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Hydrogen Storage in Solution Mined Salt Caverns: An Overview

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ABSTRACT

Solution mined salt caverns can provide safe, economic, and proven storage venues for hydrogen gas (H_2). Salt caverns have been used for storage of liquid and gaseous commodities—like natural gas, crude oil, ethylene, propylene, and, to a limited degree, H_2—for over eighty years. Here we will present a general overview of the considerations involved in the development, operation, maintenance, and retirement of solution mined salt caverns for H_2 storage. These considerations include:

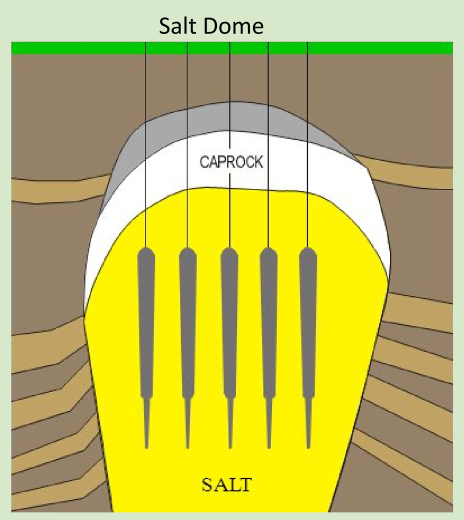
- Regional and local geology – domal salts vs. bedded salts;
- Salt physical properties – viscoplastic deformation (creep), negligible permeability;
- Material science – embrittlement caused by H_2 and influenced by material selection and physical environment;
- Thermodynamics – geothermal heating and pressure cycling;
- Wellbore integrity – creep-induced casing deformation and debonding between casing and host salt rock;
- Gas intrusion – permeability and potential gas content of non-salt media exposed in cavern;
- Microbiology – bacterial reduction of H_2;
- Econometrics – project scale, supply, and usage phasing;
- Regulatory requirements – integrity testing and cavern proximity and
- Sealing and long-term abandonment – cavern fluid pressure increases, fracture risk, long-term monitoring.

The majority of these factors are site specific, requiring each potential development site to undergo some level of characterization to inform the potential success of cavern development and operation. Presented here is a high-level view of the main factors that should be included in the investigation and planning of a H_2 storage facility in solution mined salt caverns.

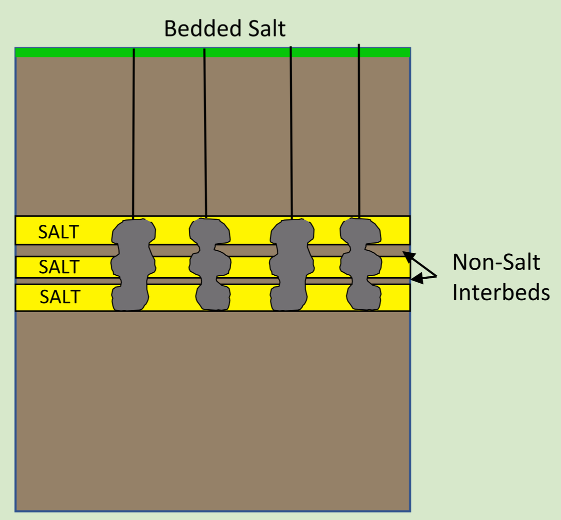
CAVERN DEVELOPMENT

Geology

There are two main types of salt deposits, domal and bedded. Domal salts are the result of deep salt deposits migrating upwards and piercing the overlying geology resulting in a salt dome. These typically have limited areal size, but a great vertical extent. Bedded salts are typical horizontal layers of salt which may have intervening non-salt interbeds. These often have large areal extent, but limited thickness.



The number and extent of caverns that can be created in a given salt formation is determined by the geology. The limited areal extent of salt domes limits the number of caverns that can be developed, but the large vertical extent facilitates larger cavern development and greater control on cavern shape. Bedded salts allow for a greater number of caverns, but these are smaller in volume and may be more irregularly shaped. The shape of the cavern is an important concern in its long term stability (1).

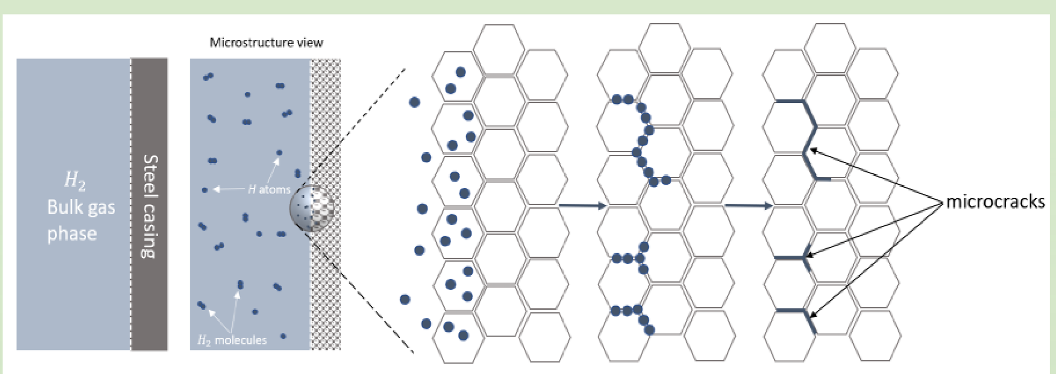


Salt Physical Properties

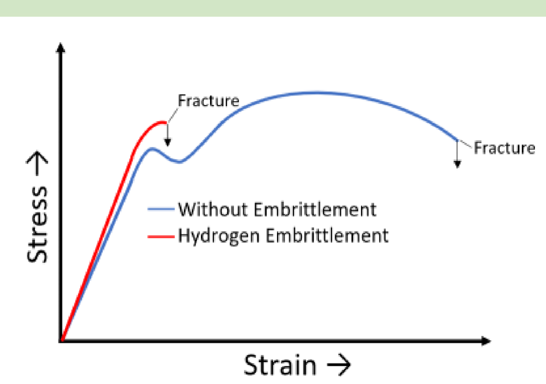
Salt-bearing formations have worldwide distribution and could benefit underground hydrogen storage. Salt has very low porosity and is impermeable to most substances, ensuring a high-quality containment for stored substances, including hydrogen (2). Other advantages of rock salt are its mechanical properties and the lack of chemical reactions between salt and the potentially stored substances (i.e., hydrogen). Rock salt is chemically neutral to hydrogen, and the plasticity of salt prevents the formation and propagation of fractures that could compromise the reservoir tightness (3). These specific properties of rock salt ensure the long-term stability and tightness of the storage facilities. The mechanical and thermomechanical responses of the rock salt during all stages of the cavern life should be understood either in bedded salt or domal salt for storing hydrogen (4). The purity of the hydrogen can also be impacted by hydrogen-brine interaction (including diffusion and convection).

Material Science

Monitoring the effects of hydrogen gas on its surrounding environment is essential for ongoing safety and long-term wellbore integrity. In salt cavern storage, wellbores are the only channel for gas injection and delivery and have the potential for extreme deformation, and potential failure. One of the most common phenomena with hydrogen storage is hydrogen embrittlement (HE) in wellbores. HE is the process of hydrogen diffusing in the grain boundaries of metal, causing a loss of ductility and toughness, manifested in localized microfractures (5).



Effects of hydrogen in the structure of steel



Influence of HE on material properties

Some preventative ways to reduce the effects of HE* are:

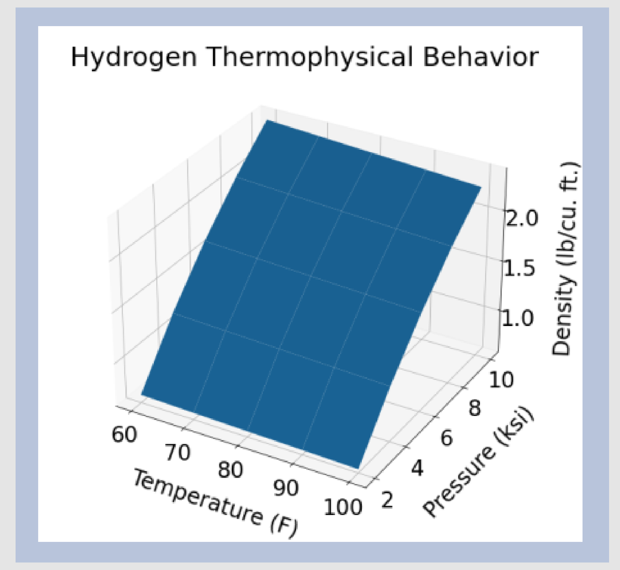
1. Careful selection of materials: steels with fewer impurities (i.e., sulfur and phosphorus)
2. Choosing lower strength (hardness) steel to increase elasticity before failure (6)
3. Surface treatments: use of surface coatings as barrier layers to retard hydrogen entry
4. Using proper welding procedures at joints to reduce H_2 absorption from the humidity and air (7)

*It is advisable that any treatment or operating procedure be studied as a function of long-term exposure to a hydrogen environment to evaluate effectiveness before actual use in hydrogen storage.

OPERATIONS

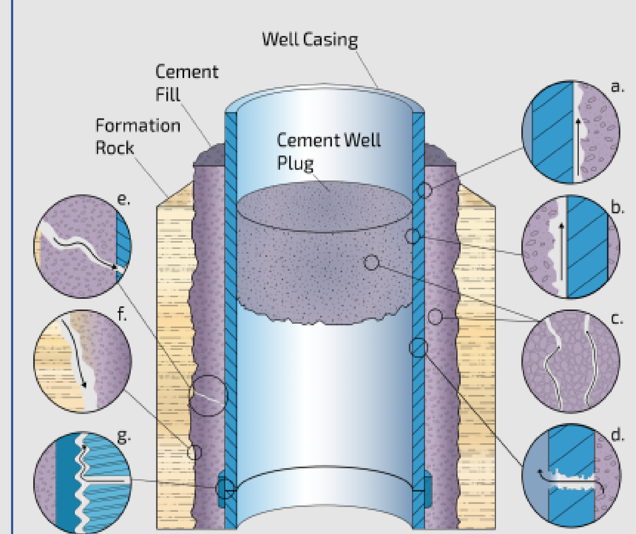
Thermodynamics

Thermodynamic modeling of the multiphase fluid system helps the operator know cavern storage potential and market value of the product. Cavern operations, including workovers, pressure cycling, and other fluid injections, can be optimized with a firm understanding of the thermophysical behavior of hydrogen (see plot). In particular, the wellhead pressure should be monitored through time to understand cavern creep rate and cavern hydraulic integrity. Downhole wireline analysis can provide periodic in-situ verification of hydrostatic column modeling. Also, surface safety and emissions modeling requirements can be met using equations of state calculations based on product compositions (8). Finally, gas saturation in the brine can also be predicted using various thermodynamic principles.



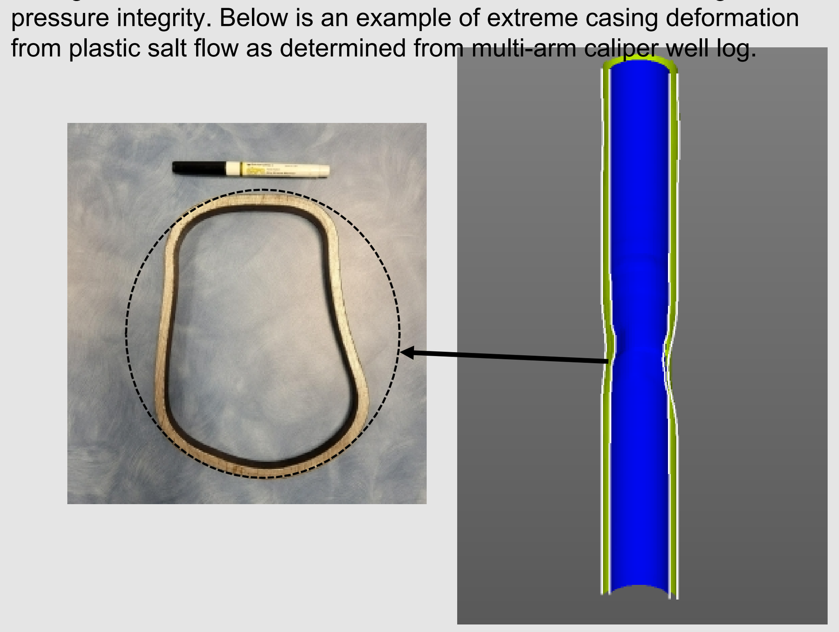
Wellbore Integrity

All well completions have several potential leak pathways. Hydrogen, with its unique molecular properties and stored as a gas presents additional challenges for well integrity.



Diagrammatic representation of possible leakage pathways through a well. a) Between casing and cement; b) between cement plug and casing; c) flow through cement pore space due to cement degradation; d) through casing as a result of corrosion or fracture; e) through fractures in cement; f) between cement and rock; and g) between coupling thread at pipe joint. (9)

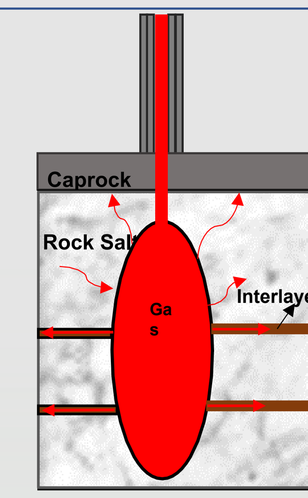
Salt will flow over time given its plastic nature. This flow can lead to casing deformation which, in extreme cases, can led to loss of gas pressure integrity. Below is an example of extreme casing deformation from plastic salt flow as determined from multi-arm caliper well log.



Casing deformation of this type can be especially problematic if the deformation occurs at a casing joint. Extreme salt-induced casing deformation can lead to abandonment of the well. Although not common, the potential for this type of deformation needs to be assessed in the planning of hydrogen storage caverns. Extreme casing deformation can be addressed via well liner installation.

Gas Intrusion

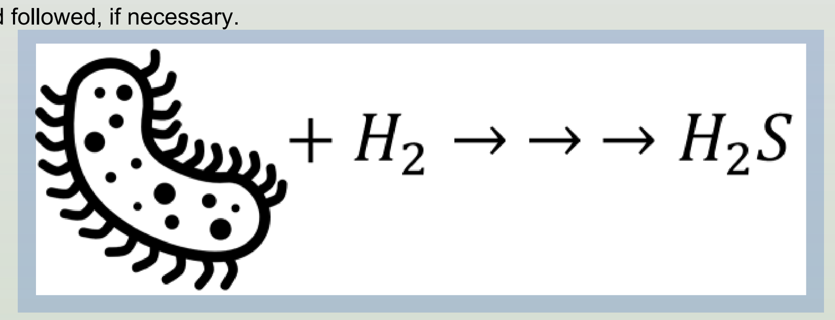
An in-depth understanding of gas intrusion is essential for underground hydrogen storage in a salt cavern. Leakage of hydrogen is essentially zero within a salt dome formation due to its impermeable character. However, the tightness of a bedded-salt formation may be compromised by potentially permeable intervening non-salt layers, all of which could be impacted by damage due to creep. These compromises may serve as a leak pathway for the stored gases within the storage caverns or gases from surrounding formations. The high diffusivity of hydrogen can lead to enhanced migration through fractures. A leak pathway can negatively impact the hydrogen's quantity and quality and result in economic loss.



Example of a potential gas leak in formations surrounding a salt cavern

Microbiology

The presence of microorganisms in the hydrogen storage system can introduce operational uncertainty and potential safety hazards (11). Although uncommon in salt formations, microbes can be introduced from the surface, in the injected gas, or in the drilling fluid. Sulfate reducing bacteria can cause buildup of hydrogen sulfide, a toxic gas. Other microbes react with hydrogen to form unwanted byproducts which can create hydrogen loss and lead to material corrosion. In order to store hydrogen safely underground, it is important to characterize the storage site for microbiology so that a good monitoring and mitigation approach can be formulated and followed, if necessary.



PROJECT DEVELOPMENT

Economics

Siting of a salt cavern hydrogen storage facility involves the consideration of many techno economic factors associated with cavern development and operations. These factors can vary depending on if a new site is being developed or an existing one converted.

Site Location Considerations
- Suitability of salt formations
- Proximity to hydrogen sources and markets
- Availability of product transportation

Storage Site Development Costs
- Property acquisition
- Permitting
- Site characterization
- Well drilling
- Cavern development
- Cushion gas
- Surface facilities

Capital Equipment Costs
- Compressors
- Post extraction treatment (drying, etc.)

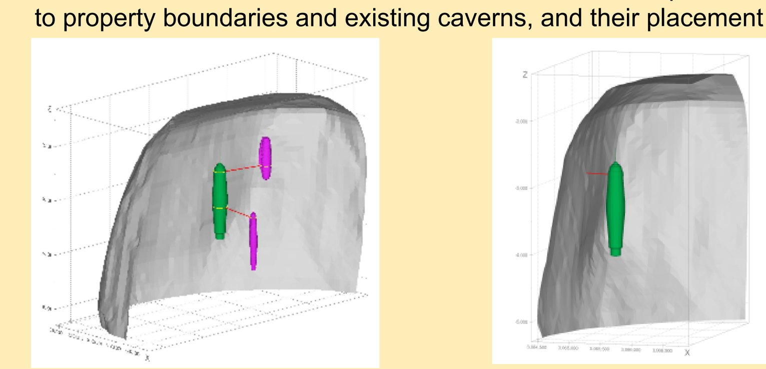
Operational Costs
- Gas compression power
- Cavern maintenance

Operational factors
- Reliability of hydrogen source – timing and quantity
- Frequency and timing of withdrawal demand
- Quality of withdrawn hydrogen

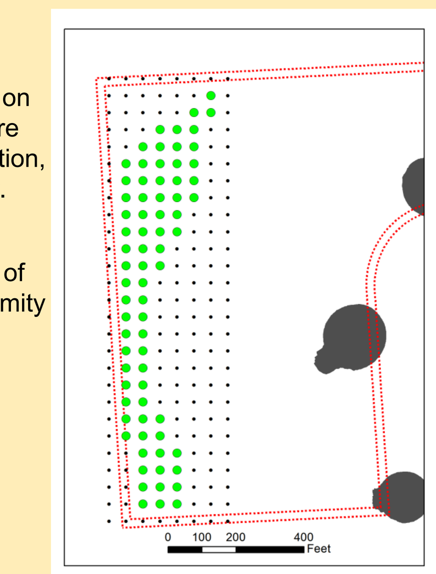
Regulatory Requirements

Regulations related to the storage of gases in salt caverns are instituted at the state level with additional Federal agency considerations (12; 13). Existing gas storage regulations have differing rigor depending on the state, with hydrogen specific language evolving as this need progresses. Regulations typically require reporting on changes to the caverns or access wells and periodic testing of cavern well integrity. In addition, some state regulations require ground subsidence monitoring as a method of monitoring cavern integrity. Required testing can impact cavern operations, taking caverns off-line for a limited time.

Development of a salt cavern storage facility requires well and cavern permitting involving various levels of site characterization. In addition it is common to have requirements related to cavern spacing, their proximity to property boundaries and existing caverns, and their placement within the salt formation (14).



Example of cavern-to-cavern (left), and cavern-to-dome (right) proximity analyses.



Analysis of potential new cavern location based on proximity to property boundary, existing caverns, and salt dome margin. Minimum requirements for salt web thickness between caverns is also considered. Grid of dots show considered locations with green circles showing locations meeting all requirements.

Sealing and Long-term

Current procedure:

The removed gas is backfilled with a brine solution, any production strings are removed, and the wells are plugged with cement. The location-specific data needed for sealing and abandonment procedures are 1. geology, 2. cavern and well data, 3. operational history, and 4. rock

Major concerns

Long-term effective containment and stability for the sealing and abandoning of salt caverns can come with risks and be resource intensive. The two major concerns regarding abandoned caverns are (15):

1. Fluid released into the environment through micro-fractures caused by pressure buildup due to the thermal expansion effects of the rock's geothermal gradient.
2. Substantial surface subsidence caused by mechanical failure of the cavern due to excessive geological stress.

The current literature on the cavern sealing and abandonment stage suggest monitoring surface movements and pressure buildup to asses the risks mentioned above (15, 16). Lastly, there is more research supporting other backfill options, such as solids, to improve cavern stability by providing a load-bearing structure and reducing pressure buildup due to the thermal expansion effect (17).

SUMMARY

Although hydrogen storage in salt caverns is a proven capability, the safe and economic development, operation, and decommissioning of these facilities relies on many factors. The characteristics of the salt formation has a primary control on the size, shape, and number of storage caverns a given site can support. The materials used in well completions must be compatible with hydrogen to minimize well integrity issues. This is of particular concern when repurposing existing caverns for hydrogen storage. Thermodynamics, gas intrusion, and microbiology impact material transfer cycling frequency, product quality, and the potential for microbial hydrogen loss. Finally, at some point salt storage caverns are decommissioned which can result in long term monitoring commitments depending on regulatory requirements. All these factors, along with regulatory considerations, play an important role in the safe and economic storage of hydrogen in salt caverns.

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