Underground gas storage: An introduction and UK perspective

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Abstract: Rising demand and the depletion of its offshore reserves has resulted in the UK becoming a net importer of natural gas. An increased reliance on imports and limited current storage availability mean that the UK faces increasing energy bills and risk of disruption to supply. Because of this the UK government has set about ensuring security of energy supply. Steps taken include the construction of major new pipelines from Norway and Holland and improvements to interconnectors in the southern North Sea. The Government also recognizes that improvements to the gas supply infrastructure are required, including the need for significant increases in gas storage capacity; best met by the construction of underground storage facilities. Focus on energy security has also raised the likelihood of a new generation of coal-fired power-stations. For such a step to be environmentally viable, clean-coal technologies with near-zero greenhouse gas emissions will be required. Underground CO_2 storage will be a key element of this strategy. This volume reviews the technologies and issues involved in the underground storage of natural gas and CO_2, by means of case-studies and examples from the UK and also from overseas. The potential for underground storage of other gases such as hydrogen, or compressed air linked to renewable sources is also reviewed.

In October 2004, the Geological Society convened a two-day conference at the Aberdeen Conference Centre: 'The Future Development and Requirements for Underground Gas Storage in the UK and Europe'. The conference was held at a time when attention was turning to the imminent import dependency facing the UK and was attended by representatives from not only industry and academia, but also local government departments who were dealing with applications to develop underground gas storage (UGS) facilities onshore UK. The conference took place shortly after the Moss Bluff incident in Texas (July 2004), which, in the light of the infamous Hutchinson incident in Kansas, highlighted one of the main concerns of residents in the areas of proposed storage facilities — safety (see **Miyazaki; Davidson; Evans**).

This volume arose from the 2004 Aberdeen meeting. In the present gas and energy supply climate, this review and appraisal of the technologies of underground gas storage and future UK requirements is particularly timely.

The UK requirements for UGS and Government views on 'need'

In 2004, Government predictions were that the UK, despite the historical riches of the North Sea, would become a net importer of gas sometime during 2006 (DTI 2003). In fact, the situation was worse than predicted, with the UK becoming a net importer of gas during 2004. Current predictions are that the UK will import over 80% of its gas by 2020, which brings with it an increased reliance upon foreign supplies and the possibility of rising gas and energy costs and disruption to supply (DTI 2006*a*, *b*, 2007*a*).

The conference was opened by John Havard, from the former Department of Trade and Industry (DTI), now the Department of Energy and Climate Change (DECC) and previously Business Enterprise and Regulatory Reform (BERR), who outlined Government's view on UK gas supply and the need for increased storage infrastructure. The opening paper (**Havard & French**) summarizes Government's views on the need for increased gas supply infrastructure, and a regulatory environment to allow such infrastructure to be delivered to the market in a timely fashion. UK requirements and storage operations as seen from the perspective of a UGS operator (Star Energy) are also presented (**Fernando & Raman**). Star Energy operates one underground gas storage facility, having converted the depleting Humbly Grove Oilfield to storage in February 2004, and is currently evaluating several other locations in the south of England and in the East Midlands (**Fernando & Raman; Evans & Holloway**).

UK annual gas consumption is around 103 billion m^3 (bcm), but current storage availability of approximately 4 bcm is only about 4% of annual consumption; equivalent to approximately 14 days supply (Table 1). This is a much smaller

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Table 1. *Comparison of annual gas consumption, gas storage volumes and approximate days storage in the UK, other European countries and the USA (based upon Fernando 2005; IGU 2006)*

Country	Annual consumption (bcm)	Storage capacity (bcm)	Storage capacity relative annual consumption (%)	Days storage (approx.)
UK	103	4	4	14
Germany	101	19	19	69
Italy	81	13	16	59
France	46	11	24	87
USA	631	114	18	66

proportion than many European countries and the USA. Forecasts are for rising demand for gas in all sectors, perhaps reaching 135–140 bcm by 2020 (DTI 2006*a*, *b*). If ageing nuclear and coal-fired power stations are not replaced by similar new plant, then they are likely to be predominantly replaced by gas-fired plants, further increasing demand. In 1990, the domestic sector accounted for 50% of UK gas usage, with gas-fired generation virtually non-existent (National Grid 2007). Low gas prices and market liberalization in the 1990s led to the 'dash-for-gas' as gas-fired power generation increased dramatically. Over the next fifteen years it produced a split between the market sectors, such that by 2004, power generation accounted for 33% of UK gas consumption, with domestic demand making up 36%, and the industrial/manufacturing sector 13% (National Grid 2007). Estimates suggest that the minimum share of gas in electricity generation will rise to 46% by 2012 with some analysts suggesting that this figure could exceed 60% (POST 2004).

Storage of gas both onshore and offshore is only possible in suitable geological structures or formations, which are present in a limited number of locations. Potential reservoir rocks have to be of a certain minimum depth and a proven trapping configuration, including a caprock must be present. Similarly, halite beds suitable for developing storage caverns have to be greater than a certain thickness and depth. Presently, however, UK UGS applications are subject to numerous and lengthy planning consent processes; both local planning controls, currently overseen by the Department for Communities and Local Government (CLG), and specialist development consent regimes currently administered by the DECC. In addition, and as noted by Government (DTI 2006*b*, 2007*a*), local communities close to proposed facilities strenuously oppose UGS development. Opposition is based mainly on the fear of a repetition of rare but major incidents seen at UFS facilities, most notably in the USA, where fatalities have occurred (**Evans**). As a consequence, almost every UGS application appears destined to undergo lengthy delays and a Public Inquiry.

The situation is highlighted by the proposals for cavern storage facilities at Byley (Cheshire) and Preesall (Lancashire) and for conversion of the depleting Welton Oilfield (Lincolnshire). Byley was eventually approved by the Secretary of State in May 2004, two years after the initial application. At Preesall, the original application was submitted in November 2003 and, on appeal, went to a Public Inquiry (October 2005–May 2006). The Secretary of State for DCLG finally refused planning permission and hazardous substance consent on 16 October 2007, almost 18 months after the close of the Inquiry. Refusal was based partly upon safety aspects, including risk of gas migration and explosion. Similarly, the application submitted by Star Energy in November 2003 to convert and develop the depleting Welton Oilfield in Lincolnshire as a UGS facility has faced a difficult passage. Despite the widespread opposition to the plan from local residents and parish councils, Lincolnshire Council officials and planners had recommended in favour of the scheme, pointing out that it was in accord with national energy policy and was supported by both the energy regulator and the DTI. No major concerns were expressed over the project by the Environment Agency, English Nature or the Health and Safety Executive. However, at a public meeting in early 2006, councillors went against their officials' recommendation and refused planning permission, citing local fears over health and safety as a main reason for refusal. The arguments and final decision were influenced by perceived risk being based upon analogy with incidents at two American gas storage facilities (LCC 2006). These incidents took place at American salt cavern UGS facilities, circumstances entirely different to that proposed at Welton, a producing oilfield with proven trap and retention capabilities. Although originally scheduled to proceed to Public Inquiry, the operators of the field may attempt to proceed under the existing 1965 Gas Act legislation (Star Energy 2006).

However, the progress of two UGS proposals is noteworthy. An application for a salt cavern storage facility at Stublach (Cheshire) was submitted in December 2005 during the Preesall Public Inquiry. It appeared to signal a change in local government views and had achieved full planning permission and hazardous substance consent by June 2006: both being granted on the basis of national need (Ineos 2006). Similarly, an application to convert the depleted Caythorpe gas field submitted in December 2005, was rejected by the East Riding of Yorkshire Council (ERYC). It went to a Public Inquiry in April–May 2007 and in February 2008 was approved by the ministers of state for CLG and at that time BERR, based in part, on national need (CLG 2008). Even prior to the Canatxx decision, the UK Government had become concerned by the fact that supply infrastructure developers were being faced with increasing risk and delay to proposals and no guarantee that a project would proceed. Government observed ‘It is all too easy to suggest that the need can be met in some other way, or that the project could be located elsewhere. All localities have a part to play in national energy policy. Just as some locations are more suitable for wind farms due to factors such as wind speed, so other localities will be more suitable for gas storage’ (DTI 2006*b*).

Of interest in the Caythorpe inquiry is that case law (the *Newport* case) was held to show that public perception of fear (risk) is capable of being a material consideration in determining planning applications (core documents cited in Newman 2007). A number of factors were seen to demonstrate that local people’s fears for their safety were neither baseless nor unfounded. First, the site would not be COMAH regulated and secondly, ERYC submitted a record of incidents associated with underground gas storage (core documents cited in Newman 2007). However, Ministers of State (CLG/BERR), in line with the Inspector, reached a different conclusion to the Preesall decision, stating ‘that risk cannot be entirely eliminated, but that is true of any form of onshore storage, and there were not such risks to human health and safety as to warrant rejecting this particular site’ (DCLG 2008).

In the event of supply disruption, the lack of storage and increased consumption would leave the UK in a position of great vulnerability. The potential for such a situation was highlighted by difficulties experienced during the winter of 2005/2006, which resulted from a combination of events (Lowery 2006). First, in January 2006, a gas dispute between Russia and the Ukraine led to difficulties in supply to a number of European countries and caused volatility in prices. Within hours, Austria, France, Germany, Hungary, Italy, Poland and Slovakia had all reported pressure drops in pipelines of 30–40%. Secondly, immediately following a fire and explosion at the offshore Rough storage field (the UKs largest gas storage facility) in February 2006, wholesale prices rose by 40%, but dropped back when the extent of the problem on the platform was clarified.

The need for additional gas storage was highlighted following the decision of National Grid to call a Gas Balancing Alert on Monday 13 March 2006 (Lowery 2006). The situation resulted from uncertainty over imports from Norway due to unplanned maintenance on platforms and pipelines and other incidents on the Norwegian Continental Shelf, as well as the prospect of supply disruptions in France due to industrial action. Rising demand and an increased dependence on gas imports when coupled with limited gas storage volumes pose an additional problem to the UK. The lack of gas storage volume means that storage facilities normally filled during off peak summer months (when gas prices are lower) fail to provide an adequate buffer of stored gas. The UK will, therefore, have to buy gas during the high demand winter months, or on the short-term market, when prices are higher. The general public is already suffering from this shortfall in storage volume in rising energy bills and more people could be forced into what the Government call fuel poverty: when households spend more than 10% of their income on fuel to heat their homes adequately (DTI 2003; DEFRA 2004). If the UK encounters harsh winters then the problem could be made much worse.

There are also important safety issues. A shortage of gas, if not managed properly, could give rise to a gas supply emergency. For safety reasons a minimum pressure must be maintained within the National Transmission System (NTS), which requires a balance between gas supply and demand. Put simply, gas taken from the network by consumers has to be replaced by gas flowing into the network from producers, gas processing facilities, storage facilities, interconnector pipelines and LNG import facilities (HSE 2008). It is dangerous if the pressure in the network is too low because appliances may not burn the gas properly, resulting in incomplete combustion and noxious fumes. Alternatively, if the appliance does not have an effective protective device, flames may go out only for the gas to be re-ignited when pressure is restored resulting in a fire or explosion (HSE 2008). In addition, air may enter the system. In the event of supply disruption and a drop in pressure in the NTS, supplies to businesses will be interrupted before domestic customers. In a worst case scenario, whole towns and villages could be progressively disconnected and this could lead to further problems as air may enter the system to mix with the gas resulting in a potentially explosive mix and fatal explosions (House of Lords

2004; HSE 2008). This would result in manpower-intensive and time-consuming procedures, as every supply point must be shut off at the meter. On reinstating the system when sufficient gas is again available, great care would have to be taken with each sub-network, each main and each meter. Furthermore, when a property is reconnected, the fitness of the appliances would also have to be checked (House of Lords 2004). This would result in a slow reconnection of gas supplies, as all premises would require inspection prior to the restoration of supplies.

Government, aware of potential supply problems and that businesses and homes in the UK require a reliable supply of energy that also maintains safety of the operating system, is concerned about delays to delivering gas supply infrastructure. It has already taken steps to increase import capacity and secure supply. This includes improvements to compressors on the existing Zeebrugge interconnector, the construction of the major new Langeled South pipeline from Norway (Ormen Lange field) and, in the southern North Sea, an interconnector pipeline from Bacton to Balgzand (Groningen, Holland). However, Government recognizes that UK applications to develop import and gas storage facilities in suitable areas face major delays in the delivery of important gas supply infrastructure (DTI 2003, 2006*b*, *c*, 2007*b*). Currently these include both local planning controls overseen by the CLG and specialist development consent regimes currently administered by DECC. The need for increased gas supply infrastructure and a regulatory environment to allow such infrastructure to be delivered to the market in a timely fashion was set out by the Government in the Energy White Paper of February 2003: '*Our Energy Future — creating a low carbon economy*' (DTI 2003). This was re-iterated in two further Government papers: '*The Energy Challenge: Energy Review Report*' of July 2006 (DTI 2006*b*) and '*Meeting The Energy Challenge: A White Paper On Energy*' of May 2007 (DTI 2007*a*).

In 2006, the Secretary of State announced plans to review the current regulatory framework in the UK for gas supply infrastructure both onshore and offshore (DTI 2006*b*, *c*). In November 2006, the Government also issued a consultation paper '*Offshore natural gas storage and liquefied natural gas import facilities: Improving the regulatory framework for offshore natural gas storage and offshore LNG unloading*' (DTI 2006*c*), aimed at finding solutions to potential regulatory and licensing problems for the construction of offshore import and storage facilities. Following consideration of responses to this consultation and given the number of parties interested in offshore developments and the UKs need for this new infrastructure, DECC intends that draft legislation be prepared and considered by Parliament as soon as Parliamentary time allows (DTI 2007*b*).

Onshore, Government recognizes the importance of local democracy in the decision-making process and that stakeholders' views must be taken into account. However, it also states that a rigorous planning system must enable decisions to be taken in a reasonable time, with a balance being struck between the concerns of local authorities and those that they represent and the national need for infrastructure that will provide us all with secure energy supplies. Indeed the Office of the Deputy Prime Minister (ODPM and now the CLG) Planning Policy Statement 1 recommends that planning authorities should 'recognise the wider sub regional, regional or national benefits of economic development and consider these alongside any adverse local impacts' (ODPM 2005). Government further states 'New energy infrastructure projects may not always appear to convey any particular local benefit, but they provide crucial national benefits, which all localities share. In particular, projects add to the reliability of national energy supply, from which every user of the system benefits' (DTI 2006*d*). However, any changes to the system designed to speed up the process must ensure that the safety of operations is addressed at all times. These operations are covered by existing HSE and COMAH regulations (HSE 2006*a*, *b*).

The Government is, therefore, consulting on proposals to address the need for a simplification of the onshore gas planning regime as part of the 2007 White Paper, *Planning for a Sustainable Future* (DCLG 2007). This sets out proposals for the new planning system and for rationalizing the regime for nationally significant gas supply infrastructure projects in England. Government took a significant step in this process on 25 June 2008 when Members of Parliament voted to speed up the planning process by creating a new infrastructure planning commission (IPC). The commission will have key powers on big projects such as nuclear plants or airport extensions (Webster & Elliot 2008). National policy statements will set out the country's requirements for key infrastructure projects and will be the subject of a 'national debate', with public and parliamentary involvement, which would then provide a framework for the commission to make decisions about individual projects. The commission could, therefore, also be required to rule on proposed UGS facilities.

Geological storage options

There are a number of ways in which hydrocarbons (including natural gas) and other energy carriers such as hydrogen or compressed air can be stored underground. The main forms relevant to natural gas storage in the UK are pore storage in reservoir rocks (depleted oil/gas fields or aquifers) and bulk storage in man-made caverns, primarily in salt, although storage has been successfully undertaken in other rocks. **Plaat** describes and reviews the nature of storage offered by the various forms of underground geological repository. In addition to those outlined by **Plaat**, other less frequently used options are available including abandoned mine storage. Although hydrocarbons have been stored in the latter, for example in America (abandoned coal mine) and France (abandoned iron ore mine), most facilities have closed due to leakage of the stored product through the caprock (e.g. Raven Ridge Resources 1998; Piessens & Dusar 2003). A little known storage facility was constructed about 180 m below ground in the Chalk at Killingholme in North Lincolnshire. Opened in 1985, liquefied petroleum gas (LPG) is stored and retained in man-made caverns by hydrostatic pressure (Trotter *et al.* 1985; Geological Society 1985).

For a number of reasons, halite (rock salt) represents a unique host material for the development of large man-made caverns at depths of 300–2000 m. These caverns offer important storage space for materials that do not themselves dissolve salt. Worldwide, salt mines and many thousands of caverns are used for the storage of a variety of products. The British and European standard for gas storage BS EN1918-3:1998 (BS 1998*b*) recognizes the efficacy of salt storage, due to its impermeable and visco-plastic properties. Caverns specifically engineered and constructed in halite offer important storage volumes that may be used for the storage of liquid (oil, natural gas liquids (NGLs and liquefied petroleum gas (LPG)) or gaseous hydrocarbons, hydrogen, compressed air (e.g. Crotogino *et al.* 2001; Leith 2001; Cheung *et al.* 2003), paper and magnetic records. Thousands of caverns are being used to store hydrocarbons worldwide with around 100 in France alone (Bérest & Brouard 2003). A total of 66 facilities with around 396 caverns are used for storing natural gas (IGU 2006). They provide an important component of a storage portfolio, offering short to medium term, high deliverability options within and complementing the longer-term seasonal storage offered by pore storage facilities (**Plaat**).

Salt caverns may also be used for the disposal of (generally solid) waste materials and radioactive waste (e.g. Veil *et al.* 1998). In the United States and Russia caverns have been used for the underground testing of munitions and nuclear weapons (Thoms & Gehle 2000; Leith 2001). Salt caverns may also have a use in the storage of carbon dioxide (Dusseault *et al.* 2001, 2002; Shi & Durucan 2005), although this does not represent a particularly sustainable use of the halite storage resource.

The UK has important oilfields and salt deposits both onshore and offshore. Onshore, two operational gas storage facilities are developed in the depleted Hatfield Moors gas field, converted to a gas storage facility during 2000 (Ward *et al.* 2003) and the Humbly Grove oilfield, which commenced operation in November 2005. A variety of hydrocarbons are also stored in operational salt cavern facilities in the Cheshire Basin and in NE England. UK geology would thus permit a significant volume of natural gas to be stored underground in a variety of subsurface facilities, providing a blend of longer- and shorter-term storage to meet the differing supply demands. The development and distribution of halite beds onshore UK and the locations of currently operational and planned gas storage cavern facilities are outlined by **Evans & Holloway**.

Environmental issues

Alongside safety issues, initial environmental review is key to gaining public acceptance of new underground gas storage facilities. Experience of UGS in the UK is limited and there are few published examples relating to environmental issues in other UGS developments. The Wild Goose Gas Storage Field in California illustrates the benefits of carrying out a thorough environmental review. In this case, permits were approved without opposition (**McClenahan-Hietter**). Key factors for success are described and the approach to environmental review can be a model for the process of granting permits to other fields, serving to reduce schedules, costs and risks when considering new storage fields.

A case study is presented for the environmental and safety monitoring of a natural gas underground storage facility at Stenlille, Denmark (**Laier & Øbro**). For safety reasons and to protect the environment it is necessary to monitor the storage operation carefully. Occasional higher concentrations of dissolved methane have been encountered in shallow observation wells. However, stable isotope analyses and radiocarbon dating show that the gas does not originate from the underground gas storage operations but is instead the result of local microbial activity. It shows the benefits of soil gas monitoring above a UGS site, with implications for safety (see below).

Gas tightness, safety and monitoring of underground storage operations

As stated previously, many local residents close to proposed underground gas storage facilities raise questions over the safety of UGS operations. As part of this opposition, one or two isolated incidents that have led to a number of fatalities are commonly cited. Most infamously at Hutchinson (Kansas), gas escaped from a salt cavern via a damaged well and migrated some 14 km to the town of Hutchinson, where it emerged at the surface via old disused brine wells, causing gas geysers around the town. One at a caravan park ignited, killing two people (Allison 2001*a*, *b*; Watney *et al.* 2003; Nissen *et al.* 2004). Hutchinson and other incidents at salt cavern storage facilities, generally in the United States, are cited by most action groups opposed to the development of storage facilities (including pore-space ones) as reason enough to refuse permission on safety grounds. However, the two storage options represent very different storage environments with operational differences and should not be compared in such a way.

Gas tightness, safety and the monitoring of underground storage infrastructure, particularly wells, are all of great importance. If most of the rock formations around the wellbore are impermeable, the situation is favourable. Soft-impermeable formations can have a very beneficial effect in that they creep naturally and tend to tighten around the well, improving the bond between the cement and the casing. For example, the salt layers in which the Tersanne natural gas facility is developed in France are overlain by 600 m of predominantly clayey strata. Geophysical logs have revealed a significant improvement in well conditions over time, which is attributed to clay creep (Bérest *et al.* 2001).

In depleted oil or gas fields, exploration and development wells form the principal breaches of the original caprock, and provide the main potential pathways for stored gas to migrate back to surface. This has proved to be a problem in California where many wells were drilled during the early years of exploration at the end of the nineteenth and beginning of the twentieth centuries. Their locations are often not well documented and many were not properly completed, even to past regulatory standards. Their condition may well be poor and permit the leakage of gas. The Mont Belvieu incident in 1980 was related to a well that dated from 1958 and illustrates a lesson that concerns the lifespan of wells. The well performed satisfactorily for 22 years with a leak occurring subsequently (Bérest *et al.* 2001). **Miyazaki** reviews well problems and explains that even modern well completions suffer deterioration perhaps more quickly than might be expected.

In the UK, oil and gas exploration onshore does not have the history of intense activity seen in parts of the United States. The systematic search for oil in Britain commenced at Hardstoft (Derbyshire) in October 1918. This was the first of a number of exploration wells drilled by D'Arcy (the forerunner of BP) in the period 1918–1920. Prior to this, drilling had taken place for water and mineral (coal, iron ore etc.) exploration purposes. A second phase of onshore drilling took place in the mid–late 1930s when many of the oilfields in the East Midlands were discovered. Since then, exploration has continued sporadically and the locations of exploration and production wells are generally well known. Many recent onshore hydrocarbon fields do not have the density of exploration wells as is often found in earlier phases of exploration. Modern drilling techniques have allowed multiple wells to be drilled directionally from just one or two platforms and from which the fields are produced. Provided locations are known, remediation of old wells can be undertaken to improve their integrity, prior to storage operations.

Salt caverns are cavities that are connected to the surface through a cased and cemented well. There may be one or more casing strings set in the well to allow injection or withdrawal of fluids into or from the cavern. The well represents the main problem in the escape of hydrocarbons both when injecting into and producing from the cavity (Bérest *et al.* 2001). Gas tightness is clearly a fundamental prerequisite for these cavities and storage wells are generally completed to a higher standard than is typical in ordinary oil-industry operations. This is achieved through carefully designed drilling programs and brining operations, and good grouting and fixing of the well casing and cement, particularly in the vulnerable salt roof above the cavern.

Many old brine wells and caverns created during brine extraction for the chemical industry were not designed or constructed with gas storage in mind, and were not subject to the design criteria of modern day gas storage caverns. The latter can be constructed within very exact tolerances, with sizes and shapes monitored accurately by sonar techniques. **Lux** reviews the current developments in salt cavity design, with sections covering the geomechanical characteristics of storage cavities, principal safety demands for their design and recent design concepts. Also covered are geotechnical methods for assessing cavern safety including criteria for determining operational pressure ranges and safety margin and abandonment procedures.

Halite beds or salt domes present a corrosive environment to both well casings and cements and may lead to problems during drilling or completion of a gas tight well. This is particularly so if water is present. Shallow halite beds may be dissolved by circulating groundwater resulting in a zone of wet rock head with collapse breccias. Salt domes in the United States are often overlain by a very permeable zone (caprock) of solution breccia, through which brine circulates and that may lead to a number of problems with any wellbores. Problems may occur due to ground instability and there may be issues with achieving good cementing and completion of wells. Important bedded halite deposits are present onshore in the UK but there are no known salt domes. These are restricted to the offshore in, for example, the southern North Sea, and any potential problems might need to be evaluated if such deposits are to be exploited. The depth and development of wet rock head in onshore salt deposits is reviewed in **Evans & Holloway**, providing an indication of locations where halite beds are probably too shallow to be developed for gas storage purposes.

For salt cavern storage, therefore, an important pre-storage stage is the mechanical integrity test (MIT). During this stage of development, the gas tightness of the newly created cavern (in effect a large pressure vessel) is tested by raising the pressure in the cavern and shutting-in the well to observe any variations in pressure over a period of time. Pressure cycling is also required to subject the cavern to storage conditions and test for damage to the cavern walls. The selection of maximum pressure is based upon rock mechanical tests of the halite, the depth of the cavern (thickness of overburden) and temperature. The depressurization rate during withdrawal must also be carefully calculated in order to avoid inducing large tensile stresses that can be damaging to the rock formation or cemented wells.

A variety of integrity tests are available with the most widely used method worldwide being the *In Situ* Balance method (ISB). However, this can be associated with errors. **Tryller, Reitze & Crotogino** present a method (SoMIT) based on ultrasonic techniques in which the interface depth, the temperature and the differential pressure at the interface depth can be measured continuously during the tightness test, thereby achieving much greater levels of accuracy to verify gas tightness than was previously the case.

Leakage of stored gas cannot always be ruled out and operators accept there are likely to be losses from storage, with operations and budgets calculated accordingly. From the economic viewpoint, viability of storage depends fundamentally on the speed of the stock rotation and the nature of the products stored. When storing compressed air to absorb daily excess electric power, for example, a loss of 1% per day is considered reasonable. But when storing oil for strategic reasons, a loss of 1% per year would be regarded as a maximum acceptable value (Bérest *et al.* 2001). From the safety viewpoint, it must be shown that any hydrocarbon product migrating from storage does not accumulate to dangerous levels in other strata, or leak to surface where it may build up in buildings.

It is, therefore, important to have detection equipment and procedures in place for dealing with any leakage of stored product. As described above, monitoring of the natural gas aquifer storage facility at Stenlille, Denmark not only illustrates the importance of monitoring with respect to safety, but also to environmental issues (**Laier & Øbro**). The facility, operational since 1989, provides an important example of the role of baseline studies and ongoing monitoring for gases following the commencement of storage operations. The soil gas monitoring programme at the Weyburn Oilfield (**Riding & Rochelle**) where CO_2 is injected both for storage and for enhanced oil recovery, has obtained baseline and post-injection soil gas survey data. These indicate a shallow biological origin for the measured CO_2 in soil gases and no evidence for leakage of the injected CO_2 to ground level. Furthermore, the long-term safety and performance of CO_2 storage was assessed by the construction of a 'features, events and processes' (FEP) risk database that provides a comprehensive knowledge base for the geological storage of CO_2.

A number of incidents at underground fuel storage (UFS) facilities have led to fatalities, casualties and damage to property, either connected to the storage facility or to surrounding developments (**Evans**). The incidents have been highlighted by objectors to the development of UGS facilities and are used to question the safety of virtually all proposed UGS facilities onshore UK. This volume carries a paper by a Local District Councillor (**Davidson**) who has been involved in the process of assessing a proposal for UGS at the depleting Welton Oilfield. **Davidson** is able to convey first hand experience of not just the current planning and application process, but the feelings and fears expressed by local residents opposed to such developments in close proximity to their communities.

Regarding the relative safety of UFS and UGS, **Evans** provides an extensive literature and web-sourced review of documented incidents or problems that have been encountered at UFS facilities. The numbers of incidents, fatalities and casualties reported at UFS facilities are compared with those sustained in other areas of the energy supply chain, particularly in connection with above ground infrastructure. The casualty figures for UGS are orders of magnitude smaller than those found in other areas of the energy supply chain. This perhaps lends support to claims that salt caverns provide the safest form of storage for large volumes of hydrocarbons (Bérest *et al.* 2001; Bérest & Brouard 2003), and that underground gas storage as well as oil and gas production can be conducted safely if proper procedures are followed (Chilingar & Endres 2005). Far graver consequences and much higher death rates are associated with incidents at, for example, above ground fuel storage tanks (Persson & Lönnermark 2004) or elsewhere in the energy supply chain (**Evans**). These figures may help to allay some of the fears expressed by local residents opposed to UGS facilities.

Other gas storage scenarios

Pore storage and salt cavern facilities offer potential for the storage of a number of other gases, including compressed air energy storage (CAES), possibly linked to renewable sources such as wind or water. The technological concept of CAES is more than 30 years old (Glendenning 1981), with the first CAES facility commissioned in Germany in 1978, using caverns created in the Huntorf salt dome near Hamburg for storage (Glendenning 1981; Thoms & Gehle 2000; Crotogino *et al.* 2001; Cheung *et al.* 2003). Hydroelectric power plants have, for many years, been used to store excess off-peak (night-time and weekends) power and provide increased peak time output. CAES facilities likewise provide the potential to store energy and could be used alongside, for example, wind turbines. Though instances of this technology are not numerous, it is likely that CAES will assume a greater importance as energy markets evolve. If widespread renewable energy is to become reality, then the utility industry might have to consider more options for energy storage including compressed air (Schaber *et al.* 2004). Distributed generation and microgrids in which small CAES plants play an important role might facilitate such a system.

Although a highly mobile molecule, hydrogen may also be stored underground, with former brine caverns already in use on Teesside. **Stone *et al.*** examine the potential for large-scale underground hydrogen storage in halite (rock salt) deposits onshore in the UK. They consider the technical, geological and physical issues of storage, the locations of salt deposits and both legal and economic aspects. Given the greater flexibility in terms of injection and withdrawal rates, most potential for compressed air and hydrogen storage is probably provided by salt caverns. However, storage in highly porous and permeable rocks is possible and is being considered in the UK.

The UK Government has recently announced targets for stringent reductions in the UKs greenhouse gas emissions in the coming decades. In addition to this, the recent renewed focus on the security of energy supply has raised the likelihood that a new generation of coal-fired power stations will be built. For such a step to be environmentally viable, clean-coal technologies with near-zero greenhouse gas emissions will be required. A key component of this strategy is the large-scale deployment of underground CO_2 storage.

A number of current research and demonstration projects are investigating the injection and long-term underground storage of CO_2 worldwide. Most current research and operational programmes are focused on pore-space storage, including depleted oil fields (where CO_2 might provide a period of enhanced oil recovery), gas fields and saline aquifers.

Aspects of two industrial-scale CO_2 injection projects currently in operation and using reservoir pore space are described, with an emphasis on how such storage sites can be monitored to ensure storage security and safety. Both studies illustrate the feasibility of underground storage and how injected volumes can be monitored and verified with the application of sophisticated geophysical and geochemical techniques. Anthropogenic CO_2 is being injected as part of a commercial enhanced oil recovery (EOR) operation into a carbonate reservoir at Weyburn in Canada. **Riding & Rochelle** describe various aspects of the storage operation related to containment integrity: geological characterization, long-term geochemical performance of the caprock and results from a suite of monitoring surveys. A diverse portfolio of potential monitoring tools is available for monitoring CO_2 storage sites, some tried and tested in the oil industry, others as yet unproven. **Chadwick *et al.*** describe the type of monitoring programme that may be required by future regulatory regimes to prove efficacy in emissions reduction and to ensure site safety and integrity. Specific reference is made to monitoring at the ongoing CO_2 injection and storage operations at the Sleipner field in the North Sea. Here time-lapse 3D seismic and time-lapse gravimetry are proving successful in imaging and characterizing the CO_2 plume in the storage reservoir. It is concluded that the technical nature and duration of storage site monitoring programmes are likely to be highly site specific, but they are essential to provide an acceptable basis for site closure.

Summary

In the current energy climate, with rising concerns about security of supply, environmental degradation and rising costs, this publication is most timely. The development of UGS, underground CO_2 storage and the storage of other gases including compressed air and halogen, will play a key role as energy technology evolves in the coming decades. Many of the issues that arise during the planning and construction phases of UGS sites are covered, including the important and related aspects of safety and public confidence. The lessons learned from ongoing research into CO_2 storage may provide valuable input into the planning, development and ultimately the abandonment procedures of UGS facilities that are only just being developed in the UK. This publication should, therefore, prove of interest to developers, planners and local communities as we encounter new issues in the energy landscape of the twenty-first century.

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