One of the key influences into the viability of geological storage of carbon is the integrity of the overlying seal.

Overview
CCUS will play a key role if the UK is to reach net zero by 2050[1]. Principally by allowing heavily energy intensive industries to decarbonise, whilst continuing current production rates. A key facet of CCUS is the storage component of excess CO_2. This is most likely to occur in former conventional oil and gas fields nearing the end of their life. Many of these fields are situated in the North Sea or Irish Sea, which have the added benefit of a lifetime of production and geological data. However, there are still uncertainties within the storage of carbon dioxide in these fields. The major uncertainty relates to the competence of the seal, which will have been physically altered during the production process, through changes in the underground stress fields. In many places data on the caprock is scarce due to the limited sampling of the cap during original production. As such novel techniques are required to utilise the samples that have been recovered, mainly in the form of cuttings to give an understanding of the likely impact of the changes in stress on the caprock as a whole.

Background- Role Of CCUS in Net Zero 2050

As the UK aims toward Net Zero by 2050, it has become increasingly obvious that Carbon Capture Utilization and Storage (CCUS) will play a key role in enabling this transition. The UK must capture 10megatonnes of carbon dioxide by the end of the decade to keep on track to reach Net Zero 2050, which in turn would mean that the CCUS industry would be worth £3.6bn in exports by 2030[1].

CCUS is initially planned to be integrated into power generation for large industrial clusters, which require a significant and local supply of power, which cannot be supported by renewable technologies at this moment. CCUS also can help reduce the carbon footprint of some of the most carbon intensive industries such as cement manufacturing and ammonia production, by removing the carbon directly from the effluent and sequestering it underground in geological storage.

This postnote outlines one of the key challenges for CCUS, which involves the lack of information available in saline aquifers, and in particular the repurposing of former conventional oil and gas reservoirs for storage of carbon dioxide.

Types of CCUS

CCUS is split into three groups[1]; conventional CCUS- whereby the carbon dioxide produced during the combustion of hydrocarbons for fuel is extracted from the effluent and pumped underground; Direct Air Carbon Capture and Storage- where sorbents are used to remove carbon dioxide from the atmosphere directly, either by directly absorbing CO_2 into the sorbent, or adsorbing onto the sorbent surface[2]; and Bio-Energy Carbon Capture and Storage- whereby the methane for power is generated through the anaerobic digestion of waste products generating methane which can be used as a replacement for geologically derived natural gas.

Of these three potential CCUS strategies, conventional CCUS is much better developed to drive forward in the next 5 years and is readily adaptable into blue hydrogen production.

The Importance of S in CCUS

A key component of CCUS enabled power generation is the feasibility of long term CO_2 storage. The knowledge base already in existence means that utilising depleted geological oil and gas reservoirs to host the carbon dioxide is a possible solution[2]. This allows reuse of existing infrastructure and knowledge of the subsurface conditions[3]. However, due to the changes in stress through long term production, and the effects of this on the sealing capacity of the caprock, the more viable option is to utilise saline aquifers in regions where conventional oil and gas exploration has occurred.

The reason for this is two-fold; the knowledge of the regional system is good and the potential reservoir and seal will most likely have been characterised in different locations. Secondly, the semi-pristine nature of the aquifer and associated seal prior to injection of CO_2 mean that many of the problems which may arise due to previous production are unlikely.

Predominant Storage Locations in the UK

In the UK we have two primary target areas for sequestration: the North Sea and Irish Sea[4]. The main target strata in the UK are the Triassic, Jurassic and Cretaceous sandstone deposits which hosted much of the North Sea oil. These deposits are sealed by either mudrocks or salt depending on location, both of which prove adequate seals for housing large quantities of CO_2.

The North Sea and Irish Sea basins are also close to three of the five industrial clusters allowing the reuse of some infrastructure[4], for example, the pipes and platforms used to extract the hydrocarbons previously.

Example: Sleipner Field- Norwegian Continental Shelf

The Sleipner field was a conventional gas field that came on-line in the mid 1990s. However the methane produced was relatively impure, and 9% of total gas produced was CO_2. As such Statoil (now Equinor) used an overlying sandstone to sequester the CO_2 underground to avoid greenhouse gas emissions[5].

The Sleipner field project has successfully sequestered 0.9Mt of CO_2 per year from 1997[5] and even sequestered carbon dioxide from another nearby field.

The Utsira formation- in which the CO_2 is sequestered, was chosen as it is non-potable, with a depth from surface of >1000m and because it has exceptionally high porosity and permeability[6]. However, one of the major challenges going forward is to utilise poorer quality reservoirs for a similar purpose.

The North Sea has a history of carbon dioxide storage dating back to the early 2000s, with the Sleipner field in the Norwegian North Sea, first used to sequester carbon in 1997[5]. The UK North Sea has the capacity to sequester >1000Mt of carbon, or 100 times the amount in the Sleipner field/ Net Zero Teesside Initiative. Most of this capacity is split between depleted oil and gas reservoirs and saline aquifers[7], and are concentrated in the Central North Sea and Southern North sea. The Central North Sea is easily accessible from industrial clusters located on the east coast of Scotland and the Southern North Sea accessible from the North East of England and from Lincolnshire[4].

Keys to CCUS- Reservoir quality

The most important aspects of any prospective geological reservoir are the volume of carbon which can be stored and the permeability of the carbon dioxide in the reservoir[2]. Both of these are controlled by the reservoir mineralogy and dimensions. Reservoir mineralogy and volume are well constrained in most mature basins.

Example- Net Zero Teesside

Net Zero Teesside is a project to decarbonise a large industrial cluster located in and around Middlesbrough. The planned project is to utilise CCUS into an offshore reservoir to sequester the carbon generated by the industrial cluster.

This project is run by a consortium of five Oil and Gas Climate Initiative members (BP, Equinor, ENI, Shell and Total). It is suggested to sequester 10Mt of carbon, which would be the equivalent to that sequestered at Sleipner. The added value of this project is projected to be in the region of £450 million and will support approximately 5,500 jobs[15].

This project involves the initial use of blue hydrogen- where methane is converted into H_2 and the produced CO_2 can then be directly sequestered into an offshore reservoir, utilising the existing infrastructure to inject into the Endurance Saline Aquifer.

Upon completion Net Zero Teesside will be the UKs first zero-carbon industrial cluster, and represents a key step in the UKs transition towards net zero by 2050, with the Teesside industrial cluster currently producing 5.6% of all industrial emissions in the UK[15].

The key reservoirs in the North Sea generally comprise Jurassic/Cretaceous sandstones[8], similar to those outcropping on the Jurassic Coast in Dorset. These reservoirs comprise packed layers of highly porous sandstones, with cemented interbeds, which exhibit good lateral permeability.

Other reservoirs in the North Sea are generally formed from the Triassic red sandstones deposited in desert conditions[8]. These sands comprise even greater reservoir quality than their Jurassic counterparts, but due to their depth in the succession require deeper drilling projects, which increase cost.

One of the key components of reservoir quality is the proportion of connected pores. In general, processes which occur during burial, and the abundance of clay minerals in the sandstone detrimentally impact porosity and permeability. However, some clay minerals form coatings around grains which enhance permeability by preventing cementing up of grains[9]. This can result in improved accessibility to porespace within a reservoir.

Keys to CCUS- Seal Integrity

The other important aspect of CCUS is the integrity of the caprock and structure under which the CO_2 is to be stored, as these determine the maximum volume of CO_2 which can be stored on anthropogenic timescales[10,11]. The most common caprocks across the UK are mudrocks and salt. Of these, mudrocks represent the majority of seals and are highly suitable for CCUS[12].

Mudrocks are defined as having a mean grain size <63micron in diameter and generally comprise a melange of clay minerals, carbonate, quartz, feldspars micas, pyrite and organic matter[13,14]. Although mudrocks can contain significant porosity, due to the mean grainsize and common cementation, these pores are poorly connected, which leaves mudrocks with exceptionally low permeabilities[14].

Many of the sealing mudrocks in the North Sea are Jurassic age mudstones and shales[12]. These caprocks all have the properties of being rich in clay minerals, and in some parts rich in organic matter.

The other major influence on the seal integrity is the structure that forms the seal. The North Sea and Irish Sea geology is different in this respect, whereby many of the conventional North Sea oil and gas reservoirs are sealed by fault closures across a broad series of subterranean hummocks and valleys or within structures formed from extensional faulting and associated reactivation[16]. The Irish Sea geology is significantly different with many of the seals comprising tilted fault blocks[16], where a section of strata have been detached, slid and rotated, causing different lithologies to be juxtaposed against one another.

Seal Integrity During CO_2 Injection

During the initial exploration and production of any conventional oil field a significant amount of information is gathered on the reservoir and to a lesser extent the seal. This information usually comprises the permeability, porosity, mineralogy, heterogeneity, and rock physics. These are key in defining the most efficient production method. Some of these attributes evolve and change during the production lifetime, in particular the permeability, porosity and rock physics are influenced by the injection method and the 'sweeping' method, used to gain the maximum return from any reservoir.

The changes in reservoir porosity and permeability are principally controlled by the reservoir mineralogy, e.g. whether the reservoir contains significant carbonate or feldspar. These minerals in particular are likely to be dissolved as part of the production process to enhance reservoir quality[17]. Due to the importance of reservoir quality during production, these changes are well tested, and observed at a high resolution, which enables adequate modelling of their future response to CO_2 injection.

The changes in the caprock are generally more subtle, and less well constrained and relate to mineralogy [11]. The change from hydrocarbons/water to CO_2 can have an effect on the sealing potential of the shale, but on a timescale greater than the lifetime of a viable CCUS reservoir (>100,000 years). The other and more significant change in the caprock is exhibited within the mechanical properties. These are influenced by the changes in stress relating to the high-pressure reinjection of CO_2 changing the stress regime.

A key uncertainty into many of these saline aquifer cap rocks is the lack of adequate samples. These saline aquifers were less likely to have core recovered during prospecting, due to their lack of associated hydrocarbons for conventional production. As such there was likely little consideration given to the possibility of injection and use of the formation. Therefore, much of the material collected was in the form of cuttings (<1cm in size) and is inappropriate for conventional mechanical testing techniques. However, in the last five years significant leaps forward have been made in the field of micro/nano-scale geomechanics[18,19,20,21].

These leaps forward have allowed predictive modelling of shale seals from cuttings, in turn leading to greater accuracy in predictions of the mechanical response of shales to the injection of CO_2, particularly around the wellbore. It is the mechanical response of the shale around the wellbore which is of most importance. These new techniques give great insight into the response of these proximal strata allowing measurements of mechanical properties at <1cm intervals, which are similar to the intervals in which other shale properties (e.g. geochemistry) are measured. A combination modelling approach can then be adopted, whereby geochemical reactions can be combined with geomechanical changes to the injection of CO_2.

This modelling is vitally important when injecting into underexplored saline aquifers or reusing depleted oil and gas reservoirs, as this allows an assesses of the impact of any new pumping regime on the seal around the injection wellbore. This information also allows for detailed analysis on any previously deformed seal, most likely as a results of production wells from secondary phases of production during a fields lifetime.

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