sufficiently detailed to support a storage permit application.

1.3 INJECTION SCENARIO AND TECHNICAL ASSESSSMENT IN CO_2MULTISTORE

1.3.1 Site A

Site A is positioned within the Goldeneye Gas Condensate Field, the storage site is the trapping structure that contains the Goldeneye Field and the adjacent saline aquifer Captain Sandstone. The rate of injection was modelled as six million tonnes (6 Mt) of CO_2 per year for 30 years, starting in 2016 until 2046.

1.3.2 Site B

Site B assumes a second storage site within the Captain Sandstone as a later 'follow-on' project anticipating the additional storage capacity required with the development of an established CCS industry. The storage formation is the saline aquifer Captain Sandstone approximately 45 kilometres west of the Goldeneye Field with the injection site positioned using the results of initial modelling. The choice of location of the injection site takes account of closer interaction with hydrocarbon fields in the vicinity and pressure dissipation in the wider Captain Sandstone to the west. The rate of injection was also modelled as 6 Mt of CO_2 per year, to meet an anticipated combined annual rate of storage need of 12 Mt (SCCS, 2009). The duration of injection was also 30 years but starting in 2021, five years after injection commenced in Site A, and continuing until 2051.

1.3.3 Technical assessment process

A risk assessment process was followed in CO_2MultiStore targeted to identify, implement and test technical measures to reduce risks specific to the operation of two injection sites within a multi-user store. External industry and research technical experts participated in assessment and reassessment workshops, facilitated within CO_2MultiStore. Firstly, the experts considered the injection scenario of two sites in a multi-user store in the scenario defined by project members. The experts then discussed and recorded possible risks associated with the operation of and potential interaction between the two sites. The probability of the risk occurring and the severity of impact should it occur were also assessed and rated. A list of potential risks was presented, ranked and used to guide the subsequent modelling work to investigate possible interactions between the injection sites. Geological modelling, dynamic simulation of CO_2 injection and geomechanical modelling investigated the defined scenario to directly address the identified risks by improving understanding of:

- ***certainty*** of the risk probability and severity ratings
- reduction in the probability and severity levels to ***mitigate*** the risk at a real site.

The risk assessment process was iterative, further risk reassessment workshops assessed the implications of the modelling work from increased understanding of the ranked list of risks. Further investigation and data gathering was initiated to reduce input parameter uncertainty and the models were updated accordingly. This reduced the uncertainty on the risk ratings. However, the ratings of some of the risks themselves remained above acceptable levels after the two iterations within the CO_2MultiStore research project. Further mitigation actions that could be implemented in a real storage operation to reduce these risks were discussed and recorded. An estimate of the risk ratings if the mitigating actions were implemented was made and none of the risks relating to the interaction between two injection sites were considered likely to be ‘show stoppers’. However, further site-specific investigation and testing would be required to improve certainty on this.

The pressure connection within the regional storage sandstone, both between the injection sites and to the under- and overlying rocks was highlighted as a key parameter effecting the timing, probability and severity of any potential interaction between the sites. Certain risks were highlighted that remained above an ‘acceptable level’ even if all the suggested mitigating actions were implemented. These are termed residual risks and were targeted by the monitoring planning activity.

The CO_2MultiStore risk assessment process has shown that the management of a regional storage asset is an essential and non-trivial activity to facilitate secure CO_2 storage. Storage management could also be of benefit to optimise the potential storage capacity and maximise returns to the leaseholder through the leasing process.

1.4 METHOD OF KNOWLEDGE CAPTURE

CO_2MultiStore followed a risk assessment-led approach to the characterisation of two storage sites within a single extensive storage asset. The focus was those issues arising from the operation, interaction and cumulative effect of injection of CO_2 at two (or more) sites using the Captain Sandstone as a North Sea case study. The process of risk assessment to determine investigations and characterisation of prospective CO_2 storage sites, described in Section 1.3, complies with the EC Directive on the geological storage of carbon dioxide (EC, 2009) and follows guidance for implementation of the directive (EC, 2011).

Capture of generic knowledge from the case study applicable to all UK storage sites was undertaken by:

- Facilitated study workshops with project members and invited industry participants with experience in CCS
- Knowledge capture sheets from meetings, discussions and activities during the progress of the project.
- One-to-one discussions
- Consideration of the process
- Elucidation of key questions
- Recording of technical knowledge gained

Outputs from these knowledge capture activities were reviewed to identify decision-making during the scenario selection, uncertainties identification, corrective measures application and consequences to the storage sites and asset. Common elements for storage sites were also identified arising from the management of a regional CO_2 storage asset. These comprise the key questions asked, the decisions made, the evolution of the process and learning from the discussion and process relevant to all storage sites.

Generic learning from the CO_2MultiStore project is intended to be relevant to the definition of storage sites, store management and store integrity for injection at two (or more) sites within any multi-user storage asset.

1.5 FORMAT OF THIS REPORT

Chapters are presented by stage of investigation of a multi-user store: development of a consistent ‘static’ geological model; increasing confidence in storage site performance by ‘dynamic’ flow modelling; increasing certainty in the geomechanical stability; monitoring planning for a multi-user store. For each stage of investigation generic learning that would apply to any multi-user storage site was elucidated by the knowledge capture activity:

- Key questions asked during the investigations
- What was learned from the process
- Technical knowledge gained

The report outlines the context of each of the points raised and the generic learning from the case study investigations is presented and discussed. The points raised are presented in Table 1.

Table 1 Generic learning from CO_2MultiStore

Table 1-1 Development of a consistent geological model of the multi-user store: generic learning from CO_2MultiStore

Key questions	Learning from the process	Technical knowledge gained
• Should models be merged, or should a new integrated model be constructed from scratch? If merged, is the key information available for the model? • Is geological correlation possible between the models to be merged? • How was the merged model constructed? • Is the merged regional geological model sensible and suitable to predict multi-user store performance? • What are the storage formation boundary conditions? What other data are needed for the multi-store geological model? • Does the geological model cover the full extent needed for a multi-user store? Is geological data available for all planned modelling activities?	• Correlation is likely and models can be merged in an area within a well-established geological framework; if not, a new model would be needed. • Merging will be needed to create regional-scale models for multi-user stores • Merging to create multi-user store models is likely to be the preferred outcome if it is technically possible. • Define data requirements early, start data transfer and access agreements early, and anticipate a lengthy duration before receipt. • The model merging process, settings, parameters and nomenclature used need to be fully documented. • A defined mechanism is needed for access and exchange of information, e.g. pressure history data from hydrocarbon operators, to inform geological models. • The model merging process needs to include agreement of the stage at which merged model output is complete. • For multi-user store modelling, the model checking process should be bespoke for CO_2 storage.	• Integration of geological surfaces in adjacent and overlapping models • Simplifying a fault model for prediction of the performance of a multi-user store • Ensuring consistency of projections and other technical parameters for model merging • Resolution of disparities between geological surfaces in overlapping models • Subdividing the merged model into 3D cells and assignment of cell-size values • Recording of the method and understanding the implications of changes to model cell size • Ensuring the merged model surfaces are geologically correct

Table 1-2 Increasing confidence in performance prediction for a multi-user store: generic learning from CO_2MultiStore

Key questions	Learning from the process	Technical knowledge gained
• Is there a good understanding of the properties of fluids within the storage model? • Does the dynamic modelling give an adequate representation of storage formation fluid properties? • Do you have the necessary pressure information to adequately assess a multi-user store? • Does the model include enough of the regional geology for dynamic modelling of a multi-user store? • Is the model resolution adequate to predict pressure change and CO_2 migration by dynamic modelling? • Can I extrapolate cap rock properties between sites in a multi-user store? • Are the injection scenarios realistic? • What is the optimal structure and operation of the modelling team?	• Proxy values may need to be used if property information for a storage site is not available • Injection scenarios simulated must be realistic and technically achievable • There are different intensities of interaction between the predictive modelling activities • An operator of a hydrocarbon field will have an existing field model • The computational resources needed for dynamic modelling may be exceeded if the static geological model is too detailed • Validation of the predictive model against any field history data is crucial • Access to any pressure data may be facilitated by a third party.	• Representation of multiple variations in fluid properties • Formation conditions at the point of injection • Initial geomechanical modelling informs subsequent dynamic flow modelling • Initial 'resource-effective' modelling of fluid properties • Access to 'lifetime' pressure data for hydrocarbon fields. • Assessment of regional-scale performance prediction using a simplified model. • Representation of hydrocarbon fields in a simplified performance prediction model.

Table 1-3 Increasing certainty in the geomechanical stability of a multi-user store: generic learning from CO_2MultiStore

Key questions	Learning from the process	Technical knowledge gained
• What is the depth to which the geomechanical model must be constructed? • Do you have the required geological information on the underlying strata to inform geomechanical modelling? • Do the injection scenarios modelled approximate what should be pragmatically expected at the sites? • Are the properties of the cap rock and adjacent strata known sufficiently to predict its response to cooling during CO_2 injection?	• The importance of engaging with the dynamic modellers very early in the multi-user store site characterisation process • Preliminary modelling work will establish agreed fluid pressure conditions before further geomechanical and dynamic modelling • An integrated workflow is needed for resource-effective and consistent geomechanical, dynamic and static geological modelling of a multi-user store • A technical overview role is needed to ensure the assumptions used, and the consequences of modelling results and their implications are fully understood	• More extensive geomechanical models and data are needed to characterise boundary conditions than traditionally used for static geological modelling or appraisal of a hydrocarbon field. • The effect of thermal stress is much less extensive than the fluid pressure increase associated with injection of CO_2 • Modelling confirms the impact of adjacent injection sites increases the closer they are. • Interaction of ‘felt’ pressure effects should be anticipated between sites in a multi-user store • The geometry of the storage formation will influence the interaction between injection sites and ultimately the storage capacity of a multi-user CO_2 store • Modelling indicates which parameters have the largest impact on the geomechanical integrity when the storage formation pressure is increased

Table 1-4 Conclusions on the design of a plan for monitoring of multi-user storage operations: generic learning from CO_2MultiStore

Key questions	Learning from the process	Technical knowledge gained
• Is there potential for injection sites to interact? If so, how might they interact and what is the scale of the potential interaction? • Is the degree of potential interaction avoidable, negligible or acceptable? • Can the effect of a second site on existing storage formation users be identified from baseline and monitoring observations? • Would operation of a proposed multi-user store have an adverse effect on the integrity of one or other CO_2 injection site? Will pressure need to be managed to operate a site without detrimental pressure changes on another existing site or field? • Would operation of a proposed multi-user store have a beneficial or adverse effect on other existing pore space users? • Can the CO_2 injected at one site be distinguished from that injected at another in a multi-user store?	• The role of the prospective Site B operators is to assess the effect on other formation users • Access to existing data to inform monitoring planning	• Monitoring planning for a multi-user store by addition of an injection site • Implications of inadequate monitoring of a multi-user store • Obligation to monitor the pressure interaction • Measuring of additional parameters to monitor the pressure interaction • Definition of thresholds for monitoring of pressure in a multi-user store • Extended monitoring and possible additional infrastructure for a multi-user store • Anticipating and planning for a future multi-user store

2 Development of a consistent geological model of the multi-user store

Defining a three-dimensional (3D) computer model, incorporating geological data and knowledge of the two prospective injection sites, is an essential step needed to predict how the sites will perform during the subsurface injection and geological storage of CO_2. The more the geological model of the site (also known as a 'static' model) is constrained by data and technical understanding, the better the predictions of storage site behaviour will be. For European storage sites the modelling of prospective sites is a specified requirement in the directive on the geological storage of carbon dioxide (EC, 2009, 2011)

A common, or consistent, understanding of the subsurface geology at both sites in a multi-user store must be in place, for a confident prediction to be made of the performance of both sites. The prediction is made over tens of years of injection and over hundreds to thousands of years into the future after injection has ceased. The geological model captures the 3D geometry of the sequence of strata and the geological structure i.e. whether and how the strata are folded or faulted. Attribution of the 3D grid or cells that comprise the model captures the characteristics of the rock layers, geological faults and bounding surfaces.

2.1 KEY QUESTIONS

2.1.1 Should models be merged, or should a new integrated model be constructed from scratch? If merged, is the key information available for the model?

Depleted oil and gas fields, where the geology and reservoir conditions are suitable, are candidates for re-use to store carbon dioxide within the pore space previously occupied by oil and gas. Where two or more depleted fields in the same geological formation are re-used for CO_2 storage they will form a multi-user store. Each field operator is likely to have already constructed a geological model of their field and the models may be merged into a more extensive model of the multi-user storage formation.

A field will be very well known by the operating oil company from data gathered during exploration, production and depletion of hydrocarbons, such as seismic survey and well data. Each model represents a very significant investment of resources in terms of the cost of data acquisition and interpretation by technical specialist staff. It incorporates the wealth of information and knowledge acquired during the lifetime of the field. Importantly, what data have been used and how has it been used to attribute the model and represent the geology at a storage site, should be recorded.

If the lifetime of the field is of long duration the geoscientist staff that initiated and developed the model may no longer be available. An existing model captures their understanding of the data and knowledge of the geology at the time it was constructed, although this may also be available as technical documentation. It may be more efficient to create a new integrated model from scratch using the underlying component datasets, if they are available. However, access to the underlying data acquired by a third party would require relicensing of the datasets with the associated additional financial resources to be committed and legal terms to be agreed and scheduled.

If models are available of one or both of the prospective injection sites in a multi-user store **merging of existing geological models should be considered** to benefit from existing knowledge and an effective re-use of resources. **Key information should be derived** to determine if it is geologically reasonable before deciding to use and merge available models. The geological modellers should review any documentation and the component models proposed to be merged. They should carefully consider if the decision-making during construction of the component models is logical and transparent. The geological modellers should use their understanding gained from the review to judge whether it is reasonable and possible to merge the models. If the models can be merged the historical knowledge gained during construction of the source models should be captured in the merged model and greater benefit gained from the cost of model construction.

2.1.2 Is geological correlation possible between the models to be merged?

It should be possible to **merge models where the geological surfaces can be correlated and the structural interpretation is consistent** in existing interpretations. A geoscientist's understanding of the concealed subsurface geology is based on interpretation of available data and their geological knowledge and experience at the time it is made. Offshore, the interpretation is likely to be based on seismic survey and well data. Other sources of information may include other types of geophysical data and the observation of rock core where available.

An interpretation is undertaken for a purpose, for example to establish a regional geological framework or development of a hydrocarbon field and therefore different interpretations may be needed for CO_2 storage. However, merging of models may be neither geologically reasonable nor justified, in terms of the effort and resources required, where the data used and the intended original purpose of the interpretation is significantly different.

2.1.3 How was the merged model constructed?

There must be a transparent understanding and thorough documentation of how existing geological models were merged to inform subsequent querying of the geological model of the multi-user store. **Re-use and merging of existing geological models for a multi-user store requires careful understanding of the methods used and initial limitations of the component models.** Merging of models based on datasets of different vintages and resolutions, constructed using software of preference for the originating organisation, will inevitably require adjustments to one or possibly both models. Compromises are commonly required. There may be a mismatch where a geological surface interpreted from reflectors in seismic data is at different depths in adjacent or overlapping surveys due to contrasts in the resolution of the data and the method used for conversion from two-way travel time to depth in metres.

Scenarios can be envisaged where geological surfaces could be markedly different and the modeller would have to return to the original source data and perform some re-interpretation. Constraining data points, such as well datasets and seismic interpretations, should always accompany model data. This is particularly important in the zone of model overlap, to allow decisions to be made on model integration. There must be a clear understanding of the implications of any merging techniques to avoid creating unrecognised artefacts within the merged model.

2.1.4 Is the merged regional geological model sensible and suitable to predict multi-user store performance?

A pragmatic approach will usually be required to generate the simplest model appropriate to represent the geology of the injection sites within a multi-user store. It should also be adequate to predict the simulation of CO_2 injection and so storage site performance, which is a key objective to investigate any interaction between two sites.

Effort should be concentrated in achieving the **required level of detail in those areas proposed for simulated injection of CO_2**. Dynamic modellers prefer the coarsest grid (3D cells) which adequately represents the input geological data, so as to minimise computer time. There is little need for grids of finer resolution if the geological input does not warrant it. The number of cells is one of the parameters that determine the rate of calculation for the prediction of site performance; the smaller the grid size, the larger the number of cells within a given area and the slower the rate of calculation. The grid size and number of cells in a geological model is important because the extent of a geological model to assess two prospective CO_2 injection sites will be significantly larger than a model of an oil or gas field. The system can be subsequently refined or coarsened within the simulation model if fine-scale resolution is needed.

2.1.5 What are the storage formation boundary conditions? What other data are needed for the multi-store geological model?

Prediction of the impact and interaction of two or more CO_2 injection sites in a sandstone of regional extent requires an understanding of the nature of the sandstone boundaries. The character of the storage formation boundaries, whether they are closed to fluid flow (low permeability) or open to fluid flow (high permeability), is needed to predict the evolution of formation pressure during CO_2 injection. In a hydrocarbon province the boundary conditions may be inferred indirectly from pressure responses within producing fields. Pressure fluctuations recorded within a hydrocarbon field due to reservoir management activities in another field can be used to infer the degree of connectivity between them. In a saline aquifer without hydrocarbon field data the boundary conditions may be inferred from the permeability values of the rocks over- and underlying a storage formation, or juxtaposed by faulting, known from geophysical well data or core samples.

Data used for interpretation, modelling and assessment of CO_2 storage formations (seismic interpretation, well correlations, information on the geological properties of the strata) has generally been collected and/or interpreted for the purposes of hydrocarbon exploration and is thus focused on reservoir rocks. More information on the cap rock sealing the upper boundary of a prospective storage formation is required for the purposes of CO_2 storage: rock type; distribution of porosity and permeability; thickness; any lateral variations in character; continuity of the sealing strata. These data are not usually acquired for non-reservoir rocks during oil and gas exploration. Acquisition and interpretation of these data to assess store integrity should be included at an early stage in the project.

2.1.6 Does the geological model cover the full extent needed for a multi-user store? Is geological data available for all planned modelling activities?

The extent of a geological model to investigate and predict the performance and interaction for two or more sites will span the area between the prospective injection sites and also extend beyond them. The distance between the sites may be tens of kilometres whereas a single hydrocarbon field and a model constructed for field development will be less or much less than ten kilometres in extent.

The geological model of the prospective injection sites must be sufficiently extensive to encompass the predicted migration of the injected CO_2, the extent of the increase in formation pressure due to injection and also any additional geoscientific modelling activities that will be part of the assessment. Output from the static geological model is input data for geomechanical modelling of the two injection sites. Geomechanical modelling requires additional geological information which might not be included in the existing static geological models of the component sites. The base of the geomechanical model, defined by the depth to impermeable strata, may be considerably deeper and include more geological formations than a model needed for other site characterisation activities. The geomechanical modeller should indicate the greater volume and the additional strata for which geological information should be collated, when acquiring data as part of the geological modelling activity. Geological information, such as the porosity, permeability, proportion of sandstone and thickness should be acquired for the strata overlying, underlying and laterally equivalent to the storage formation. Geomechanical modelling assesses the mechanical impact of changes in pressure due to CO_2 injection and predicts the response in the site storage formation and is covered in more detail in Section 4.

2.2 LEARNING FROM THE PROCESS

2.2.1 Correlation is likely and models can be merged in an area within a well-established geological framework; if not, a new model would be needed.

The area investigated in CO_2MultiStore lies within the North Sea hydrocarbon province which has been exploited for four decades. Atlases presenting the subsurface strata within a regional framework, interpreted from hydrocarbon industry data and knowledge, enables correlation of strata between fields and, broadly, a common interpretation of geological structure. Integration of the geological surfaces to enable merging of models in the case study was relatively simple to achieve using geologically reasonable judgements. Prospective injection sites in areas without an accepted regional geological framework should assume additional resources and over a longer timescale may be required to collate, compile and interpret regional geological datasets to construct a new single integrated model.

2.2.2 Merging will be needed to create regional-scale models for multi-user stores

Ideally, construction of a fully integrated modelling study using consistently interpreted source data should be undertaken across the entire region of interest. However, the resources required to undertake such a study are seldom available. Extensive offshore saline aquifer sandstones are known because they host oil and gas fields. Data, knowledge and models are already captured at the fields which, once depleted become candidates for reuse as CO_2 injection sites. **Model integration and merging will be required to benefit from detailed knowledge of the hydrocarbon fields**, cost-saving to reuse existing models and the large extent of the storage sandstones that will need to be assessed to optimise their very significant theoretical storage capacity.

2.2.3 Merging to create multi-user store models is likely to be the preferred outcome if it is technically possible.

Assuming a consistent stratigraphical and structural interpretation in the models to be merged, the **technical model compatibility must be checked at an early stage in the merging process**. Comparison of the two (or more) models requires appraisal by specialist modellers, preferably from the organisations contributing the component models. It may not be possible to merge models that at first observation might appear consistent due to the underlying principles on which modelling software, gridding, cell structure and data architecture are based.

2.2.4 Define data requirements early, start data transfer and access agreements early, and anticipate a lengthy duration before receipt.

All of the data to be used and model files to be incorporated in a merged model should be collated prior to the start of model merging activities. Access to existing datasets and geological models is commonly a formal process requiring agreement of terms for a data licence or a legal collaboration and non-disclosure agreement. The process to arrange access to data may include: selection of the data; review of an illustration of data quality; contractual agreement; payment for the data licence; technical checking of the data immediately on receipt; exchanges with the data or model provider for data that is incomplete or for missing files. All steps must also be completed to the satisfaction of all parties. Some data may not be accessible due to confidentiality restrictions and additional data may need to be licensed if there are gaps in the coverage.

Late receipt of underpinning data and issues associated with intellectual property rights from contributing parties, and uncertainty as to what will be received is a common cause of delay in geological modelling projects. Enquiries as to the data that are to be made available, the terms under which they can be exchanged, formal agreements and signatures required should start as soon as reasonably possible to minimise the impact of any delays. **Early review by the modellers to define what information is needed and alternative sources of data** if it is not provided by contributing organisations, such as published or analogue values from scientific or technical literature may minimise the impact of delayed receipt of data. Trickling-in of additional datasets after modelling is well advanced *will* require remodelling of all the data and associated additional resources and time taken.

In practise, acquisition and collation of data required for merging models may take longer than planned and this expectation should be included in the modelling schedule. **An appropriate duration to exchange agreements of at least four to six months to arrange access to data should be a part of the schedule** before interpretation and geological modelling can commence. An additional month may need to be included in the schedule to accommodate data checking and for any exchanges of files with the data provider.

2.2.5 The model merging process, settings, parameters and nomenclature used need to be fully documented.

The benefits of comprehensive documentation of all aspects of the model merging process justify the effort taken and resources used. A full understanding of the geological model enables interrogation of the results by a skilled modeller, whether part of the original team or not, incorporation of later revisions if required by additional data or modelling activities and confident responses to enquiries from regulators or authorities.

The process of merging models <u>must</u> include an explicit stage at which the correlation and usage of a common nomenclature for the surfaces and units in the static geological model is agreed and documented. The 'audit trail' for model merging could include: a record of the stratigraphical units in the source models, their correlation and output of units modelled; identification of the source data files; adherence to a consistent file naming protocol; documentation of parameters used in the source models and the output merged model; definition of the parameters and settings in the software used to create the merged model; description of the workflow to integrate stratigraphical surfaces, geological faults, gridding of surfaces, layering of volumes and attribution of properties; details of model validation checks; a log of model development listing activities, by whom and when.

2.2.6 A defined mechanism is needed for access and exchange of information, e.g. pressure history data from hydrocarbon operators, to inform geological models.

Datasets that are needed for confident prediction of any interaction between two prospective injection sites may have been collected but are not publicly available. Datasets associated with hydrocarbon exploration and production are collected by a field operator but are held in confidence and are not available to external parties.

The increase in pressure due to CO_2 injection within a storage formation will be determined by its connectivity and fluid flow across the formation boundaries. The increased pressure of injection will extend further and dissipate more rapidly the greater the connectivity and/or more permeable the bounding surfaces. The degree of connectivity and flow character of the boundaries may be inferred from pressure history and well flow rate data, recorded at adjacent hydrocarbon fields and held in confidence. A regulator, leaseholder or other impartial body may have to provide some authority or compulsion to acquire required model/data in a timely manner, along with the arrangement of information exchange with model provider, to ensure such crucial information is available to assess the possible interaction of two prospective injection sites.

2.2.7 The model merging process needs to include agreement of the stage at which the merged model output is complete.

Planning of the geological modelling activities should include agreement of the stage at which model merging is deemed completed. At this point it is agreed that the model is suitable for, and prior to, prediction of storage site performance by dynamic simulation and geomechanical modelling. The geological modelling activities and the requirements of the subsequent modelling disciplines should be defined and listed and the point of output and ‘hand over’ agreed. It is always possible to continue further refinement and update of the static geological model. However, the objective is to provide a geological model that is sufficiently detailed and fully adequate to represent the geologist’s understanding of the geology and appropriate for the following modelling activities.

2.2.8 For multi-user store modelling, the model checking process should be bespoke for CO_2 storage.

Model validation, a reality check once the model merging activities are mostly completed, ensures the geological model is suitable for predictive modelling of multi-user storage performance. The original, unmerged models may not have been constructed for this purpose. The validation activities focus on model characteristics that would be expected to influence the behaviour of two (or more) injection sites during and after CO_2 injection. Validation will consider whether the model accurately reflects the properties of the geology and structure at the two injection sites and if potentially important detail has been lost during the integration exercise.

The strata overlying and underlying the prospective storage formation, not ordinarily included for a hydrocarbon field, must be included in the model. To assess containment of the injected CO_2, the model should incorporate the sealing properties of the cap rock above the storage formation and the character of the underlying sequence to establish the lower boundary conditions. The latter is essential as it determines if the pressure of injection is dissipated by fluid flow into underlying porous and permeable strata. The lower boundary conditions also determine the geomechanical response of the entire underlying sequence down to rocks that form an impermeable basement. The topography of the top storage formation surface must also be carefully checked, as this may have an important influence on CO_2 migration during the flow simulation studies. Smoothing of the surface during model merging affects the volume of CO_2 trapped within the storage formation due to the reduction in roughness of the surface. Additionally, loss of structural closure in the regions of the proposed injection sites due to the model merging activities could have a marked effect on the prediction of CO_2 migration.

2.3 TECHNICAL KNOWLEDGE GAINED

2.3.1 Integration of geological surfaces in adjacent and overlapping models

Integration of the geological surfaces was relatively simple to achieve using geologically reasonable judgements for the North Sea case study. This should be expected in strata hosting oil and gas fields, particularly where the data acquired during exploration and production have been used to interpret a regional framework, and where interpretation of the overall structural disposition is not controversial. Geological interpretations of the adjacent datasets should be expected to be broadly similar but will differ in detail; this characteristic is common to all geological interpretations.

The interpretations should not be expected to exactly ‘match’ due to the differing data sources, vintage, processing, manipulation, the interpreter and edge effects as the data distribution becomes ‘one-sided’ toward the periphery of a dataset. Even where the horizons and faults can be correlated, merging activities will be required. The single consistent integrated model must not contradict the data points on which the interpretation is based. Adjustments, for example where a geological surface has been inferred from either a deeper or a shallower seismic reflector on adjacent or overlapping models, must ensure the integrated model honours intersections of that surface in boreholes and hydrocarbon wells and does not create a structural distortion or artificial thinning or thickening of the modelled strata. Surfaces included in only one model may need to be inserted from additional data or constructed using an assigned thickness.

2.3.2 Simplifying a fault model for prediction of the performance of a multi-user store

Features within a static geological model may be curved, such as fault planes or folded strata. Curved surfaces cannot be easily accommodated within the mathematical model that represents the prospective injection sites. A simplified fault model is needed but this must not compromise the prediction of the performance of the strata during the dynamic simulation of CO_2 migration and pressure response at the injection sites. This is especially important for a multi-user store because of the regional extent and large numbers of cells in the geological model. A simplified fault model will also make the interaction between the static and dynamic modellers easier.

Simplification of the fault model is acceptable provided the simplified structure is within an area of the model away from the proposed injection sites. That is, in an area that experiences a predicted far-field variation in the increased pressure of CO_2 injection sites, rather than near the modelled injection points.

2.3.3 Ensuring consistency of projections and other technical parameters for model merging

Technical parameters must be consistent if geological models are to be successfully merged. The geographical projection of the co-ordinate systems for the two models must be the same to enable them to be mapped together. The model units must also be the same both for the geographical map co-ordinates and for depth and thickness values. Projection systems, units, geological surfaces and so forth will vary within, and between organisations. Use of metres should not be assumed as the hydrocarbon industry commonly uses non-metric units or in combination with metric units. Check and agree the projections, units and any conversions that might be needed as part of the technical model compatibility assessment. This requires specialist modelling skills, review of the models and agreement between different contributing disciplines at an early stage.

2.3.4 Resolution of disparities between geological surfaces in overlapping models

Model merging requires discussion and agreement as to which datasets are to be honoured where there are disparities between adjacent or overlapping models. Constraining data points (such as hydrocarbon well data and seismic interpretations) should always accompany any model data. This is particularly important in a zone of model overlap to allow decisions to be made on model integration.

Where there are disparities, agreement must be made of which model is to be given priority over another. This is assessed on the quality of the data on which the modelled interpretations are based. Those models interpreted from data that are most recently acquired and more finely resolved are likely to be prioritised and honoured. Alternatively, a sensitivity analysis may be undertaken to assess the degree of uncertainty associated with the differences between the models to be merged. If one model takes priority over another model within the same spatial area, it is important to be aware of edge effects. Where density of data is greatest, this may be in the centre of a dataset, there is highest confidence in the interpretation; data density and confidence of the interpretation decrease at the periphery of a dataset. It may not be appropriate to preserve 'edge effects' within the priority model at its periphery if this lies within the centre of the lower-priority model to which it is to be joined (Section 2.3.1). The resolution of input model data may affect the prediction of CO_2 migration by dynamic simulation. One model may look smoother, the other more rough (rugose) which will enhance trapping of CO_2 beneath the surface, the second having been derived from a model with greater density of data.

2.3.5 Subdividing the merged model into 3D cells and assignment of cell-size values

Vertical subdivision of the intervals between merged model surfaces to construct 3D cells is a component of geological modelling. Judgement is needed to ensure the geology is adequately represented by the model. Each of the geological intervals is assigned zones based on information derived from wells. There may be a different number of zones defined within the geological intervals for the models to be merged. For example, a judgement may be made that greater subdivision in one model, and corresponding level of detail, reflects a real variation in the geological sequence. The subdivision of the relevant interval would be appropriately extrapolated into the adjacent model. Each zone may be further subdivided by the modeller into layers. The number of layers is selected to represent the variation in rock types present; the more heterogeneous the rock unit the greater the number of layers, with fewer layers representing more homogeneous strata. The strata of interest within the storage formation interval will be the most finely layered and overlying and underlying zones most coarsely layered. For numerical flow simulation it is preferable not to construct a model with cells of large volume directly above or below the storage formation.

2.3.6 Recording of the method and understanding the implications of changes to model cell size

The method of cell size assignment needs to be recorded as their size will vary across a regional-scale model of a multi-user CO_2 store. The resolution of the grid used to create the 3D model cells determines how large the cells will be; a fine-scale grid at the injection sites will represent the geological strata by more, smaller cells than a coarser-scale grid. Coarse- and very coarse-scale versions of a model enable up-scaling in areas away from the injection sites and so faster iterations of the dynamic flow simulations. Up-scaling to increase the model cell size then subsequent down-scaling should be avoided. It is important to check that up-scaling of finer-scale model cells and down-scaling of coarser model cells does not degrade the topography of the upper surface of the storage formation; the roughness of the surface influences the predicted rate of migration of CO_2 gas beneath it (Section 2.3.4).

2.3.7 Ensuring the merged model surfaces are geologically correct

The process of merging two geological models can create artefacts, such as implied thinning of cap rock units. The integration of geological data can result in an elevated perception of risk due to apparent thinning of the storage formation and cap rock succession arising from the integration processes. Where this occurs it is important to re-visit the input data to assess whether the cap rock units do in fact thin. If it is found that they do not and that thinning is indeed an artefact of the integration process the grid should be amended. Checking for and amending artefacts should be undertaken prior to flow simulation studies.

2.4 GENERIC LEARNING FOR DEVELOPMENT OF A CONSISTENT GEOLOGICAL MODEL OF A MULTI-USER STORE

1. Static geological models need to be constructed in an agreed, standard format and the details of model construction and design fully documented if they are to be re-used and merged.
2. If models are available of one or both of the prospective injection sites in a multi-user

store merging of existing geological models should be considered. This will enable benefit to be gained from knowledge entrained within existing models and an effective re-use of resources.

3. Ensure all model construction activities are documented. During construction of the static geological model, all technical steps should be recorded. This includes model merging, model prioritisation, correlation, attribution and manipulation and will enable confident use and interrogation of the merged model.
4. Merging of static geological models captures the knowledge and understanding of the original modellers. However, the effort and resources needed to merge models will still be significant.
5. Where there is inheritance of two or more models it is more likely that re-use of models will be an efficient process only if, or when, they can be sourced from the model originators with the accompanying knowledge or detailed documentation.
6. The additional cost and time taken for construction of a single integrated model of a multi-user store from scratch rather than merging of existing models, although significant, may be justified by considering whether the:
    - underlying data is available <u>and</u> readily accessible
    - model construction is well understood and documented
    - modelled geological surfaces can be correlated
    - structural interpretation in both models is consistent
7. Planning and so scheduling of sufficient time for static geological model construction is needed as the duration is likely to be longer than might reasonably be expected.
8. Static geological modelling for a regional-scale multi-user store needs to start as early as possible.
9. Preparatory modelling activities may need to start before all contracts are in place, and this might be achieved by initial non-disclosure agreements.
10. Additional model iterations to amend and adjust the merged models, which can be as time-consuming as initial model merging, should be anticipated and included in the schedule.
11. Knowledge of the storage site boundary conditions, and so the degree to which the increased pressure of injection can be dissipated by fluid flow across them, is crucial to the characterisation and increased understanding of a multi-user store.
12. The static geological model must take into account what will be needed for all predictive modelling activities. The extent of the geological model and provision of information on geological properties must be sufficient to inform geomechanical modelling and to predict pressure changes due to storage site operations by dynamic modelling.
13. It is essential that all geoscience modellers (geomechanical, dynamic and any other modelling activities) are included in development of the static model.

3 Increasing confidence in performance prediction for a multi-user store

Prediction of the performance of a second CO_2 injection site within a multi-user store is essential to anticipate and mitigate any adverse effects from the possible interaction with existing storage operations. Prediction of injection site performance is also required to assess any impact on existing uses of the pore space for hydrocarbon production or groundwater supply (EC, 2009, 2011). The static geological model of a multi-user store is the basis for the dynamic simulation of CO_2 at two (or more) injection sites.

Dynamic three-dimensional simulation of CO_2 injection within a multi-user store is informed by realistic and practical injection scenarios at both sites, knowledge of the fluids within the storage site strata, and an initial two-dimensional prediction of the behaviour of fluids within the sites.

Where two or more injection sites are assessed within a multi-user store there are several key differences from the simulation of injection at a single site: the dynamic model will be more extensive: the model may include two or more hydrocarbon fields containing differing proportions of oil, gas and brine; all strata that are affected by changes in pressure must be encompassed within the model. Rocks in which the pore spaces and contained fluids are connected and so can transmit a change in pressure between them are described as *hydraulically connecte*d.

3.1 KEY QUESTIONS

3.1.1 Is there a good understanding of the properties of fluids within the storage model?

Knowledge of pore fluids within the rocks of a prospective injection site and their behaviour at the elevated pressures and temperatures deep within the subsurface is critical to reliably predict injection site performance. Prediction of the behaviour of an injection site by the simulation of CO_2 injection using dynamic modelling software requires knowledge of the fluids present within the storage strata and their properties. Fluids occupy the pore spaces within subsurface strata, this is most commonly water. Fresh groundwater saturates rocks on land and in the shallow subsurface, at greater depths and in offshore strata groundwater contains dissolved salts (brine). A small proportion of rocks are host to oil and gas which displaces water occupying the pores.

Where depleted hydrocarbon fields are re-used as sites to contain injected CO_2 the operator of the field will have a good understanding of the fluids (oil, gas and brine) within the prospective site. The saturation of the different hydrocarbon components, the composition of any oil or gas, the rate of flow where there are two or more fluids within the rocks (relative permeability) will all be well understood by the field operator. Unless the field contains naturally occurring CO_2 the operator will not know its properties or flow characteristics for the prediction of injection site performance unless they have conducted specific laboratory experiments. In general, understanding of the fluid properties in a hydrocarbon field can be extrapolated into the surrounding brine-saturated sandstone where knowledge is sparse.

3.1.2 Does the dynamic modelling give an adequate representation of the storage formation fluid properties?

The properties of the fluids within the multi-user store can be represented by a box model, a two-dimensional model used to predict the behaviour of fluids within the rocks during CO_2 injection. The box model calculations include the physical properties of each of the fluids within the rocks, e.g. water, brine, oil, 'natural gas' or CO_2. Hydrocarbons compress more than water allowing greater capacity to store CO_2 so their properties and volume are very important model parameters. To validate whether the fluid properties for a merged model give an adequate representation of the contained fluids the box model within the multi-user store can be compared with one from an adjacent and hydraulically connected hydrocarbon field. The box model for the merged multi-user store can be amended and adjusted to reflect the understanding of fluids within component or nearby hydrocarbon fields. This is a resource-effective method as calculation of the full three-dimensional dynamic model will take much longer to run. Where the operator of an adjacent hydrocarbon field is part of the storage venture a box model for the field might be anticipated to be available. Fluid property information for hydrocarbon fields is not usually publicly available.

3.1.3 Do you have the necessary pressure information to adequately assess a multi-user store?

Injection at any depth into an extensive storage formation must take account of the effect of the increased pressure beyond the immediate injection site. The consequences of a local pressure increase to the integrity of another store or fault structure should be appraised within a hydraulically connected unit. Appraisal of the potential impact of one injection site on another requires consideration of both the pressure variation over time (lifetime of both stores) as well as the spatial extent of the pressure perturbation.

Pressure information is essential to appraise sites within a multi-user store and maximum acceptable pressure values determine the constraints for the operation of sites within the multi-user store. The initial pressure values at both sites, i.e. the pressure that has naturally and securely contained fluids within the storage strata over geological time before any abstraction or injection of fluids, is essential to confidently assess the sites. The lowest value for two injection sites is an eventual constraint for both sites.

Pressure information is measured during production of hydrocarbons from a field. Where the operator of a hydrocarbon field is part of the storage venture, the initial pressure for the field might be anticipated to be available and the pressure history assumed to be available. However, due to the commercially highly sensitive nature of this data, detailed pressure history information for hydrocarbon fields is not publicly available but might be accessed by participation of the field operator in the storage project.

3.1.4 Does the model include enough of the regional geology for dynamic modelling of a multi-user store?

The objective for dynamic modelling is to represent those strata that are affected by the operation of a multi-user store. It is used to predict the impact of injection from the migration of the injected CO_2, both as gas and dissolved in the pore water, and the change in pressure ('pressure footprint'). All strata in which the pore space is connected and can transmit a pressure change are to be included in the model. The entire connected pore volume is to be represented by the dynamic modelling, such as strata underlying the storage formation. These are to be included even if parts are judged unlikely to influence the CO_2 storage at the site(s) of interest. Hydraulically connected strata may not necessarily be represented by the three-dimensional static geological model but can be incorporated in the dynamic model by a calculation and the simulation of underlying porous strata by an appropriate choice of boundary condition.

3.1.5 Is the model resolution adequate to predict pressure change and CO_2 migration by dynamic modelling?

The wide extent of a dynamic model needed to predict the performance of two or more sites in a multi-user store will require some degree of up-scaling to reduce the number of model cells and so achieve realistic durations and computing resources for the calculations (Section 2.3.6). Additionally, the static geological model incorporates far more detail than is needed for some aspects of dynamic modelling of a multi-user store.

There is more than one purpose for injection site performance prediction by dynamic modelling. It is important to distinguish between a model to predict the extent and character of the pressure footprint and a model to predict migration of injected CO_2 gas. A model with fine-scale gridding is required to predict the migration of injected CO_2 as a gas and also dissolved in pore water. A coarse-scale (low-resolution) grid more readily enables calculation of the extensive pressure footprint by up-scaling to a regional-scale model. Up-scaling presents fewer, coarser three-dimensional cells where appropriate within the model. Up-scaling, away from the prospective CO_2 injection well positions, can optimise the resources needed for dynamic simulation by a variable grid resolution within one model by coarsening and reducing the number of cells within the model.

A drawback of up-scaling for a regional-scale model for a multi-user store is that subtleties that influence CO_2 migration may be reduced or lost during the process. Subtleties might include the vertical resolution of the grid cells, small irregularities on a modelled surface or local details of highly permeable rocks. Modelling of the upper storage formation interval with cells that are too coarse (large vertical dimension) after up-scaling will give a low, overly optimistic, rate of lateral CO_2 migration beneath the cap rock. Reduced roughness (rugosity) of the modelled top surface of the storage formation may predict the injected CO_2 to migrate further in a more coarse-scale model in the vicinity of the injection point than in reality. Local irregularities forming traps, of whatever size, will each retard CO_2 migration. The presence of narrow zones of highly permeable rocks, such as sandstone-filled channels, will influence the rate of CO_2 migration. Their presence may enhance or retard the rate of migration if aligned along or across the dip direction, respectively. Up-scaling to coarser grids may produce model cells that are too large to represent the property variation of narrow channels. If the high permeability values are dispersed more widely by up-scaling this may result in a predicted rate of CO_2 migration that is too rapid. If the high permeability values are under-represented after coarsening of the model cells the predicted rate of migration will be too slow and so generate an overestimate of the rate of CO_2 dissolution into the surrounding pore water. Care must be taken in up-scaling, as failure to adequately account for thin zones of highly permeable storage formation rock may result in unpredicted rapid migration of a tongue of CO_2 beneath the top surface of the storage formation.

3.1.6 Can I extrapolate cap rock properties between sites in a multi-user store?

Hydrocarbon fields demonstrate that the sealing properties of the overlying cap rock have been sufficient to retain oil and/or gas over geological timescales. Because the cap rock above a hydrocarbon field or fields will always be sealing, it might also be assumed that that the cap rock above the brine-saturated strata in zones between hydrocarbon fields is also sealing and will retain injected, stored CO_2. The presence of hydrocarbons is evidence that a number of very specific conditions have been met. For geological storage of CO_2 only the presence of a storage formation and trapping mechanism is required. If the characteristics of the reservoir and cap rock between two depleted hydrocarbon fields is consistent (thickness, continuity and rock type) it might be assumed that the cap rock has sufficient sealing properties to retain CO_2. However, if local trapping structures within the brine-saturated parts of the prospective multi-user store do not contain hydrocarbons, the question has to be asked why. The regional model should be interrogated as to why hydrocarbons are not present. The answers may include that there were no hydrocarbon migration pathways that could have led to charging of structure, or that it is not a trap, in which case the sealing properties of the cap rock could be assumed to be sufficient for the multi-user store. However, CO_2 has different properties from hydrocarbons. A field stable to natural gas will not necessarily be stable to CO_2 which is more mobile than natural gas in a liquid. Modelling of the performance of a storage site should include the fluid properties appropriate for injected CO_2.

3.1.7 Are the injection scenarios realistic?

The injection scenarios simulated by dynamic simulation need to be realistic as each simulation, and associated consideration of sensitivities to settings within the model, is a significant commitment of resources. The scenarios should reflect what is likely to happen rather than an optimistic or pessimistic view for capture and delivery of CO_2 for storage, availability of a depleted hydrocarbon field for storage, position of injection wells relative to existing infrastructure and rates of injection for that storage formation. The position of injection wells is particularly important as adjustment of the well locations after up-scaling of the regional model has taken place would require a subsequent decrease (down-scale) in grid size which is both undesirable and reduces confidence in the resulting model to adequately represent the injection sites. Note that adjustments to the well locations should be more than the size of the model grid cells for a different prediction to be calculated.

3.1.8 What is the optimal structure and operation of the modelling team?

The project team structure and operation must support close and integrated working by the geological, dynamic flow simulation and geomechanical modellers to set up and predict the performance of a multi-user store. An oil company approach, with an integrated team of experts from all the predictive modelling disciplines (asset team), should be followed. If there is a question during the process of transfer of the static model to the dynamic model it can be raised and addressed rapidly without delaying progress. Minor amendments may have significant impacts or contradict data on which the model is based and these can be readily assessed and advised within the project team. Not every detail of the static model is known or needed or translates into the dynamic model. But a static modeller should have a direct meeting with dynamic modellers at each stage of the model transfer and a geologist should check the final dynamic model is geologically reasonable and matches the static model. The maximum acceptable pressure for both sites assessed within a multi-user store is the main technical constraint for dynamic modelling of CO_2 injection and prediction of site performance. Geomechanical modelling to inform the threshold for the maximum acceptable pressure at both sites should be conducted prior to and in conjunction with simulation of CO_2 injection.

Ideally, a single integrated asset team should be used and is recommended here.

3.2 LEARNING FROM THE PROCESS

3.2.1 Proxy values may need to be used if property information for a storage site is not available

Detailed information about storage site rocks, contained fluids and their properties, are unlikely to be available for stores that do not contain hydrocarbon fields. Where hydrocarbon field data are not available proxy values from alternative justifiable sources of information can be used. These might be either published values from the scientific and technical literature or reasonable assumed values based on the experience and judgment of the dynamic modeller. Use of appropriate proxy sources of information or fluid property values taken from other sources, such as predictions or analogues, must be discussed, agreed and recorded as part of the model documentation. This will ensure transparency of understanding for the selection and values of fluid properties used for the dynamic modelling activity.

3.2.2 Injection scenarios simulated must be realistic and technically achievable

In order to model and confidently predict how a regional storage formation might respond to the injection of CO_2 planned at more than one site, the models must incorporate sufficient rates of CO_2 supply and volumes to be injected to test the response of the store. At the same time the parameters of supply rate and total volume stored must be realistic and achievable based on engineering principles, such as well design, and the temperature and pressure at the bottom of the injection well, i.e. the modelled injection scenarios must not exceed what is physically possible.

3.2.3 There are different intensities of interaction between the predictive modelling activities

There is interaction between all disciplines of modelling activity in the understanding and performance prediction of a multi-user store. The intensity of interaction varies between the differing modelling disciplines. The relationship between the static geological model, its extent, structure, attribution and outputs is closely integrated and coupled with the dynamic modelling of CO_2 injection. The dynamic simulation of CO_2 injection is also closely integrated and coupled to geomechanical modelling of the multi-user store. The static and geomechanical modelling interaction is mainly by information exchange and so is not coupled to the same degree of intensity as the static and dynamic modelling activities. This interaction, either closely coupled and information exchange, requires commitment between all the predictive modelling teams. Interaction between the disciplines might be enhanced by those modelling teams being from different organisations or equally could be easier as different departments within an organisation.

3.2.4 An operator of a hydrocarbon field will have an existing field model

If one or more of the injection sites within a multi-user store is within a hydrocarbon field it is likely and reasonable to assume the field operator will have a model of that field. The model constructed and used by an operator will be detailed and likely to be restricted to the vicinity of the hydrocarbon field. In a field operators model the distance from the edge of the field to the model boundary will be the same order of magnitude as the distance from one side of the field to the other. The extent of the model beyond the field boundary will be determined by the operator's need to understand the pressure of the surrounding aquifer.

3.2.5 The computational resources needed for dynamic modelling may be exceeded if the static geological model is too detailed

Existing static geological models, whether from a hydrocarbon field operator or constructed to permit merging of existing model surfaces, are likely to be far more detailed than needed for dynamic predictive modelling of a multi-user store. The level of detail within a model used for dynamic simulation, particularly of the large extent of a multi-user store, has important implications to the time taken for processing. The computational resources available to the dynamic modeller of two sites within a merged model are a significant constraint on the resolution and level of detail within the static model that is used for dynamic simulations. Up-scaling to produce fewer larger model cells and variable grid resolution, with a fine-scale grid only in the vicinity of the injection sites, will be needed (see also Section 2.3.6).

3.2.6 Validation of the predictive model against any field history data is crucial

Validation of the predictive model results against any data from hydrocarbon field production within the multi-user store is known as 'history matching'. Comparison of the predicted dynamic modelling results against records of pressure variation and well flow rates during hydrocarbon production is a very important process. The model should be calibrated to reflect the pressure history. It is crucial that the predictive dynamic model is compared and validated against any pressure history data from hydrocarbon fields within the multi-user store.

3.2.7 Access to any pressure data may be facilitated by a third party.

Access to pressure data from any hydrocarbon fields within a multi-user store, crucial to validate the predictive dynamic model (Section 3.2.6), may be negotiated if the operators of fields are all members of the storage venture. However, due to the commercially highly sensitive nature of this data, pressure history information for hydrocarbon fields is not publicly available. We learned that sometimes an impartial, single third-party focal point or authority may be needed to catalyse and enable data availability. The third party might provide the compulsion needed to complete the actions and assign the resources needed to facilitate history matching.

3.3 TECHNICAL KNOWLEDGE GAINED

3.3.1 Representation of multiple variations in fluid properties

The large extent of multi-user stores may encompass one or more hydrocarbon fields. Each field will contain fluids specific to it and each field model attributed with its own fluid properties. Dynamic modelling software designed for investigation of individual oil and gas field reservoirs may not be able to accommodate two or more fields and the consequential multiple variations in fluid properties. It is problematic for one regional-scale merged model to incorporate the different detailed fluid properties of each field. Where the dynamic modelling software does not accommodate multiple variations in fluid properties expert judgement will need to be used and documented when defining fluid properties to adequately and appropriately represent fluids within two or more hydrocarbon fields. A practical solution is for the properties attributed in one of the component models to assume hydrocarbon behaviour in each of the fields is similar, with differences to account for compressibility effects, but not detailed properties that would allow for accurate estimation of hydrocarbon recovery. For hydrocarbon equilibration between different oil fields, a pragmatic approach is to specify one pressure at a datum deep within the brine-saturated storage formation that is host to the fields.

3.3.2 Formation conditions at the point of injection

The formation conditions at the point of injection are key parameters for the confident prediction of the behaviour of injected CO_2. The temperature and pressure of the formation at the bottom of the injection well, which determines both the volume and character of the injected CO_2, is required for the confident prediction of store performance by dynamic simulation.

3.3.3 Initial geomechanical modelling informs subsequent dynamic flow modelling

Geomechanical modelling needs to be closely coupled with fluid dynamic modelling. Realistic parameters should first be generated by geomechanical modelling for use in subsequent dynamic (and any other) predictive modelling. Output of fracture pressure values for the storage formation and cap rock generated by geomechanical modelling are essential input for subsequent fluid dynamics modelling.

3.3.4 Initial 'resource-effective' modelling of fluid properties

The fluid properties within a storage site can be represented by a relatively simple 'box' model. Where models are merged box models will have been prepared by each source organisation. When different organisations are contributing to a merged model it is sensible to start by preparation and comparison of simplified box models from each contributing organisation. The agreement of the fluid properties appropriate for the merged model can be made by the relatively simple fluid modelling activity. It is also an opportunity to run more sensitivities to refine the parameters before commencing dynamic simulation of CO_2 using the full 3D static geological model, which will take significantly longer to run.

It is here considered unlikely that data on fluid properties from operators of nearby hydrocarbon fields who are not part of a storage venture would permit access to their box model so a 'third party' may be necessary to facilitate access to the data.

3.3.5 Access to 'lifetime' pressure data for hydrocarbon fields

Pressure data throughout the development of hydrocarbon field within the storage site is essential and must be sought, possibly from a range of sources. The initial reservoir pressure at the start of hydrocarbon production can be difficult to obtain and field history data during oil and gas production is regarded as confidential to a field operator (see Section 3.2.7). Ideally, a pressure database across all fields in a hydrocarbon province would be useful for the appraisal for re-use of fields for CO_2 storage. This would be a significant undertaking and would need to be led by an appropriate authority, but could be a lengthy process.

3.3.6 Assessment of regional-scale performance prediction using a simplified model

The potential CO_2 storage capacity of UK regional formations remains a significant storage resource of greater magnitude than within depleted oil and gas fields (SCCS, 2009; Bentham et al., 2014). Where the formations do not host hydrocarbon fields, without the associated well and production data, their character is much less well known. A comparison was made of site performance prediction in CO_2MultiStore using a data-rich model with a simplified model appropriate for a prospective site in a data-sparse area. The comparison illustrated how well the capability of an individual formation to host one or more CO_2 injection sites can be assessed from a simplified model. A simplified three-dimensional 'static' geological model with smooth surfaces and coarse-scale model cells attributed with average property values in the vicinity of the injection site was used. The wider extent of the storage sandstone was represented as numerical or 'calculated' sandstone volumes to the west and east of the simplified model.

Comparison of results using the simplified model and the more complex data-rich model for the same prospective injection sites illustrates a regional-scale pressure response can be predicted using the simplified model. The pressure response from the simplified model is acceptable for a regional-scale assessment of the storage formation to inform a prospective storage site operator and the permitting authorities of its overall performance during CO_2 injection. More detailed modelling would be needed to assess the pressure at the injection well, maximum acceptable pressure, and migration of the injected CO_2 including the effect of roughness or angle of modelled surfaces. The simplified model requires much less data and resources to construct and the predictions of performance can be run more quickly to give a cost-effective 'first-pass' indication of store performance.

3.3.7 Representation of hydrocarbon fields in a simplified performance prediction model

A simplified site model is desirable for a first-pass indication of regional-scale storage site performance in areas of sparse data (Section 3.3.6). Where oil and gas fields are present within the extent of a prospective multi-user store representation of the hydrocarbon fluids within a simplified model is important as they are more compressible than water. The increased pressure from injection will be reduced within the strata allowing storage of a greater volume of CO_2. However, a simplified model that has smooth geological surfaces will not trap and retain buoyant oil and gas. To represent one or more hydrocarbon fields within the extent of a regional-scale model for performance prediction of a multi-user CO_2 store artificial 'barriers' to horizontal fluid flow should be incorporated. Model cells attributed with reduced flow properties can be used to artificially contain the compressible hydrocarbon fluids at the position of the fields within a simplified model.

3.4 GENERIC LEARNING TO INCREASE CONFIDENCE IN PERFORMANCE PREDICTION FOR A MULTI-USER STORE

1. Dynamic models need to be newly developed to predict performance of multiple sites for CO_2 storage, with a wider range of fluid characteristics than traditionally used in hydrocarbon field modelling, in order to take account of the additional fluids and their properties.
2. Fluid property information may not be available so the use of proxy values or analogue data must be agreed between the modellers and fully documented.
3. Less complex and more rapid two-dimensional modelling or very coarse-scale three-dimensional 'box' modelling of fluids within the regional-scale multi-user store should be validated by data from hydraulically connected hydrocarbon fields, where possible. The results should be assessed and revised prior to any (more resource intensive) high-resolution three-dimensional dynamic modelling.
4. Initial hydrocarbon field reservoir pressure information is essential to confidently appraise sites within a multi-user store and determine the maximum acceptable pressure. The lowest value that is calculated from the initial reservoir pressure for the sites assessed being the eventual constraint for all.
5. Calibration of the predicted pressure results against records of pressure variation (pressure history) during hydrocarbon production is very important.

6. Pressure history should be used to validate the predicted performance of injection sites within the multi-user store, so access to pressure history from across a regional storage site, if available, is crucial.
7. Hydrocarbon field pressure information is commercially sensitive and detailed data are not publicly available to either another hydrocarbon field or prospective CO_2 storage site operator. For multi-user store assessment access to pressure data and fluid property data may require an impartial third party with consequent requirement for legal agreements.
8. Dynamic modelling activities to assess a multi-user store by simulation of CO_2 injection need to be coupled with both static geological modelling and modelling of the geomechanical response to CO_2 injection in a multi-user store. A single integrated asset team is recommended.
9. Dynamic modelling must represent all geological strata that have hydraulically connected pore space and transmit pressure changes due to CO_2 injection at the prospective sites. For a multi-user store this is at a regional scale.
10. Dynamic model iterations of injection sites within a multi-user store need to be run for sufficient time, e.g. the lifetime of each of the proposed sites, in order to inform the performance and any possible interaction of the sites and to refine a realistic injection scenario.
11. Operation of a later injection site will be affected by the pressure increase from an earlier licence to inject and subsequent storage site development should be anticipated when an earlier licence is awarded.
12. The impact of one site on another suggests that consideration should be given to optimal management of the entire connected pore volume, and not just individual sites in isolation. Regional-scale pressure management might be achieved in a variety of ways, e.g. multi-lateral agreements between storage site operators, integrated monitoring of injection sites and dialogue between operators to manage pressure.
13. Predictive modelling of the performance of a regional-scale multi-user store for regulation and leasing might want to use a single modelling team for all types of predictive modelling to minimise the risk of overlooking the consequences of the results of the differing modelling activities.
14. The results of up-scaling must be carefully scrutinised to ensure subtleties that influence CO_2 migration, such as roughness of the upper storage formation surface or adequate representation of narrow zones of highly permeable rocks, are not reduced or lost during the process.
15. Because of the regional scale of the predictive modelling of a multi-user store only one or two simulations may be possible due to the time taken and computer resources needed. Careful thought needs to be given to parameterisation of model layers as it is likely that only a few iterations will be carried out.
16. A regional-scale pressure response can be predicted using a simplified model, in areas where data are sparse, for a cost-effective indication of store performance. Hydrocarbon fields should be represented in a simplified model. More detailed modelling is needed to assess the pressure at the injection well, the maximum acceptable pressure and to predict migration of the injected CO_2.

4 Increasing certainty in the geomechanical stability of a multi-user store

It is essential to understand the interaction and cumulative effect of pressure changes from more than one injection site within a storage formation. This is to ensure the integrity of the initial and 'follow-on' sites and also to correctly predict the ultimate storage capacity for the storage formation. The objective for predictive geomechanical modelling at two (or more) injection sites in a hydraulically connected multi-user store is to ensure the cap rock does not fracture from the cumulative effect of injection and so the integrity of the store maintained. The interaction and effects should be assessed over short, intermediate and long timescales.

4.1 KEY QUESTIONS

4.1.1 What is the depth to which the geomechanical model must be constructed?

The depth dimension for a geomechanical model needed to predict the thermal, mechanical and hydraulic effects of CO_2 injection may differ from that required for dynamic modelling of a hydrocarbon field. The base of the dynamic model may extend to and represent strata immediately below the basal surface of the storage formation. Whereas a regional-scale geomechanical model will need to extend to the depth of those underlying strata that are closed to flow (impermeable), which may be much deeper and include strata that are not represented in the static geological model of the injection sites. For assessment of CO_2 storage use of the same lower boundary for dynamic modelling as that used for geomechanical modelling is recommended here.

4.1.2 Do you have the required geological information on the underlying strata to inform geomechanical modelling?

Geological information is required for those strata that underlie the prospective injection sites and down to the strata that are closed to fluid flow (Section 4.1.1). It is important to have property data on the deeper geological layers beneath the storage strata also an understanding of the character of the lower boundary of the storage formation. These are input data to analytical and numerical geomechanical modelling of the strata. Property information, such as porosity, permeability, rock type and proportion that is sandstone are derived from oil and gas exploration well datasets. Data may need to be sought from beyond the extent of the storage site if exploration wells within it do not extend down to impermeable strata.

Knowledge or assumption of the nature of the lower boundary of the storage strata is essential to inform the prediction of the geomechanical response to CO_2 injection as this is required to assess the impact on the hydraulic and stress conditions at the injection sites. If the flow properties are not known from pressure information recorded from beneath and above the lower boundary of the storage site it may be inferred from the property information of the immediately underlying rock formation (Section 2.1.6).

4.1.3 Do the injection scenarios modelled approximate what should be pragmatically expected at the sites?

When predicting the geomechanical response to injection at a second site the rate of CO_2 injection at both sites is needed. The values used must be pragmatic, to neither significantly over- nor under-estimate the anticipated rate because it will influence the nature of the pressure interaction between the two sites. The rate of CO_2 injection, combined with the physical properties of geometry, porosity, permeability and compressibility of the storage strata will determine how long it will take for a change in pressure at a second injection site will be 'felt' by an existing user of the storage strata. More rapid propagation of pressure may result in earlier than expected changes in pressure and reduce the storage capacity at an existing injection site.

4.1.4 Are the properties of the cap rock known sufficiently to predict its response to cooling during CO_2 injection?

Injected dense phase CO_2 is cooler than the storage strata and the thermal properties of the cap rock need to be sufficient understood to predict the effect of temperature changes. CO_2 in dense supercritical phase is at a temperature of more than 31°C. Temperature increases with depth beneath the Earth's surface at an average rate of 25°C per kilometre. In the central North Sea the rate is mostly between 30°C to 40°C per kilometre (Kubala et al., 2003) so at the depths proposed for storage the geological strata will be warmer than the injected CO_2. Cooling during CO_2 injection causes local contraction of the storage formation rock. Where contraction occurs this causes localised reduction and redistribution of the rock pressure. Redistribution of pressure is very dependent on the heterogeneity of the rock present and so it is important to understand the associated range of properties.

4.2 LEARNING FROM THE PROCESS

4.2.1 The importance of engaging with the dynamic modellers very early in the multi-user store characterisation process

Engagement between all of the disciplines modelling the predicted performance of the multi-user store should start as early as possible. This should commence at the start of the geomechanical analysis, as soon as model(s) available from their originators are accessible to the modelling team. The geomechanical (and dynamic) modellers need to work together with the static modellers to define the geological model and ensure it includes the requirements and extent of geological information needed for geomechanical modelling.

4.2.2 Preliminary modelling work will establish agreed fluid pressure conditions before further geomechanical and dynamic modelling

Preliminary 'box' modelling of the properties and pressure conditions of fluids within the multi-user store is needed to establish a common understanding and values used by both geomechanical and dynamic modellers (this follows after the initial discussion with the static modellers). The preliminary box modelling should establish first-pass fluid pressure predictions for the multi-user store. The results from the initial geomechanical and dynamic modelling should be compared and corroborated to establish an agreed common understanding of fluid pressure conditions. This is very important as the results of the geomechanical modelling determine constraints of the maximum acceptable pressure values that will ensure cap rock integrity and prevent fault reactivation at all sites in a multi-user store.

4.2.3 An integrated workflow is needed for resource-effective and consistent geomechanical, dynamic and static modelling of a multi-user store

An integrated workflow enables the close interaction needed for cost-effective and consistent modelling of a multi-user store. The large extent of the static, dynamic and geomechanical models needed to encompass multiple injection sites, the computer calculation resources needed to assess a multi-user store and the data used in common by the modelling disciplines can only be effectively addressed by an integrated workflow. Geomechanical modelling of the mechanical, hydraulic and temperature response to CO_2 injection should use the fluid properties 'box' modelling results agreed from the comparison of results of preliminary work by both the dynamic and geomechanical modellers. A series of two-dimensional model cross-sections exported from the static geological model is used to construct a three-dimensional geomechanical model.

Geological property attribution of the geomechanical model is in common with that of the static model. The results of the geomechanical modelling determine the maximum acceptable pressure values that are key constraints to the three-dimensional multiple fluid phase dynamic simulation of CO_2 injection. Validation of the geomechanical model and dynamic model against each other should be undertaken where possible, for example, by checking initial fluid pressure predictions are consistent. The dynamic models are in turn also validated against pressure history data observed during oil and gas production from nearby hydrocarbon fields. Any adjustments to the boundary conditions and parameterisation of the model are fed-back to the geomechanical model to incorporate, as necessary.

4.2.4 A technical overview role is needed to ensure the assumptions used, the consequences of modelling results and their implications are fully understood

Technical overview of the closely integrated modelling disciplines characterising a site for CO_2 storage and understanding of the impact on the wider hydraulically connected system of a multi-user store is required to ensure all consequences are fully understood. Active participation and interaction by all members of the predictive modelling disciplines is needed to assess the geomechanical, dynamic and static geological modelling planning, iteration, and discussion of results. Also, importantly, to understand the assumptions included within the respective models and their consequences. The 'asset team' approach should include a technical expert whose role is to comprehend and consider the implications of all modelling assumptions, decisions, results and their consequences.

4.3 TECHNICAL KNOWLEDGE GAINED

4.3.1 More extensive geomechanical models and data are needed to characterise boundary conditions than traditionally used for static geological modelling or appraisal of a hydrocarbon field.

The models needed to appraise the geomechanical response to injection of CO_2 at two sites within a multi-user store have to span the lateral and basal boundaries of the storage strata. To assess the lateral boundary conditions the models need to extend beyond the margins of the storage formation strata and so are more extensive than static models constructed solely for dynamic simulation of CO_2 injection. The basal boundary for geomechanical modelling is determined by the depth to impermeable strata which are likely to be deeper or much deeper than the lower boundary of the storage formation or that traditionally used for exploitation and production from a hydrocarbon field.

Geological information to attribute the wider extent and depth of the geomechanical model needs to be collected by the static geological modellers to enable definition of the nature of the flow conditions across all boundaries for geomechanical and dynamic modelling. Additional data sources may need to be sought, for example data from hydrocarbon exploration and production wells beyond the extent of the prospective storage site.

4.3.2 The effect of thermal stress is much less extensive than the fluid pressure increase associated with injection of CO_2

Modelling of an exemplar multi-user store in the North Sea has shown that the geomechanical response generated by temperature change associated with CO_2 injection will not affect an adjacent injection site within a multi-user store.
The thermal impact of CO_2 injection is localised. Generally, the thermal effect is confined to within a few hundreds of metres of an injection well, at a distance of 500 metres or more cooling does not have a notable effect.

The small radius of effect related to temperature change is in contrast to the impact from fluid pressure increase due to CO_2 injection which is of regional extent.

4.3.3 Modelling confirms the impact of adjacent injection sites increases the closer they are

Sandstones that have the potential capacity to store many millions of tonnes of CO_2 each cover thousands of square kilometres beneath the North Sea. Although they have the capacity to accommodate multiple CO_2 injection sites modelling confirms that the impact of adjacent injection sites increases the closer they are. The effect of the increased pressure generated by injection at one site on another adjacent site is dependent on the proximity of the sites and rate of propagation of the pressure increase. The impact is likely to be greater if the injection sites are in closer proximity (tens of kilometres) than if they are further apart (100 kilometres or more).

4.3.4 Interaction of ‘felt’ pressure effects should be anticipated between sites in a multi-user store

The geomechanical response generated by an increase in pressure caused by CO_2 injection at one site within the storage formation should be expected to affect an adjacent injection site within a multi-user store. Modelling has shown interaction by a ‘felt’ pressure effect even though injection sites are tens of kilometres apart.
Where there are two injection sites within a hydraulically connected regional storage sandstone widespread pressure increases should be expected across the sandstone in a period of months from the start of injection.

4.3.5 The geometry of the storage formation will influence the interaction between injection sites and ultimately the storage capacity of a multi-user CO_2 store

Geological formations vary naturally in the angle at which they are inclined and their thickness. Strata may be inclined at shallow or steep angles and geological formation thickness may be uniform, increase or decrease with depth. The overall geometry of a storage formation in terms of any variations in depth and thickness, will influence the interaction between two or more injection sites within a multi-user store.

The influence of injection at a deeper site on a shallower site within a multi-user store is affected by any variation in the thickness of the storage strata. If the storage strata thin toward the shallower site the increase in pressure will be enhanced but if the strata thicken toward the shallower site the effect will be reduced. The overall regional storage capacity, the estimate of how much CO_2 a sandstone can contain, should take account of the impact of deeper sites on shallower sites. The maximum acceptable pressure at a deeper site may be constrained by the maximum pressure threshold determined for a shallower site in a multi-user store.

4.3.6 Modelling indicates which parameters have the largest impact on the geomechanical integrity of a storage formation

The formation pressure increases when CO_2 is injected into a storage site. The impact of the increase in pressure on the storage site can be mitigated by the inherent properties of the storage and cap rock strata. The pressure increase may be lessened by the capacity of the underlying strata to dissipate pressure by fluid flow through the lower boundary of the storage formation and into the underlying connected strata. Rocks may deform rather than fracture when the formation pressure increases. Plastic deformation of the cap rock will help to accommodate any distortion caused by a pressure increase and so reduce the likelihood of brittle fracture of the cap rock strata that contain stored CO_2.

Modelling indicates which parameters have the largest impact on the geomechanical integrity when pressure is increased. Where the underlying strata are porous and permeable and they are well-connected with the storage formation the pressure increase due to injection may dissipate downwards.

Geological faults or fractures may already be present within the storage site rocks. They were created over geological time in response to previous pressures and stress directions. Fracture orientation will have been determined by former stress directions. The potential for reactivation of existing faults is determined by their orientation with respect to the stress direction. Mapping of the orientation of existing geological faults relative to the change in pressure caused by CO_2 injection will indicate which fault structures would be most susceptible to an increase in pressure. It will be analysis of these fault structures which will contribute to the determination of the maximum acceptable pressure for the storage site.

4.4 GENERIC LEARNING TO INCREASE CERTAINTY IN THE GEOMECHANICAL STABILITY OF A MULTI-USER STORE

1. Geomechanical modellers need to work together with the static modellers to define and include the requirements and extent of geological information needed for geomechanical modelling.
2. Geological information needs to be collected to enable definition of the nature of conditions across all boundaries for geomechanical and dynamic modelling.
3. The base of the regional-scale geomechanical model will be to the depth of those strata that are closed to flow (impermeable) and used in common for the dynamic modelling.
4. Knowledge or assumption of the nature of the lower boundary of the storage strata is essential as this is required to assess the impact at the injection sites.
5. Preliminary work by geomechanical and dynamic modellers should establish first-pass fluid pressure predictions. This is very important as the results of the geomechanical modelling determine constraints for cap rock integrity and fault reactivation at all injection sites in a multi-user store.
6. Validation of the geomechanical model and dynamic model against each other should be undertaken where possible, e.g. by checking initial fluid pressure

predictions are consistent.

7. Technical overview and active interaction is needed for modelling planning, iteration, and results discussion to understand the assumptions included within the respective models and their consequences.

8. We have shown by predictive modelling that the effect of the increased pressure of injection from one site on another is dependent on the proximity of the sites and rate of propagation of the pressure increase.

9. The rate of pressure propagation between the two sites will be determined by the rate of CO_2 injection as well as the geometry, porosity, permeability and compressibility of the storage strata.

10. Where there are two injection sites within a hydraulically connected regional store widespread pressure increases can occur across the store in a period of months from the start of injection and the increase will be less if pressure can dissipate beyond the storage site boundaries.

11. The geometry of the storage formation will influence the interaction between sites and ultimately the storage capacity of a multi-user store.

12. Cooling during CO_2 injection causes local contraction of the storage formation rock. Cap rock and overlying strata at each site need to be individually assessed for the impact of thermal stress.

13. The thermal impact of CO_2 injection is localised. The local radius of effect is in contrast to the impact from fluid pressure increase due to CO_2 injection which is of regional extent.

14. Model parameters that have the largest impact on the geomechanical integrity when pressure is increased are: porosity and permeability of underlying strata and its connectivity with the storage formation; the orientation of existing geological faults relative to the change in pressure.

5 Conclusions on the design of a plan for monitoring of multi-user storage operations

Monitoring of injection sites by the operator is an obligation, overseen by competent authorities, as explicitly specified in the European directive on the geological storage of carbon dioxide (EC, 2009). Monitoring of a multi-user store must meet the requirements associated with the operation of an individual injection site as well as addressing potential interactions arising from multiple injection sites.

Generic learning on the design of a plan for monitoring multi-user stores draws on the risk assessment-led characterisation of two injection sites by CO_2MultiStore. Operation of a first site (Site A) and subsequent implementation and simultaneous operation of a second injection site (Site B) was assessed. The potential for interaction between two, or more, injection sites was identified and investigated by technical experts to increase understanding of the probability and reduce the consequence of any interactions. During multi-user store characterisation it is essential to identify potential interactions, and design and implement activities to reduce the likelihood and effect of any adverse consequences of potential interactions (preventative measures). Mitigation of potential interactions should take place during planning (as presented here), and throughout the design and operation stages of multi-store development.

A balanced approach is needed to integrate the perspectives of both the prospective operator and storage regulators. The regulatory requirements must be met by the operator. Monitoring requirements must be met but site operation might not proceed unless the monitoring techniques are cost effective.

5.1 KEY QUESTIONS

5.1.1 Is there potential for injection sites to interact? If so, how might they interact and what is the scale of the potential interaction?

A monitoring plan defines what is monitored, by what technique and where the measurements and observations are made, the frequency of the monitoring and the conditions under which monitoring might change. The objectives for monitoring specifically to address potential concerns arising from the operation of two or more injection sites in a multi-user store were defined by the risk assessment process (described in Section 1.3.3) and are to ensure cap rock integrity is maintained, to verify there is no leakage of CO_2 and identify the impact of a proposed storage operation of existing injection site or sites. For award of a storage permit where there is more than one site in the same hydraulic unit, the potential pressure interactions must still meet the requirements to securely store CO_2 (EC, 2009). The storage permit application at Site B must take account of the conditions of the permit award at Site A, i.e. including, amongst others, the volumes and rates of injection and maximum allowable pressures.

Predictions of the performance of two or more sites, by simulation of CO_2 injection, geomechanical and other predictive modelling techniques, will indicate if there is potential for interaction. Potential interactions relevant to monitoring planning are the migration of injected CO_2 gas, pressure increases and detrimental effects on other users of the storage formation. Predictive modelling of pressure changes in CO_2MultiStore indicated that injection at each site is affected by injection at the other site (Sections 3.4 and 4.4). Detailed modelling of the geomechanical stability of the storage and cap rock formations determines the maximum acceptable pressure values (Section 4.3) and for alert- and action-level pressure threshold values to be defined.

Monitoring should seek to use maximum acceptable pressure values determined by detailed, site-specific analyses rather than assumed values. Comparison of maximum acceptable pressure values from detailed analytical results in CO_2MultStore with a value derived by applying a principle has shown both under- and over-estimates from these assumed values. Where the strata are at shallower depths the assumed maximum value is too low whereas at greater depths the value is too high resulting in a lower potential CO_2 storage capacity.

There is potential for the pressure to exceed acceptable limits if preventative measures are not undertaken. Monitoring will determine if alert- or action-level pressures have been approached or exceeded, by the cumulative effect of operations within the storage formation. Definition of these levels is based on the maximum acceptable pressure determined for each injection site. Monitoring of pressure within a formation used as a multi-user CO_2 store will contribute to ensuring integrity of all injection sites.

Propagation of an observable pressure change is widespread and so a regional approach to monitoring should be considered. Monitoring of pressure over the injection interval at each site in a multi-user store is therefore essential to ensure cap rock integrity is maintained and to avoid unexpected or unacceptable pressure increases should the alert-level threshold pressure values be approached.

When anticipating the potential for interaction between a proposed injection site and existing injection and other operations within the same storage formation, it is the primary risk that should be distinguished. In CO_2MultiStore the potential interaction and cumulative effect of increased pressure from injection at two sites is the primary concern. There are also consequential concerns arising from increased pressure of the potential for CO_2 migration through the cap rock, detrimental impacts on other users and detrimental reductions in storage capacity. Monitoring planning should address the primary risk of interaction between two injection sites to ensure integrity at all injection sites in a multi-user store; the consequential risks will then also be addressed.

5.1.2 Is the degree of potential interaction avoidable, negligible or acceptable?

The consequence and/or probability of many potential interactions between injection sites, as assessed during expert appraisal, can be reduced after implementation of preventative investigations and actions. Preventative measures to avoid detrimental interaction should be taken at all stages during the development of an injection site.

Predictive modelling of the CO_2MultiStore injection scenario found that the effect of cooling of the storage formation was localised. The temperature change had no notable effect more than 500 metres from the injection well and would not affect an adjacent injection site within a multi-user store (Section 4.4). The effect of the increased pressure generated by injection at one site on another adjacent site was found in part to be dependent on the proximity of the sites. The pressure interaction may be deemed acceptable, since the impact of increased pressure of injection is likely to decrease the greater the distance, if injection sites are 100 kilometres or more apart. Such distances can be contemplated where multi-user storage formations are of regional extent.

5.1.3 Can the effect of a second site on existing storage formation users (injection site or hydrocarbon field) be identified from baseline and monitoring observations?

A prospective operator of an additional injection site in a multi-user store must demonstrate to the regulator that their proposed injection site does not have an adverse effect on existing users of a storage formation. An extended record of baseline monitoring may be required to establish any pressure interaction from an existing injection site, or hydrocarbon field, and the likely variation due to expected storage or field operations. This baseline for a Site B proposed in a saline aquifer where there is no prior access to the storage formation, may need to be derived from monitoring data obtained at Site A. Prediction of the performance and determination of operating constraints of the second site should integrate the baseline observations including the effects of other users. Monitoring during operation of a second site using the threshold levels determined in this way will ensure cap rock integrity at all injection sites.

Provision of monitoring data to the prospective operator from existing users within the hydraulically connected formation would be highly desirable. Such provision might be indirect, via a recognised authority, since such data may be confidential to the originator. The benefit to all users will be to demonstrate the existing baseline variation, inform determination of operating constraints for a proposed injection site and so avoidance of adverse effects on existing users.

5.1.4 Would operation of a proposed multi-user store have an adverse effect on the integrity of one or other CO_2 injection site? Will pressure need to be managed to operate a site without detrimental pressure changes on another existing site or field?

The potential for interaction of pressure effects by simultaneous operation of more than one site within a hydraulically connected storage formation is recognised by the EC (2009). CO_2MultiStore investigations have found that pressure interactions between injection sites in a multi-user store should be expected (Section 4.3) and the impact of one site on another will determine acceptable threshold values at each (Sections 3.3 and 4.3).

The implications for monitoring are that the maximum acceptable pressure threshold will be determined by the need to ensure integrity at all injection sites in a multi-user store. Pressure values sustainable where the strata are deeper or thicker may exceed the acceptable value where they are shallower or thinner (Section 4.3) regardless of the relative timing of site development. Should pressure management be deemed appropriate, to ensure storage integrity or avoid an adverse effect on hydrocarbon operations, then monitoring of the pressure management method becomes a preventative measure.

5.1.5 Would operation of a proposed multi-user store have a beneficial or adverse effect on other existing pore space users (hydrocarbon production and/or CO_2 storage, gas storage, geothermal heat or groundwater supply)?

Documentation and monitoring of CO_2 storage site pressure, operation within stated maximum pressure values and an understanding of potential pressure interactions are requirements of the EU CO_2 storage directive (EC, 2009). By contrast, in hydrocarbon production the potential impacts of additional production on pre-existing fields is not taken into consideration. However, UK storage regulations explicitly state that hydrocarbon production will take precedence over CO_2 storage and therefore any potential impacts on existing hydrocarbon production or potential impacts on future production must be taken into account. The potential impacts of CO_2 storage would include a decrease in the rate of pressure reduction at a producing field, which may be considered a positive benefit to the producer, but may also result in increased water production in some wells.

Monitoring of the regional-scale pressure increase due to CO_2 injection or pressure management by the operation of a multi-user store presents an opportunity to benefit existing and proposed operations. Consideration should be given to optimal management of the entire connected pore volume, and not just individual sites in isolation. Regional-scale pressure management might be achieved in a variety of ways, by bi-lateral and multi-lateral agreements between injection site and field operators, integrated monitoring of injection sites and dialogue between operators to manage pressure.

5.1.6 Can the CO_2 injected at one site be distinguished from that injected at another in a multi-user store?

Development of a multi-user store raises the unlikely possibility of a need to distinguish the source of any CO_2 gas in the shallow subsurface or at the sea bed in the area of the injection sites. The source might be either anthropogenic and from one or other injection site or from a naturally occurring source. Naturally generated CO_2 has a distinctive carbon isotope ratio. The source of anthropogenic CO_2 is likely to be easily determined if leakage occurs along a well or can be indirectly imaged as it migrates to the storage complex boundary. However, the potential for lateral migration along higher permeability strata may result in CO_2 leakage at some distance from the injection point. In areas of multiple injections the source of the CO_2 may not be identifiable with confidence. In these circumstances it would be prudent to use an inherent or introduce a co-injected tracer with the CO_2 that is unique to each operator. The distinctive character would demonstrate whether gas in the monitoring samples is from one of the injection sites or another source.

Monitoring to determine the source of any CO_2 by laboratory analysis of fluids collected at or near the sea bed would be a component of the monitoring plan. Should the CO_2 be traced to an injection site it has implications to the operation of that site, any financial penalty via the EU emissions trading scheme and liability for any environmental damage. For the latter, research indicates that small-scale leakage at the sea bed is highly unlikely to have a significant environmental impact (Blackford et al., 2014).

5.2 LEARNING FROM THE PROCESS

5.2.1 The role of the prospective Site B operators is to assess the effect on other formation users

Where a Site B CO_2 injection site is proposed it is the role of the new prospective operator to assess the effect on existing formation users. The proposer of the additional injection site should assess and mitigate the potential effect on and interaction with existing Site A injection sites and other subsurface pore space uses (hydrocarbon field and gas storage operations, geothermal heat source or groundwater users).The options to the prospective operator are to design the new storage operation to reduce any interaction to a negligible or acceptable level, to co-operate and manage the interaction to be beneficial to storage formation users or to make a financial agreement with the effected parties.

5.2.2 Access to existing data to inform monitoring planning

To enable a prospective Site B operator to make a realistic appraisal of the effect of the proposed injection site on existing operations they should have access to data and models from existing formation users. This will ensure consistency of assessment of the effect of the operation of a Site B injection site on an existing Site A and other pore space uses. Access should be given to their existing site models so that the character of the formations and fluids in geoscientific models is consistent. Provision of monitoring and production data will ensure predictive modelling of the formational response, storage site performance and potential interactions are based on the best available data. Reciprocal provision of predictive results for the proposed storage operation would form the basis of any mitigation activities, pressure management or financial agreements. Access to existing data will significantly enhance the relevance of the properties to be monitored and their threshold values, the spatial extent and techniques required for monitoring. Increased understanding and planning to ensure the integrity of the storage formation will be considerably enhanced by access to existing data. Where these are regarded as commercial-in-confidence, such as hydrocarbon field models and production data, such access may be via an impartial third party.

5.3 TECHNICAL KNOWLEDGE GAINED

5.3.1 Monitoring planning for a multi-user store by addition of an injection site

The nature of the interaction of a proposed site with existing operations in a storage formation may be more or other than the effect of increased pressure of injection. Each injection site has its own character, technical and non-technical constraints and so the potential for interactions to be monitored might include: migration of injected CO_2 as gas or dissolved in formation water; interference with hydrocarbon production infrastructure and operations (which take precedence over CO_2 storage in the UK); increased cost per tonne of CO_2 stored for the existing and proposed operations. The character and likelihood of any potential interaction and so monitoring planning should be carefully considered, and not assumed, for the addition of any injection site to a multi-user store.

5.3.2 Implications of inadequate monitoring of a multi-user store

Monitoring planning will include an assessment of the cost-effectiveness of any technique suitable to measure the property to be monitored for the proposed injection site. Only monitoring to demonstrate the site is performing as predicted and detect irregularities will be included, as it is a significant cost to the proposed operation as a commercial proposition.

The effect of any potential interaction between sites will need to be established and monitored, e.g. migration of injected CO_2. The assessment should also include the implications of not adequately monitoring the pressure interaction (or other factor) between sites and the consequential potential cost of the interaction appraised. This aspect is particularly relevant to an additional Site B injection site in a multi-user store as there may be consequential effects and costs for other operations within the storage formation. Each operation adversely effected by an undetected irregularity in injection site performance will have its own commercial and contractual obligations. The cost implications of inadequate monitoring must be assessed against the cost of mitigation as proposed in the monitoring plan.

5.3.3 Obligation to monitor the pressure interaction

Monitoring observations for any CO_2 injection site must allow comparison of predicted and actual site behaviour and detect significant irregularities, CO_2 migration, CO_2 leakage and any adverse impact on the environment (EC, 2009). A proposed injection site that creates or operates within an existing multi-user store must also ensure that the potential pressure interactions also meet these requirements (EC, 2009). Concerns regarding potential pressure interactions, including the primary and consequential effects, may be successfully mitigated by appropriate project design and definition of maximum operation pressures. However, the monitoring plan must also enable careful observation of pressure changes during injection. Pressure monitoring would therefore be a key component of a site operator’s monitoring plan. Given the commercial implications of an adverse interaction the prospective operator might plan to carefully monitor and quantify, from baseline and monitoring data, the contribution of the proposed site.

5.3.4 Measuring of additional parameters to monitor the pressure interaction

There is an obligation to monitor pressure at CO_2 injection sites (Section 5.3.3) and, from the investigations by CO_2MultiStore, an interaction of pressure between sites in a multi-user store in which sites are hydraulically connected should be expected (Section 4.3.4). It is assumed here all effort would be made during site characterisation to predict and reduce any adverse effects of pressure interaction and to mitigate it by appropriate injection project design (Section 5.2.2). However, in a multi-user store the prospective operator should expect to undertake monitoring of additional parameters over and above the expected mandatory minimum level of storage formation pressure. Measuring of parameters attributable to a consequential effect of a pressure increase might include monitoring of micro-seismic activity or pressure monitoring of secondary storage strata. A micro-seismic event, if attributable to small movements on faults might indicate decreased store integrity should the faults intersect or cut across the sealing cap rock. Similarly, monitoring of pressure in secondary storage formations is suggested, above the containing primary sealing cap rock. Pressure monitoring in strata overlying the storage formation would detect any unexpected pressure rises that could be attributed to CO_2 leakage or be initial indicators of potential leakage through pressure communication.

5.3.5 Definition of thresholds for monitoring of pressure in a multi-user store

The proposed addition of a second CO_2 injection site to create a multi-user store must be accompanied by a prediction of its potential pressure interaction with existing storage operations. The maximum acceptable pressure should be assessed using the most detailed available geological and property data, extended baseline pressure monitoring and fluid flow data. The pressure threshold at all sites in a multi-user store is constrained by the maximum acceptable pressure where it is most likely to be exceeded during operation of the existing and proposed injection sites (Sections 3.1.3, 4.3.5 and 5.1.5). For monitoring purposes, the maximum acceptable pressure is the action level which, if exceeded, is a significant irregularity and triggers a corrective measure. An alert level should also be defined to ensure the action level is not achieved, e.g. 85% of the maximum acceptable pressure. Should the alert level be reached the model parameters should be reviewed and the store performance predictive models revised.

5.3.6 Extended monitoring and possible additional infrastructure for a multi-user store

Extended baseline pressure monitoring prior to the start of CO_2 injection will be needed for an additional injection site that creates or operates within a multi-user store. The extended baseline is intended to establish the extent of pressure communication from existing operations since it can be assumed that changes in pressure at the proposed site would result from existing operations. The extended baseline will inform prediction of interactions between the sites and define the maximum acceptable pressure and storage capacity at all sites. Extended baseline pressure observations would not be needed for a first-implemented injection site. An additional monitoring well may be needed at the proposed additional injection site to observe pressure increases as a result of injection at the additional and existing sites. Another monitoring well solely to capture the effect at another injection site is a costly undertaking and would not be expected unless required for site-specific concerns by the relevant regulators

5.3.7 Anticipating and planning for a future multi-user store

Anticipating and planning to operate a multi-user store, in contrast to creation by addition of an injection site or sites, presents additional costs and responsibilities but also benefits. For an extensive storage formation in which multiple injection sites are expected then the benefits of strategic planning may outweigh the technical challenges and associated costs. The benefits would be the efficient management of pressure and security of supply of capacity within the storage asset and monitoring of the regional integrity of the cap rock.

A joint venture between operators and stakeholders might fund a regional monitoring well that also provides data to verify the character of storage and cap rock formations away from injection sites. The challenges would include the cost and logistics of an isolated well, also to identify the responsible party to co-ordinate the operation, maintenance and closure on behalf of a joint venture. A 'storage regulator', a stakeholder member of the joint venture, might assume the responsible role. The cost and logistics of commissioning and operation of an isolated monitoring well may be justified where a multi-user store is planned and may be required by an impartial third party.

The anticipation by first-movers of the subsequent development of a multi-user store, may encourage them to protect their assets by seeking a storage permit to store more CO_2 than is expected. For example, consider the following scenario: Site A might seek a storage permit for injection of e.g. 6 Mt per year, although in reality only 2 Mt will be injected initially with the 4 Mt reasonably expected following additional capture. This would therefore create an unfair disadvantage to developers of Site B who would have to assess the impact of their operation on Site A assuming 6 Mt were being injected annually. This potential for 'land banking' should be avoided. A fairer approach would be to award Site A a permit for 2 Mt pa initially, and a subsequent increase in injection rate would require a revision to the permit conditions. At this point operators of Site A would need to evaluate the potential impact of increasing injection both on Site A and on Site B.

5.4 GENERIC LEARNING ON THE DESIGN OF A PLAN FOR MONITORING OF MULTI-USER STORAGE OPERATIONS

1. The principle risks that arise from two or more injection sites in a multi-user store are related to unexpected and unacceptable pressure rises. The consequences of these risks include: reduced storage capacity; reduced injectivity; increased risk of reduction in cap rock integrity; increased likelihood of reduced containment by the primary seal. Unexpected and unacceptable pressure increases could lead to a need for changes to permit conditions, and changes to leases, and possibly site closures in extreme cases.
2. Pressure monitoring in the storage strata and in overlying formations is fundamental to mitigating these risks and providing the necessary data to manage the risks during injection.
3. Discussions between operators planning to inject into a potentially hydraulically connected formation and sharing of data obtained on the formation could mitigate potential risks during and arising from follow-on projects. These are in addition to preventative measures taken during project design, and monitoring planning and operation.
4. Storage operators that might be affected by new storage proposals should expect to be asked to comment on the proposals (or some form of the proposals) to determine how the new project might affect existing operations.

5. Risk reduction could be achieved by pre-competitive testing of the formation through injection tests and appraisal wells designed to establish the degree of connection between potential storage sites.
6. Risks to existing operations would need to be addressed by the prospective storage developer during project design and operation. Injection strategies would be designed to minimise unacceptable pressure increases and monitoring plans would be designed to track pressure responses as a consequence of injection within the formation.
7. Later projects may be required to undertake additional monitoring to ensure their projects do not adversely affect existing operations. This additional monitoring may include establishing extended baseline data to determine the degree of pressure connectivity between sites, during injection at the first site but prior to injection at the second site. Furthermore, dedicated monitoring wells might be needed to provide observation points in the formation (and in overlying formations) where pressure increases may potentially affect cap rock integrity. Pressure management may also be necessary at follow-on sites to maintain pressures below maximum acceptable pressure values and still maintain appropriate injection rates.
8. Co-ordination of injection operations may be needed in order to maximise the storage capacity of the formation as a whole. This may require a strategic planning of the timing, location and total volumes stored at each site. Co-ordinated monitoring of the formation as a storage asset, including the possible construction of independent monitoring wells (outside storage complexes) could also be considered, though the costs and resources needed for this are recognised as being significant.
9. It is considered very beneficial to take advantage of data acquired on reservoir pressure responses from hydrocarbon production operations. Hydrocarbon field operators have a wealth of data on their fields and this data should be appropriately archived for the benefit of future storage developers.

6 Overview generic learning

1. Integration of existing models should be considered for assessment of a multi-user CO_2 store. The large extent of a model needed to appraise a multi-user store may encompass one or more hydrocarbon fields. Depleted oil and gas fields within a prospective storage formation are candidate storage sites. Where there are hydrocarbon fields models will exist, prepared by their operators. The models capture understanding of the formations, the rock types, the fluids contained within them and subsurface conditions which are all appropriate for re-use to inform assessment for CO_2 storage:
   - Three-dimensional 'static' geological models of the sites may be merged and integrated to construct a regional-scale model suitable for multi-user store assessment provided they are consistent, logical and well documented.
   - Fluid property data from a hydrocarbon field 'box' model, either within or adjacent to a storage site, can be used to validate the representation of contained fluids in the multi-user store model.
   - Rock property and initial fluid pressure data would inform prediction of geomechanical stability of the prospective storage sites and pressure history information can be used to validate that the predictions are correct.
2. Access to field production data, where hydrocarbon fields are present within or adjacent to a multi-user store, is essential to validate the predictive site performance models and to inform monitoring planning. The initial reservoir pressure at the start of hydrocarbon production can be difficult to obtain, and the pressure history and well flow data during production is regarded as confidential to the operator. Access to such data by participation of the field operator in the storage project or via an independent third party might be arranged. Ideally, a field history database across all fields in a hydrocarbon province would inform the appraisal of fields for re-use for CO_2 storage.
3. Integrated working is essential when appraising a multi-user store. This is not solely best practice (initial fluid property modelling provides input data for geomechanical modelling that determines the maximum acceptable pressure which, in turn, is a constraint for flow modelling), but to consider the interaction of one site on another and the implications of the results of one predictive modelling discipline on another. The effect of the 'footprint' of increased pressure from a later storage prospect on an existing site with the interaction and cumulative effect of two (or more) sites, for example, must remain within the maximum acceptable pressure at both.
4. A regional, basin-scale approach must be taken if a multi-user store is being assessed. All strata that have connected pore space and where the contained fluids are in hydraulic communication must be considered. The connection, and so transmission of changes in pressure due to CO_2 storage site operations, must be considered both in their extent and over time. In terms of a multi-user store the maximum acceptable pressure is defined by the lowest value for the two (or more) sites; a regional store (the parts in hydraulic communication) is only as strong as the weakest point. The duration and timing of the components of a multi-user store should also be assessed, as interactions from a later site may potentially be detrimental to an existing site. Extended baseline monitoring observations for a later-implemented site will be needed to define appropriate pressure thresholds which determine the storage capacity for all injection sites in a multi-user store.

5. Exploitation of a regional storage formation to optimise the CO_2 storage capacity of the resource as a multi-user store should be planned strategically. Additional monitoring infrastructure may be cost-effective to optimise storage capacity if a regional approach is taken. Multiple iterations of storage scenarios should be modelled to optimise capacity by different injection scenarios (relative timing of development of sites, and varying injection rates, volume of CO_2 stored and well positions etc.).
6. Resource-effective assessment of the predicted pressure effect for a multi-user store can be achieved using simplified basin-scale models. Comparison of predictions using a simplified and a complex model for the same prospective multi-user CO_2 storage illustrates that a simplified model is acceptable for a regional-scale assessment of pressure change. Pressure prediction using a simplified regional-scale model would inform a prospective storage site operator and the permitting authorities of the overall performance of a formation for CO_2 injection before undertaking more detailed site characterisation modelling.

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