Environment Agency

The geomechanics of hydrogen storage in salt caverns: environmental considerations

Chief Scientist’s Group report

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Dr Robert Bradburne
Chief Scientist

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Executive summary

The path to Net Zero[1] emissions will require a transition to renewable technologies to generate energy. Hydrogen will likely play a key role in the transition, as both an energy source and for storing surplus energy generated from renewable and other low carbon sources.

Hydrogen is useful for storing energy as it has a high specific energy (energy per unit mass). However, it has a low energy density (energy per unit volume), which means it requires more storage space than methane for the equivalent quantity of energy. Significant storage capacity will be needed for energy storage with hydrogen.

Using salt caverns (cavities leached from salt deposits in the subsurface) for gas storage is an established technology. Salt caverns are good for storing gas because they have a very low permeability and cracks or fractures can re-seal to prevent leakage. The UK has salt deposits that are suitable for cavern storage and that have been used store natural gas since the 1960s. Hydrogen, used as a chemical feedstock, has been stored in salt caverns in Teesside since the 1970s.

Geomechanical failure of a salt cavern could lead to geological impacts, such as ground movement (subsidence) and/or some seismic activity. Failure could also result in the release of hydrogen from the borehole or the cavern. Hydrogen is a small, highly mobile molecule so can travel easily within the environment once it is released. The ultimate receptors for gas releases are either the geology, ground- or surface water, or the air. Hydrogen is flammable, and due to its mobility, will disperse quickly in air, unless it is contained, where it is also a secondary greenhouse gas.

The use of hydrogen to balance energy supply and demand would not only require additional storage facilities but would also require different operational management of salt caverns, with higher frequency injection and production cycles than for use as a feedstock or longer-term storage of methane. At present, little is known about the impact of these ‘fast’ cycles on salt cavern integrity.

This report summarises a literature review and supplementary discussions with experts working in the industry and Environment Agency that were conducted to understand the geomechanical impacts of using salt cavern storage for hydrogen to meet our fluctuating daily and seasonal energy supply and demand as part of the energy transition.

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[1] In 2019 the UK became the first major economy to pass laws to reach Net Zero emissions by 2050. This means the amount of emissions removed from the environment by the UK will be equal to, or greater than, the amount produced in the UK. [UK becomes first major economy to pass net zero emissions law - GOV.UK]

The report discusses geomechanical considerations throughout the lifetime of a salt cavern, from planning to eventual decommissioning, including; design and construction factors, such as the size, shape and positioning of the salt cavern, both within the geological formation and relative to nearby caverns; the geomechanical impacts of operational requirements in terms of pressure, temperature and injection-production cycling; and decommissioning considerations, particularly in relation to pressure and temperature.

The report draws upon historical examples to highlight geomechanical considerations in salt cavern storage but also provides mitigation and monitoring strategies that reduce the risk of environmental impact. The report highlights the need for further research to be conducted into the effects of frequent cycling, in relation to temperature and pressure, on salt behaviour and cavern security.

Introduction to underground hydrogen storage

The Environment Agency is responsible for protecting and enhancing the environment[2]. This includes managing the environmental risks associated with the implementation of a Net Zero economy, of which hydrogen is likely to be a significant component (DESNZ, 2023). Storage is an integral part of the hydrogen supply chain and salt cavern storage is likely to be the first technology capable of providing this amenity on a large scale (TWh/PJ-scale). Caverns created through salt leaching, with a capacity up to several million cubic metres, have been used for natural gas storage since the 1960s (Evans, 2008). Salt is effective for storing hydrogen because it is almost impermeable to gas and can self-heal due to its ductility. However, caverns have not been used for hydrogen storage at the scale needed for the energy transition, and will be required to operate differently than existing use cases, as demand for hydrogen increases. This report investigates the geomechanics of salt caverns, and potential environmental impacts, in light of an increase in scale and a change in demands.

This report combines information from literature about salt caverns (academic papers and reports from industry and statutory organisations) with knowledge from industry professionals, regulators and academics, obtained through interviews, to provide a current understanding of possible geomechanical impacts of storing hydrogen in salt caverns. The report includes a source-pathway-receptor table to map potential environmental impacts, considers ways of mitigating and monitoring the impacts and highlights knowledge gaps.

Overview of the need for underground hydrogen storage (UHS)

Meeting the challenge of Net Zero requires a switch to low and zero-emitting greenhouse gas (GHG) fuel sources, including hydrogen (IPCC, 2023). Hydrogen is a suitable fuel for large-scale transport (such as shipping, buses and HGVs), certain industrial processes (including production of ammonia or steel), domestic heating and storing energy for reconversion to electricity (IEA, 2023). To balance our daily and seasonal demand for energy with the fluctuations in energy supply, particularly from renewables, TWh/PJ-scale storage will be necessary (DESNZ, 2021). Hydrogen has already been stored in salt caverns in the UK and it is this technology that is most advanced in meeting the storage needs at the desired scale (DESNZ, 2021). Several of the industrial clusters (East Coast cluster, comprised of the Humber and Teesside clusters, North West cluster and Solent

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[2] Environment Agency: EA2025 creating a better place - GOV.UK

Cluster) are planning to employ this technology to reduce their greenhouse gas emissions (ARUP, 2024; HyNet, 2024; UKEnergy storage, 2024).

Storage in salt caverns

Salt deposits in the UK

The UK has two main rock groups that contain salt (Figure 1). The older, and generally deeper, salt was deposited during the Permian (298.9 Ma to 251.9 Ma). It is part of the Zechstein Group, contained within the South Permian Basin, that covers northern Europe and reaches the east coast of the UK, principally north of the Humber but spans southwards to North Lincolnshire (Evans, 2008; Daniels et al., 2023). The Triassic period salt (251.9 Ma to 201.4 Ma) is part of the Mercian Mudstone Group (MMG). The MMG salts are found in the west of the UK, from Larne, Northern Ireland, through the Cheshire Basin down to the Wessex Basin on the south coast (Daniels et al., 2023).

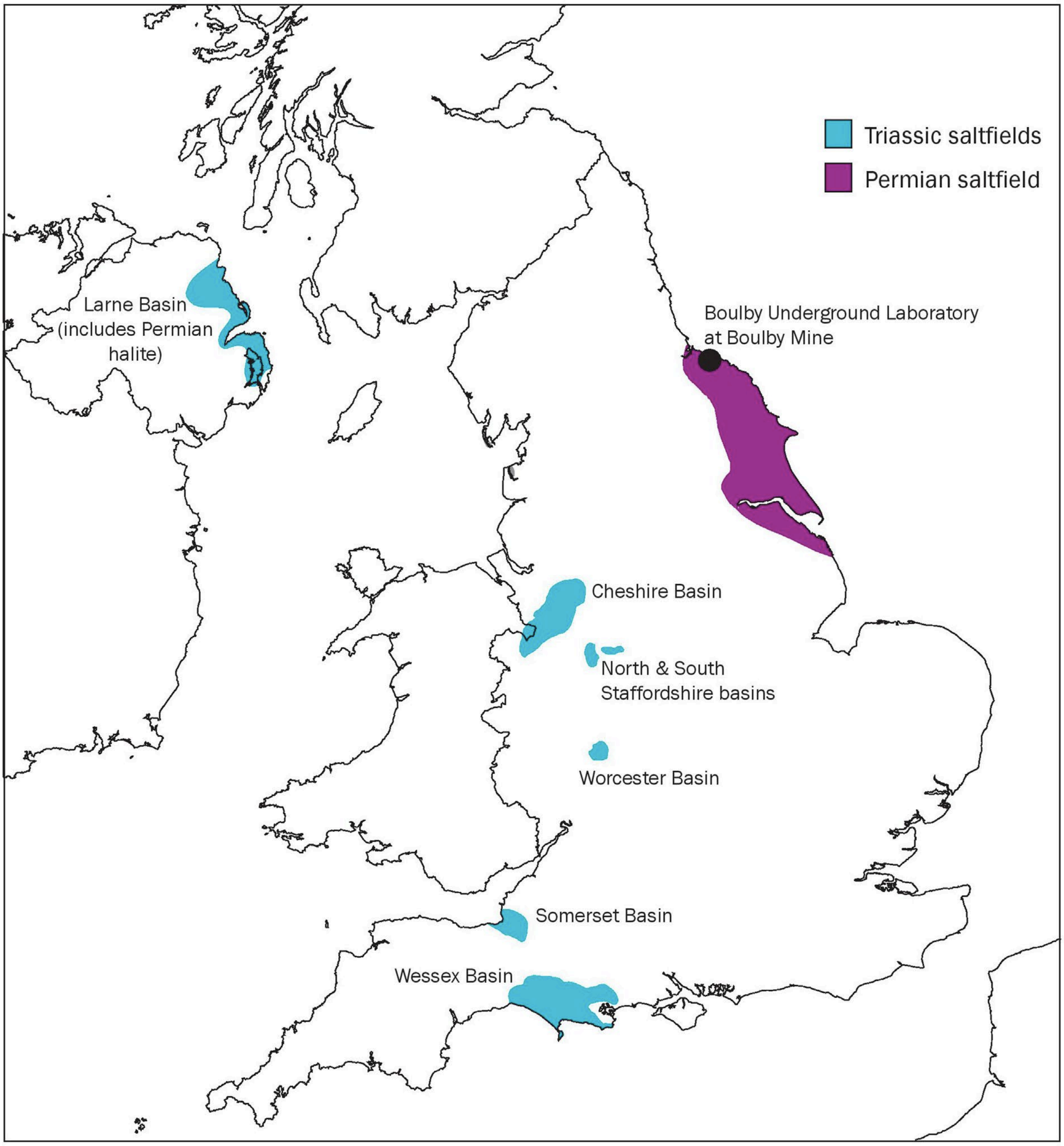

Figure 1: The UK's Permian and Triassic Saltfields (from Daniels et al., 2023)

Onshore in the UK, both rock groups contain bedded salts, as opposed to diapiric salt (salt domes), which occur in the North Sea (Williams et al., 2022). Bedded salt consists of layers of salt interspersed with non-salt deposits, such as mudstones, anhydrite and dolomite (Evans, 2008). Non-salt deposits can be insoluble and create challenges when solution mining salt caverns, i.e. leaching salt with water via a borehole. This is especially true of gypsum and anhydrite, both of which are species of calcium sulphate ($CaSO_4$). These species are soluble, particularly in flowing water, but the dissolution is much slower than for the salt. In addition, gypsum contains water, which is released as it converts to anhydrite at higher temperatures, usually at depths of more than 1000 m (Evans, 2008). The conversion is accompanied by a volume change (anhydrite is about 60% of the volume of gypsum), which may cause fractures in the surrounding rock. In addition, the released water can dissolve surrounding salts, leaving empty spaces in the rock, which may contain gases (Evans, 2008). The process is reversed if anhydrite comes into contact with water at a low enough temperature (somewhere between 42 to 60 °C) (Evans, 2008).

The Zechstein salt is partitioned into five layers, Z1 to Z5, oldest to youngest, respectively (Figure 2). There are currently salt storage caverns within the Fordon Evaporite Formation (Z2, at more than 500 m depth inland but deepening to more than 1500 m towards the coast) and the Boulby Halite Formation (within Z3, between 274 and 366 m depth) (Williams et al., 2022; ARUP, 2024). The Fordon Evaporite hosts caverns at Aldbrough and Hornsea (both at more than 1600 m depth) and the Boulby Halite contains the Teesside salt caverns at Wilton and Saltholme (Evans, 2008; Williams et al., 2022).

The Triassic MMG is about 1200 m thick, however salt is a minor constituent of this sequence. In the northwest, two significant halite formations are the Northwich Halite, in the Cheshire Basin, and the equivalent Preesall Halite, further north in the Fylde area of the East Irish Sea Basin (Evans, 2008; Willliams et al., 2022) (Figure 2). The former deepens to about 1500 m at its southeast edge and is a maximum of about 300 m thick, however, contained within this is a 10 m marlstone sequence (known as the ’thirty-foot marl’) (Evans, 2008). Where boreholes have been drilled through the Preesall Halite, to extract brine, it is generally between 100 – 135 m thick although it thickens to in excess of 200m thick in the west. The top of the Preesall Halite is found at depths of more than 100 m in the east and deepens to 350 m in the west (Evans and Holloway, 2009).

In the south of England, the Dorset Halite (400 to 2000 m depth and over 400 m at its thickest) provides potential for salt caverns (Figure 2). However, it is more structurally complex than the halite in the northeast and northwest, with widely varying thicknesses and many mudstone interbeds, which may make creating caverns more challenging (Evans and Holloway, 2009; Williams et al., 2022).

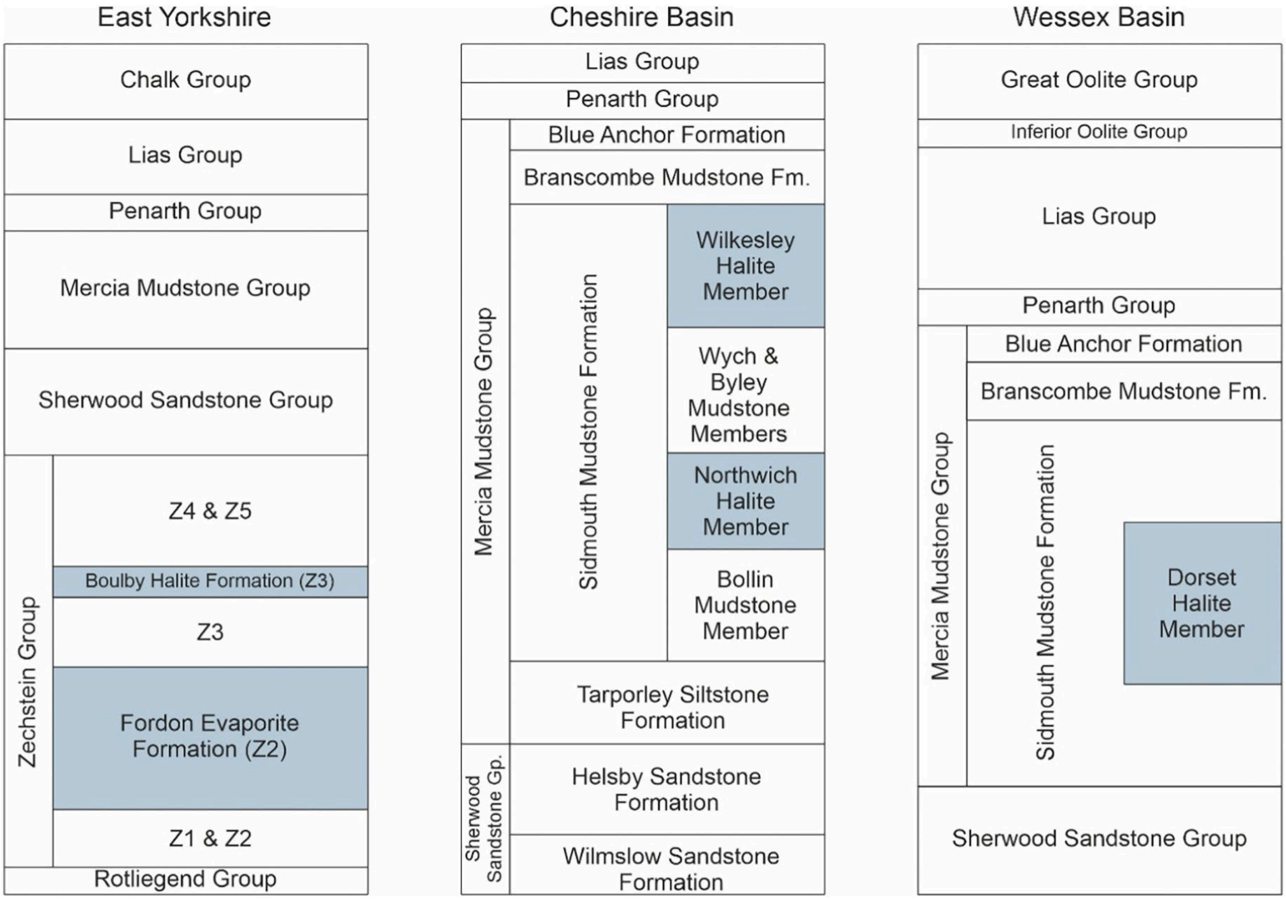

Figure 2: Representative stratigraphy from the three regions in the UK with salt formations that could be developed for hydrogen storage (in blue) (from Williams et al., 2022).

Williams et al. (2022) consider that the Fordon Evaporite in the northeast has the greatest potential for large-scale UHS, due to its thickness (in excess of 300 m in places) and depth, since the additional pressure allows more gas to be stored.

Overview of properties of salt

The two properties that make salt attractive for hydrogen storage are that it has very low permeability and that it moves or flows, this is sometimes termed salt creep (Forbes-Inskip and Ougier-Simonin, 2021). Salt flow on a large scale is called halokinesis, a process driven by the relatively low density of salt, as it will want to rise above denser rock, which is enabled by its ductility. Halokinesis is the reason for the creation of diapirs, domes of salt that have migrated upwards, changing the form of the salt and the structure of the subsurface around it over geological timescales. Salt creep enables the salt to repair any fractures that form as a result of stress over time, however, it also means that any cavities in the subsurface will close over time unless the pressure in the cavern is equalised with the surrounding rock (geostatic pressure). Both an increase in temperature and pressure increase salt flow rate, which in turn affect the cavern closure rate. Therefore, the depth of a cavern is important to the behaviour of the salt, since both temperature and pressure increase with depth. It is for this reason of stability, as well as the increased cost of development and maintenance for deeper caverns, that most salt caverns are shallower than 2000 m (Warren, 2016; ARUP, 2024).

Conversely, if a salt cavern is too shallow it may be vulnerable to loss of integrity as the thickness of salt and other rock above the cavern roof may not provide sufficient strength to maintain cavern structure (Warren, 2016). A lack of salt rock at the top of the cavern, and strength from other geology above it, can result in vertical fractures (termed chimneying), roof fall and ultimately subsidence may occur at the surface. In addition, at shallower depths, there is a higher likelihood of encountering groundwater (Warren, 2016). Groundwater is often found in shallower layers that previously contained halite (now dissolved). The remaining rock mostly consists of non-soluble material, such as mudstones (often termed wet rockhead), which may extend over 100 m into the subsurface allowing water to permeate to the deeper salt layers (Evans, 2008). The groundwater not only dissolves remaining salt, but also facilitates salt flow (pressure-solution creep). Only very low volumes of water are required for this process (Cornet et al., 2018).

Shallow caverns also do not benefit from the additional geostatic pressure that can increase storage capacity, as mentioned above. Therefore, there is a generally accepted preferred depth of between 600 and 1700 m for salt caverns, although the actual depths that salt caverns are created range between 200 and 2000 m (Williams et al., 2022; ARUP, 2024).

Halite or rock salt (NaCl) is the most common and most utilised type of salt for caverns. Other salts, such as sylvite or carnallite, both compounds containing potassium chloride (KCl) and therefore types of potash, can be more soluble (which can cause problems when creating and operating a cavern as they distort the cavern shape); these are principally found in the Permian formations (Evans, 2008; Daniels et al., 2023). As salt is an evaporite, the most soluble salts are at the top of each sequence as they were the last to be deposited.

Gas storage in salt caverns – the current situation

Salt cavities have been created in the UK since the 19th century to extract rock salt from the subsurface; Winsford mine in Cheshire has been mined since 1844 using a room and pillar (20 m x 20 m) method (Highley et al., 2006). Salt caverns have also been used to store fluids that do not dissolve salt, and some solids, since the mid-20th Century (Evans, 2008). Globally, stored materials include liquid petroleum gas, crude oil, waste materials, compressed air and natural gas (methane, CH_4). Originally old brine caverns were repurposed for storage, however, cavern storage is now created with the intention for storing fluids and the cavern specifications are matched to the geomechanical demands of the stored fluid and its use (quantity and frequency of injection and production; Evans, 2008). A list of the current upper-tier Control of Major Accident Hazards (COMAH) salt cavern storage sites, i.e. those that store more than 50 tonnes of hydrogen, are contained in Appendix A.

Solution mining is the current method of creating salt caverns, this is the controlled injection of water into a well to dissolve the salt (Zivar et al., 2021). As a guideline, it takes about 7 m^3 of fresh water to dissolve 1 m^3 of salt (Evans, 2008). During the dissolution process, a fluid blanket, often nitrogen or compressed air, is injected to prevent further dissolution of the salt at the top of the cavern. This reduces the risk of roof collapse and protects the well casing while the cavern continues to be enlarged (Evans, 2008). The extracted brine can either be used as a chemical feedstock or be disposed of (subject to environmental regulations) once insoluble particles have been allowed to settle out (Evans, 2008). It is not possible to extract all the brine, and some highly saline brine remains, with any insoluble material that is not produced with the extracted brine, in the base of the cavern (the sump).

The first salt caverns to store hydrogen were constructed in Teesside in 1971, although these caverns have recently been emptied of hydrogen and filled with brine (Crotogino et al., 2018; pers. comm. Simon Mann, 20 August 2024). In 2024, the UK capacity for hydrogen storage in salt caverns was about 25 GWh (Williams et al., 2022). Two further hydrogen storage salt cavern arrays are planned, at the HyKeuper and Aldbrough facilities, which would add a further 1.5 TWh storage (ARUP, 2024).

In a desk analysis of salt storage capacity, Williams et al. (2022), found that the UK had the potential to store 2150 TWh (64 million tonnes of hydrogen) in salt caverns in the three main geographical areas with salt deposits i.e. northeast (East Yorkshire, Humber and the North Sea), northwest (Cheshire and East Irish Sea basins) and the Wessex basin. They predict that about 13,100 caverns would be required to create this capacity. As stated previously, the Fordon Evaporite in East Yorkshire was considered to have the largest potential storage capacity. A report by ARUP for the East Coast Cluster (ARUP, 2024) challenges the finding and arrives at a more conservative 22 – 48 TWh for the east coast region, compared to 747 – 1465 TWh predicted by Williams et al. (2022) for the same region: the lower and higher values relate to the potential spacing of the caverns (see pillar width, below).

The lifetime of a salt cavern is usually measured in decades; the same hydrogen storage salt caverns in Teesside were operational for about 50 years (Crotogino et al., 2018; Forbes-Inskip and Ougier-Simonin, 2021). At the end of their life, caverns can either be temporarily shut-in or decommissioned, at which point they are filled with brine and plugged (see below).

Hydrogen

Hydrogen is the smallest and lightest molecule (2.016 g mol^{-1}, compared with methane at 16.043 g mol^{-1}) and is therefore highly mobile and buoyant. It has a high specific energy, with an energy per unit mass of 142.2 MJ kg^{-1} (compared with 54.0 MJ kg^{-1} for methane) at standard temperature and pressure. However, it has a lower energy density, energy per unit volume, than methane (12.79 MJ m^{-3} compared with 40.39 MJ m^{-3} at standard temperature and pressure). The energy density is the reason that more storage capacity is needed for hydrogen for the same energy content, compared to methane (natural gas).

Hydrogen has a higher flammability range than methane (4 to 75% compared to 4.4 to 16.4% respectively, both at 20°C). This relates to the concentration of the gas in air, above and below which the gas cannot ignite. However, unless hydrogen is contained, its high mobility means that it tends to disperse quickly.

Hydrogen has a relatively low solubility in water (0.0016 g kg^{-1} at 20°C at 1 atm, reducing as temperature increases), which is more than an order of magnitude lower than the solubility of methane in water (The Engineering Toolbox, 2008). This is important in case there is a hydrogen leakage from the storage facility, particularly if the gas encounters ground and surface water.

Although hydrogen is not a greenhouse gas, it impacts upon ozone, the lifetime of methane, the production of water vapour in the stratosphere, and the production of aerosols (Sand et al., 2023). It therefore has a secondary impact upon global warming, albeit its lifetime in the atmosphere is short-lived (about 2 years), and so leakages should be minimised.

Research questions and project scope

This report addresses the following questions:

- How do the pressures and cyclicity of hydrogen storage compare with storage of other gases in salt caverns?
- Has geomechanical failure or leakage occurred from salt caverns in the past? What were the reasons for this and the consequences?
- What are the environmental risks of geomechanical failure from hydrogen storage? How might these be mitigated?

A literature review was undertaken to understand the processes and challenges of creating, operating and monitoring salt caverns to store hydrogen. The literature review included a search of the published literature using the Web of Science. A ‘snowball’ approach was taken, whereby references within papers were traced, given the relative paucity of information on the subject. Grey literature, including industry and government reports, was accessed through relevant institutions and reviewed for further information. Supplementary discussions were held with stakeholders from industry, regulatory bodies (Environment Agency and Health and Safety Executive) and academics to gain insights from ongoing projects including unpublished information.

This research does not cover the potential biogeochemical reactions, surface infrastructure, processing and transport of hydrogen or the regulatory framework, and how different regulators interact to ensure safety and prevent negative environmental impacts.

Geomechanical considerations for salt cavern storage

This section addresses the geomechanical considerations throughout the lifecycle of salt caverns, from their planning and creation, through operation, to decommissioning. It outlines geological characteristics that impact upon UHS in salt caverns, some of which have been encountered previously in relation to storage of other materials and discusses challenges that have occurred in the past and the mitigation strategies that could help prevent further accidents.

There are two alternative strategies for operating salt cavern storage which impact on a number of the factors discussed in this section. The first is to maintain the cavern at a constant pressure. The pressure is maintained by producing or injecting brine as the stored fluid is injected or produced, respectively, this is called brine-compensated or ‘wet’ storage. The alternative is to allow the pressure of the cavern to fluctuate as the stored fluid is injected or produced, termed ‘dry’ storage (ARUP, 2024). For dry storage, a certain amount of gas needs to remain in the cavern to ensure that a minimum pressure is maintained. The unproduceable, pressure-supporting gas is termed ‘cushion gas’ and the produceable gas, available to meet energy needs, is the ‘working gas’ (Williams et al., 2022). According to ARUP (2024), ‘dry’ storage is the preferred option for hydrogen storage as ‘wet’ storage requires additional infrastructure, such as brine ponds. However, both operations are discussed below as the salt caverns at Teesside, previously used to store hydrogen, were operated as brine-compensated caverns.

Cavern planning and creation

Geological formation

All the salt caverns in the UK onshore subsurface are in bedded halite. Factors such as halite thickness and depth, thickness and frequency of interbedding, and the presence of faults, other higher solubility salt, or wet rockhead dictate the initial feasibility of creating salt caverns. After this the geology affects the depth, shape, size and number of caverns that can safely be created (see below).

Initial feasibility for salt cavern creation is determined from seismic reflection data, which provides information about the depth and thickness of the salt and thick layers of non-soluble rock, historical borehole data, and other site-specific data. The placement of any new exploration wells requires good planning as they provide potential weaknesses in the salt and pathways for gas to escape (Evans, 2008).

Once the potential placement of the salt caverns has been determined, drilling takes place. A borehole is drilled through the overburden, the salt layer, and into the underburden so that geological samples can be removed for testing. Borehole logging can be performed to increase the resolution of the geological information. The hole into the underburden will be cemented, and the cement plug will reach several metres up into the salt (pers. comm. Evan Passaris, 15 July 2024). If the salt and geological environment is still considered suitable for siting a salt cavern, the cavern can be created using the annuluses in the leaching tubes within the borehole.

Inadequate geological characterisation of storage sites can lead to poor cavern design. For example, salt caverns in Clovelly and Napoleanville, Louisiana, did not have sufficient thickness of salt remaining between the cavern and adjacent rock, leaving potential pathways for fluids to escape the caverns. As a result, the caverns did not pass their mechanical integrity tests and were not commissioned (Evans, 2008; Bérest et al., 2020). This case highlights the need for good geological information at the planning stage and, although it occurred at the edge of a salt dome, a similar situation could occur in bedded salt if there are potential fluid pathways through non-halite interbeds or faults.

In addition, site characterisation needs to include previous infrastructure. In 1965 a salt mining operation at Winsford, UK, intercepted a historical borehole, which caused significant flooding in the mine (Highley et al., 2006).

If there is a leak from a cavern, the surrounding geology will also determine the pathway to a receptor. An extreme example of this occurred in 2001, where damage to a borehole casing in the Yaggy storage facility, Kansas, led to natural gas escaping (Evans, 2008). Vertical gas migration was prevented by shale and gypsum beds but the gas travelled along a microfractured seam of dolomite. The gas leak caused several incidents over 14 km, including explosions at two different sites (town of Hutchinson and a mobile home park) about 3 km apart, hence it is known as the Hutchinson incident.

Depth

The depth of potential salt caverns is constrained by several factors. The presence of groundwater and the requirement for a sufficient thickness of salt, caprock and overburden at the top of the reservoir tends to prevent the creation of caverns at depths of less than 200 m (Williams et al., 2022). At depth, higher temperatures and pressures increase salt creep rates, leading to loss of cavern volume (closure), so that it is currently unusual for caverns to be created at more than 2000 m depth (Williams et al., 2022). There is an accepted “sweet spot” for caverns within this range, where cavern closure rates are minimal, but where geostatic pressure allows more gas to be stored in the cavity and less energy is required to recompress gas, prior to transmission (Evans, 2008; Williams et al., 2022; ARUP, 2024).

One other advantage of deeper caverns is that any microfractures that occur as a result of use are more likely to be self-healing (Evans, 2008). The deepest caverns in the UK are in East Yorkshire at Atwick (near Hornsea) and Aldbrough, at depths of 1700 m and 1800 m, respectively (Figure 3). However, the Ningjin salt cavern project, China, is currently exploring the feasibility of a salt cavern at 2700 m (Liu et al., 2023). A salt mine at Harlingen, Netherlands, experienced closure rates of nearly 70% per year at depths of 3000 m (Evans, 2008). Shallower caverns tend to experience slower closure rates, typically closer to 0.5% percent per year at depths of 2000 m and 0.001% per year was measured in a cavern at 250 m, although other factors can impact upon the rate (Brouard et al., 2013; Cornet et al., 2018). At deeper facilities, cavern closure can be reduced by balancing pressure in the cavern with the geostatic pressure, as per wet storage, or maintaining a higher cavern pressure by increasing cushion gas in a dry storage system.

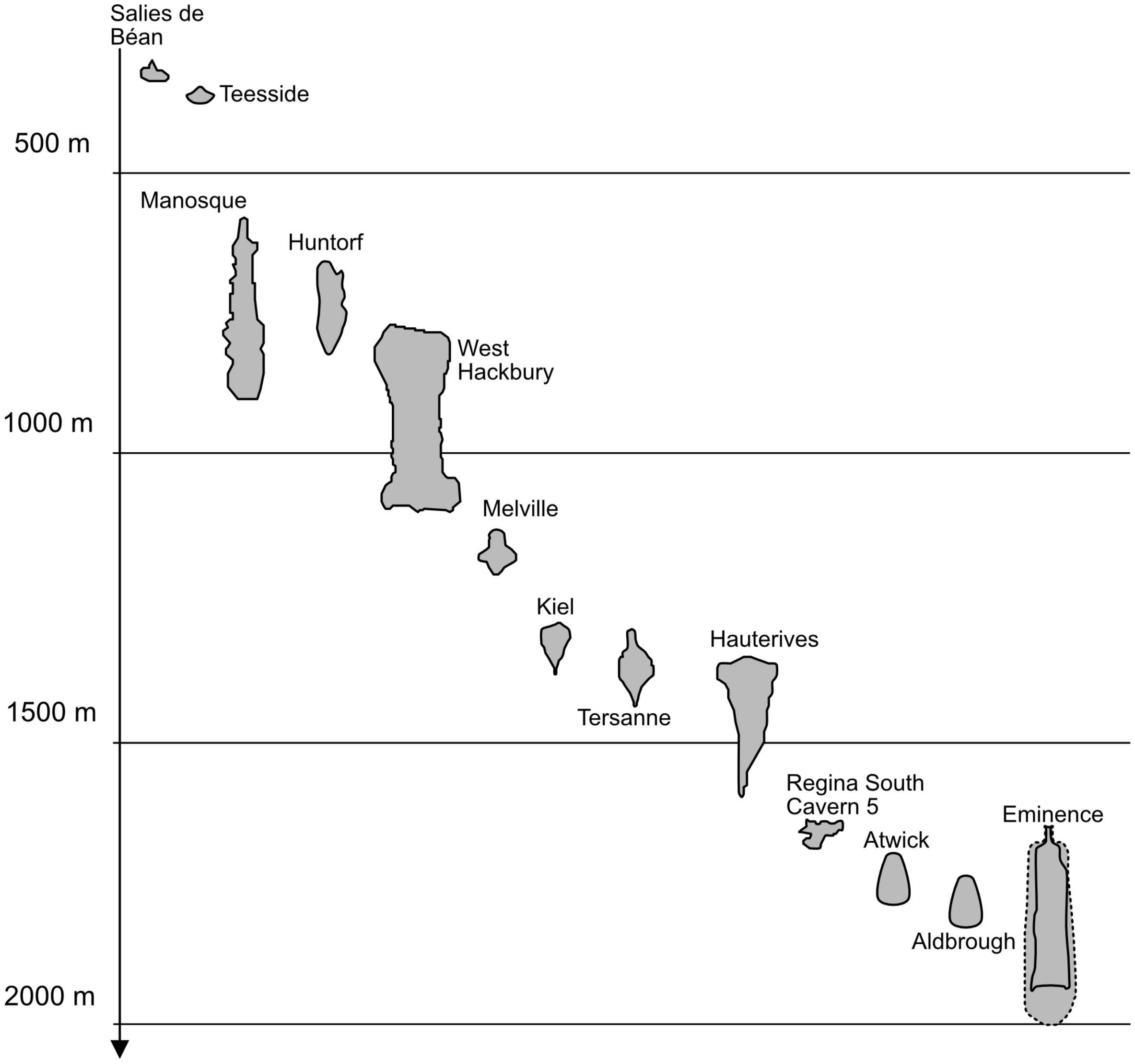

Figure 3: Depths, size and 2D profiles of selected salt caverns. The dashed outline at Eminence shows its profile in 1970 and the solid outline shows the cavern's profile in 1972, due to closure. The profiles of Atwick and Aldbrough are illustrative to show the depth of the caverns. Adapted from Warren (2016) and Liu (2023).

Shape and size

Outside of the geological limitations (salt layer thickness, interbedding and presence of high-solubility salts), the shape and size of a cavern is linked to its planned usage, and particularly its operational strategy.

The idealised cavern is lozenge-shaped (a cylinder) with a domed roof and base, although the base (sump) is filled with highly saline brine and non-soluble material that has fallen into it during the creation process (Evans, 2008). Caverns in salt domes are usually orientated vertically and are tall and thin. Caverns in bedded halite are still vertical but usually shorter and wider and more cylindrical, bell-shaped or even spinning-top-shaped, as their height is often constrained by the thickness of the salt (Evans, 2008; Kumar et al., 2021; ARUP 2024). In thinner layers of bedded salt, horizontal (short and wide), tunnel-shaped caverns can also be created (Evans, 2008). Caverns that are designed to be operated as brine-compensated (wet) storage can be broader as the constant pressure reduces the geomechanical stress on the walls and consequent issues that would result from pressure changes (ARUP, 2024).

Highly soluble salts create irregular cavities and non-soluble interbedding can create shelves or ledges that protrude into the cavern. The result is a non-uniform, asymmetrical cavern shape, with uneven walls (Figure 4). In some cases the shelves are removed by undermining (creating a cavity below the shelf so that it collapses pre-operation), as shelving failures during cavern operation can affect the integrity of the cavern walls and potentially damage the injection/production tubing (Evans, 2008). The asymmetry also increases the geomechanical vulnerabilities of the structure as stresses will focus on the irregularities, increasing the likelihood of microfractures (sometimes called wing-tip cracks) at these points (Forbes-Inskip and Ougier-Simonin, 2021). If microfractures propagate, because the stress environment does not allow their repair, this leads to spalling (loss of integrity of the first salt layers in the walls and roof). Damage to walls from spalling and tubing from falling debris, could lead to gas escape (Evans, 2008).

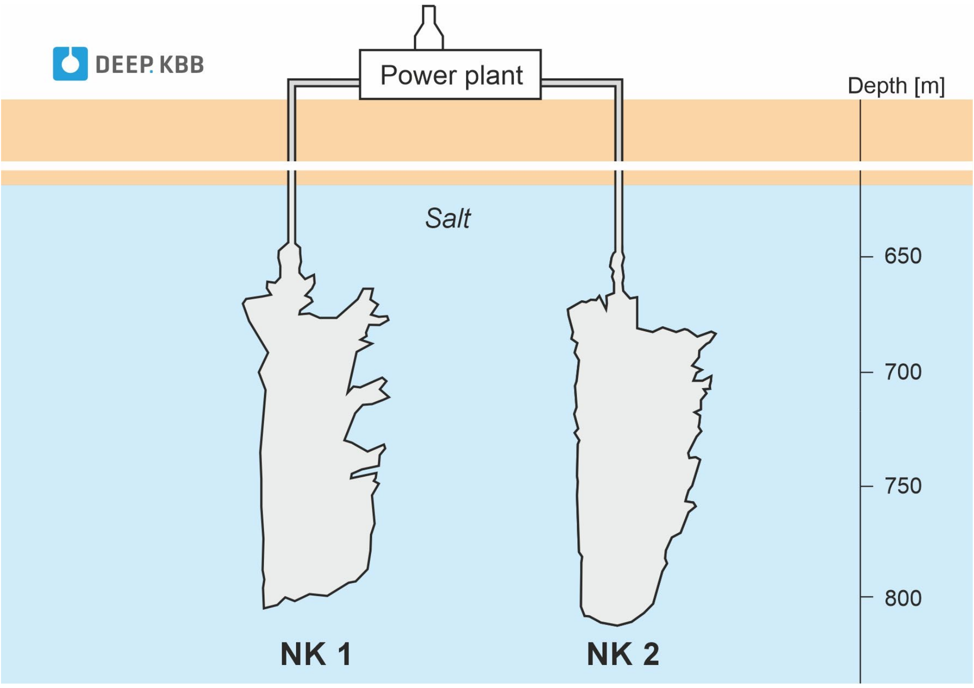

Figure 4: Vertical profile of two salt caverns at Huntorf, Germany used for compressed air storage (from Crotogino et al., 2001).

Caverns are created from the base upwards and are shaped using annular tubes in the leaching pipes (concentric tubes that fit inside each other and allow fluids to flow in between the different sized tubing) (Highley et al., 2006). To obtain the required cavern shape, the tubing position, water flow rate, water discharge timing and thickness of the blanket protecting the roof (see above) are adjusted. In addition, the direction of flow, is regulated to give more control over the shape. Therefore, the central tubing can be used to inject fresh water and the encircling annulus to remove brine, or the process can be reversed (Khaledi et al., 2016; Kumar et al., 2021). For geological stability, a thickness of salt needs to be left between the top of the cavern and the caprock. This was not always the practice in salt mining operations, leading to roof collapse and subsidence, as in the case of the old salt fields in Preesall, Lancashire, which have left a crater at the surface (Evans, 2008).

Caverns range in size depending on their intended purpose and the geological limits. It is common for caverns to be up to 200 m in height and 145 m in diameter, with volumes of over 1 million m^3 (Highley et al., 2006; Warren, 2016). However, much larger caverns exist, for instance there are two caverns in Texas that are over 670 m in height and 180 m in diameter, with capacity over 17 million m^3 (Leith, 2001). Caverns that stretch over a large vertical distance will be subject to different geostatic pressures at the base compared to the top, which could cause challenges during operation. Also, it is important to remember that the sump at the base of the cavern, containing highly saline brine and non-soluble material, may occupy more than 20 m of the cavern height (Evans, 2008).

Due to the properties of salt, a cavern's shape and size will change over its lifetime. In wet storage, cavern size is likely to increase as the brine used to support the pressure is not fully saturated and therefore will cause some leaching of the cavern during its injection and production. In dry storage (fluctuating pressure), caverns will experience closure as a result of salt creep. Historically, there have been a number of cases where there has been significant loss of volume, such as Tersanne (France), Eminence (Louisiana, USA) and Kiel (Germany) (Evans, 2008). All three facilities have continued to operate and regain storage volume, by further solution mining and increasing the minimum operating pressures (Evans, 2008). Salt creep can also lead to subsidence, as at West Hackberry (Louisiana, USA), where ground movement was measured at 76 mm yr^{-1}, even after salt caverns were repressurised to slow the subsidence (Evans, 2008).

Sonar surveys are generally carried out at the end of the cavern creation stage (brining) and at regular intervals (5 to 10 years) throughout the lifetime of the cavern to monitor any changes in shape (Lux, 2009). In some cases, laser monitoring has also been used and allows a 3D image of the cavern to be created, showing its position in relation to the formation geology and to other caverns (Crotogino et al., 2001). As stated, a sufficient thickness of salt is maintained at the roof of the cavern to protect against subsidence at the surface, however, in some circumstances, subsidence monitoring has been used to identify any possible problems (Evans, 2008).

Array and pillar width

A cavern is usually part of an array and larger facilities may have tens, and sometimes hundreds, of caverns with different caverns storing different fluids (Evans, 2008). For hydrogen, where there may be frequent injection and production cycles, multiple caverns could help meet the injection/production targets. Utilising multiple caverns within the array reduces pressure and temperature stress on each individual cavern, either reducing the frequency of the cycles or the change in fluid levels per cavern with each cycle.

When there are multiple caverns, consideration needs to be given to their spacing, or pillar width. The pillar width is the shortest distance between caverns and provides the geological stability (vertical and horizontal) for the caverns. Spacing is usually proportional to cavern radius or diameter; a pillar width of three times the radius is often considered the minimum safe distance (Evans, 2008). This distance can be larger for deeper caverns and should be site-specific (Evans, 2008; Wang et al., 2015). Any problems with subsidence, as a result of inadequate pillar widths, is magnified for a cavern array. At Retsof mine, USA, a pillar collapse led to a 3.6 magnitude earthquake and a 10 m deep crater with a diameter of 180 m (Evans, 2008).

Pillar width is even more important for wet (brine compensated) caverns as spacing is likely to reduce as brine used to support the pressure is likely to have a leaching effect. This occurred at Mineola, East Texas, where an explosion was caused by communication between caverns containing liquid petroleum gas (LPG) (Evans, 2008). This situation was exacerbated by the adjacent caverns having significantly different pressures so that there was a horizontal force acting on a pillar that had been thinned by brining.

The potential risks associated with operating a cavern array can be reduced by ensuring that the minimum pillar width is appropriate for the size of caverns. Risks can be further mitigated by ensuring that pressures within the caverns are synchronised and regular monitoring of the cavern size, shape and position in relation to other caverns is undertaken.

Well configuration, casing and wellhead spacing

It is not uncommon for there to be only one borehole into a salt cavern, particularly if the cavern is tall and thin. However, there may be a second borehole if the cavern is more tunnel-like or if there was a historical borehole already in place (Kumar et al., 2021). In the former situation the well in the borehole will be dynamic (for fluid transportation), whereas historical boreholes may be used for monitoring temperature and pressure within the cavern, in which case fluid will be prevented from moving along that borehole. Many of the challenges with cavern storage relate to the dynamic wells and their casing, such as poor connections, corrosion or deformation caused by salt movement (Bérest et al., 2019).

The walls of a borehole are lined with casings (large diameter pipes, often steel) that are cemented in place (Evans, 2008). The casings reduce in diameter as the borehole extends deeper into the rock. At the downward end of each casing is a shoe (a collar, often made of steel) that prevents the cement, which binds the casing to the rock or to a larger casing, from moving past the bottom of the casing. The shoe also helps protect the casing when it is lowered into the borehole (Evans, 2008). In dynamic boreholes, the centre of the casing accommodates hanging tubing, which may contain up to three annuluses, that is lowered into the cavern. The tubing can be extracted, for example during sonar surveys. Both the tubing and the casings can be referred to as ‘strings’ (Bérest et al., 2019).

The last cemented casing extends from above the salt layer hosting the cavern, down to some way above the roof of the cavern (Evans, 2008). It is this casing that will be subject to any salt movement in the salt layer containing the cavern. In two cases in Texas, the casing failed due to salt movement. At Boling, in 2003, the casing became stretched, whereas, at Clute, in 1998, it was likely that the casing failed due to shear (lateral) forces (Bérest et al., 2019). Both incidents occurred in domal salt, and are less likely to occur in bedded salt, however, design changes have been introduced that reduce the risk of casing breach or allow for monitoring of the last cemented casing. These include: reducing the amount of salt that the tubing extends through by creating a longer chimney (neck up to the last cemented shoe) within the cavern roof to reduce the forces on the casing from the salt; introducing a second casing (double casing) anchored in the salt; or monitoring pressure in the last cemented casing (Bérest et al., 2019). In respect of the pressure monitoring, this takes place in the annulus between the production tubing and the casing, which can be filled with a fluid (usually a corrosion inhibitor, aminated polymers, azoles (such as triazole and benzotriazole) and pyridines) and sealed so that the pressure in the annulus can be checked to ensure that there are no leaks (pers. comm. Evan Passaris, 21 August 2024). The last cemented shoe is also often where ongoing cavern pressure data is collected if there is not a second, data-collection well that extends into the cavern.

Cavern and borehole tightness (or ability to prevent leaks) is tested once the casings are in place using a mechanical integrity test (MIT). To do this, nitrogen, or another fluid, is injected into the top of the cavern, to just below the last cemented casing shoe. The well is then shut-in (the borehole closed) for a period (usually several days). A leak is indicated if there is any change in the interface height between the nitrogen and fluid in the cavern (Bérest et al., 2019). A tracer can be added to the nitrogen to help trace a leak and its pathway. MITs need to be repeated regularly (often every 5 years), to ensure that leaks do not appear over time. In addition, downhole tools can check the casing and cement integrity and can be used in the regular inspections.

The wellheads, the part of the well that is seen at the surface, contain various valves and safety mechanisms that allow the flow of fluid into and out of the cavern. Pressure data can also be obtained at the wellhead. They are usually laid out in a regular grid with several hundreds of metres spacing, depending on the spacing of the wells (see above) (Evans, 2008).

Cavern Operation

Internal cavern pressure

Once the cavern is in operation, pressure measurements are the main indicator of a system's integrity. Pressure can be monitored continuously so that any unusual activity in the cavern can be detected. Most of the following applies to dry cavern storage, however, pressure will also be monitored in brine-compensated storage to ensure the facility remains secure.

A maximum and minimum internal cavern pressure needs to be established for salt cavern operation. In both cases an incorrect pressure (too high or too low), could lead to microfractures and spalling, or roof falls (Evans, 2008). The surrounding formation pressure is used as the guide for the pressure range, for instance Jahanbaksh et al. (2024) quote a range of 24 to 80% of the overburden pressure as the desired operating range. Therefore, cavern depth impacts upon the operating pressure range. Strength testing, which provides further guidance about the safe pressure range, usually takes place on cored salt during the exploration phase of development (Evans, 2008). The change in pressure during injection or production is also important, this is discussed below.

Outwith injection and production, a loss in pressure tends to indicate leakage. For hydrogen, a rapid pressure change would indicate a substantial change in volume due to its compressibility and could indicate that the gas has an escape pathway (Bérest et al., 2019). This was seen at Teutschenthal/Bad Lauchstädt, Germany in 1988, where a large pressure drop was followed 1 hr later by several surface eruptions (Bérest et al., 2019). A slow leakage would be less noticeable. For instance, in the Hutchinson incident it is thought that it took about 8 years for the gas to permeate throughout the fractured layer that the gas used as its escape pathway (Bérest et al., 2019). Here, a significant drop in pressure was only identified at one of the wells once the gas had escaped to the atmosphere (Evans, 2008).

A pressure increase could indicate cavern closure. As stated above, this is normally only an issue with deeper mines (more than 1000 m), such as in Harlingen, Netherlands which reached depths of 3000 m and experienced a volume reduction of about 70% in a year (Evans, 2008). The Eminence cavern storage facility, Mississippi, with caverns between 1750 and 2000 m depth experienced a 40% loss of volume in its first two years of operation (Evans, 2008). At Eminence, volume decrease was thought to be due to the minimum cavern operating pressure being too low.

Small changes in cavern volume or geometry may not be picked up by sonar surveys, as the resolution is too low (Forbes-Inskip and Ougier-Simonin, 2021). In addition, there may be small pressure changes with a compressible fluid, such as hydrogen, and frequent injection and production cycles could disguise abnormal pressure changes, so there is also a need for regular inspection and maintenance to ensure cavern and casing security (Bérest et al., 2019). A change in pressure may also indicate microbial activity (Dopffel et al., 2021) but this is beyond the scope of this report (for an overview see Hydrogen TCP, 2023).

Internal cavern temperature

The background environmental temperature in a salt cavern is controlled by the geothermal gradient, which increases with depth by about 27 °C km^{-1} in the UK; the temperature at 1000 m depth is about 40 °C (BGS, 2024). However, internal cavern temperature is affected by other factors, including the temperature of the brine used to create it (Bérest, 2019). So, unusually, there may be a negative temperature gradient in caverns, as the brine at the base may cool the gas above it (Bérest, 2019). This effect may be greater if the cavern is operated as wet (brine-compensated) storage.

While higher temperatures increase salt flow, temperature fluctuations create thermal stress that increase the likelihood of brittle behaviour in salt, leading to microfracturing and spalling (Forbes-Inskip and Ougier-Simonin, 2021). Stress is also affected by injection or production flow rates, the shape of the cavern, and the temperature of the injected hydrogen (Forbes-Inskip and Ougier-Simonin, 2021).

The injection or production of gas induces temperature fluctuations, with higher flow rates creating larger fluctuations. As the surrounding rock salt does not have time to adjust to the change in temperature, there is a contrast between the injected gas and the cavern, causing thermal stress. However, the temperature stress will usually only be experienced in the first few centimetres of the salt unless there is a blowout (Forbes-Inskip and Ougier-Simonin, 2021).

Caverns that are spherical will distribute temperature more evenly as the ratio of surface area to cavern volume is smaller. However, as stated earlier, caverns tend to have a non-uniform shape and so thermal stress, like pressure stress, may be focused on certain parts of the cavern. In addition to this, in large, elongated caverns pressure gradients, created by geothermal gradient and injection and production of gas, may cause convection currents within the cavern, adding to the complexity of heat distribution, and therefore thermal stress, within the cavern (Bérest, 2019).

In relation to the cycles for hydrogen storage, at present the effects of small temperature fluctuations over time is not understood and more research is needed to determine the long-term effects on the properties of the salt (Forbes-Inskip and Ougier-Simonin, 2021). Effects of temperature-induced stress can be mitigated by heating or cooling the gas or fluid before it is injected or by reducing injection and production rates.

Salt cavern temperature can be measured as part of ongoing monitoring. Temperature logs from fibre optic temperature sensors can also be used to identify leakage sites, as the expansion of the escaping gas (with decreasing pressure) presents as a temperature difference (Evans, 2008). This was the case at Boling, Texas (Bérest et al., 2019).

Injection and production cycles

Even if the pressures (and temperatures) are maintained within the geomechanical limits, there is little evidence available regarding the impact of frequent cycles of injection and production and whether this will result in fatigue of the salt cavern. Fatigue manifests as the reduction of salt strength, the inhibition of salt to repair any microfractures and reduction of cavern integrity. Increased frequency of cycling is the main difference from previous uses of salt caverns and could have a more marked effect on fatigue (Kumar et al., 2021).

One of the reasons for using hydrogen in the energy sector is to balance the intermittent supply of energy from renewables with fluctuating demand. Caverns may need to cope with a variable supply of hydrogen, unless there is short-term storage after hydrogen production that can smooth provision to the caverns (ARUP, 2024). On the other hand, the frequency of the production cycles for hydrogen storage will ultimately depend on the demand and use but could be as frequent as daily.

In addition to the maximum and minimum pressures, laboratory experiments show that salt cavern fatigue is increased by cycling frequency and the loading/unloading rate (the rate at which a fluid is injected into or produced from a cavern; Ma et al., 2017). As a result, salt cavern properties could change over time, with peak strength reduced by as much as 30%, particularly if there is frequent cycling (Fuenkajorn and Phueakphum, 2010). However, in a modelling study, Khaledi et al. (2016) found that the main reason for damage propagation within the salt cavern was a low minimum internal pressure and not the cycling per se. In relation to the rate of change, Bérest et al. (2011) states that changes of 0.8 to 1 MPa per cavern per day is not unusual but that pressure changes can be significantly higher than this, particularly where salt caverns have been used to store compressed air.

As with temperature, the non-uniform shape of the caverns will concentrate stress in certain parts of a cavern, which will be more likely to fail (Forbes-Inskip and Ougier-Simonin, 2021). However, further research is needed to understand the implications and optimisation of more frequent injection and production cycles (ARUP, 2024). The use of salt caverns for higher-frequency cycling in hydrogen storage makes the regular surveying of caverns and the wells more important.

Decommissioning

At the end of a cavern’s lifecycle, the hydrogen will be extracted and the well string (tubing) removed. The cavern is filled with brine to just below lithostatic pressure to stabilise the formation (Evans, 2008) and then plugged with cement and capped at the top to prevent fluid escaping. There are two reasons for ensuring that the brine pressure should be lower than the surrounding rock. Firstly, salt creep will continue for some time after decommissioning, reducing the size of the cavern and increasing the pressure in the cavern. The closure rate decreases over time as internal and external pressures equalise (Forbes-Inskip and Ougier-Simonin, 2021). Secondly, there may be some thermal expansion of the injected brine, again increasing cavern pressure. An increase in the internal pressure of a decommissioned salt cavern at Preesall, Lancashire, resulted in high pressure releases of brine in 1994 (Evans, 2008).

In some cases, a borehole into a cavern could be re-drilled for repurposing or reuse. This could result in damage to the borehole. This happened at Hutchinson, Kansas, leading to fluid escape that led to the subsequent explosions (Bérest et al., 2019). In England it is unlikely that boreholes that have been fully decommissioned will be repurposed (Environment Agency, 2022).

Environmental considerations

A recent Environment Agency report details the potential environmental impacts of UHS (Environment Agency, 2021). Risks associated with salt caverns themselves are broadly associated with two types of hazard. The first is geological, which may result in ground movement (subsidence), and some seismic activity. The second is the release of gas from either the borehole or the cavern. Both can result in the leakage of hydrogen or other fluids into the surrounding rock strata and the wider environment. The potential sources of leakage from the salt caverns are shown in Figure 5 and in relation to each stage of the lifecycle in Table 1.

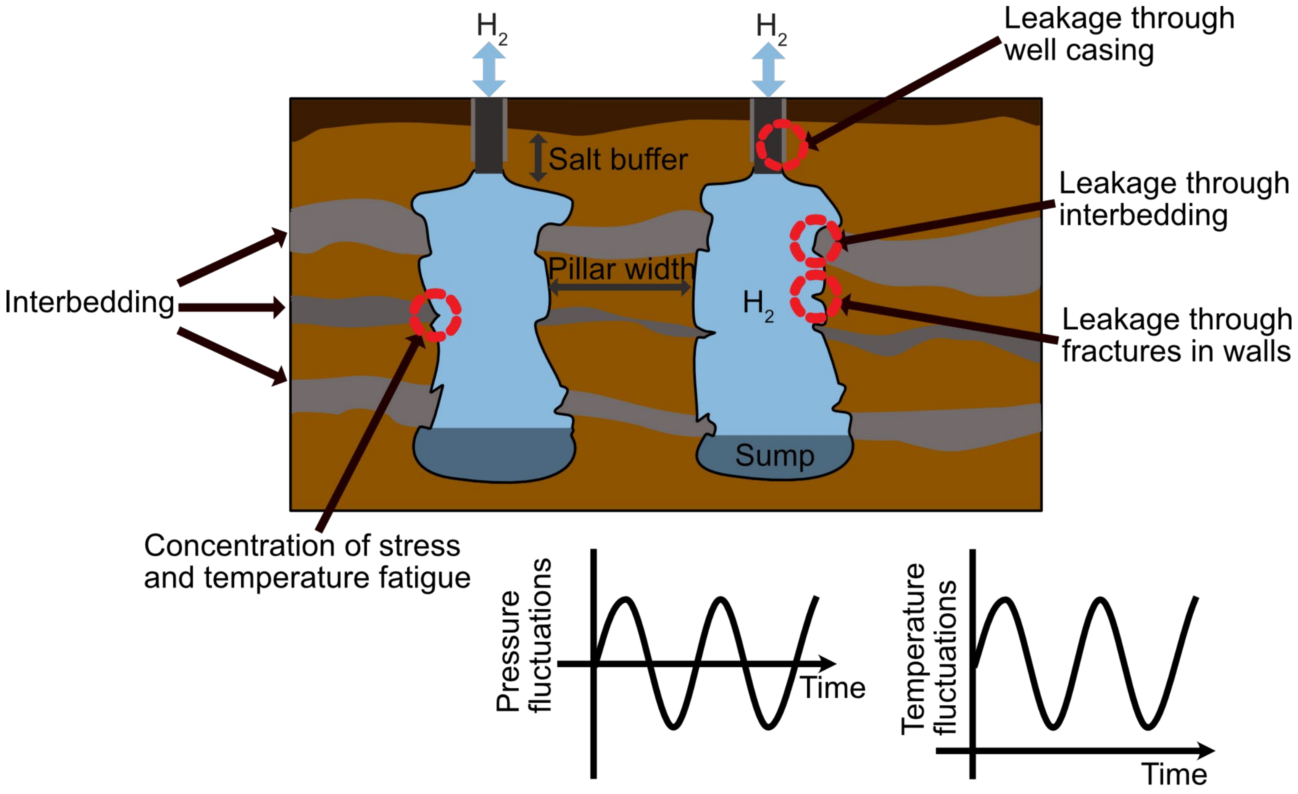

Figure 5: Potential geomechanical sources of hydrogen leakage from salt caverns

In respect of a major hydrogen leak, there can be a clear pressure indicator. Incidents at Eminence (Texas, USA), Teutschenthal (Germany) and Boling (Texas) all experienced rapid pressure drops, albeit the pressure drop at Boling continued over several weeks (Bérest et al., 2019). However, slower leaks may not be so easy to detect, such as at Hutchinson (Kansas), highlighting the need for regular inspection of a facility.

The receptors for hydrogen will initially be the surrounding geology, then ground and surface water and ultimately the air (Figure 6). Escaped fluids can accumulate within the ground for some time, either at the breach depth, or by migrating upwards through a pathway to a different receptor, as was the case at Hutchinson (Bérest et al., 2019). For hydrogen, the accumulation may be limited due to the molecule’s size and mobility. Once hydrogen reaches the surface it will disperse very quickly unless it is captured (ARUP, 2021). Hydrogen is considered to be a secondary GHG because it increases the impact of other GHGs, therefore its leakage should be minimised.

Table 1: Source-pathway-receptor model for the geomechanical hazards at each stage of the salt cavern lifecycle. Note, table only includes hazards related to subsurface cavern creation or use and not those resulting from management of processes occurring at the surface or chemicals used for drilling (for example, handling of brines).

Hazard	Source	Pathway	Receptor
Cavern Creation			
Ground subsidence	Cavern construction – solution mining	Loss of integrity (cavern) – roof fall, spalling, fracturing	Geology Land surface
Water pollution	Brine – used to solution mine cavern	Leakage of brine as a result of loss of integrity (cavern or well), existing faults, fractures or porous interbedding	Groundwater Surface water
Operation			
Ground subsidence	Injection and production cycles	Cavern closure Loss of integrity (cavern) – roof fall, spalling, fracturing	Geology Land surface
Gas release	Stored hydrogen	Leakage of fluid through the geology or well	Groundwater Surface water Atmosphere
Water pollution	Brine – if operated as a brine-compensated cavern		
Decommissioning			

Hazard	Source	Pathway	Receptor
Ground subsidence	Cavern pressure too low	Closure Loss of integrity (cavern) – roof fall, spalling, fracturing	Geology Land surface
Pressurised release of fluid	Overpressurised brine	Escape of fluid through the geology or well	Geology Groundwater Surface water

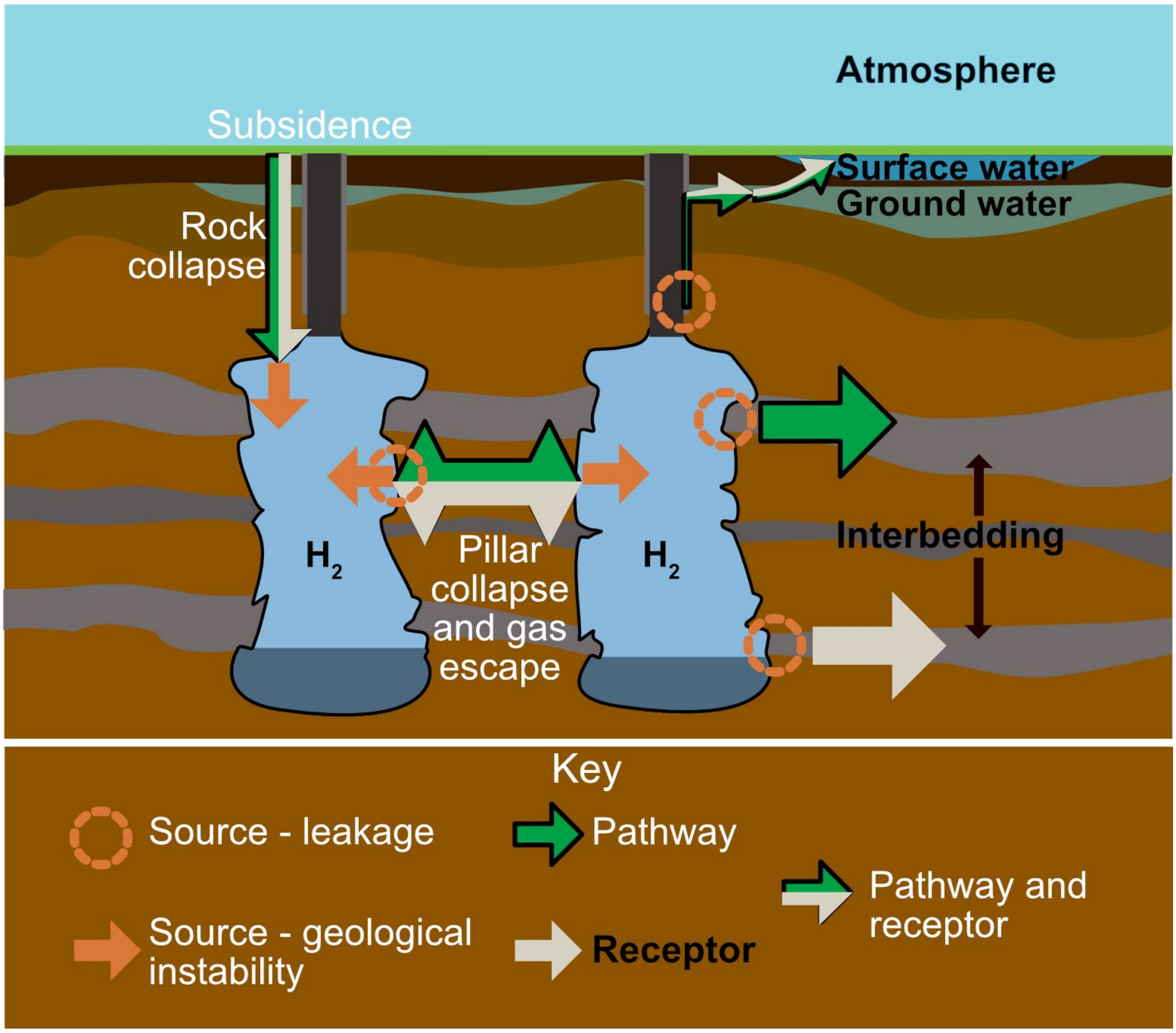

Figure 6 Schematic of source-pathway-receptor model for hydrogen storage in salt

Mitigation and monitoring

The British Standard, BS EN 1918-3:2016[3] (covers design, creation, operation and decommissioning of the caverns up to the wellhead.

Table 2 lists potential monitoring and mitigation activities that could reduce risk and help identify geomechanical issues when managing salt caverns throughout their lifecycle. The British Standard contains additional safety measures, such as valves and materials specifications, not covered in this report. Many of the considerations contained in Table 2 will already be standard practice in managing salt caverns.

Table 2: Monitoring and mitigation activities applicable to each stage of a salt cavern lifecycle

Lifecycle stage	Monitoring and mitigation activities
Planning	Adequate characterisation of geology (using seismic data, historical borehole logs and cores and site-specific knowledge) before drilling; particularly examining salt thickness, position of salt bed in relation to other bedding, type/thickness/frequency of interbedding and presence of faults or historical boreholes. Characterisation should be updated throughout the cavern creation process.
Design and creation	Drill and extract core from overburden, salt and underburden. Borehole logging to increase knowledge of the geology, particularly thickness, frequency and rock-type of interbedding and fracture characteristics. Assess salt composition and strength. Monitor cavern shape and size during development and after brining (using a sonar survey). Check: sufficient salt thickness at the roof of the cavern; no unstable interbedding projecting into cavern; no excessive cavities in cavern; and positioning in relation to other caverns (pillar width). Leak test the formation and cement around the last cemented casing shoe. Mechanical integrity test after cavern creation and tubing insertion.

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[3] BS EN 1918-3:2016 - TC | 31 Mar 2016 | BSI Knowledge

Lifecycle stage	Monitoring and mitigation activities
	Subsidence monitoring – to continue throughout lifetime of cavern. Select appropriate casing size for purpose (leaching and gas injection/production rates). Select appropriate last casing shoe depth.
Operation	Continual pressure monitoring (in the cavern, at the last cemented shoe or at the wellhead). Continual pressure monitoring of the annulus in between the last cemented casing and the tubing. Temperature monitoring. Subsidence monitoring. Regular (5-10 year) inspections of: - Cavern size, shape and salt thickness at the cavern roof (sonar survey). - Cavern spacing (pillar width). Well (casing and cement) integrity.
Decommissioning	Monitoring for residual gas. Subsidence monitoring.

Summary

Hydrogen has been stored in salt caverns in the UK since 1971, for chemical processes. Salt caverns provide an opportunity to store quantities of hydrogen that would significantly contribute towards meeting Net Zero targets. However, the demand for energy storage as part of the Net Zero energy transition presents new challenges regarding the scale of hydrogen storage and frequency and rate with which hydrogen is injected and produced.

The benefits of using salt are its very low permeability and ability to repair itself. Self-reparation is due to the salt's capacity to flow (creep), which is increased by temperature, pressure and the presence of small amounts of water. Salt movement presents geomechanical challenges with respect to cavern closure and potential changes in stress on wells.

The geomechanics of salt caverns should be considered during the planning stage and be included in a comprehensive geological characterisation. The geology determines the feasibility for caverns and their size, shape and spacing. During construction and operation, the integrity of the cavern and borehole is essential as this prevents gas escape and surrounding rock movement, which can manifest as subsidence, seismicity or environmental harm. Often the first indicator of an issue is an unexpected change in pressure in the cavern or borehole. In addition to continual pressure monitoring, regular inspections of each cavern and borehole in an array should be undertaken to ensure their integrity.

Before decommissioning a cavern, the hydrogen will be removed and the cavern will be filled with brine. It is important at this stage that pressure within a cavern is equilibrated with the geostatic pressure prior to the plugging of the well. This is to prevent any ground movement or fluid escape as a result of under or overpressure.

This report outlines the monitoring and mitigation strategies that are used to reduce the risks of storing hydrogen in salt caverns. However, it highlights the need for further research in respect of the effects of frequent injection and production cycles on salt properties and therefore the caverns' integrity and longevity.

List of abbreviations

COMAH – Control of Major Accident Hazards

GHG – Greenhouse Gas

MMG - Mercian Mudstone Group

PJ – Peta Joules (10^{15} joules)

TWh – Terawatt hours (10^{12} watt hours, where 1 watt hour is 3600 J)

UHS – Underground Hydrogen Storage

Glossary

Decommissioning – this is an overarching term that relates to the indefinite shut-in of a cavern and encompasses industry processes known as AB1, AB2, and AB3 (NSTA, 2022).

Dry storage (also known as variable pressure storage) – where the pressure in the salt cavern is allowed to fluctuate as the fluid is injected or produced.

Ductility – ability to deform plastically, without fracturing.

Geostatic pressure – pressure at a point in the earths surface due to the weight of the rock and fluids above it.

Leaching – loss or extraction of a substance from a solid material into a fluid carrier (in this case, salt into water or brine).

Mechanical integrity test – a test for cavern and borehole tightness, completed once the casings are in place.

Overburden – the rock and soil above (shallower than) the mineral layer being studied (salt in this case).

Rock group – one or more rock formations that are contiguous and have similar lithostratigraphic characteristics.

Underburden – the rock below (deeper than) the mineral layer being studied (salt in this case).

Wet storage (also known as brine-compensated storage) – where the pressure in the salt cavern is maintained by the injection or production of brine as the stored product is conversely produced or injected.

Appendix A – Current upper tier COMAH salt cavern storage facilities

For underground hydrogen storage the facility would need to store more than 50 tonnes of hydrogen for it to be considered an Upper Tier site but the threshold for each stored fluid is different.

Storage facility	Information
Hornsea Storage Installation (aka Atwick Gas Storage)	8 caverns with 309 million cubic metres of gas storage capacity. Operated commercially since 1979.
Aldbrough Gas Storage Facility	9 caverns with 282 million cubic metres of gas storage capacity.
Holford Brine Field	8 caverns with 160 million cubic metres of gas storage capacity. Operational since February 2013. A maximum injection and withdrawal rate of 22 million cubic metres of gas a day.
Holford H165 Gas Storage Cavity	1 cavern with 2.5 million cubic metres of gas storage capacity.
Warmingham (this includes Hill Top and Hole House facilities)	Hill Top Farm – 5 caverns with 60 million cubic metres of gas storage capacity. 3 operated since 2014 and a further 2 from 2018. Hole House – 4 caverns. These are not currently operational.
Stublach Gas Storage Site	20 storage caverns with 400 million cubic metres of gas storage capacity.

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