OFFICE OF GROUND WATER AND DRINKING WATER
WASHINGTON, D.C. 20460

SUBJECT: Distribution of Final Work Product from the National Underground Injection Control (UIC) National Technical Workgroup- Subsurface Storage of Hydrogen – Technical Considerations

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TO: UIC Program Managers EPA Regions I-X

The Office of Ground Water and Drinking Water is pleased to provide the final product of the UIC National Technical Workgroup (NTW) entitled, Subsurface Storage of Hydrogen – Technical Considerations. The NTW white paper focuses on the potential risks to USDWs due to injection and subsurface storage of Hydrogen (H_2). This report is intended to compliment the Department of Energy (DOE) Energy Storage Grand Challenge which, as described by DOE, looks to accelerate the development, commercialization, and utilization of next generation energy storage technologies, and sustain American global leadership in energy storage. Additionally, the U.S. Geological Survey (USGS) has developed an energy storage white paper for its Energy Resources Program and is currently developing methods to assess subsurface energy storage in the United States.

This paper includes background information on H_2 as an energy source, the current status of subsurface H_2 storage, some technical issues of subsurface H_2 storage, non-technical considerations (e.g., regulatory and resources) for subsurface H_2 storage, and suggested next steps. The information in the white paper may be used by EPA and State regulators to better inform a strategy to assist in the review and permitting of proposed H_2 storage projects to make environmentally protective decisions and mitigate potential threats to human health or the environment.

Key technical considerations addressed within this white paper include storage formation integrity, geomechanical evaluations, caprock integrity, use of cushion gas, interactions with host rocks, and well construction and integrity.

A copy of this report is provided to you so you may distribute it to EPA and state UIC program personnel in your region to assist UIC permit writers during the review of H_2 injection and storage projects to help ensure the protection of USDWs and human health.

The report is available on EPA's UIC NTW documents webpage. If you have any questions, please contact Felicia Chase, NTW Chair by email, or by phone at 312-886-0240.

Attachment:

cc: (w/attachment)
Dan Yates, Executive Director - GWPC

HEADQUARTERS APPROVAL:

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Subsurface Storage of Hydrogen – Technical Considerations

Underground Injection Control National Technical Workgroup

EXECUTIVE SUMMARY

The U.S. Environmental Protection Agency (EPA) was tasked under Section 1421 of the Safe Drinking Water Act (SDWA) to develop an Underground Injection Control (UIC) program to protect underground sources of drinking water (USDWs) and human health by regulating the subsurface emplacement of fluids through injection wells. The injection of hydrogen (H_2) using wells for subsurface storage must be done in accordance with the Safe Drinking Water Act and EPA's UIC regulations. While underground injection activities occurring at a facility would be regulated under the UIC program, any pipelines used to transport the H_2 to or from a facility would likely be regulated under the Department of Transportation's (DOT) Pipeline and Hazardous Materials Safety Administration (PHMSA) rules and regulations, which are available at https://www.phmsa.dot.gov/regulations.

For decades, H_2 has been produced and stored in the subsurface as a feedstock for refineries and chemical plants. Recently, there has been renewed interest in utilizing H_2 as a clean energy carrier, by converting renewable energy to H_2 to be stored in the subsurface to provide a reliable, non-intermittent energy source that can assist in the transition from fossil fuels and could help meet climate change goals. To get there, safe, reliable storage for large volumes of H_2 is needed. To support this effort, the Department of Energy (DOE) launched the Energy Storage Grand Challenge which, as described by DOE, looks to accelerate the development, commercialization and utilization of next generation energy storage technologies and sustain American global leadership in energy storage. Additionally, the U.S. Geological Survey (USGS) has developed an energy storage white paper for its Energy Resources Program and is currently developing methods to assess subsurface energy storage in the United States. (Buursink et al., 2023) Both initiatives may spur projects or research which could involve UIC permit applications.

Considering how rapidly the topic of underground energy storage is developing, the UIC National Technical Workgroup, which is composed of EPA Regional and State UIC representatives, was tasked by EPA UIC management to author this white paper to evaluate potential risks to USDWs due to injection related to subsurface H_2 storage. Little focus will be given to conditions to optimize storage (e.g., maintaining H_2 purity, minimizing irrecoverable H_2) and economic feasibility of H_2 storage. This paper, which is written for UIC permitting authority staff and others who may have an interest in H_2 storage, includes background information on H_2 as an energy source, the current status of subsurface H_2 storage, some technical issues of subsurface H_2 storage, non-technical considerations (e.g., regulatory and resources) for subsurface H_2 storage, and suggested next steps. A review of existing research and projects determined that the three primary types of subsurface formations that could be used for H_2 storage are:

- Salt deposits in the subsurface present an ideal storage environment due to the low permeability of salt and the ability to solution mine caverns which can effectively store fluids under pressure. At the moment, both domal and bedded salt deposits appear to be the most researched and globally utilized subsurface formations for H_2 storage. While salt deposits may be an ideal storage environment, one concern is cavern stability and subsidence, which may affect the integrity of the storage cavern for continued use or result in escape of H_2. With this in mind, it is important to ensure adequate pressures are used during the injection and withdrawal cycles to maintain the stability of the cavern. Furthermore, distribution of amenable salt deposits is geographically limited.

- Depleted hydrocarbon reservoirs may also present an effective injection zone in the subsurface for the storage of H_2. These depleted reservoirs have exhibited the potential to retain hydrocarbons over long periods. Once original in-place hydrocarbons have been produced from these reservoirs, their pore space could allow for the storage and removal of H_2 with less concern of migration outside the storage interval. While these reservoirs may have the structures and confining layers for storage at pressure, it is important to review these in detail as H_2 molecules are much smaller and more buoyant than hydrocarbons and have a greater potential for migrating through the confining rock. There may also be a potential for biochemical alteration through reactions of H_2 with minerals in the formation. Additionally remaining hydrocarbons in the subsurface may be recovered during the H_2 storage injection and withdrawal cycles and would need to be handled properly.
- Saline aquifers have recently been evaluated and even used for the sequestration of carbon dioxide (CO_2) and have the benefit of being found in almost every geographic area of the world. While these formations may be widely available to store gases, there are drawbacks such as: potential coproduction of a large quantity of water that will need to be properly handled, potential migration from the injection zone along undetected faults or fractures, and potential biochemical alteration through reactions with minerals in the formation.

All three types of subsurface formations present their own benefits and limitations; however, there are common concerns which should be addressed during H_2 storage UIC permit application technical reviews. These areas of concern include storage formation integrity (geomechanical considerations and caprock integrity), interaction with host rock, subsurface biota, cushion gases, and well construction. Each of these areas is integral to a permit application review to ensure that USDWs and human health will be adequately protected from the proposed injection activities.

During the development of this white paper, a sub-workgroup identified several gaps in research, resource needs and potential policy decisions (including whether and what type of UIC permit should be required) that should be addressed to assist UIC permit writers during the review of these projects to help ensure the protection of USDWs and human health. These are addressed later in the document.

I. BACKGROUND

Increases in atmospheric greenhouse gases since 1850 can be linked to the Industrial Revolution and the switch to a fossil fuel-based economy. Development of a H_2-based economy as a replacement for the fossil fuel economy has been suggested as one of the feasible long-term solutions to climate change by organizations such as the International Renewable Energy Agency (IRENA), the International Energy Agency (IEA), and the Intergovernmental Panel on Climate Change (IPCC). H_2 has the potential to replace fossil fuels for transportation, electricity generation, and the heating of buildings; it can serve as a low-emission substitute for fossil fuels and help curtail total greenhouse gas emissions.

To be able to transition away from a fossil fuel economy to renewable energy sources, the intermittency of the renewable resources will need to be resolved to meet current energy demands. Wind, solar, geothermal, hydroelectric, and tidal may vary on a daily or seasonal basis and can only replace fossil fuels if surplus produced energy can be stored for use when renewable energy is not being produced. Conventional energy storage options such as batteries are limited by scale. They work well for individual homes but are not feasibly scaled-up to meet the demands of a large electrical grid. A 2011 report by Sandia National Laboratory states, "Hydrogen energy storage is an ideal match for renewables of all scales, especially large-scale wind." (Schoenung, 2011)

Considering a single energy-generating facility, the intermittency of renewable energy is a significant problem without a large energy storage facility to back it up. When several renewable energy facilities are interconnected in a grid (such as exists over much of the continental United States), the intermittency balances out somewhat, and the grid itself can provide much of the back-up. (Fares, 2015) The integration of several mixed source generating facilities with back-up storage capabilities provides for the best grid resiliency. H_2 gas storage is a potential solution to these issues. Large volumes of H_2 can be produced using renewable energy, stored in tanks or underground, then used as needed to meet intermittent energy demands at a large scale.

Presently, H_2 is produced predominately through steam reforming of natural gas (methane, CH_4) and electrolysis to a lesser extent. (Zhang et al., 2019; Bessarabov and P. Millet, 2018)

- In steam reforming, CH_4 and water (as steam) are heated to high temperatures (greater than 800 °C) in the presence of a metal catalyst (e.g., Ni) to produce carbon monoxide (CO) and H_2. A water-gas shift reaction further reacts the CO with steam to produce CO_2 and more H_2 in the following chemical reaction:

$$CH_4 + 2H_2O \leftrightarrow CO_2 + 4H_2$$

- In electrolysis, an electric current is applied to two opposite electrodes submerged in water containing an electrolyte (e.g., hydrogen sulfate). Water molecules break apart into H_2 gas and oxygen gas as follows:

$$2H_2O \rightarrow 2H_2 + O_2$$

To indicate which process is used to produce the H_2, the words “gray,” “blue,” or “green” are sometimes added as adjectives.[1] Most H_2 today is produced as “gray hydrogen” through steam reforming of CH_4 (IRENA, 2020) where CO_2 is created as a by-product and directly emitted into the atmosphere. When steam reforming of CH_4 is paired with technologies to completely capture the CO_2 for geologic sequestration, it is referred to as “blue hydrogen.”

Alternatively, “green hydrogen” is produced through electrolysis with energy supplied by renewables, e.g., wind, solar, geothermal, hydroelectric, or tidal. Green hydrogen is considered to be zero carbon because there are no direct carbon by-products of electrolysis. Other green hydrogen production methods are being researched, such as from algae; however, they are not currently operating on a large scale.

For a H_2-based economy to be zero-carbon, green hydrogen needs to be generated by excess renewable energy and then stored for subsequent use. The subsurface could be used for the large storage volume of materials that are gases at standard temperature and pressure. This makes the subsurface storage of H_2 potentially an important part of a H_2 economy in many parts of the world.

II. CURRENT STATUS OF SUBSURFACE HYDROGEN STORAGE

Three potential types of host formations for subsurface H_2 storage are salt caverns, depleted hydrocarbon reservoirs, and saline aquifers. Laboratory and field studies of storage capacity, confinement, physiochemical, geochemical, and biochemical or microbial aspects of subsurface storage throughout the world have demonstrated the feasibility of the technology. (Zivar et al., 2021) Table 1 provides a few examples of the current and planned demonstration and operational projects around the world. Most of the currently operating global and US-based projects are within salt caverns. There are a few projects where H_2 is stored along with other gases within depleted petroleum reservoirs.

Salt caverns are created by injecting water from the surface into thick underground salt deposits to create a cavity, in a process known as solution mining. Salt deposits have been successfully deployed for large-capacity H_2 storage. The benefits of using salt caverns for H_2 storage are that salt has a low porosity and demonstrates plasticity under pressure to contain and prevent loss of H_2 gas. Plastic behavior means that if a buried salt deposit is somehow fractured during drilling or while pressuring up, the surrounding salt may have the ability to slowly flow and fill the fracture, in a process sometimes called “self-healing.” This process can also result in cavern creep which leads to a loss in storage volume over time and may need to be accounted for. Additionally, compared to other subsurface storage alternatives, losses due to contamination, mineral dissolution, interactions with native microbial environment are also reduced (Zivar et al., 2021).

[1] Additionally, the term “pink” hydrogen is sometimes used to refer to hydrogen produced through electrolysis powered by nuclear energy, “yellow hydrogen” is from direct solar energy electrolysis, “turquoise hydrogen” is from methane pyrolysis, “brown hydrogen” is from lignite coal gasification, and “black hydrogen” is from bituminous coal gasification.”

Table 1: Global Hydrogen Storage Projects

Project	Location	Host formation	Status
Teeside[1]	United Kingdom	Salt cavern	Operational since 1972
Underground Sun Storage[1,2]	Austria	Depleted reservoir	Demonstration since 2016
HyChico[1,3]	Argentina	Depleted reservoir	Demonstration since 2016
HyStock[1,4]	The Netherlands	Salt cavern	Anticipated start in 2026
HYBRIT[1,5]	Sweden	Lined rock caverns	Pilot phase 2022-2024
HyCavMobil[1,6]	Germany	Salt cavern	Pilot; testing began in 2023
HyPster[1,7]	France	Salt cavern	Pilot underway as of 2023
HyGéo[1,8]	France	Salt cavern	Feasibility study; engineering and construction studies start in 2022; anticipated start in 2024
HySecure[1,9]	United Kingdom	Salt cavern	Phase 3: solution mining and surface facilities for transport applications (2021-2023); anticipated start mid-2020s
Bad Lauchstädt Energy Park [1,10]	Germany	Salt cavern	Feasibility study; anticipated start in 2026
Sources: 1: IEA (2021); 2: RAG Austria AG (2020); 3: Pérez, A. et al. (2016); 4: HyStock Hydrogen Storage Project (2021); 5: HyBrit (No date); 6: Research Project HyCavMobil (no date); 7: HyPSTER Hydrogen Storage (2023); 8: HyGéo Project (2020); 9: Stevenson, R., A. Leadbetter, and L. Day (2019).			

The United States has a wealth of salt deposits. Salt deposits are located in 24 of the 50 states and nine of the ten EPA Regions. In the Gulf Coast area alone, there are over 500 salt domes. (Ege, 1985; Lang, 1957) There are at least four operational or planned H_2 storage projects in salt deposits in the United States (included in Table 2 below), including:

- Three operational subsurface H_2 storage projects are permitted in salt domes in Texas.
- A Utah project also stores H_2 in salt domes. The project is supported by DOE and will provide seasonal storage for green H_2.

To date, no Federal EPA UIC permits have been issued for H_2 storage facilities; the current planned and operational H_2 storage projects are in states with primary enforcement responsibility for UIC permitting and enforcement. Table 2 summarizes some of the existing H_2 storage projects in the United States. (Railroad Commission of Texas Hearings Division. 1983, 2007, and 2016; Utah Division of Water Quality. 2022)

Table 2: Hydrogen Storage Projects in the United States

Project and location	Cavern depth	Storage capacity	Number of wells	Status
Clemens Salt Dome B; Brazoria County, TX	2,800 – 5,000 ft	44,880,000 ft^3	1 well	Operational since 1983
Moss Bluff Field; Liberty County, TX	2,700 – 4,600 ft	22,440,000 ft^3	1 well	Operational since 2007
Spindletop Field; Jefferson County, TX	3,700 – 5,400 ft	56,100,000 ft^3	2 wells	Operational since 2016
Advanced Clean Energy Storage; Millard County, UT	3,000 ft	61,710,000 ft^3	2 wells	Permit issued in April 2022

Depleted hydrocarbon reservoirs are another potential geologic scenario for H_2 storage, but with more complications. While natural gas reservoirs in particular have shown that they can store gases likely without significant leakage, they are depleted of only commercially viable hydrocarbons as opposed to all hydrocarbons.

Depending on the enhanced recovery technologies used (which may remove up to 60 percent of the hydrocarbons in the reservoir), the hydrocarbons and other compounds that remain in the rock would be a source of contamination to the injected H_2 (nitrogen could be especially problematic). (U.S. DOE, 2022) This could limit the potential uses of the H_2 after withdrawing it from underground storage. Though petroleum reservoirs held hydrocarbons for millions of years, the much smaller, more buoyant H_2 molecules may have greater potential to leak through very small openings in the confining rock. Studies would need to be conducted to learn how H_2 moves through various types of formations that have the potential to serve as cap rocks.

In recent years, **saline aquifers** have been used for sequestration of CO_2. Saline aquifers can be found all over the world, making them a widely available option for H_2 storage. While these aquifers may be able to permanently store gases, there could be issues with using them for the temporary nature of H_2 storage. Drawbacks to H_2 storage in aquifers include the large amounts of water that are produced with withdrawal of the H_2 gas, the potential for leakage along undetected faults, and potential biochemical alteration of H_2 via reactions with minerals in the rock. (Zivar et al., 2021) These would have to be addressed before large-scale use of such repositories for H_2 storage. To date, no pure H_2 storage in saline aquifers is reported in the literature; however, storage projects injecting mixtures of gases which include H_2 exist in Europe. (Zivar et al., 2021)

In the future, there may be more interest in other H_2 storage options, such as abandoned coal mines, hard rock caverns, plastic or steel- lined hard rock caverns, limestone reservoirs, and refrigerated mined caverns, if the demand for H_2 gas storage grows, particularly in regions where salt deposits, depleted reservoirs, and saline aquifers are not readily available.

III. TECHNICAL ISSUES OF SUBSURFACE HYDROGEN STORAGE

The technical challenges for H_2 storage are similar to those encountered in other subsurface injection activities. In this section, current research will be presented, along with characteristics of H_2 gas that pose a unique risk to USDWs. Technical issues to be examined include: the integrity of salt caverns, hydrocarbon reservoirs and saline aquifers as storage formations; interaction of the H_2 with host rock; biogenic reactions due to the interaction of H_2 with subsurface biota; use of cushion gas; and well construction and integrity issues. Each of these issues, along with considerations for protection of USDWs, is discussed in the subsections below. It is important to note that this white paper focuses solely on H_2 storage issues and thus does not include general UIC permitting considerations that apply to all underground injection activities.

Storage Formation Integrity

H_2 storage in depleted hydrocarbon reservoirs and saline aquifers necessitates similar considerations as other injection projects, including a host rock/injection zone (e.g., sand or sandstone) with sufficiently high porosity and permeability to allow adequate injection and withdrawal flow rates, overlain by a competent, laterally extensive impermeable confining layer/cap rock (e.g., shale or claystone).

Anticlinal structures, found in many depleted reservoirs, are particularly suitable for storing a high- mobility gas such as H_2 because they better confine the gas plume to a limited area. Anticlinal structures provide structural traps, which have the proven ability to securely store pressurized and buoyant fluids. (U.S. DOE, 2022) While anticlinal structures associated with depleted reservoirs can be desirable for storage operations, one primary concern is ensuring that any artificial penetrations associated with prior oil and gas recovery are properly identified and addressed through corrective action, as warranted. This will help ensure the H_2 stored within the structure won't migrate outside the injection zone and can be recovered.

In addition to anticlinal structures, domal structures are useful for trapping buoyant gases. As noted above, the current H_2 storage projects in the United States are in salt domes, which are typically created by solution leaching of salt deposits and tend to be primarily salts. Impurities may also be present, including potassium and magnesium salts, anhydrite stringers, or quartz.

In contrast, bedded salt formations represent a variety of lithologies (e.g., sand, shale, anhydrite, halite, and potash) that may be trapped together during the formation of a salt dome or bedded salts. (Ennis-King et al., 2021) This heterogeneity can affect the geometry stability and geomechanical properties (e.g., elastic modulus and mechanical/hydraulic properties) of the storage cavern. (AbuAisha and Billiotte 2021)

Caverns that are created in bedded salt formations may not be as stable as those created within salt domes, and slippage between bedding planes induced by pressure increases could cause gas to migrate laterally. (Ennis-King et al., 2021) Due to salt's plasticity, inward salt creeping can cause subsidence, displacement, or partial collapse of the salt dome into the salt cavern, and shear zones within salt domes have been documented. (AbuAisha and Billiotte, 2021; Duffy, 2021) This can also cause well casings to be sheared (see additional discussion under "Well Construction and Integrity," below).

Appropriate siting of a storage cavern is important. Typically in domal salt, the quality and purity of the salt body degrades closer to the flanks of the dome, as does the grain size and orientation of the rock salt. Drilling a storage cavern within any of the aforementioned areas such as boundary shear zones, may lead to microfractures or porosity and permeability changes within the salt.

Maintaining pressure within the salt cavern using cushion gas or saturated brine is necessary to prevent inward salt creep and maintain cavern integrity. (U.S. DOE, 2022) Additionally, sonar surveys can be used to obtain measurements of a cavern's configuration and capacity, which assists in monitoring the cavern for stability. Sonar logs are also useful when several caverns are located near one another to ensure adequate spacing between each storage cavern.

Geomechanical considerations

To avoid potential issues during normal operations, geomechanical evaluations to determine proper operating pressures, safety factors and appropriate test gradients should be conducted prior to the commencement of normal operations.

Inherent to H_2 storage projects is the repeated cycling of injection and production of H_2, whose frequency will vary depending upon application. For energy storage, the cycle could be seasonal or more frequent to meet peak demand. Geomechanical considerations within depleted reservoirs used for H_2 storage include the tensile fracture pressure of the reservoir rock and the stresses at which faulting or other mechanical damage may be induced. (Ennis- King et al., 2021)

In salt caverns, the pressure and temperature changes due to the repeated cycling can impose stress on the host rock. (AbuAisha and Billiotte, 2021) Stress from operations may cause microfractures and cracks in salt cavern walls to grow, increasing porosity and permeability, which can allow H_2 gas to leak.

Pressure changes due to cyclic injection-withdrawal operations can also produce temperature variations. These variations can lead to modification of H_2, alterations in the hydraulic properties of rock salt, and in some cases can alter brine viscosity. (AbuAisha and Billiotte, 2021)

Cyclic stress fluctuations may also cause depleted reservoir compaction, leading to porosity reduction and reduced fluid flow, subsidence, and/or fault reactivation with or without (micro)seismicity. (Heinemann et al., 2021)

Caprock integrity

A low permeability caprock is critical to ensuring containment, particularly in bedded salt formations. A low-density molecule such as H_2 can migrate upwards toward the caprock and exert buoyancy pressure. Salts and clay layers are the most common type of caprock for H_2 storage formations and have demonstrated tightness and hydraulic integrity in the presence of H_2. (Zivar et al., 2021)

Caprocks with low permeability due to small pores are suitable, if not ideal. The small pores in the water-saturated caprock represent a highly impermeable barrier to H_2 that may prevent leakage because of high capillary pressure, i.e., the threshold pressure required of the gas to enter the pore spaces in the rock. (Zivar et al., 2021) Therefore it is important to understand conditions that can reduce capillary entry pressure for H_2. Additionally, these physical properties are also important in understanding fluid movement through pore spaces and management of reservoir storage.

Capillary pressure is a function of the interfacial tension, pore size, and wettability. As interest in H_2 storage increases, research to improve understanding of these parameters has recently become available.

Rock-fluid interfacial tension is the tension on the phase boundary between reservoir rock and the H_2 injectate. While rock-fluid interfacial tension measured data are rare, one study (Pan et al. 2021) calculated rock-fluid interfacial tension for H_2 and found that it decreases with increased pressure, temperature, organic acid concentration, and carbon number.

Wettability is the ability of a fluid to spread over a surface. It can be measured by the contact angle between the fluid and rock interface where low H_2 wettability corresponds to a lower project risk. A study by Hosseini et al. (2022) found that H_2 wettability increases with higher pressures, salinity, and organic surface area and decreases with higher temperatures and surface roughness in carbonate reservoirs. Another experimental study on the wettability of H_2, concluded that caprock comprised of mica and quartz (minerals that comprise shale) provided adequate confinement; however, that diminishes in the presence of organic acid. (Ali et al., 2021)

In depleted reservoirs, H_2 leakage may be less of an issue because the pore water has been saturated with methane, making it more difficult for H_2 to enter the overlying cap rock. (Bai et al., 2014)

Use of Cushion Gas

Cushion gas (or base gas) is a set volume of gas that may be pre-injected into the storage formation to maintain a reservoir/cavern minimum pressure to optimize injection and extraction of working gas (here, H_2). Typical cushion gases include residual natural gas in depleted oil and gas reservoirs, such as CO_2, CH_4, N_2 and H_2 itself. The gas accounting in a H_2 storage system can be divided into two parts: cushion gas that permanently remains in the system and working gas, which is the H_2 portion that is cyclically injected and withdrawn.

In salt caverns, H_2 injection and withdrawal can be operated under variable pressures, where approximately one-third of the cavern volume will contain cushion gas. This cyclic nature can cause variations in pressure within the formation. Cushion gas can undergo alternate compression and expansion during the H_2 injection and withdrawal cycles to maintain the required pressure. (Zivar et al., 2021) Alternatively, salt caverns can be operated under constant pressure if saturated brine is injected to compensate for pressure decrease due to gas withdrawal. In this case, cushion gas would not be needed. (Ennis-King et al., 2021) Regardless, maintaining pressure within the salt cavern is necessary to prevent inward salt creep and maintain cavern integrity. (U.S. DOE, 2022)

In depleted reservoirs, the cushion gas volume needed to maintain adequate pressure and withdrawal is typically around 30-50% of reservoir volume but can range from 15 to 75%. (Ennis-King et al., 2021) Cushion gas requirements are higher in saline aquifers than for depleted reservoirs because there is no naturally occurring gas present to offset the total volume needs; cushion gas volumes could be as high as 80% of the reservoir volume for saline aquifers. (U.S.

DOE, 2022)

The use of a cushion gas can reduce the stress on subsurface formations and confining zones associated with the cyclic injection and withdrawal in H_2 storage operations. Injected cushion gases are confined within the geological formation during and after injection in each cycle.

While migration or leakage of the cushion gas is not expected, this should be monitored throughout project operations. (Zivar et al., 2021)

Considerations for USDW Protection

Thorough site characterization of each individual storage cavern is key to ensuring site-suitability, and particularly to ensuring protection of USDWs. Thorough characterization involves open-hole logging and collection and analyses of core samples, which can provide information on depositional environment/lithologies and geomechanical conditions.

The need for reservoir modeling used in other types of UIC permitting applications (e.g., Class VI geologic sequestration) is likely less applicable due to the cyclical nature of H_2 storage and the lower reservoir pressure in H_2 storage projects. While the cyclical nature of H_2 storage may limit the areal extent of H_2 storage projects, modeling could still be utilized to determine the maximum extent of the H_2 in the subsurface in addition to modeling the pressure front generated during anticipated normal operations. Additionally, modeling could be used to evaluate or simulate hydrogeochemical, microbial, and geomechanical (salt caverns) mechanisms at H_2 storage sites to better understand the different mechanisms that can affect caprock or cavern stability and fluid behavior. Thorough documentation of modeling to predict the behavior of the storage activities would include a discussion of the appropriateness of the model to the processes being studied, the inputs to the model, its results, and any uncertainties and their implications for the results.

USDW-protective considerations include the following:

- Until additional research becomes available to better understand the appropriateness of a caprock's ability to contain H_2 (i.e., threshold capillary pressure of the caprock in contact with the H_2), additional monitoring may be warranted.
- Consistent injection pressures are important to maintaining cavern integrity. Limiting injection pressures and rates can reduce the potential for viscous fingering, avoid exceeding fracture pressure, and prevent roof creep and instability. However, operating at too low a pressure for too long can increase cavern closure rates, floor rise, salt dilation, and salt falls. Properly maintaining operating pressures also reduces the likelihood of sloughing of cavern walls, salt falls, and rapid floor rise. Low and steady injection rates can also help to avoid fluid coning that can result from high withdrawal rates. (Zivar et al., 2021)
- It is also important to maintain adequate cavern pressures while a cavern is idle to avoid sloughing of side walls or roof falls or to offset cavern creep. Another critical aspect to consider is the amount or volume of product that remains in a cavern after a withdrawal cycle. The cavern should never be empty enough (e.g., with less than 60% of product for extended periods) to induce salt creep.

- Groundwater monitoring to detect chemical or pressure changes can identify water quality changes due to H_2 leakage. Surface-based geophysical monitoring (e.g., magnetic, gravity, or seismic surveys, or electrical resistivity tomography) can complement downhole monitoring methods because it can monitor changes over a larger area than individual monitoring wells. (U.S. DOE, 2022)
- Because subsidence or collapse of salt caverns could be a concern, monitoring changes in the injection interval, elevation of the ground surface, salt cavern size and shape, and/or roof thickness may be needed.
- The proximity of a salt cavern to the top of salt (or salt edge) and pillar thickness between salt caverns is also of major concern in regard to subsidence or potential cavern collapse. Requiring a minimum distance (e.g., of 300 ft) to the edge or top of the salt may be appropriate.
- Because salt flow can cause shear that can displace well casings, well construction using materials that can withstand anticipated shear, coupled with mechanical integrity testing (MIT), are important to prevent and detect any effects on the well.
- In addition to understanding H_2 compatibility with well components, if non-H_2 cushion gas is used, the impact of the gas to the reservoir and well components will also need to be evaluated.

Interaction with Host Rock

For H_2 storage in depleted reservoirs or saline aquifers, chemical reactions between H_2 and minerals found in the reservoir rock or caprock can lead to precipitation or dissolution that can affect porosity and permeability, which can, in turn, affect the injectivity of the storage formation. (Zivar et al., 2021; Heinemann et al., 2021) Likewise, calcification (an abiotic, geochemical process that reacts H_2 to yield calcium precipitates) can plug pores and lead to a loss of H_2 and injectivity. (U.S. DOE, 2022)

There is little research on the mechanisms and kinetics of redox reactions with H_2 in sedimentary rock, which is generally comprised of nonreactive silicate rocks. However, H_2 may react with sulfide, sulfate, carbonate, and oxide minerals that may be found on the surface of the silicate minerals. (Lord, 2009) Lord further suggests that reaction with these chemical species would be unlikely because the reservoir temperatures would not be high enough to catalyze a reaction. Experimenters studying the effect of H_2 for nuclear disposal in a clay-rich reservoir rock similarly found no significant effect on the other minerals present in the natural rock (clay minerals, quartz, calcite, dolomite and feldspars). However, sulfide anions were released when pyrite was partially reduced. (Yekta, 2018) The low density and viscosity and the high mobility and diffusivity of H_2 can lead to unique hydrodynamic behavior such as gas viscous fingering[2] and gravity override. (Heinemann et al., 2021) During the gas viscous fingering process, the contact area between the H_2 and reservoir rock and fluid expands. This expansion can increase the potential for dissolution of H_2 into formation water or for its interaction with the host rock where it pools.

[2] "Viscous fingering refers to the unstable displacement of a more viscous fluid by a less viscous fluid [which] can influence reservoir flow behavior and adversely impact recovery." (Fanchi, 2018)

This pooling further increases the contact area between the gas and reservoir rock and fluid creating more potential for dissolution into formation water or interaction with host rock. These processes lead to a greater lateral spread of the H_2 and increased amounts of unrecoverable gas.

Considerations for USDW Protection

To ensure the protection of USDWs, one important goal of site characterization should be to identify potential interactions that can lead to porosity and permeability changes, which could affect injectivity or containment. Site characterization can inform an understanding of:

- The presence of disturbed or damaged zones in salt where H_2 can migrate, and reactions can occur.
- The presence of minerals with a potential for precipitation/dissolution reactions that can affect porosity and permeability, particularly interactions with the mineral constituents most commonly found in caprock that may compromise its integrity. Due to limited research, particularly under the same conditions (temperature and pressure) encountered during storage, monitoring wells above the caprock may be warranted.
- Production of sulfide gas, which can adversely affect well components and worker safety.
- Potential for viscous fingering/H_2 loss due to the heterogeneity and structures of the reservoir. (Zivar et al., 2021) This can be addressed by:
    - Proper spacing of wells and the use of multiple injection wells (including injection of fluid in the bottom of the reservoir and withdrawal from the top through a different well) can limit lateral spreading, dissolution, and viscous fingering of the H_2. (Zivar et al., 2021)
    - Limiting Injection pressures and rates to reduce the potential for viscous fingering.

<u>Interaction with Subsurface Biota</u>

H_2 is an electron donor, which makes it a source of energy for microorganisms and can be found within any subsurface formation. (Zivar et al., 2021) Microbial reactions that can occur in H_2 storage formations at various temperatures and pressures include:

- Methanogenesis is the conversion of H_2 to methane which may occur in the subsurface if certain microorganisms are present. (Zivar, et al., 2021)
- Sulfate reduction occurs when sulfate-reducing bacteria consume H_2 and produce hydrogen sulfide and may occur when sulfate is present in the reservoir. This may be more important in low salinity reservoirs. (Dopffel et al., 2021)
- Acetogenesis is the conversion of acetate to acetic acid which creates a weak acid which can corrode steel. (Heanjia Super Metal, 2015) This may be more important in low salinity reservoirs. (Zivar et al., 2021)
- Iron reduction results in the precipitation of ferric iron minerals when dissolved iron and either nitrate or low concentration oxygen is present. (Zivar et al., 2021; Dopffel et al., 2021)

An overview of microbial activity at several major H_2 storage projects by Dopffel reports that no microbial activity has been reported in several operating H_2 salt caverns; however, microbial activity was reported in saline aquifer and depleted reservoir storage projects. (Dopffel et al. 2021)

Microbial growth on subsurface formations may lead to microbial-induced plugging (from microbial biomass or microbial-triggered mineral precipitations), which can affect injectivity. Conversely, mineral dissolution may occur if acid-producing microbes lower reservoir pH, causing dissolution of carbonates or other dissolvable minerals; this can change formation permeability and porosity, and compromise caprock integrity. (Dopffel et al., 2021; Heinemann et al., 2021)

Sulfuric acid or acetic acid formed through microbial reactions or biotic microfilms can grow in the presence of H_2 and form on steel well materials, causing corrosion and adding to abiotic corrosion. (Dopffel et al., 2021)

Considerations for USDW Protection

USDW-protective considerations associated with microbial growth are similar to interactions with the host rock described above and may focus on site characterization to identify whether biogenic-optimal conditions exist and include monitoring to detect the results of microbial reactions.

Site characterization should include collection of data on subsurface physical conditions (including pressure and temperature), water chemistry, and host rock mineralogy. Geochemical modeling tools can also predict microbial behavior.

Because modeling studies have shown that methane growth rates depend on the amount and activity of biomass present and the amount of residual water, site characterization that informs an understanding of the biomass content of formation fluids may help to predict these reactions. (Zivar et al., 2021) Formation water sampling to determine the presence of biomass should employ appropriate sampling techniques, including sterile containers and protection of samples to prevent the introduction of oxygen. (Dopffel et al., 2021)

USDW-protective monitoring for indicators of microbial reactions or to detect the effects of microbial growth may include:

- Use of monitoring wells above the caprock to monitor for acetate, methane, hydrogen sulfide, pH reduction, decline in sulfate content, microbial activity/biomass, and H_2.
- Monitoring for changes in fluid flow/behavior or temperature increase.
- Monitoring for changes in water volume to detect large quantities of water that are generated via sulfate reduction and iron reduction.
- Monitoring to detect precipitation of ferrous iron minerals or microbial-induced carbonate precipitated minerals.

<u>Well Construction and Integrity: Monitoring of wells/well components for stress cracking, corrosion characteristics or corrosion products</u>

The high diffusivity of H_2, relative to other gases such as natural gas and CO_2, enables H_2 to more readily permeate wellbore components including valves, packer, and cement. (Reitenbach, 2015)

H_2 damage to metal components includes H_2 blistering, H_2-induced cracking (HIC) and H_2 embrittlement (Reitenbach, 2015; Bai, 2014). As H_2 diffuses through the metal, collecting at inhomogeneities, micro-voids form resulting in H_2 blisters.

H_2-induced cracking occurs when the solubility limit is reached and the molecular H_2 precipitates out. When metal thickness has been sufficiently reduced, sudden failure can occur. The crack can propagate due to the H_2 pressure in the crack and does not require external applied stress. (Martin, 2022) At the atomic level, when an H_2 molecule is transported to the metal lattice, a loss of ductility and increase in brittleness occurs, which is referred to as H_2 embrittlement. Unlike HIC, an applied force is generally required for H_2 embrittlement, and H_2 gas precipitation does not take place within the metal. (Martin, 2022) High-strength carbon steel and low alloy steels are most vulnerable to H_2 embrittlement, while HIC is primarily a concern in non-austenitic steels. To avoid these issues, selection of well casing materials should consider compatibility with H_2. When possible, operation at lower pressures will also reduce H_2 damage to metal.

Slowing diffusion using H_2 “traps” can decrease the susceptibility of well components to the negative effects of exposure to H_2 during operation. Metallic alloying agents can create “traps” for the H_2. These traps also reduce the maximum diffusion rate because they build up micro-gradients that slow diffusion. (Avery et al., 2001) For instance, the addition of 1.5% titanium to iron can increase the time taken for the diffusion of H_2 to reach its maximum. Alloying with molybdenum and nickel also can reduce susceptibility.

Corrosion inhibitors can be added to process fluids to reduce the general corrosion rate. In turn, they slow the generation of H_2 ions at the surface, reducing the concentration gradient that drives the H_2 inward. (Avery et al., 2001)

H_2 diffusion can also affect elastomers, which are commonly used materials for packers. At this time, it is unclear how well elastomers can resist the diffusion of H_2. H_2 permeation into these seal elements may increase their rate of degradation and result in failure over shorter time scales. Understanding its effects and improving durability is a DOE research focus. (U.S. DOE, 2022)

Research has found that reactions between H_2 and wellbore cement may occur, but these reactions do not significantly affect cement porosity and were negligible for the tested cements. (Jacquemet et al. 2020) The high diffusivity of H_2 is thought to contribute more to project risk than its reactivity; however, there is little data available on H_2 diffusion through cement. (U.S. DOE, 2022)

Considerations for USDW Protection

Considerations for USDW protection include evaluating proposed well construction plans and schematics to ensure the use of appropriate materials is planned. Specifically, the casing should be of the highest strength steel that is needed, while avoiding very high-strength steels that are susceptible to H_2 embrittlement. Corrosion inhibitors can also reduce the general corrosion rate.

Due to specific operational considerations and downhole conditions associated with H_2 storage, it is not recommended to convert natural gas wells for use with H_2 storage unless the well completion will be converted using appropriate well designs and materials. Prior to conversion, wells should be closely evaluated to ensure they are not susceptible to H_2 embrittlement. Additionally, a larger tubing diameter is recommended to handle the higher flowrates expected for H_2 withdrawal. (Zivar et al., 2021)

Because legacy oil and gas wells near H_2 storage facilities can pose a leakage risk (U.S. DOE, 2022), identification and appropriate corrective action of these wells are needed to prevent fluid movement into USDWs. Artificial penetrations impacted by H_2 storage operations will have similar considerations as other injection projects. However, one additional consideration when determining corrective actions is to ensure that appropriate materials and methods are used so that the corrective action will be adequate for downhole conditions associated with H_2 storage operations.

As noted under "Interaction with Subsurface Biota" above, microbial reactions can lead to the creation of sulfuric and acetic acid, which can lead to corrosion of well materials and cements.

Additionally, salt flow (as described under "Storage Formation Integrity" above) can cause wellbore shear. Therefore, it is important that well materials used in H_2 storage projects have corrosion-resistant design and sufficient strength to withstand any shear forces.

IV. ADDITIONAL NON-TECHNICAL CONSIDERATIONS FOR SUBSURFACE HYDROGEN STORAGE

In addition to the technical concerns described above, there are several policy and general considerations that the UIC Program will need to address in advance of wide-scale permitting of H_2 injection for subsurface storage.

Legal/Regulatory/Policy

- Under 40 CFR §144.1(g)(2)(iv), "injection wells used for injection of hydrocarbons which are of pipeline quality and are gases at standard temperature and pressure for the purpose of storage" are excluded from regulation under the UIC program. When H_2 and hydrocarbon mixtures are injected, will UIC regulations apply and if so, what is that hydrocarbon threshold? Regardless of the classification, how can USDW protection be ensured?
- What is the appropriate UIC well class for H_2 storage to ensure protection of USDWs? Similar to CO_2 injection for sequestration, Class V Experimental can be a starting point, but once the technology matures, it may need to transition to either a new well class or Class V other (based on risk to USDW). If Class V is the appropriate well class, is authorization by rule ever an appropriate approach or should authorization by permit be sought for these projects? Given the dynamic nature of H_2 storage facilities (e.g., the susceptibility of salt to movement), are shorter-than-lifetime permits or requirements for periodic permit renewal/review appropriate?
- Are there lessons to be learned from existing regulations for H_2 storage (States, other countries)?

General

- Are experts available (e.g., chemists, geochemists, microbiologists, geologists, hydrologists, modelers/modeling specialists) to improve our understanding of the behavior of H_2 in the subsurface? When available, tap into existing technical expertise at Ada Lab, USGS, DoE, State Dept, DOT's PHMSA.

V. SUGGESTIONS FOR NEXT STEPS

The UIC Program has identified several next steps to support oversight of H_2 injection for subsurface storage, including additional research, evaluation of permitting options, communication with other government agencies to support research, and guidance/guidelines development.

Research Needs:

- Salt cavern storage projects have been in operation for decades and are well studied. However, more research is needed on depleted hydrocarbon reservoirs and saline aquifers to help review proposed projects utilizing these formations.
- Additional research regarding well design and materials compatible with H_2 would assist technical reviewers to ensure proposed materials will be adequate for proposed operations, required corrective actions for artificial penetrations, and plugging and abandonment of the injection well.
- Identification of appropriate method(s) to conduct MITs for all storage operations and methods for detecting the H_2 interface in storage caverns. If current methods are inadequate to demonstrate MI, then additional research on new methods should be conducted.
- Better understanding of optimal H_2 injection and withdrawal rates to avoid compromising caprock and cavern integrity and potential thermal effects of H_2 cycling.
- Induced seismicity implications of injection-withdrawal cycling and understanding fault stability is an important site characterization activity.
- Understanding appropriate workover schedules (for salt caverns and any other type of UIC storage project) is crucial to continued safe operations – and has not been addressed in this white paper.

Permitting H_2 Storage Injection Wells:

- Evaluate the technical and legal rationale for the most appropriate UIC well classification. Should these wells have a new class or subcategory of Class V or rely on Class V experimental? If Class V experimental is appropriate, are minimum requirements needed (e.g., for proper well design and construction, MITs and inspections, financial assurance, reporting, etc.)?

Track H_2 Storage and Related Research and Issues:

Given the potential for the expansion of H_2 storage, continued work and communication with other government agencies to support research and address emerging issues would be beneficial. Entities EPA could work with include IRENA, IPCC, SINTEF (part of Norwegian Institute of Technology), US Department of State, US Department of Energy (especially National Renewable Energy Lab), and US Geological Survey.

EPA could also engage with regulatory agencies in states where salt storage is occurring, since experts in these agencies have knowledge of the intersection of salt geology and well operations. Trade/industry groups, such as the Solution Mining Research Institute, may also have information to support the body of knowledge.

Develop Guidelines or Guidances:

UIC injection well permits will be needed for subsurface injection of H_2 for storage. To assist permit applicants as well as EPA permit writers, development of guidelines or guidance documents would be helpful to navigate the permit process. This would be similar to what was done to assist progress in UIC Class VI CO_2 sequestration permitting efforts.

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