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SALT CAVERN STORAGE HYDROGEN INTEGRITY REPORT
HYKEUPER MATERIAL CHANGE TO HYDROGEN APPLICATION

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TABLE DES MATIERES

1. INTRODUCTION 4
2. STORENGY SAS EXPERTISE: GEOSCIENCES ET SOLUTION MINING 5
3. INFORMATION SOURCES 5
4. NEW INFORMATION ON HYDROGEN STORAGE 6
5. HYDROGEN STORAGE SALT CAVERN INTEGRITY 7
   5.1. Permeability of salt 7
   5.2. Cavern Design 7
   5.3. Comparison between NG and H2: chemical and physical properties, cavern cycling, pressures and temperatures 11
   5.4. Leakage and monitoring 12
   5.5. Geochemical, biogeochemical and microbial reactions 13
6. WELLS 14
7. PROCESS SAFETY 17
8. CONCLUSION 20
9. REFERENCES 20

1. INTRODUCTION

Keuper Gas Storage Limited (KGSL) was granted planning consent under a Development Consent Order (DCO) for natural gas storage in 2017 at the Holford Brinefield Site in Cheshire, UK. The Keuper Gas Storage Project (KGSP) includes up to 19 salt caverns to be solution mined for the storage of gas, together with surface facilities to allow the processing of gas and connection to a gas network.
Since the granting of the DCO, interest in the use of hydrogen gas as an alternative to natural gas, as a fuel for industry and to allow the generation of low carbon dispatchable power for the electricity network, has grown considerably. It is now proposed to develop the project for the storage of hydrogen gas in support of the UK Government's plans for net zero emissions and to support the HyNet NW project. Hydrogen storage is a vital component of HyNet to provide system resilience, energy storage and allow the delivery of significant quantities of hydrogen for clean power generation.

The 2017 DCO application was accompanied by three separate geological reports:

- The seismic survey report.
- The sub-surface safety assessment report.
- The preliminary study of gas design capacity.

These reports were updated in 2021[1] to include new information in support of hydrogen storage:

- The seismic survey report – updated to Revision A (18 June 2021).
- The sub-surface safety assessment report – updated to Revision B (22 Oct 2021).
- The preliminary study of gas design capacity – updated to Revision B (31 May 2021).

This report builds on the original geology reports, as updated, to provide additional information on some broader topics, the latest industry information and practice related to hydrogen storage. Information from the original reports is referenced but not reproduced here, except where context requires, thus reference should be made back to the updated reports of 2021.
In November 2022 KGSL, the Applicant, submitted a non-material change application to the Secretary of State for Energy Security and Net Zero to allow the storage of hydrogen at the project site. Whilst some of the proposed changes not related to hydrogen were accepted and written into an Amendment Order dated 15 May 2024 [The Keuper Underground Gas Storage Facility (Amendment) Order 2024], the principle of a change to hydrogen was not considered to be non-material by the Secretary of State. This report addresses some of the questions raised in the response from the Secretary of State dated 15 May 2024.

[1] Both the sets of original and updated reports are available on the project website found at https://www.kgsp.co.uk/library-archive/.

2. STORENGY SAS EXPERTISE: GEOSCIENCES ET SOLUTION MINING

Storengy operates 21 underground gas storage sites in Europe (in aquifers, salt caverns and depleted fields). Storengy has designed and created 6 storage sites in salt caverns, each comprising between 2 and 20 caverns, in France, Germany, and the UK. Storengy is one of the world leaders in underground gas storage, with expertise across subsurface sciences and surface engineering.

Storengy is well established in the HyKeuper area, with its subsidiary Storengy UK operating the Stublach gas storage site nearby. Storengy designed and controlled the leaching process of the 20 Stublach caverns, all of them being in safe and successful operation for natural gas storage to support the UK energy supply network.

3. INFORMATION SOURCES

INEOS Inovyn and its forebear ICI have been actively solution mining the Holford Brinefield in a process known as 'controlled solution mining' since the late 1920's, replacing the previous 'wild brining' techniques employed elsewhere in Cheshire. Since that start period over 200 boreholes have been drilled and caverns created for the extraction of brine for the Cheshire chemical and salt supply industries. Both natural gas storage and ethylene gas storage first began at the Holford Brinefield site in 1985. These facilities have provided considerable operating experience of gas storage to help inform this Project.

As well as brine production boreholes, over that period there have been numerous exploratory boreholes drilled to confirm the extent and nature of the salt in the Holford Brinefield area. From some of these borehole's salt and or rock cores have been collected to further characterise the strata and allow additional testing to be undertaken. More recently there have been a series of seismic surveys undertaken in support of the various gas storage projects. These surveys provide a detailed map of the salt subsurface extension and show any boundary faults for the wider brine field area. Details of the results of the seismic surveys and the salt maps produced are given in the seismic survey reports listed above in section 1.

To the west of the Holford Brinefield site is an active rock salt mine, where it is possible to go below ground to see the actual salt in situ. Exploratory boreholes associated with the mine development have further documented the general geological picture of the area. Using all the borehole data, previous seismic surveys of the Holford Brinefield and data from the neighbouring gas storage projects the project team has produced a very detailed 'structural model' of the site based on their years of experience and knowledge. This model has been used to confirm the locations of the proposed boreholes and caverns as specified in the 2017 DCO and refine the exact shape and size of the storage caverns, optimised for hydrogen storage.

The Solution Mining Research Institute, Inc. (SMRI) is a world-wide, non-profit, member-driven organization that provides specialized education, technical reference information, and research on current issues to those in the solution mining and storage cavern industries. SMRI members include salt, potash and trona based companies, support organizations, operators, researchers, suppliers, consultants, educators, government regulators, students, and others with interest in solution mining and cavern utilization.

The SMRI has been involved in research to support the industry since the 1960s and continues to actively research subjects of current and future interest to its members and the cavern

industry. Historical research funding has produced software that is used by industry professionals, best practices for cavern design and operations, and an extensive catalogue of the world's salt deposits and storage caverns. Current research activity includes cataloguing and comparing mineral characteristics, the abandonment of deep underground storage caverns, and comparing the storage of hydrogen versus natural gas in salt caverns.
Both INEOS Inovyn and Storengy have been active members of SMRI for decades, with the current SMRI president for 2025 being Y. Charnavel from Storengy.

For HyKeuper the specification of cavern size, shape and position is based on multiple factors following detailed geomechanical modelling and thermodynamic modelling using specific hydrogen gas parameters as well as site specific parameters for the salt and geology of the HyKeuper site and salt cavern storage industry norms.

4. NEW INFORMATION ON HYDROGEN STORAGE

There is a great deal of valuable technical and safety information shared between the various parties and operators in the gas storage industry, which date back many decades for natural gas and more recently for hydrogen storage. The SMRI is one such organisation to coordinate and share this technical information, although operators also cooperate directly with each other to ensure the overall safety of the industry.

In recent years, many hydrogen projects and pilot studies have added to Storengy's previous experience on natural gas. Storengy completed the HyPSTER project, the first EU-funded demonstrator for hydrogen storage in salt caverns[2]. A hundred cycles of variations in hydrogen pressure inside the cavern were completed, allowing Storengy to study the cavern's response to different cycle profiles and provided initial verification of the selection of materials for wellhead and downhole components. The HyPSTER project was just the first step, as Storengy has other ongoing projects and pilots in several salt cavern storage sites: SaltHy in Harsefeld (Germany), GeoH2 in Manosque (France), and FrHyGe (Harsefeld and Manosque)[3].
Storengy is ensuring they are up to date with technology required for H2-ready gas completions and innovations. The 2 newest wells in Etrez (France) that are currently undergoing their first filling with natural gas were equipped with H2-ready completions in 2025.

Storengy also works on projects at laboratory scale: for instance, a large project of material testing is in progress with CFer[4]. Previously used well/wellhead components as well as new materials are being tested with hydrogen in conditions close to *in situ* cavern conditions.

Many other companies are carrying out their own projects and pilot studies, and shared experience is very valuable to Storengy. For example, with their first pilot HyStock, Gasunie put hydrogen in a well equipped with a suitable hydrogen gas completion[5]. They are currently working together with StoragEtzel on the H2Cast project, to fill and cycle large amounts of hydrogen between two caverns[6].

[2] https://hypster-project.eu/
[3] https://frhyge-project.eu/
[4] https://www.cfertech.com/
[5] https://www.gasunie.nl/en/projects/hystock-hydrogen-storage
[6] https://h2cast.com/

5. HYDROGEN STORAGE SALT CAVERN INTEGRITY

5.1. Permeability of salt

Rock salt (halite) is a crystalline mineral composed primarily of sodium chloride (NaCl). It is known for its low permeability and porosity, making it an excellent natural barrier for storing gases and liquids. Scientific publications (Minas & Skaung, 2021) describe salt as a 'suitable storage medium for gaseous hydrogen' due to its 'very low permeability'.

The results from different research studies indicate that salt permeability of hydrogen is practically equal to zero. In particular, some experiments have been conducted on salt cores to investigate and compare salt permeability to hydrogen, methane, and air, and conclude that 'practically no difference in the permeability of rock salt for natural gas, hydrogen and air could be observed. Thus, rock salt can be expected to be suited as geological barrier for hydrogen and compressed air as it has been verified for natural gas for several decades' (Schlichtenmayer & Bannach, 2015).

Natural rock salt may contain impurities and inclusions (e.g., anhydrite, clay), which can create pathways for fluid migration. As demonstrated in the work Storengy have done (Fargetton, 2024), the occurrence of impurities or faults in the salt strata around HyKeuper has been identified and a minimum standoff distance (salt thickness above caverns) has been included in the design. There is a 270 m distance between wells (cavern axis) and a 300 m distance between wells and major faults at cavern depth included in the design. These distances have been established to maintain cavern integrity and are normal for all types of gas storage within this type of strata.

In addition to hereabove laboratory tests on salt cores, two important in situ cavern tests were performed during projects HyStock and HyPSTER. In both R&D pilot projects, the traditional nitrogen Mechanical Integrity Test (MIT), was duplicated with hydrogen MIT in the same conditions. This allowed a check of the behaviour and integrity of the gas completion and the exposed salt at the casing shoe. The in situ salt performance was similar with nitrogen and hydrogen at maximal pressures and furthermore validated the future need for nitrogen MIT only in standard industrial cases.

5.2. Cavern Design

Storengy controlled the leaching process of the 20 Stublach caverns and has been successfully operating them for over a decade. The geology is very similar across all Stublach and HyKeuper zones. Both are close to each other, with caverns in the Northwich Halite formation. This salt formation is well known and has been extensively studied by Storengy for Stublach drilling. Additional seismic data have been acquired for the HyKeuper project, allowing to refine geological data precisely in the HyKeuper zone. Previous and recent data have been computed in a geological study (Fargetton, 2024) to provide best estimates of salt depth and thickness; and identify the potential for other disturbances in the salt. HyKeuper caverns locations were confirmed and are at least (measured at the top of the salt):

- 270 m away from each other,
- 270 m away from existing wells or caverns,
- 300 m away from the first family faults.

Moreover, all caverns are located in places with sufficient:

- Salt thickness: 100 to 140 m with an average of 122 m,
- Depth: casing shoe between 520 and 690 m with an average of 618 m.

HyKeuper's cavern design is the same as that for Stublach's caverns and is detailed in the HyKeuper design and capacity report (Labaune, 2024). This design allowed for the delivery of Stublach's 20 operational caverns with regular shapes and at target capacity, cognisant of the site conditions such as usable salt thickness, insoluble content, a 30-ft marl band in the lower layers of the salt, and the demands of the hydrogen storage facility. Solution mining conditions for HyKeuper are expected to be very similar to those of Stublach.

Figure 1 shows the provisional shape of a typical HyKeuper cavern and its position relative to the geological layers. We can see that the focus is on salt layers F and deeper. Leaching through the shallowest salt layers (G to J) would allow larger volumes, but setting the casing shoe deeper allows the project to achieve higher operating pressures. To ensure sufficient volume and pressure, it has been decided to leach as deep as the salt layer B, although it means leaching through the layer C, also known as the 30-ft marl band. It does make the leaching slightly more difficult, but with a specific leaching design and careful monitoring the issue of the 30-ft marl band will be addressed. The challenge for leaching only relates to the integrity of the temporary leaching strings and the behaviour of the marl band debris.

Due to high (25 %) insoluble contents over the salt layers, a large proportion of the final cavern is filled with fallen insoluble materials (2/3) and brine (1/3); this is referred to as the sump (grey in Figure 1) and includes the 30-ft marl band. The sump will never be filled with hydrogen. As can be seen in Figure 1, the 30-ft marl band is never exposed to the storage gas. Although previous exploratory well tests (all 20 Stublach Gas Storage wells) have demonstrated that the marl band is indeed 'gas-tight'.

Using precise leaching control, Storengy creates bell-shaped caverns. This regular dome roof is geomechanically very stable and maximizes the final volume of the cavern with a limited salt thickness. Similarly to Stublach cavern design, maximum cavern radius is set at 50 meters.

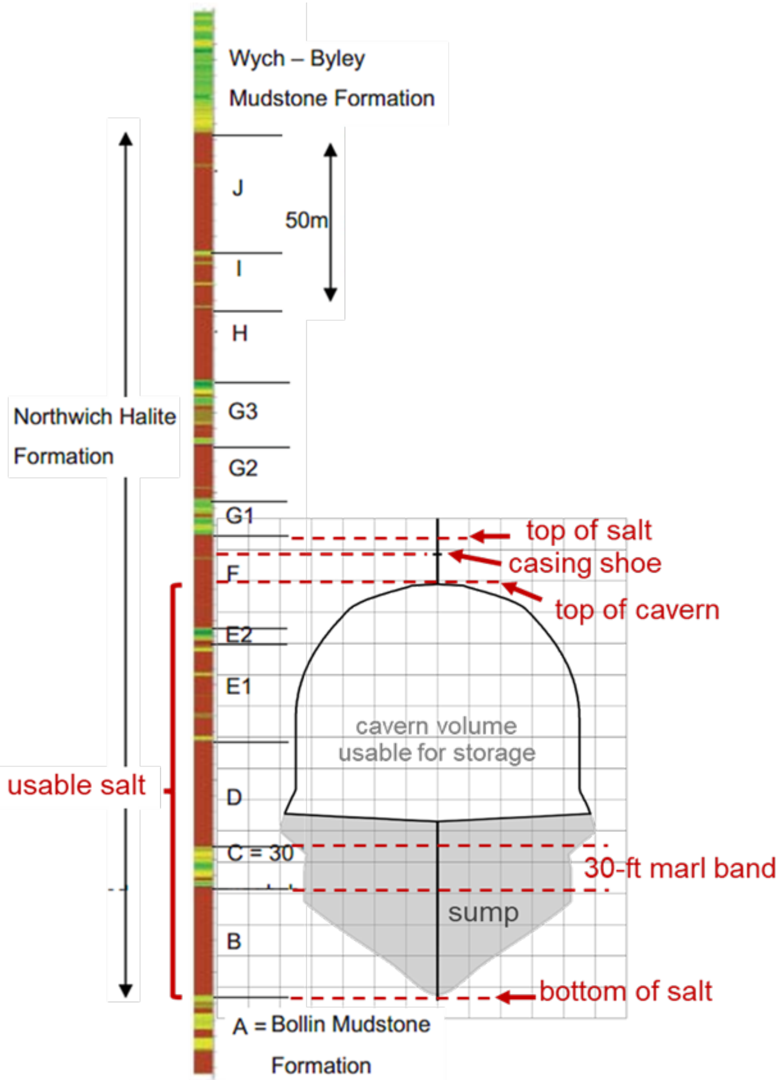


Figure 1: Final cavern shape relatively to geological data (Labaune, 2024).

In addition to its own projects, Storengy benefits from other companies' experience in hydrogen storage in salt caverns. Table 1 shows a few examples of existing and projected hydrogen storage facilities. Teesside storage, in the UK, is the oldest hydrogen storage in salt caverns and has been in operation since the 1970s. The main differences between Teesside and HyKeuper are the operating pressures, Teesside only shows fairly low pressures; and the operation mode: HyKeuper plans regular hydrogen pressure cycles between a minimum and a maximum pressure, while Teesside is using brine compensation, meaning that brine is withdrawn or injected to balance hydrogen pressure when hydrogen is injected or withdrawn. Despite these operational differences, Teesside is a very valuable example of successful long-term hydrogen storage in salt caverns. Closer operating conditions to HyKeuper exist and have been in operation for 1 to 4 decades: Clemens Dome, Moss Bluff and Spindletop, in the USA. Those storages operate with the American standards in well completion and safety equipment. The HyPSTER project gathers higher operating pressures with wells and completions similar to HyKeuper.

Site ***Operator***	***Clemens Dom*** ***ConocoPhillips***	***Moss Bluff*** ***Praxair***	***Spindletop*** ***Air Liquide***	***Teeside*** ***Sabic Petrochemicals***	***HyPSTER pilot*** ***Storengy***	***HyKEUPER Project*** ***KGSP***
Drilling **Commissioning**	N/A 1983	N/A 2007	N/A 2016-2017	~1965-1966 ~1971-1972	1981 Beginning 2024	Project
Cavern geometry volume (m^3)	1 × 580 000	1 × 566 000	1 × > 580 000	3 × ~70 000	7 400	19 x ~300 000
Reference depth (m)	930	> 822	LLC shoe @ 1104m cavern roof @ 1204m	350 to 380	842	~520 to 690
Pressure range	70-135bar	55-152bar	68-202 bar	~46 bar	60-151 bar	~30-130 bar
Estimated Working gas volume	~2 500 tons H_2 ~100 GWh	~3 800 tons H_2 ~150 GWh	~5 400 tons H_2 ~200 GWh	3 x 260 tons H_2 ~3 x 10 GWh 30 GWh	For the pilot only the top of the cavern is filled with hydrogen	19 x 1800 tons~ H2 ~19 x 70 GWh
Completion	In USA, no double barrier concept, i.e. no production tubing nor subsurface safety device. Last cemented casing is the production tubing. No subsurface safety valve..			Use of brine to balance H_2 pressure when injecting / withdrawing.	Double barrier concept (well + completion). Presence of subsurface safety valve.	Design based on HyPSTER pilot

Table 1 : Examples of existing and projected hydrogen storages in the world.

5.3. Comparison between NG and H2: chemical and physical properties, cavern cycling, pressures and temperatures

The mechanical and physical reactions of salt in the context of underground gas storage have been studied extensively and the parameters for safe operation have been incorporated into industry standards and norms. ‘The operational envelope for safe storage operations in a cavern is established… This methodology is independent of the fluid stored, and therefore equally applicable for hydrogen storage as well as natural gas storage.’ (IEA, 2023).

Several salt cavern thermodynamical simulators are existing which can calculate hydrogen’s thermodynamic behaviours. A review of salt cavern design and gas storage using simulation software was carried out and concluded ‘thermal effect of frequent injection/withdrawal cycling are less’ for hydrogen when compared to natural gas (Minas & Skaung, 2021).

A study of the thermodynamics of hydrogen storage in salt caverns modelled the storage of hydrogen in a number of salt caverns already developed for natural gas in Europe (including one at Stublach site). They found that ‘temperature variations are smaller for hydrogen’ adding that the isochoric heat capacity of natural gas is ‘5 times larger’ than hydrogen (Louvet, Charnavel, & Hévin, 2017).

These findings are also verified by (Nieland, 2008) who compared hydrogen with natural gas for different frequencies of cycles per year and concluded ‘temperature fluctuations in the caverns are the highest for natural gas and lowest for hydrogen’.

In addition to the simulated effects on salt, SMRI sponsored research led by Storengy was conducted in an existing salt mine (Hévin, et al., 2016). A cold room was constructed over a salt surface and put under test conditions to simulate sudden temperature drops resultant from fast cycling of gas. The experiment confirmed software simulations in that thermally induced fractures may exist. It also confirmed that penetration of the crack system did not extend with repeated cycles. More importantly, the extent of the fractures produced corresponds to thermo-mechanical stress in the salt as calculated with the software. Given that hydrogen produces a lower thermo-mechanical impact on salt than natural gas this is further supporting evidence of the diminished effects hydrogen has on salt cavern walls when compared to natural gas. Natural gas has been safely stored at the Holford Brinefield site since 1985 with daily fluctuations in pressure and temperature.

The cycling scenario intended in the design of HyKeuper has been modelled against the established operations of Stublach site (with 8-10 equivalent cycles max for HyKeuper when compared to 12 for Stublach). As we have seen, salt formations react to an operational envelope of fast cycling independent of the gas fluid stored. Stublach trades with natural gas and has a proven and confirmed record of safe operations without geological failure for over 10 years. Stublach is an established and tested fast cycling storage site in the same rock salt formation as HyKeuper and therefore acts as a demonstrator for the storage of hydrogen from a geomechanical perspective.

In review, the thermodynamic changes produced with hydrogen as a storage gas are in all cases less than that of natural gas in the same operating conditions. Lower density and higher mass specific energy content mean that hydrogen could be cycled at the same withdrawal and injection velocities, used in the Stublach site, with less impact on the cavity stability in terms of temperature swings associated with operating cycles. Therefore, when taken in the case of the HyKeuper project, the storage of hydrogen instead of natural gas would have a reduced thermodynamic effect on the caverns.

5.4. Leakage and monitoring

For each well/cavern several tests are carried out at different stages of the well/cavern creation process, these are known collectively as a well/cavern acceptance scheme.

1. During the well drilling process, extensive checks are done to ensure effectiveness of the integrity of the last cemented casing. This casing, which is the final one reaching salt where the cavern will be created, is a premium gas tight threaded connection casing, i.e. the connection has a special metal to metal seal. In order to guarantee this metal- to-metal seal is effective, a special make-up procedure is applied: visual inspection of the metal seal prior to making up and torque turn record for each connection. Any anomaly is investigated and in case of non-standard make up, the casing is removed and replaced with a new one. Once the last cemented casing is run and cemented, wireline logging operations are performed to check the quality of the cementation between the casing and the formation.
2. With leaching completion (dual string) and leaching wellhead in place, a brine pressure test is conducted to check the mechanical resistance of the well and to measure if there is any leak of fluid in the salt open hole section. Prior to commencing creation of the cavern by solution mining, a test is also conducted with nitrogen; nitrogen is the fluid that will be used as blanket during solution mining.
3. Once the cavern creation by solution mining is complete, the leaching completion and well head is removed. The gas completion, gas wellhead and the debrining completion is installed. Prior to the start of first filling of the cavern with hydrogen, the integrity of the cavern and well completion are verified through Mechanical Integrity Testing (MIT) with a detailed programme that is agreed with the administration prior to implementation. This MIT is expected to be very similar to the one used for Stublach natural gas caverns.

These measures are critical to demonstrating compliance with environmental and safety obligations under the Development Consent Order (DCO) and relevant statutory instruments, such as the COMAH Regulations (2015) and Borehole Regulations (BSOR 1995).

Mechanical Integrity Testing (MIT) standard steps

The well is equipped with a gas completion and a debrining completion. The cavern is full of brine, additional brine is injected in the cavern through the debrining tube to rise its pressure to test level and nitrogen is injected into the annulus establishing a nitrogen/brine interface in the chimney between the last cemented casing shoe and the cavern roof.

Pressure and temperature data are recorded continuously, and nitrogen volume calculations are used to assess containment performance. The test duration typically spans 24-72 hours, but can be longer depending on the risk assessment and conditions during the test, the ultimate goal is to achieve stabilization and accurate leak detection. At beginning and end of MIT a pulse neutron logging tool is used to measure the interface depth of brine/nitrogen interface. Eventual interface movement will be used in nitrogen volume calculation. The calculated nitrogen quantity variation during test is checked against predefined test criteria.

Operational Integrity and Risk Management

During hydrogen cycling operations, cavern pressure will be maintained within pressure limits defined with administration. These limits were checked by geomechanical simulations to prevent roof falls, fracturing, or closure. Cavern spacing and depth have been modelled to ensure long-term structural stability, with consideration given to thermal and pressure fatigue effects (as described in 5.2). The project will implement a comprehensive integrity management system, including annulus pressure monitoring, leak detection protocols, and emergency shut-down procedures. The management of these operational parameters are well established and tested in the Stublach Gas Storage site. Over 10 years of operation Storengy has refined safe and robust operating procedures and parameters. Remote data streaming will support real-time oversight and facilitate transparent reporting to regulators.

Decommissioning and Post-Closure Integrity
At the end of operational life, caverns will be decommissioned in accordance with Environment Agency guidance. Hydrogen will be withdrawn, and the cavern will be filled with saturated brine to ensure long-term containment and stability. Final integrity verification will be conducted to confirm isolation from surrounding formations and groundwater systems.

Ground Water
Ground water intrusion when developing and/or operating UGS is raised by (Environmental Agency, 2025), however the risk of ground water intrusion in HyKeuper is greatly reduced for two main reasons. Firstly, geological data and assessments have shown no presence of ground water at the depth HyKeuper will be developed. This is further supported by the presence of multiple underground gas storage facilities in the immediate vicinity (Holford Gas Storage & Stublach Gas Storage) which have experienced no incidence of ground water detection in the decades of their construction and operation.

Secondly, as shown in the above sections, salt is a barrier to hydrogen; hydrogen has favourable thermodynamic effects when compared to natural gas; and natural gas has been stored safely in caverns of the same design as HyKeuper for many years with no incidences of release.
When considering gas storage in a wider context, other technologies such as depleted reservoirs or aquifers use a method of gas storage which can directly interact with ground water. In these storage sites ground water interaction would be a legitimate concern, but not in the case of salt caverns.

5.5. Geochemical, biogeochemical and microbial reactions

Hydrogen is a proton donor, so there are a number of interactions with sulphate and carbonates, present in abundance in salt cavities, which could degrade H2 to form H2S or CH4. However, the potential reactions are unlikely to take place in salt cavities operating at a temperature below 200 °C due to the slow reaction kinetics. HyKeuper design parameters are between 5 and 40°C from maximum and minimum inventories, and therefore outside of the range for potential reactions.
Regarding the concern over microbial activity in hydrogen storage raised in 'Hydrogen TCP-Task 42 Underground Hydrogen Storage Technology Monitor Report' (IEA, 2023). Linde Inc operate a hydrogen storage at the Spindletop Hydrogen Storage Facility in Texas, US. Hydrogen storage has occurred at this site since 2014. A study of operations was performed and concluded that 'no H2S formation has been detected so far in the withdrawn hydrogen'. (Grange, Hévin, & Djizanne, 2023).
There are also ongoing studies on the effects of microbes on hydrogen storage in several types of storage facilities. The establishment of testing methods for microbial cultures which will present risk of hydrogen-oxidization are tested and available. Additionally, the research suggests mitigation measure which can be included in novel microbial control programs such as 'biocide delivery' (Dopffel, 2024).

HyLIFE is pan European research programme investigating underground hydrogen storage (UHS), aiming to address the challenges of storing and using hydrogen as a key component of a low-carbon energy system. A specific objective of HyLIFE is to investigate and reduce microbial activity, which can impact storage efficiency and integrity. Samples of sump brine from 2 active cavities (H155 & H213) in the Holford brinefield, which returned 'no evidence of hydrogen consumption was observed in 6 months of experiments at the laboratory.' (CETP, 2025).

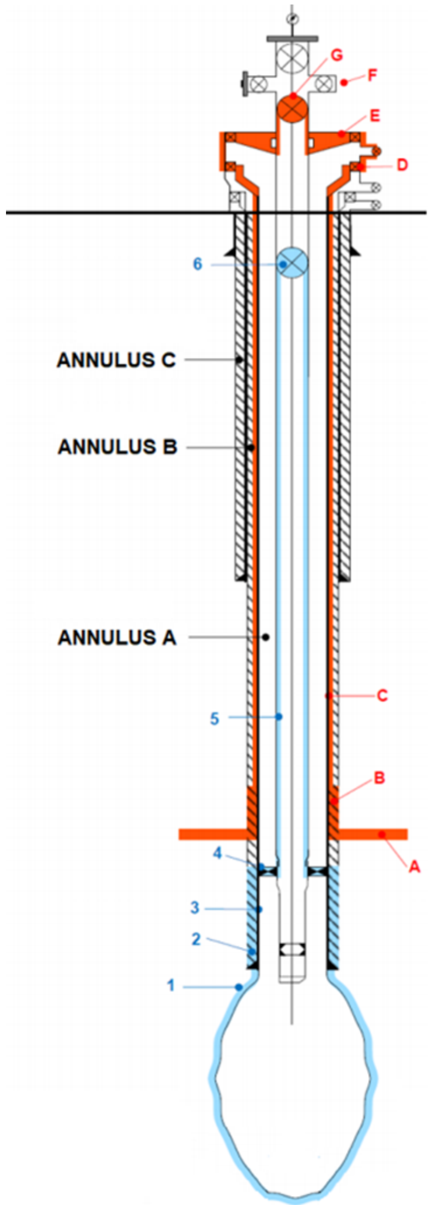
When performing operations of hydrogen storage in the HyPSTER project, France, H2S was below the measurement precision in all the samples taken. Therefore, no H2S formation was detected.

Additionally, further brine samples have been taken at the HyPSTER cavern and are intended to be collected from the Stublach gas storage site that will be tested for microbiological activity. The results of which will inform the design of the HyKeuper project.

6. WELLS

The underground storage of natural gas has reached a very high safety standard in Europe. The current completion designs for natural gas caverns for instance in Germany, France and UK are based on many years of operational experience, which are ultimately reflected in various operator's policies and standard regulations or guidelines. For example “Borehole Integrity Guide” from German Federal Association of Natural gas, Petroleum and Geoenergy (July 2021), “Well Life Cycle Integrity Guidelines”, issue 4 (March 2019) in the UK (Oil & Gas UK), “Well integrity standard D-010” (NORSOK Standard, 2021) and “Recommended guidelines 117” revision 6 (Norwegian Oil and Gas Association, 2017) in Norway are all addressing the same issue of keeping a well integer all over its full lifecycle. With the existence of these guidelines and regulations, a frame for the storage industry exists, which is to be applied analogously for the underground storage of hydrogen.
Integrity of a well and its completion is considered as being effective if the fluids it contains are safely controlled at every possible combination of pressure and temperature that can be reached during any operating conditions. This is achieved through the application of technical, operational and organizational measures, which include the design and creation of the well and its completion with physical/mechanical barriers.

In the case of a natural gas cavern well with a high open-flow potential, two independently verified well barriers must be established. The first barrier is in contact with the storage medium and pressure. The second barrier serves as a fallback and guarantees safety in case the first barrier fails. If possible, the second barrier should envelop the first. The two-barrier system applied for natural gas cavern storage is schematically illustrated in Figure 2, showing the individual barrier elements.



BARRIER			
WELL BARRIER ELEMENT	Code	Initial integrity control	Integrity monitoring (examples)
PRIMARY BARRIER			
Salt formation*	1	Tigthness test Geological model	Model + Pressure-Volume check (regular cavern volume/shape control using sonar)*
Production casing cementation (below packer)*	2	Tightness test Cementation quality control (logs)	Annulus B pressure monitoring
Production casing (last cemented casing, below packer)*	3	Pressure test Welding procedure or Making up graph for threaded casing	Annulus B pressure monitoring
Production packer	4	Tigghness test	Annulus A pressure monitoring
Completion	5	Pressure test Welding procedure or Making up graph for threaded casing	Annulus A pressure monitoring
Subsurface Safety Valve	6	Tightness test	Periodic functional/tightness test
SECONDARY VARRIER			
Salt formation or caprock formation in overburden*	A	Tigthness test Geological model	Model + Pressure Volume check (regular cavern volume/shape control using sonar)*
Production casing cementation (above packer)*	B	Tightness test Cementation quality control (logs)	Annulus B pressure monitoring
Production casing (last cemented casing, above packer)*	C	Pressure test Welding procedure or Making up graph for threaded casing	Annulus B pressure monitoring
Wellhead	D	Tightness test Pressure test	Pressure test, visual examination, monitoring of test ports if existing.
Tubing hanger	E	Tightness test Pressure test	Annulus A pressure monitoring
Wellhead body	F	Tightness test Pressure test	Periodic pressure test
Mastervalve	G	Tightness test Pressure test	Periodic pressure test

Figure 2: Salt cavern barrier schematic (Natural gas cavern with subsurface safety valve)

Note: The well barrier schematic has been taken from “Borehole Integrity Guide” (BVEG) as an illustration (*part modified from original).

The transferability of the primary/secondary barrier concept and its individual barrier elements from natural gas storage to hydrogen storage will be ensured by the application of a standardized approach like the one already used for natural gas storage caverns, i.e.: preliminary design, selection of best suitable technologies and monitoring during operation. Hydrogen differs from methane in many physical and chemical properties, thus these differences must also be considered. For example, hydrogen could penetrate barrier elements such as steel, cement and elastomers more easily than natural gas and thus have a negative impact on operational safety.
Borehole completions for hydrogen underground storage will be designed in such a way that they are adapted to these special influences to ensure hydrogen cannot negatively impact the structural integrity of the materials of construction, should some hydrogen penetrate the barriers put in place (see Figure 3).

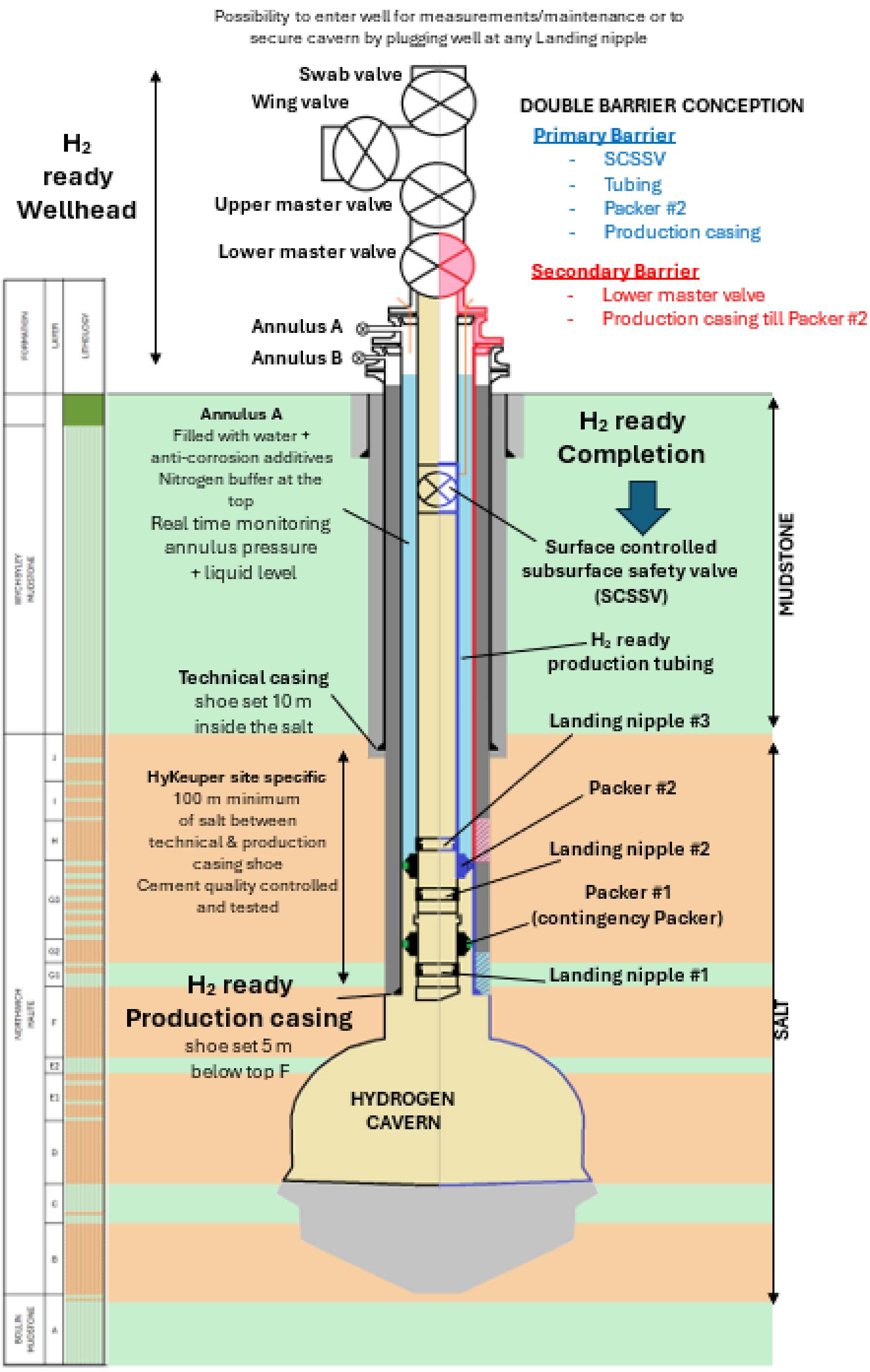


Figure 3: Theoretical HyKeuper Hydrogen Completion with primary (blue) and secondary (red) barrier

HyKeuper hydrogen completion will be based on Stublach natural gas completion double barrier design, which has proven its efficiency in term of well integrity management, and will benefit from latest hydrogen equipment development (design and/or material selection) which have been tested on Storengy HyPSTER hydrogen storage pilot project in France (H_2 pressure cycling in a salt cavern).

The main lessons learned from the HyPSTER project are (Thirion 2023 & 2024):

- Absolutely no unexpected annulus pressure change has been recorded over the 6 months period of hydrogen pressure cycling test, which indicates full hydrogen tightness of every individual element composing the primary barrier of the well completion, i.e.:
  - This first demonstrates that the premium gas-tight threaded connections and special steel grade selected for the HyPSTER project are suitable and adapted for hydrogen.
  - Also that the packer (chosen technology, setting method and material selection) used for the project is also suitable for H_2.

- The Surface Controlled Subsurface Safety Valves installed in HyPSTER cavern were tested in real field condition with hydrogen and successfully passed the criteria defined by American Petroleum Institute Specification 14A "Subsurface Safety valve and annular Safety Valve equipment", which is the worldwide accepted standard for this kind of equipment.

- Finaly, absolutely no leaks have been detected at surface and the special hydrogen designed wellhead, which was developed specifically for the project, proved also to be a success.

Similar results have been obtained on completion equipment/wellheads from different suppliers on another hydrogen pilot project, the Gasunie HyStock project in the Netherlands for which tests were conducted before leaching the cavern, with smaller hydrogen volumes, which does however not affect the validity of the results regarding integrity (Roordink, Horváth, Kepplinger, & Haydl, 2022).

The H2Cast project from StoragEtzel and Gasunie in Germany aims to go a step further with the testing of hydrogen cycling and surface process using two nearby salt caverns (balancing brine and hydrogen from one cavern to another one). Both caverns have been completed with different kind of equipment (Kürzel, Donadei, Reekers, & Kuperus, 2024). Initial hydrogen integrity tests have now been successfully conducted and, since May 2025, the project is injecting the 90 tons of hydrogen required prior to start hydrogen cycling.

7. PROCESS SAFETY

Hydrogen has been safely stored in underground salt caverns for many years, both in the USA and here in the UK. INEOS Inovyn and predecessor companies have been producing and handling hydrogen in the North West for over 100 years and have expertise in the storage of natural gas and ethylene in underground salt caverns.

Hydrogen is flammable in the presence of air or oxygen, and this hazard is managed with robust measures. Importantly, when considering the energy density of hydrogen as defined by the amount of energy contained within a given volume which is the important factor for salt cavern storage, rather than energy density for a given mass, then the energy density of hydrogen is actually lower than that of natural gas. Based on the average storage volumes (total gas including work and cushion gas) of HyKeuper, a cavern would contain an energy content of 470 GWh with natural gas or 115 GWh with hydrogen.

The facility has been designed and will be operated to the highest standards to minimise the likelihood of accidents or loss of containment, and to limit any harmful effects throughout the life of the facility.

A comprehensive hierarchy of control is applied to ensure personal safety, protect the environment and safeguard assets. Safety measures are grouped into four categories: Inherent, Preventative, Detection & Control and Mitigation Safety measures are put in place to manage the risk to a level which is 'As Low As Reasonably Practical' (ALARP).

Inherent safety, built into the design from the outset:

- Careful site selection and layout to separate people from hazards and minimise piping distances.
- Minimisation of hydrogen inventory, process temperatures, and pressures.
- Equipment designed for maximum foreseeable operating conditions.
- Use of materials and technologies suited to hydrogen service and minimising other hazardous substances.
- Caverns engineered for long-term stability, with multiple containment barriers.
- During construction and commissioning rigorous tests are performed on the cavern and well completions to ensure integrity (as detailed in Leakage and monitoring).

Preventative measures reduce the likelihood of incidents:

- Robust pipeline and vessel design for hydrogen service.
- Planned Preventative Maintenance (PPM) programmes.
- Protection against impact damage.
- Safe systems of work and operator competency assurance.

Detection and Control - If a hazardous event does occur, it is important to be able to detect it and implement control measures to limit the consequences:

Examples of detection and control measures can include:

- Automated fire and (hydrogen) gas detection systems.
- Routine operator inspections and monitoring of process parameters.
- Control systems with executive actions and emergency shutdown capabilities.
- Pressure relief systems and Safety Instrumented Systems (e.g. automatic trips).

It may be necessary to supplement the control measures by applying active mitigation to limit its consequence. Mitigation measures can include:

- Active fire suppression and passive fire protection.
- Ignition control via hazardous area classification tailored to hydrogen.
- Emergency response procedures and secondary containment.
- Minimisation of personnel and vehicle presence on site.

When required for decommissioning of the facility, the gas inventory would be removed and the cavern filled with brine. After a period of time to stabilise the temperature of the brine with that of the surrounding strata, the cavern could ultimately be permanently abandoned (plugged) using proven techniques from the underground gas storage and solution mining industry or the cavern could be used for further solution mining to provide salt to the chemical or food industries.

Regulatory Oversight and Assurance

Many internal processes are followed by the company to ensure that the facility is safe. In England regulation is by the Health and Safety Executive (HSE) and the Environment Agency as the competent authorities. The initial planning assessment includes an assessment by the HSE of the suitability of the proposed location for the storage of hydrogen. Hazardous Substances Consent for hydrogen has already been granted by the Hazardous Substances Authority (Cheshire West and Chester Council) following a recommendation from the HSE. Relevant regulations include the COMAH (Control of Major Accident Hazard) Regulations (2015) and the Borehole Safety and Operations Regulations (1995). The company is actively engaged with the competent authority with respect to this project. A COMAH demonstration is made in the form of a safety report, which is provided to the competent authority and is updated and resubmitted over the life of the facility. Many specialist interventions are proactively carried out by the competent authority over the life of the facility, to ensure that the measures described in the COMAH safety report are actually being applied at the site.

Design Assurance and ALARP Demonstration

FEED design is ongoing with process safety studies forming part of the crucial first steps in establishing safe and robust design. These include HAZID, HAZOP, QRA, studies which form the basis of the safety report that is submitted to the competent authority (HSE) as part of the COMAH regulations.

The ALARP (As Low As Reasonably Practicable) demonstration is made to the competent authority using the safety report and considers the types of safety measures described in this section. Significant hazards are rigorously identified in specialist studies and are modelled to determine safety and environmental consequences. Frequency analysis is carried out to determine the residual risk to people (workers and the public) and the environment. The acceptability of the risk is assessed against company norms and by the competent authority to prove that the risk to people and environment is indeed ALARP.

Applications to the regulator will provide oversight to design ensuring independence and verification of ALARP achievement.

8. CONCLUSION

The evidence presented in this report demonstrates that the HyKeuper salt caverns and the site are technically and geologically well-suited for the safe and effective storage of hydrogen. Extensive modelling, laboratory testing, and operational experience from comparable facilities confirm that hydrogen poses no greater risks to cavern integrity than natural gas, and in several aspects exerts lower thermodynamic impacts.

Storengy's proven expertise in solution mining and underground gas storage, including the Stublach Gas Storage Site; combined with the experience gained through pilot projects such as HyPSTER; provides a strong foundation for adapting the HyKeuper design to hydrogen applications. The double-barrier well completion strategy, rigorous integrity testing protocols, and comprehensive safety management systems ensure that risks to people, assets, and the environment are reduced to a level that is demonstrably As Low As Reasonably Practicable (ALARP).

Importantly, ongoing studies and pilot projects, including HyPSTER and others across Europe, will continue to generate valuable data on hydrogen storage behaviour. The outcomes of these projects will inform the detailed design and operation of HyKeuper, further strengthening confidence in the robustness and safety of the facility.

Hydrogen storage in the HyKeuper caverns will play a vital role in enabling the UK's transition to a low-carbon energy system, by providing large-scale, flexible storage capacity in support of HyNet NW and national net zero targets. With appropriate regulatory oversight, adherence to established standards, and incorporation of the latest research findings, the HyKeuper development can deliver safe, reliable, and long-term hydrogen storage capability to the UK energy system.

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