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Well Integrity in Salt Cavern Hydrogen Storage

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Abstract: Underground hydrogen storage (UHS) in salt caverns is a sustainable energy solution to reduce global warming. Salt rocks provide an exceptional insulator to store natural hydrogen, as they have low porosity and permeability. Nevertheless, the salt creeping nature and hydrogen-induced impact on the operational infrastructure threaten the integrity of the injection/production wells. Furthermore, the scarcity of global UHS initiatives indicates that investigations on well integrity remain insufficient. This study strives to profoundly detect the research gap and imperative considerations for well integrity preservation in UHS projects. The research integrates the salt critical characteristics, the geomechanical and geochemical risks, and the necessary measurements to maintain well integrity. The casing mechanical failure was found as the most challenging threat. Furthermore, the corrosive and erosive effects of hydrogen atoms on cement and casing may critically put the well integrity at risk. The research also indicated that the simultaneous impact of temperature on the salt creep behavior and hydrogen-induced corrosion is an unexplored area that has scope for further research. This inclusive research is an up-to-date source for analysis of the previous advancements, current shortcomings, and future requirements to preserve well integrity in UHS initiatives implemented within salt caverns.

Keywords: subsurface hydrogen storage; salt dome; hydrogen-induced impact; well stability; hydrogen corrosion; renewable energy; salt creep; geomechanics; casing failure; solution mining

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1. Introduction

Conventional energy sources like fossil fuels have significantly contributed to the development of the modern technological era [1]. However, climate change and its outcomes, e.g., global warming and greenhouse gases, are threatening life on the Earth [2]. Many efforts are being made in the field of using new and renewable energies to replace fossil fuels and provide the energy needed by mankind [3–8]. One of the most attractive options is the utilization of the most abundant element on earth, hydrogen.

Natural hydrogen gas is a suitable alternative to fossil fuels to achieve a cleaner and more sustainable environment. However, global hydrogen supply may be vulnerable due to different political, environmental, and economic factors. Countries around the world are using hydrogen fuels to bring their carbon dioxide emissions to net zero. Shipping, air and ground transportation, steel companies, cement plants, and fertilizer industries are all looking for hydrogen as the best alternative to fossil fuels. Therefore, investing in UHS and creating reliable reserves for it appears extremely seminal in terms of security of supply. The advantages of UHS are the use of less land area, keeping hydrogen safe from surface problems, and storing in substantial volumes [3]. However, safe storage of this gas is one of the most important challenges in using hydrogen.

UHS is feasible in aquifers, exhausted hydrocarbon reservoirs, and salt caverns. As suitable formations vastly found on the outskirts of big cities, aquifers are a good option in terms of accessibility and proximity to energy consumption points [9,10]. The exhausted hydrocarbon reservoirs are another appropriate storage option, as the necessary drilling equipment and engineering facilities are already available on those sites [11]. Salt formations are other geological structures for hydrogen storage. Salt cavern construction is achieved by injecting hot fresh water to salt domes or thick salty strata. One of the most important advantages of salt structures is low permeability and low chemical reaction with stored hydrogen [12–15].

Implementation of UHS initiatives within salt caverns may face two problems; firstly, substantial H_2 storage can be strongly expensive. Therefore, neither industrial users nor exporters are likely to invest in it because liquid hydrogen-derived fuels (such as kerosene) are cheaper to store than hydrogen gas and hydrogen-derived fuels. However, importing governments should probably build strategic reserves of these liquid fuels, just like oil. Secondly, saline geological formations are not uniformly distributed around the world. Europe and North America have a lot of salt deposits; nevertheless, there are insufficient salt formations in South America and East Asia. To be more specific, for instance, Japan, which is likely to be one of the early adopters of hydrogen fuel, has no salt reserves at all. Japan's lack of salt caverns has made it difficult to store natural gas. Even though 40% of the whole electricity production in Japan is dependent on gas, it has gas reserves only for 36 days [16].

Since a few decades ago, salt caverns have been utilized for UHS purposes on a limited scale, mostly in the UK and US. Currently, UHS projects are running in the Moss Bluff, Colmenardum sites in the USA, and Teesside sites in England [17–20]. Several projects, including Hyunder [21], H_2 store [22,23], Hyuspre [24,25], and Sun Underground Storage in Austria [26], have been initiated to study various characteristics of UHS initiatives. These characteristics included the hydrodynamic behavior of hydrogen of H_2 in the cavern, the selection of the well drilling site, and H_2 reactions with well materials. Therefore, this information mainly includes cavern pressure and volume. Nevertheless, information about well integrity issues is not usually released for security reasons. This lack of access makes it difficult to fully understand and use hydrogen storage experiences.

According to the NORSOKD-O1O standard [27], well integrity means employing operational, technical, and managerial methods for prevention and reduction of the risks associated with abnormal fluid influx into a well. In other words, it describes the safe designation, construction, and installment of physical infrastructure for prevention of subsurface fluid intrusion into the well using materials such as cement, steel casing, or any sealing material that creates a barrier between these fluids and the well. Defect occurrence and the formation of voids or fractures in the subsurface structure of the well lead to fluid intrusion to the well, lowering the safety of the project. Therefore, controlling and maintaining well integrity is vital [28,29]. Threatening factors to well integrity include inadequate design, failure to adhere to superior standards, use of non-standard materials in well construction, as well as factors such as faults, earthquakes, and high operational temperatures and pressures. Vulnerable well integrity can lead to leaks, contamination, and environmental damage. This issue is universal because wells are used globally for oil, gas, and water extraction. Failures can result in widespread pollution, water resource depletion, and safety hazards, affecting ecosystems and communities worldwide. Ensuring robust well integrity is crucial for sustainable resource management and environmental protection on a global scale [30].

The key target of this research is elaboration of the challenges related to well integrity that may arise in hydrogen storage in salt caverns. Those challenges encompass the corrosion of casing steel, hydrogen-induced decomposition of cement, and durability of the materials used in the well wall. The research was conducted by collating and integrating the previous reports and studies pertinent to well integrity issues in UHS initiatives in salt caverns. The research strives to provide an inclusive reference for the engineers, drilling companies, UHS investors, and policy makers to better understand and manage the crucial challenges in the UHS-relevant well integrity domain.

2. Characteristics of Salt Formations

2.1. Geological Structure

Rock salt has been seen underground in various forms due to its fluidity. The most widely used type of classification divides salt formations into layered, cushioned, vaulted, sandwich, dome, plug, and welded [31].

Salt domes are basically the result of tectonic activities on salt deposits [32]. Each salt dome contains a central core made of salt, and the part that surrounds the central core which is usually made of younger salt deposits. Salt domes are only those forms of salt formations that have a stone coating [31]. In some salt domes, the thickness of the stone coating reaches several hundred meters. The overburden rocks usually consist of limestone, gypsum, and anhydrite. In some cases, they contain sulfur deposits [32].

Salt domes are present in almost half of the known salt formations in the world. The most important centers of accumulation of salt domes are the Gulf of Mexico, Central Europe, the Middle Eastern countries, and Kazakhstan. Salt domes have different shapes, whose dimensions sometimes reach several kilometers. Figure 1 shows the different shapes of salt domes found in some global locations. The shape of salt domes is not the same throughout the world. Salt dome shape chiefly relies on parameters including the time of formation, the salt dissolution rate (which is controlled by the erosion pace), the rate of salt rising from its origin, the overburden rocks, and regional tectonic activities [33].

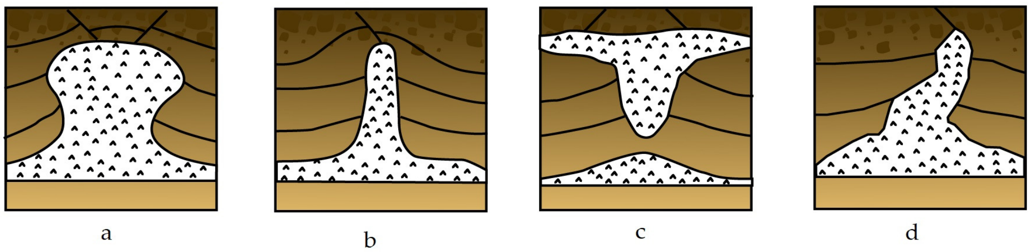

Figure 1. The different shapes of salt domes in some global locations; (**a**) Germany (Etzel, Huntorf), and Denmark (LI, Torup), (**b**) U.S. Gulf coast basin, and Kazakhstan (Pricaspian basin), (**c**) Offshore U.S. Gulf Coast basin, and Germany (Osterholz, Ostervesede), (**d**) Portugal (Carrico), Germany (Barkholt, Bockstedt, Greetsiel).

Except the shape, dimensions and depth of salt domes are also different. For example, the dimensions of salt domes in southern Iran are from 1 to 15 km [33]. Also, the upper surface of the salt domes lies in the depth of 1 km to the depths of more than 3 km.

The most important feature of salt domes is its steep walls. The origin of salt domes is from thick layers of salt, which initially form a pillow, and then over time, due to tectonic and halotectonic activities, they penetrate to the surface of the earth. Figure 2 shows the stages of salt dome formation. Salt domes usually have a circular horizontal cross-section, except in cases where their shape is out of symmetry due to proximity to large faults [34].

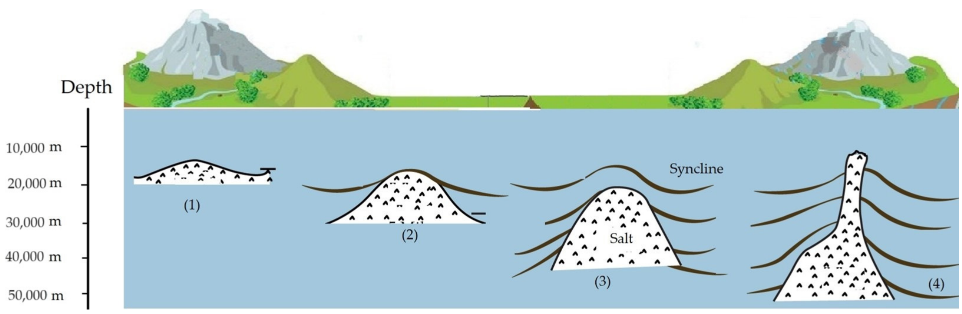

Figure 2. Salt dome expansion stages.

2.2. Criteria for Selection a Suitable Salt Dome for UHS

The selection of salt caverns for UHS purpose generally depends on three factors: (1) the presence of a suitable extent of the salt mass, (2) the presence of water necessary for solution mining, and (3) the possibility of disposing or recovering the brine liquid resulting from solution mining [35].

For the study of salt domes, early surface studies are performed before conducting exploratory studies. The first step is area studies with the aim of identifying areas with salt potential, which usually begins with the study of existing maps and continues with the use of aerial photographs, water geochemical studies, and aerial geophysical surveys. If the area is promising, ground geophysical methods such as geoelectric, gravimetry, electromagnetic and seismic operations are used to identify the geometry and depth of the salt complex [36,37].

The selection criteria of salt domes should be expressed in such a way that exploratory data can be collected. These properties are generally divided into surface characteristics, subsurface characteristics, physical–chemical characteristics, and creep behavior. Each of these conditions are discussed briefly below.

2.2.1. Surface Characteristics

In the early stage, the subsurface information is not remarkably accessible. Hence, the use of surface information can be a very good guide to find a suitable salt dome. Some of key surface characteristics of salt domes encompass:

- Surface expansion: The wide expansion of the salt formation is a proof of the vastness of the salt area, which is a positive factor for storage. But in order to compare the surface expansion and salt outcrop in the basins, the depth and age of the feeding salt formation, the material of the upper layers, and the tectonic conditions of the regions should be considered [38–43].
- Lithology and structural condition of overburden rocks: The strength of overburden rocks is highly effective in preventing the ceiling collapse. Therefore, investigation on the structural condition of the overburden rock is of particular importance [43]. The strength properties of overburden rock layers are critical, especially when the ceiling is not a salt medium. The ceiling mechanical resilience relies directly on the characteristics of overburden formation (Figure 3). Although the intact salt roofs provide unlikely collapse, the weak roof causes failure and instability [44].

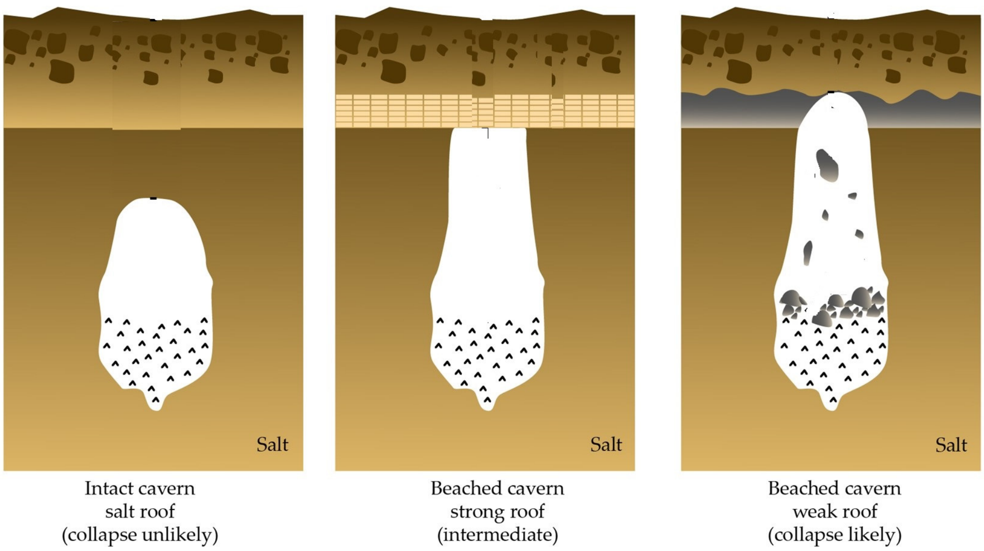

Figure 3. The role of overburden rock type in collapse of salt cavern roof.

- Tectonics and seismicity: Considering that active tectonics can increase the rate of dome formation and rising salt, great care should be taken in selecting the salt dome. Proximity to active faults increases the risk of salt creep. Also, self-doming and rising salt increase the creep intensity [43].

2.2.2. Subsurface Characteristics

Subsurface information is extremely important to identify suitable locations for H_2 storage. Most of this information is obtained by geophysical surveys. The key subsurface characteristics are:

- Diapirism: The rate of activity and rising of salt in salt domes has a direct influence on cavern stability. The diapirism process is generally grouped into three stages: reactive, active, and passive. In the passive stage, there is an outcrop of dome salt on the surface of the earth, and in active or reactive diapirism, there are no traces of dome salt on the surface of the earth.
- The best way for storage is to construct a cavern in reactive diapirs. Among active and passive diapirs, the cavern location should be selected according to the rise of salt, volume of salt, surface and subsurface conditions of salt, and their geometric shape. The morphological characteristics of diapirs are directly related to their activity level. The more the activity of the salt dome, the more height and slope of the dome walls. Therefore, salt domes with high height and steep vertical walls definitely have more activity [43].
- Thickness: The thickness and expansion of the salt dome are critical factors that determine the cavern geometric shape. Large caverns are usually formed in salts with a thickness of 150 to 400 m. Of course, solution mining can also be conducted in lower thicknesses between 60 and 100 m, but the created caverns have a smaller volume [43].
- Depth: The depth of salt dome has a significant effect on determining the maximum operating pressure (MOP). MOP has a direct relation to the ultimate storage capacity of the cavern. As the depth increases, the MOP increases which is not desirable. Also, by constructing a cavern at a shallow depth, the minimum operating pressure can be reduced. Nevertheless, by reducing the depth, the MOP also reduces. The construction depth of UHS caverns in salt domes is commonly between 500 m and 1500 m [38]. In salt layers, caverns are more compact and located at shallower depths (around 500 m to 650 m).
- Discontinuities and faults: discontinuities and faults form weak zones, e.g., cracks and joints, in the upper layers through which salt can rise and form domes. Moreover, the storage efficiency can be affected as those discontinuities form potential paths for H_2 leakage. Active and large faults have a negative effect on the selection of salt domes [43].

2.2.3. Physico-Chemical Characteristics

The physico-chemical characteristics of salt domes and overburden layers are measured by various tests in the laboratory or field. The results of these tests are used for feasibility studies as well as cavern and well designation. In what follows, some of those important properties are described:

- Purity and homogeneity: the presence of impurities in salt during the development and operation of the cavern causes many problems. In addition, the presence of insoluble substances in water prevents the continuation of solution mining operations. Therefore, determining the number of impurities and their location is effective in the mining process [43].
- When elements such as manganese or potassium are present in the salt formation, there is a potential of creating inappropriate shapes of salt cavern [39]. Therefore, the construction of storage caverns in salt domes requires conducting sufficient exploration studies on the identifying anomalies.

- Porosity and permeability: Salt porosity is usually less than 1%. Salt rocks have low permeability. Hence, it can be assumed to be impermeable with a good approximation [43].

2.2.4. Creep

Geomechanical behavior of salt depends on the dimensions of the salt crystal, intercrystalline bonds, solubility, time, temperature, humidity, and impurities [37,41]. Therefore, the behavior of salt rock is different from other rocks due to different behaviors in different loading conditions, temperature, strain, and strain rate [37]. For example, rock salt shows a brittle behavior in a uniaxial compression test, but large-scale salt formations on a geological scale show a fluid-like (viscous) behavior.

Creep is a type of plastic behavior; it is usually divided into three different stages. At the beginning of loading, an instantaneous elastic strain, ϵ_e, is created. After this early elastic strain, the transient creep occurs. Laboratory studies show that by removing the load in the first stage, the strain is quickly reduced and then, with the passage of time and asymmetrically, the amount of strain reaches zero. At this stage, by removing the load, no permanent deformation occurs in the material.

If the loading continues, the strain linearly increases with time. This stage is usually identified by its constant slope and is called the stable or secondary creep stage. By removing the load in this stage, a permanent deformation is made.

In the third stage, which is called third creep or accelerated creep, a fracture occurs in rock salt. The third creep includes a combination of joint development processes, salt creep and joint improvement [32,42,43]. It should be noted that all these three stages are also dependent on the ambient temperature [44].

3. Salt Cavern Construction Process

The salt cavern construction is conducted via a solution mining process. In this method, firstly, a well is drilled until it reaches the target salt dome. After reaching the desired depth of the well, the cavern space is excavated using solution mining which is based on injecting hot fresh water to the well and moving out the resulting brine mixture. Over time, the inflow rate of water and the retention time of water in the cavern increase as the operation progresses.

At the end of the solution mining operation, a large cavern containing brine remains. Fresh water is sourced from nearby groundwater aquifers and rivers. Before injecting water into the well, it passes through filters and separators to remove impurities. Then, in the degassing unit, the oxygen content in the water is reduced. This process significantly reduces corrosion in facilities such as pipes, pumps, and fittings, thereby extending their lifespan. Additionally, degassing greatly reduces the risk of rupture in containment pipes. The brine exiting the cavern undergoes processes such as storage in tanks, filtration, dilution with fresh water, and compliance with all environmental aspects before returning to primary sources [45].

Solution mining is performed in two main ways: Direct leaching, and Reverse leaching. In the first method, fresh water enters through the drilling pipe in the well, and the brine mixture exits from the space between the drilling pipe and casing pipe (Figure 4a). In the second method, fresh water enters from the annular space, and the resulting brine exits via the central pipe (Figure 4b). The casing pipe is illustrated in green.

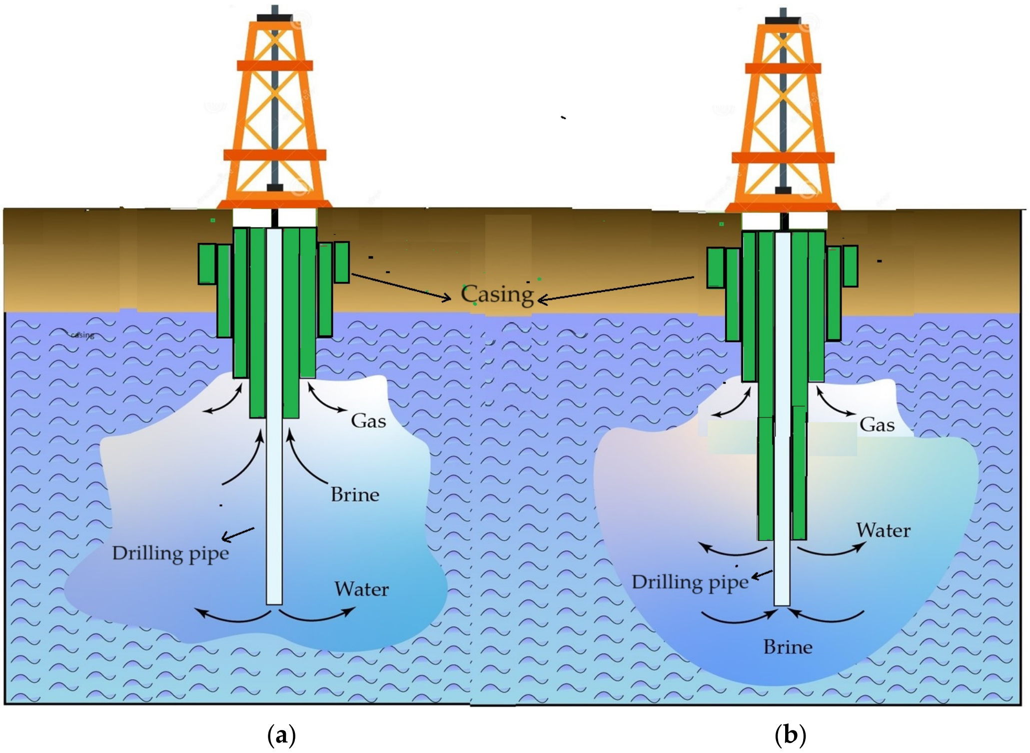

Figure 4. The methods of salt cavern construction: (**a**) direct leaching, and (**b**) reverse leaching.

As illustrated in Figure 4, the expansion of space near the region of fresh water injection is higher than in other areas. Considering this, and to create a uniform and regular space, in most cases, both methods are used alternately [45]. Moreover, controlled depth adjustment of the pipes can be achieved for this purpose. To prevent uncontrolled dissolution and maintain the appropriate and stable shape, a protective substance is used. Any substance that is non-corrosive, non-reactive with water, and lighter than brine can be used as a protective material. Natural propane gas, diesel, and nitrogen are common protective materials. To control the dissolution and cavern formation processes, the flow rates and salinity of inflow and outflow streams are measured. These measurements help determine the volume of dissolved salt. Additionally, acoustic surveys are used to monitor the cavern shape during and after the dissolution process. After cavern construction, mechanical integrity tests are conducted, and if conditions are suitable, the well strings and surface facilities are modified to provide necessary conditions for H_2 storage [46–48]. Once the cavern reaches the desired dimensions, the injected gas is introduced, and the remaining brine is expelled.

From the operation perspective, caverns should have the highest storage capacity and maximum withdrawal capability, with minimal convergence due to salt creep. In other words, they should effectively and sustainably support operational needs [49–51]. Salt caverns allow for multiple injections and withdrawals of gas per year. Injection and withdrawal operations can be performed through a single well, and high-rate gas withdrawal is possible. The preparation time for salt cavern construction is shorter compared to other methods. The probability of gas leakage is very low, and the base gas volume is relatively small, around 20% to 30% [49].

Cavern diameter, cavern height, ceiling shape, cavern spacing, and the distance between salt caverns and adjacent formations are the most important parameters affecting cavern design [52,53]. Incidents observed in salt storage reservoirs are primarily due to salt creep and cavern volume loss, uncontrolled salt dissolution, leaks from pipes, and proximity of the cavern to salt formation boundaries leading to increased gas leakage probability and high shear stresses. These factors have destructive impacts on the cavern stability and well integrity [54,55]. Having said this, salt caverns are considered as highly reliable spaces not only for H_2 storage but also for compressed air, natural gas, CO_2, etc. [56–91].

To ensure the secure containment of hydrogen within salt caverns, a comprehensive knowledge of the geomechanical characteristics of salty formations is needed. Halite, the primary constituent of rock that has inherent impurities within its lattice structure [92–94]. Moreover, Dislocation creep predominates in the regions with higher stress, such as those that are close to cavern perimeters. Solely relying on the dislocation creep mechanism for predicting strain rates underestimates the rates of creep strain at lower stresses. Many experimental tests show that salt creep has a substantial impact on salt cavern lifetime [95–100].

4. Well Integrity Issues

So far, several well integrity issues have been reported in different underground storage of hydrogen and other hydrocarbons in salt caverns [3]. Table 1 outlines 10 significant incidents related to underground storage of hydrogen and other hydrocarbons due to well integrity issues [3]. According to this table, well integrity issues in global underground gas and hydrogen storage projects are often caused by factors such as the break of the central column, oil leakage around the wellhead, wellhead flange breakage, brine circuit leakage, gas leakage from casing pipes, wellbore blowouts, and gas influx from the cement surrounding the casing [3].

Table 1. Some well integrity issues reported in underground storage of hydrogen and other hydrocarbons.

Country	Project Location	Year	Stored Gas Type	Reported Problem	Outcomes
France	Manosque	2012	Diesel	Break of central column	Not reported.
France	Manosque	2007	Fuel oil	Oil leakage around wellhead	Contamination of ground surface by the leaked oil.
USA	Texas, Odessa	2004	Propane	Wellhead flange break	Air pollution by the released gas.
USA	Moss Bluff, Louisiana	2004	USA-LPG	Brine circuit leakage	A blast and fire resulted in the release of 170 cubic meters.
USA	Magnolia, Texas	2003	Natural gas	Gas leakage from casing pipe	An amount of 9.9 million cubic meters of gas were released within a few hours.
USA	Brenham, Texas	1992	LPG	Blowout of the wellbore	Huge gas release to the atmosphere as well as explosion and fire resulted in 3 deaths and 23 injuries.
USA	Clute, Texas	1988	Ethylene	Gas leakage from casing pipe	Subsurface contamination by the leaked gas.
USA	Mont Belvieu, Texas	1985	Propane	Gas leakage from casing pipe	Explosion and fire resulted in 2 deaths.
USA	Belvieu, Texas	1980	LPG	Gas leakage from casing pipe	explosion and fire.
USA	Mississippi	1980	Natural gas	Gas influx from the cement around casing	Subsurface contamination by the leaked gas.

The main actions following these incidents include checking the condition of the covers and the concreting section before the operation of the caverns, standardizing tightness tests, setting a pressure limit to ensure protection against maximum working pressure, and implementing a specific safety method regarding brine completion in case of gas intrusion [3].

The unique properties of rock salt, including creep behavior, impermeability, and solubility in water, make drilling in salt formations accompanied by specific challenges, especially at greater depths. Increased temperature and pressure further exacerbate these challenges [101].

Salt dissolution leads to the creation of cavities and non-uniform well diameters. Additionally, salt creep results in reduced well diameter and challenges in running casing pipes. Water and brine facilitate corrosion and damage to drilling pipes. The significant depth of caverns subjects casing pipes to high lateral pressures. Furthermore, the lack of wall straightness and non-uniform well diameter induce bending stresses. The low density and creep behavior of salt cause displacement at the salt-formation interface and exert shear forces on casing pipes [101].

High pressure within the caverns creates conditions for gas leakage through the cemented space around the casing. The combination of these conditions necessitates high knowledge and experience for proper drilling operations [102].

Arguably, designing casing pipes is the most critical part of drilling operations. This involves appropriate geometric design considering specific conditions at each depth and the use of materials with high resistance and consistent quality, especially for the inner casing wall [102]. In addition, creep creates a plastic transition layer in the formation. The pressure from this plastic transition layer increases the force exerted on the interface between the cement and the formation, which can threaten the well's integrity throughout its lifespan. The geomechanical effects of plastic creep formations, although not detectable from surface observations, can have detrimental consequences for cement integrity [103].

An important parameter in well designation is the well resistance against the stresses from external or internal forces. This ensures the safety and preservation of the well during the project life span. Compared to methane-storage salt caverns, the small size of H_2 elements results in a higher rate of dispersion and diffusion. This matter poses challenges for the stability and preservation of the well.

The high affinity of hydrogen to combine with mineral elements in rocks and fluids in the well leads to erosion and corrosion of the well walls and infrastructure due to the pressure and temperature resulting from these reactions. Considering the small size of hydrogen, it tends to escape from the cavities around the well. Furthermore, the reaction between hydrogen inside the well and sulfur in the earth creates water and corrosive fluids, which degrade the casing used in the well.

Sand and fine rock particles resulting from pressure changes, pore openings, and stresses applied to the well walls lead to erosion and penetration into the well [104]. Injecting hydrogen into empty salt dome cavities is ideal for energy storage and carbon mitigation. However, ensuring the safety and integrity of the well is essential to prevent any environmental challenges and is crucial for environmental health. The mechanism of UHS as well as the cyclic injection-production through the well creates pressure cycles that can lead to erosion and corrosion of the well.

The safety and stability of the well and its components, including the materials and connections used in the well body and bed, are essential. Following risks may threat the well integrity in the UHS projects:

4.1. Casing Mechanical Failure

The wells drilled in salt formations may undergo minor or large deformations as a response to the salt creeping motion. This may lead to occurrence of well instability issues mainly in the form of casing failure, or casing blockage. Casing failure issues are categorized in the drilling high-risk challenges leading to well instability problems. Those issues may lead to casing collapse or total loss of the well. The motion of salty rocks towards the drilled well gradually increases with time. If the stress distribution around the casing becomes intensive, the salt motion deviates the casing from its main trajectory. Consequently, this gradually bends the casing string, and finally shrinks and blocks the well. After that, the casing string may undergo severe deformations in the form of shear, compression, and tension failures. Mostly, depending on the creep nature of the salty rocks, one or more mentioned failure types can occur [105]. The casings may fail in the under tension, lateral compression, axial compression, shear, and bending lading conditions.

The effect of the creeping motions directly pertains to the geomechanical properties of the salty formations. Such properties are the elemental composition, grain size, creep nature, thermal properties, Poisson's ratio, etc. The geomechanical properties of the subsurface formations can be measured through the exploratory boreholes, seismic surveys, measurement while drilling (MWD) techniques, etc. Creation of a suitable geomechanical model for salt formations is an indispensable task to consider the salt creep hazards for the casing integrity.

To design a casing string, some factors such as the well purpose, well geometry, in situ lithology, bit geometry, cementing jobs, rig performance, safety requirements, and environmental regulations must be considered [9]. Furthermore, it is essential to determine the induced stresses created around the well. This requires adequate knowledge of the vertical, tangential, and radial stresses around the well, as each of these induced stresses or their combination can lead to a specific failure mode in the casing.

In addition, for selecting a suitable casing, the engineer must consider the different types of casing strength which are critical in their bearing capacity against the different loading conditions. Such major strengths can be divided into three categories: the burst strength, the yield strength collapse, and the plastic collapse. In the following paragraphs, these terms are elaborated:

- Burst Strength: when the inner pressure of the casing is larger than the outer pressure, it is expressed that the burst pressure is applied to the casing. The burst pressure conditions take place in the well control operations and integrity tests. The following equation is used for calculation of the casing burst strength [106].

$$P_B = 0.875\left(\frac{2\,Y_p\,t}{D}\right) \tag{1}$$

In this equation, P_B represents the least burst pressure (psi), Y_p indicates the minimum casing yield strength (psi), and t represents the nominal wall thickness (in). Furthermore, D stands for the nominal outer casing diameter (in).

- Yield Strength Collapse: this parameter is defined as the yield status in the internal wall of the casing string. When the casing is thick ($D/t < 15$), the tangential stress overcomes the casing yield strength prior to the failure occurrence. The corresponding relationship is expressed as:

$$P_{YP} = 2\,Y_p\left(\frac{\left(\frac{D}{t}\right)-1}{\left(\frac{D}{t}\right)^2}\right) \tag{2}$$

where P_{YP} is the yield strength collapse.

- Plastic Collapse: this parameter was developed using a series of experimental tests on different casing strings utilized in the oil/gas drilling activities. The relevant relationship is:

$$P_P = Y_p\left(\frac{A}{\left(\frac{D}{t}\right)} - B\right) - C \tag{3}$$

where P_P represents the plastic collapse strength. Moreover, A, B, C, and (D/t) ratio are obtained from the American Petroleum Institute (API) drilling standards.

The above-mentioned equations are commonly used for designation and quantification of casing safety factor.

4.2. Seismic Hazards

The application of high pressures to underground structures increases the likelihood of seismic events. Wells are artificial holes created through a solution mining process, which may lead to local effects such as subsidence. Without proper investigation and testing, implementing these changes underground may significantly elevate the potential for seismic events during the storage period [107]. Any seismic activity may treat the well integrity.

To mitigate the risk of seismic events, the pressure applied to the underground structure must be controlled within a safe range to reduce seismic hazards. Prior to commencing the storage process, a specific quantity of gas must be injected into the well to fill the void spaces and to maintain the minimum well pressure.

Controlling the minimum well pressure reduces the risk of seismic events. The gas used to ensure the maintenance of minimum well pressure should have low reactivity with hydrogen and minimal tendency to undergo chemical reactions with minerals and underground fluids within the well. This gas, applied to ensure the stability, is commonly named as cushion gas, and its ideal state is permanent stability within the storage location. UHS wells, due to their continuous geometric structure and smaller construction, require less cushion gas. Nitrogen (due to its low reactivity with hydrogen) and other underground fluids are among the gases used as cushion gas in hydrogen storage processes [107].

4.3. Hydrogen Chemical Impact on Cement

During drilling and well completion operations, to prevent uncontrolled subsurface fluid influx into the well, hydraulic and mechanical barriers are used. Hydraulic barriers are made of a grout column (such as cement) to create a favorable environment for drilling and prevent damage from impacts that cause fracturing and geometric deformation of the well. Cement is a permanent hydraulic barrier; however, cement structure may deteriorate and erode due to contact with subsurface fluids and minerals present in the well.

Past studies on cement behavior in wells injected with hydrogen suggest that safe interaction between hydrogen and cement is feasible under medium pressures and temperatures. However, it is necessary to note that the depth of the well where cement hydrates depends on temperature and pressure. Under high temperature and pressure, hydrogen reactivity with cement increases, leading to fractures, cracking, and corrosion of the cement. When the cement around the well is subjected to hydrogen injection, hydrogen penetrates into the cement structure, creating bubbles within the cement texture. This phenomenon reduces the ultimate compressive strength (UCS) of the cement by up to 50% after one week. Consequently, hydrogen injection damages production and injection wells [108,109].

4.4. Hydrogen Chemical Impact on the Casing

Mechanical barriers such as casings are made of steel and plastics that are chemically degraded by subsurface fluids. Defects or failures in these barriers can result in hydrogen leakage and economic damage, leading to project failure.

High reactivity of hydrogen gas and its small atomic size, along with its high diffusion rate in solids, can pose a threat to well integrity. Therefore, to prevent hydrogen intrusion and maintain well integrity, the use of insulating materials in the well structure is essential [110,111].

Hydrogen atoms can have significant effects on the geometric structure of casing, leading to fractures in the crystalline structure of steel. Consequently, steel components installed in the well are weakened against any damage, and are prone to time-dependent degradation or disintegration. Excessive small hydrogen atoms have the ability to enter the metal structure or steel crystalline lattice and cause problems such as reducing steel strength, altering mechanical behavior, and creating defects in its microscopic structure [112]. In this section, the different effects of hydrogen on steel are discussed [113–119].

4.4.1. Hydrogen Embrittlement (HE)

During this mechanism, the H_2 atoms ingress into a metallic material leads to the formation of cracks, reduction in ductility, and subsequent deterioration. Fracture of metallic materials due to hydrogen embrittlement is often unpredictable and sometimes catastrophic. In this condition, external forces are not required for fracture to occur, and the presence of residual stresses can act as a source of stress. Additionally, the threshold stress levels for crack initiation are usually lower than the yield stress; therefore, the steel may fail suddenly and internally without undergoing sufficient deformation or exhibiting visible signs of damage. The threshold for hydrogen embrittlement depends on the amount of hydrogen and the duration the material is exposed to it.

Hydrogen may penetrate into the metal structure during fabrication processes or while the metal component is in use [118]. Processes such as acid pickling, electroplating, welding, and generally all processes that expose the steel surface to hydrogen make the material susceptible to hydrogen absorption and penetration.

The following chemical reaction shows how hydrogen sulfide reacts with iron:

$$H_2S + Fe \rightarrow FeS + 2H, \tag{4}$$

This reaction creates deep pits in iron and steel; as a result of sulfide hydrogen corrosion, atomic hydrogen is generated. The generated hydrogen enters the steel and imparts a brittle property to it. Additionally, atomic hydrogen inside the steel can be converted to molecular hydrogen, and the volume expansion resulting from it causes steel to crack. In many cases, it is observed that casings have become embrittled when in contact with hydrogen gas. Often, these fractures occur in the joint areas, which are observed during drilling or pipe opening.

Increasing the concentration of hydrogen sulfide reduces the life of steel. The tendency of steel to become embrittled in a hydrogen sulfide environment drastically decreases at a pH above 10. Furthermore, recent research has shown that the susceptibility of steel to cracking in the vicinity of hydrogen sulfide decreases as the temperature increases up to 66 °C. It is assumed that increasing the temperature increases the mobility of trapped atomic hydrogen in the steel crystalline lattice. This leads to the release of hydrogen from the steel. In drilling formations containing H_2S, casing pipes should always be monitored, and the torque applied to the connecting tool should be considered [118,120]. To prevent the formation of surface cracks, the coverage inside the pipes and wrench area should be examined and kept under control. Therefore, casing pipes should be inspected continuously.

4.4.2. Hydrogen-Induced Cracking (HIC)

HIC is a form of wet H_2S cracking that usually occurs due to the accumulation of high concentrations of hydrogen in metals. This mechanism involves atomic hydrogen that diffuses through a metal structure. HIC cracks are created parallel to the surface in the direction of hoop stress. Hydrogen-induced cracking in acidic service environments due to the presence of moist H_2S is more common [119].

Some elements such as arsenic, antimony, and cyanides contribute to the HIC process. The HIC issue is more prevalent in common iron alloys. Generally, HIC occurs to damage steel with a Rockwell hardness of 22 or higher at relatively low temperatures.

In a moist H_2S environment, the HIC mechanism begins with the formation of atomic hydrogen, which disperses throughout the metal or alloy and accumulates in voids or impurities within the metal structure. When hydrogen atoms combine and form hydrogen molecules, high pressure is created in the voids. The chemical combination of H_2S introduces these hydrogen atoms into the metal structure, thereby leading to reducing the tensile strength of the metal. Consequently, internal cracks, recognized as hydrogen-induced cracks, are slowly formed [118,120].

4.4.3. Hydrogen Blistering (HB)

HB issue occurs as a consequence of H_2 gas penetrating to the steel. In this scenario, localized deformation may occur in the steel, or in some special cases, it can even lead to complete disintegration of the metal. If hydrogen atoms reach a cavity while passing through the steel, hydrogen molecules form in this cavity. Since molecular hydrogen cannot pass through the metal, the concentration and pressure of hydrogen inside the cavity increase, thereby leading to metal disintegration [119].

Hydrogen blisters are subsurface plate-like cavities formed within the metal as a result of excessive internal pressure from hydrogen-induced corrosion in moist hydrogen environments. Hydrogen blisters are usually parallel to the surface and are formed in about one-third of the wall thickness near the surface. These blisters typically create visible surface protrusions in low-strength metals. It is worth mentioning that cracks may form between one blister and another.

The driving force for crack formation is the high stresses around the hydrogen blisters generated by internal pressure in the blisters. These internal pressures in the blisters are related to the flow of hydrogen diffusion in the steel. This phenomenon usually has a destructive impact on steels [118].

5. Well Integrity Preservation and Assessment Techniques

During the design and construction of UHS wells, necessary measurements must be taken for preservation of the well integrity. Figure 5 shows those measurements.

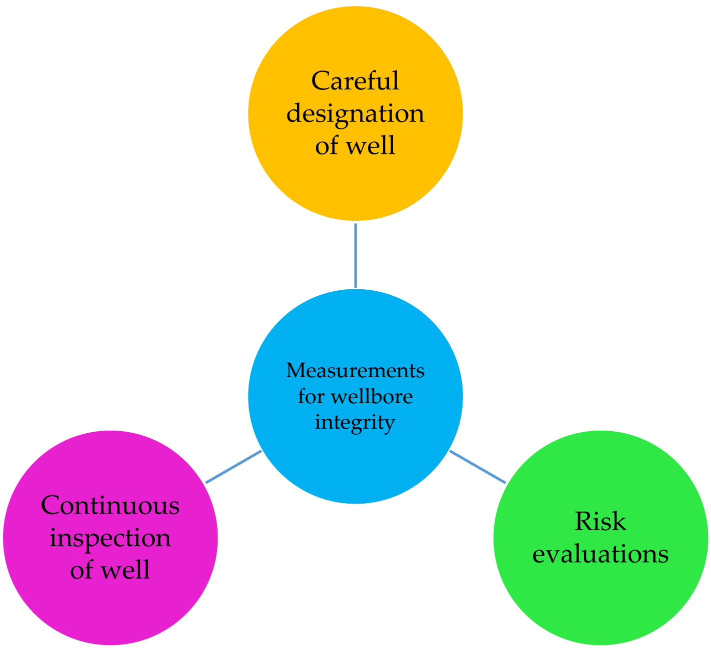

Figure 5. Necessary measurement for preservation of well integrity in UHS projects.

The above measurements are briefly described here:

- Well design and implementation: A UHS well must be appropriately designated to withstand high pressures and corrosive fluids resulting from hydrogen storage and extraction. This requires the materials used in its infrastructure to have high resistance to corrosion and mechanical stresses.
- Continuous inspection during well construction and maintenance: Continuous control and inspection according to the defined checklist during well operation are necessary to quickly identify and rectify any signs of a defect in the well structure. These techniques include continuous pressure monitoring, installation of acoustic sensors, and periodic inspections.

- Measurement and evaluation of risks: Identification and evaluation of risks before hydrogen injection can help identify and mitigate hazards. These assessments should include geological characteristics, and distances from water sources, and potential leak paths.

Hydrogen-induced degradation and stress-induced failure of the casing are relatively intertwined [113–116]. Hydrogen-induced degradation may impose significant issues on the casing stability [117,118]. Different methods are employed for detecting and mitigating hydrogen ingress in steel [117].

Numerous experiments and research have been conducted to optimize and reduce material sensitivity to hydrogen-induced failure in metals. Commonly used methods include techniques like Hydrogen Microscopic Testing, spectroscopy, Thermal Desorption Spectroscopy, Devanathan method, Electrochemical Noise analysis, and Starkocsky (OS) technique [119].

Some measures to minimize damages resulting from hydrogen exposure to steel:

- Use of vacuum-degassed killed steels devoid of voids.
- Surface protection of steel using mineral and organic coatings (rubber and ceramic coatings).
- Steel optimization using chemicals to reduce corrosion and prevent hydrogen-induced failure.
- Removal of harmful substances (sulfides, cyanides, and harmful ions).
- Alloy modification of steel such as nickel-containing steels and nickel alloys.

On the other side, well integrity assessment includes a set of methods and techniques that are used to ensure the strength, stability, and proper functioning of drilled wells [120,121]. These evaluations are very important in preventing the H_2 leakage and maintaining the safety of the environment and operations. In evaluating the integrity of the UHS wells, various methods such as pipeline pressure testing, cement tests, continuous monitoring, logging tools, modeling and simulation, and risk assessment are suggested [122].

Pipeline pressure testing, which includes applying pressure to the well and measuring pressure changes to detect leaks and weak points in the well structure, which can include static and dynamic pressure tests. In this test, a pressure of 500 pounds per square inch is applied inside a chamber for 12 h [120]. This test is performed in a closed chamber and any pressure drop within 12 h indicates a leak. On the other hand, the disadvantage of this method is that the location of the leak is unknown and there is no information about the location of the leak [122]. One way to detect the location of leakage in the well is adding radioactive tracers to injected fluids in pipe pressure testing. The use of this method requires the special skill of the operators and the provision of high costs [121].

Cement testing is utilized for evaluation of the cement resistance properties. Some tools such as cement logs are adopted for this purpose. Cementing logs, e.g., cement bonding log (CBL), are utilized to detect the separation of areas by checking the quality of cement and reducing sound energy. These tests provide us with data on the formation of the bond between the cement and the well. Those logging instruments can recognize the presence of micropores and channels [120,122].

Audio and electrical image logs also can be employed to detect and characterize the properties of fractures between the casing pipe and cement. In addition, use of ultrasonic cement imaging logs (UCIT) and ultrasonic imaging (USI) gives valuable data about the connection between the cement and the well [121,122]. Furthermore, other geophysical logs can be utilized to characterize the medium around a well [123].

Numerical studies are a suitable and economic tool to predict the integrity of the well during its useful life-time. The specification of the geomechanical constitutive model to the salt, cement, and casing should be made correctly. The numerical analysis is a helpful tool in maintaining well integrity.

Operational management and risk assessment methods have been used to perform spill simulation and risk mapping. However, these methods do not make it possible to provide a general assessment of the stability of the well, but the analysis of their results can be used to achieve the goals and control the stability of the well [124,125].

6. Discussion

In this research, the different aspects of UHS in salt caverns with focus on well integrity were elaborated. The main emphasis was given to the description of the salt geomechanical characteristics, the potential threats to well integrity, and the necessary measurements for well integrity preservation. According to the implemented research, it was found that due to the limited extent of published data related to global UHS projects in salt caverns the well integrity issue requires further considerations and investigations.

Although the experience of UHS projects in salt caverns is limited, natural gas has been successfully stored underground since 1961. Hence, the lessons achieved from these operations can be a beacon for UHS plans [126–130]. Using the results obtained from the natural gas storage sites can aid the UHS initiative in acquisition to efficient preservation of well integrity. Except for natural gas, the CCS projects are other sources to find well integrity data [128].

Mechanical stability of the well is chiefly dependent on the salt creep behavior, on-site stress state, and the native pore pressure. Due to the drilling of the well, the on-site stress state as well as the native pore pressure regime around the well change [131–134]. Furthermore, for implementation of the UHS projects, there is a need for a large amount of fresh water to perform solution mining [135–137]. After solution mining, the brine mixture must be discharged in a suitable location. Any water production in the area, or brine disposal into the adjacent rocks may redistribute local stress and pore pressure regime. Moreover, water extraction and brine injection alter the poroelastic rocks of the on-site properties [138–141]. Thus, in examining the state of hydrology and hydrogeology, careful attention must be given to the direction, speed, and volume of the local groundwater resources. Also, because the humidity and circulation of underground water strongly influence the plasticity of salt, identification and determination of the parameters of groundwater are of paramount significance. For this purpose, geoelectrical surveys or exploratory boreholes can be used.

Creep is the most influential characteristic of salt formations. There are different creep constitutive models by which the creep response of salt rocks to the well drilling operation can be numerically modeled and analyzed. Some of those main creep constitutive models are: Maxwell model, Burger model, and Power-Law model. The parameters of these constrictive models are commonly obtained during the laboratory tests conducted on salt samples. Furthermore, these three constitutive creep models can also be combined with desirable visco-plastic parameters to create additional creep models. Appropriate selection of the creep model dramatically influences the accuracy of the numerical results predicted for well stability. Thus, before the drilling commences, laboratory and field experiments are strongly recommended to determine the constitutive creep model of the in situ salt rocks.

Recent research using computer imaging has shown that hydrogen bubbles may become trapped in the cement structure, reducing cement strength by creating small cracks in the cement. Further investigations are needed to comprehend the H_2 impact flow on the different types of cement. These findings may lead to the discovery of new additives to increase the wellbore infrastructure's density, as well as to reduce hydrogen embrittlement and long-term leakage risks.

Hydrogen storage materials play a crucial role in the development of hydrogen-based energy systems, offering various methods for safe and efficient storage of hydrogen gas. Relative costs of the required equipment vary widely depending on factors such as depth, well complexity, and the specific technologies employed [106].

The cost of casing materials can vary significantly depending on factors such as material type, thickness, and manufacturing processes. Common materials used for casing include high-strength alloys, composite materials, and specialized polymers designed to withstand high pressures and prevent hydrogen leakage. High-strength alloys such as titanium or aluminum alloys are more expensive compared to polymers or composites.

Moreover, thicker casing materials provide higher safety margins but increase material costs [142].

Apart from casing, effective cementing and sealing materials are all so crucial for maintaining structural integrity and preventing hydrogen leakage in storage systems. These materials are used in joints, seams, and connections within storage units to ensure gas sealing under varying pressures and temperatures. Cementing materials range from conventional sealants to advanced epoxy resins or silicones tailored for hydrogen compatibility. Costs can vary based on application complexity, such as manual vs. automated application processes. Materials designed for high-pressure hydrogen environments may incur higher costs due to specialized formulations [143].

7. Conclusions

Up to now, a dozen studies have been conducted to evaluate different aspects of UHS initiatives in salt caverns. Nevertheless, inadequate attention has been dedicated to the well integrity issue. This inclusive survey was conducted to explore the research gap as well as the much-needed considerations required for efficiently addressing the well integrity issues in UHS projects implemented in salt caverns. Key factors such as geomechanical characteristics of storage salt domes, salt creep mechanism, salt cavern construction process, appropriate well designation, potential risks of well integrity, and necessary measurements for preservation of well integrity were elaborated. The insights gained from this study shed light on the multifaceted challenges and considerations involved in maintaining the integrity of well infrastructure throughout the lifecycle of UHS projects.

According to the conducted research, the seminal risks threatening well integrity include the creeping salt motion, casing mechanical failure, seismic hazards, hydrogen-induced impact on cement, and hydrogen-induced impact on metal casing. The first three threats are pertinent to mechanical and geological characteristics of UHS site. On the other side, the latter two threats are derived from the chemical reactions between the H_2 atoms, and cement and casing. Hence, to guarantee the well integrity in the UHS projects, both geomechanical studies and geochemical investigations must be conducted to analyze those risks. Various evaluation techniques, including pressure testing, cement quality assessment, and advanced logging tools, are recommended to use for continuous inspection and monitoring the well integrity.

Mechanical deformation of casing seems to be the most critical threat jeopardizing the well integrity. During and after the drilling operation, the in-situ and drilling-induced stress distribution change to reach an equilibrium around the wellbore [144,145]. This is due to the viscous nature of the salty rocks. Such stress change can easily lead to salt strain (flow) which consequently results in well integrity degradation [146]. Thus, it is recommended to select appropriate casings which provide a high safety factor. Numerical modelling can be highly helpful to analyze casing mechanical stability.

Another important point is the simultaneous effect of temperature on the salt creep behavior and hydrogen-induced degradation of cement and casing. The laboratory experiments show that as the temperature increases, the salt creep behavior is further intensified. Consequently, salt motion, due to the creep behavior, heightens the stresses on the casing [144,147]. On the other hand, H2 high reactivity leads to casing corrosion and cement erosion. Some studies have reported that high temperature increases the mobility of trapped atomic hydrogen in the steel casing structure, leading to release of hydrogen from the steel, and less corrosion. However, under high pressure and temperature, the hydrogen reactivity with cement escalates, leading to further cracking, and erosion of the cement. Hence, for future investigations, it is suggested to simulate the simultaneous effect of temperature on the salt creep, mechanical casing failure, casing corrosion, and cement cracking. For this purpose, temperature logs can be used since they provide data about the temperature gradient along the drilled wells.

Well integrity preservation is paramount to gain success and safety in UHS projects implemented in salt caverns. The findings of this research can be utilized by the geomechanics engineers to further detect and manage the well integrity challenges. Addressing those challenges contributes to sustainable energy solutions and promoting green energy sources such as natural hydrogen.

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