Investigation of wellbore material design for underground hydrogen storage considering the potential hydrogen leakage

Integrated Research Project

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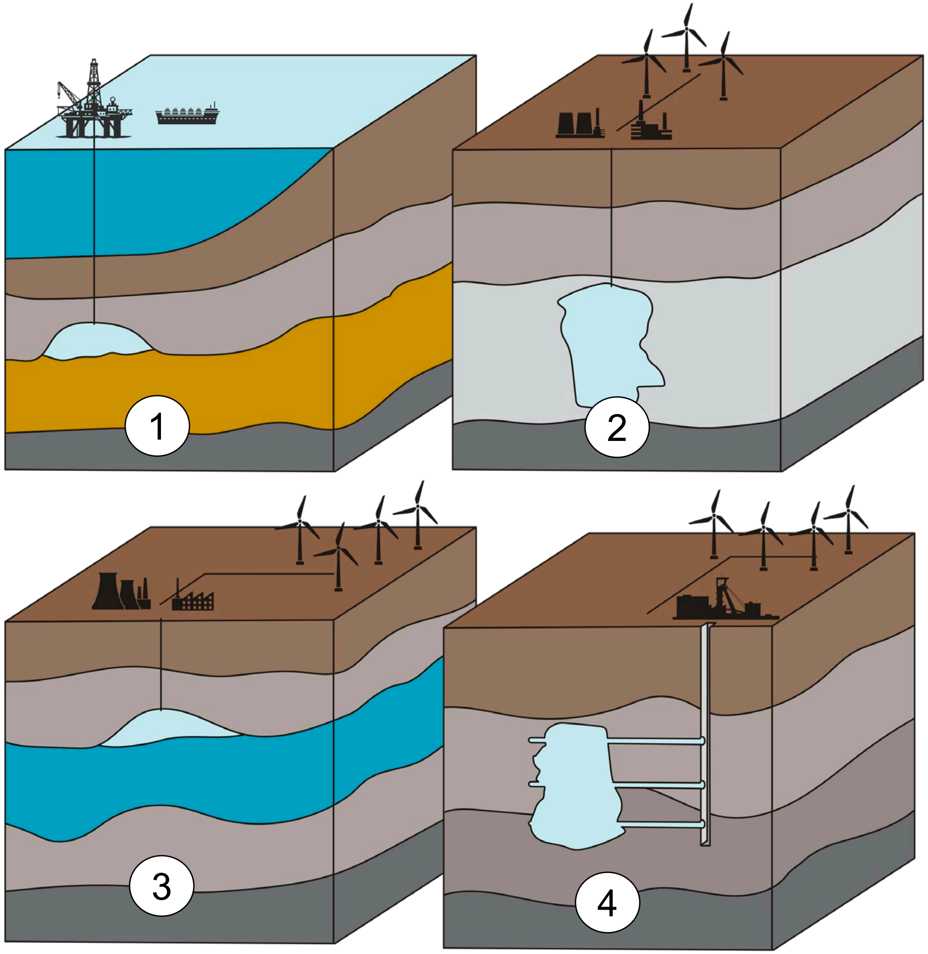
1-1. Research Proposal

- Hydrogen energy is gaining attention for its potential to reduce carbon emissions.
- Hydrogen storage is a pivotal part of the hydrogen energy systems.
- Large-scale underground storage systems hold promise as a viable option for hydrogen storage.
- Underground Hydrogen Storage options
  - **1) Depleted hydrocarbon reservoirs**
  - 2) Salt caverns
  - 3) Aquifers
  - 4) Underground mining excavations



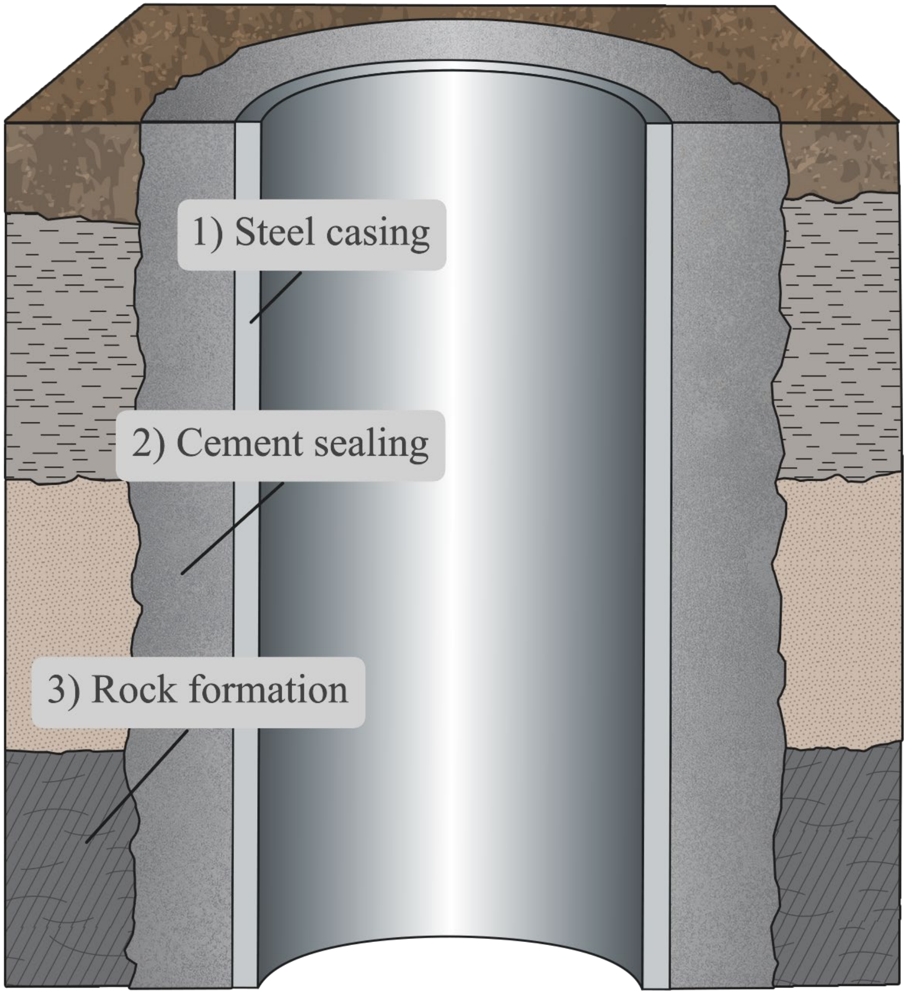
1-2. Research Scope

Advantages of the utilization of depleted hydrocarbon reservoirs.

- Sealing capacity of the reservoir
- Large volume/capacity
- Availability of cushion gas
- Operational convenience with existing infrastructure

Research Focus

- **Wellbore integrity**
- **Hydrogen leakage**
- **Wellbore material design**



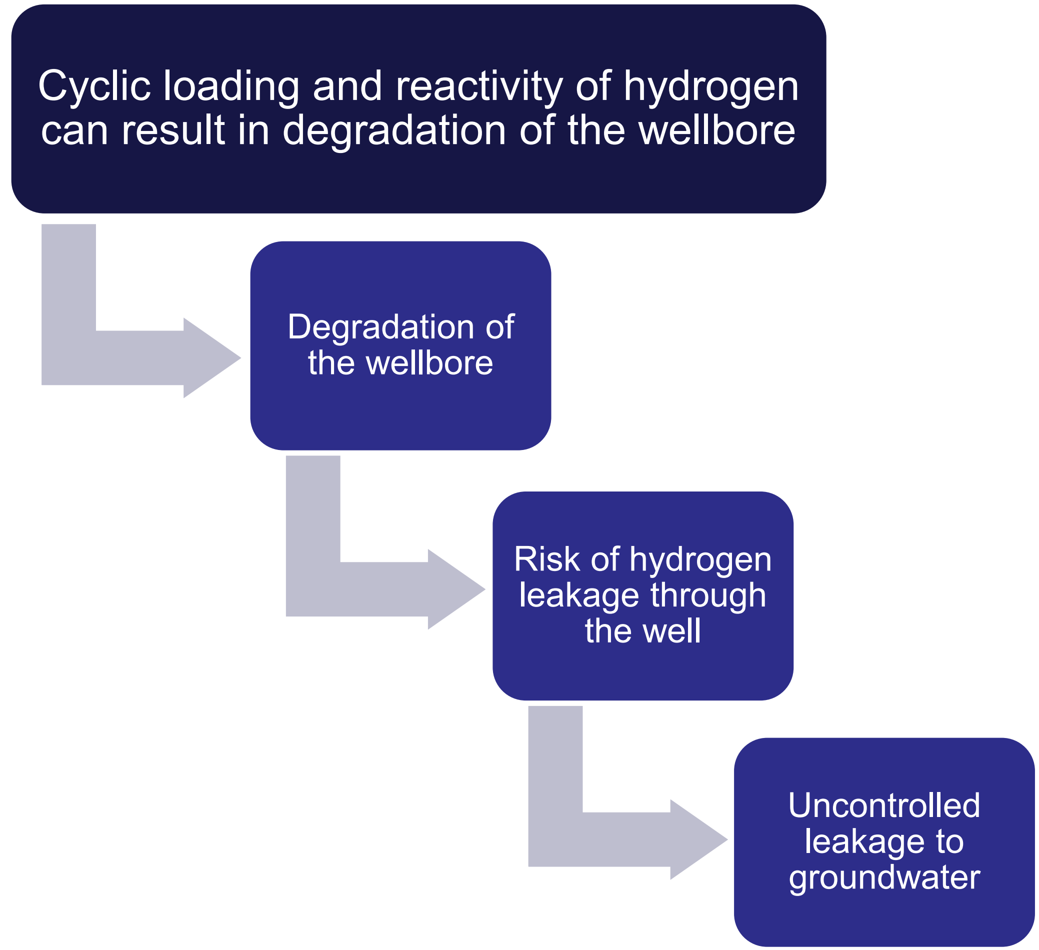
2. Engineering Challenges

Utilization of existing wellbore

- Operational designation of the well
- Degraded wellbore
- Maintenance difficulties

Factors affecting the wellbore integrity

- Wellbore design
- Construction of the well
- Operational temperature and pressure
- Hydrogen cycling



Research Objectives

- To maintain well integrity, it is crucial to investigate the well material properties and key factors affecting the integrity.
- This study aims to conduct a literature review on wellbore material design considering well integrity.
- To investigate the applicability of the wellbore utilized in UHS.
- To put forward the significance of wellbore integrity and highlight the research gap regarding well material design.
- The goal is to establish critical design criteria for wells, enabling the safe and efficient conversion of existing infrastructure for UHS.

The key publications concerning well integrity in various underground storage

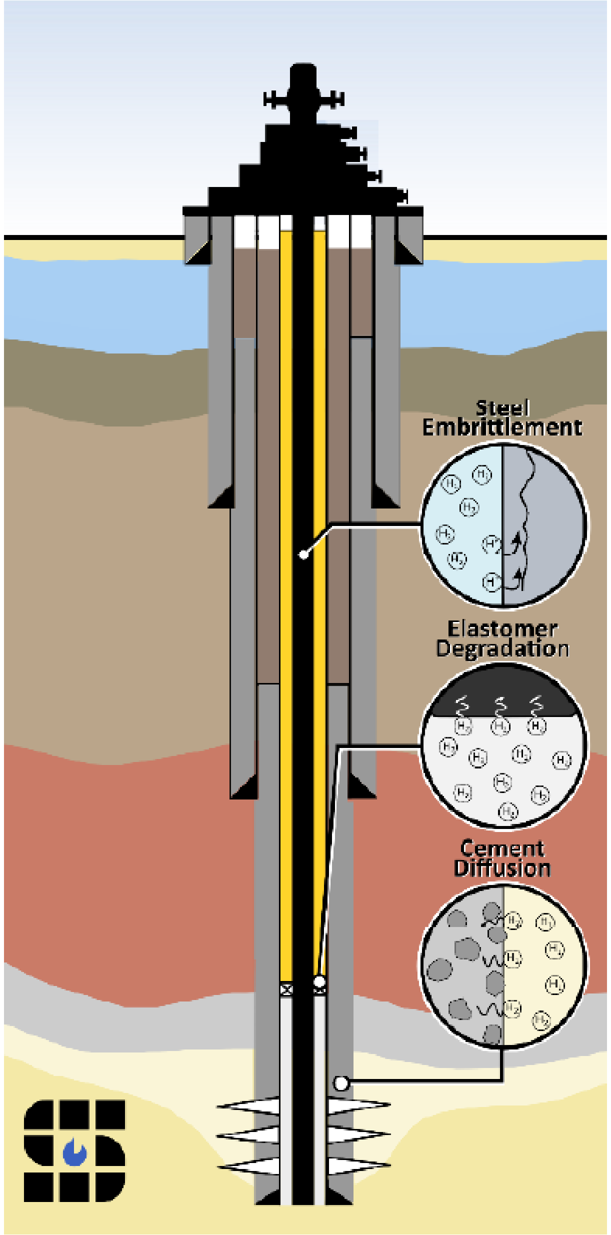
Article Type	Focus Points	Storage Types
Review	Wellbore integrity; Cement; Hydrogen damage; Corrosion; Legacy wells;	Depleted oil and gas reservoirs
Review	Hydrogen-induced impact; Well stability; Hydrogen corrosion; Casing failure;	Salt cavern
Review	Well integrity; Leakage monitoring; Risk assessment of legacy wells;	Geological CO_2 storage
Research	Underground gas storage well; Risk analysis model; Well integrity failure;	Underground gas storage
Review	Wellbore integrity; Cement carbonation; Failure analysis; Well integrity evaluation;	Conventional/unconventional oil and gas reservoirs
Review	Well integrity; Cement integrity; Casing failure; Corrosion	CO_2 and H_2 storage
Review	Casing damage; Cement/sealant failure; Hydrogen embrittlement; Microbiological corrosion	Natural hydrogen reservoirs
Research	Hydrogen-cement interactions; Well integrity, Leakage risk; Geochemical processes;	Underground hydrogen storage
Research	Wellbore integrity; Cement seal; Cement degradation;	Depleted gas reservoirs
Research	Wellbore integrity; Cement sheath; Experimental investigation; Cement sample;	Depleted oil and gas reservoirs
Review	Cements; Corrosion; Failure; Leakage; Wells; Steel; Sealing;	Underground hydrogen storage
Research	Wellbore failure; Integrity analysis; Optimized operating pressure;	Salt cavern
Research	Wellbore integrity failure; Risk assessment; Gas leakage; Wellbore hazardous zone	Depleted reservoirs

Research Focus points

- Wellbore integrity,
- Failure mechanisms of well components,
- Leakage concerns,
- Corrosion/degradation of the wellbore,
- Risk analysis.

Wellbore integrity

- Casing failure
  - Hydrogen embrittlement
  - Hydrogen Induced Cracking
- Cement failure
- Corrosion effect
- Elastomer deterioration



Wellbore integrity

Well integrity relies upon the mechanical barrier and the hydraulic barrier.

- The mechanical barrier consists of solid, pressure-containing steel elements (casing, tubing, connections) and elastomer seals (packers).
- The hydraulic barrier is the cement sheath that provides the protection of the casing integrity and the stability of the borehole.

There are two main failures of wellbore integrity.

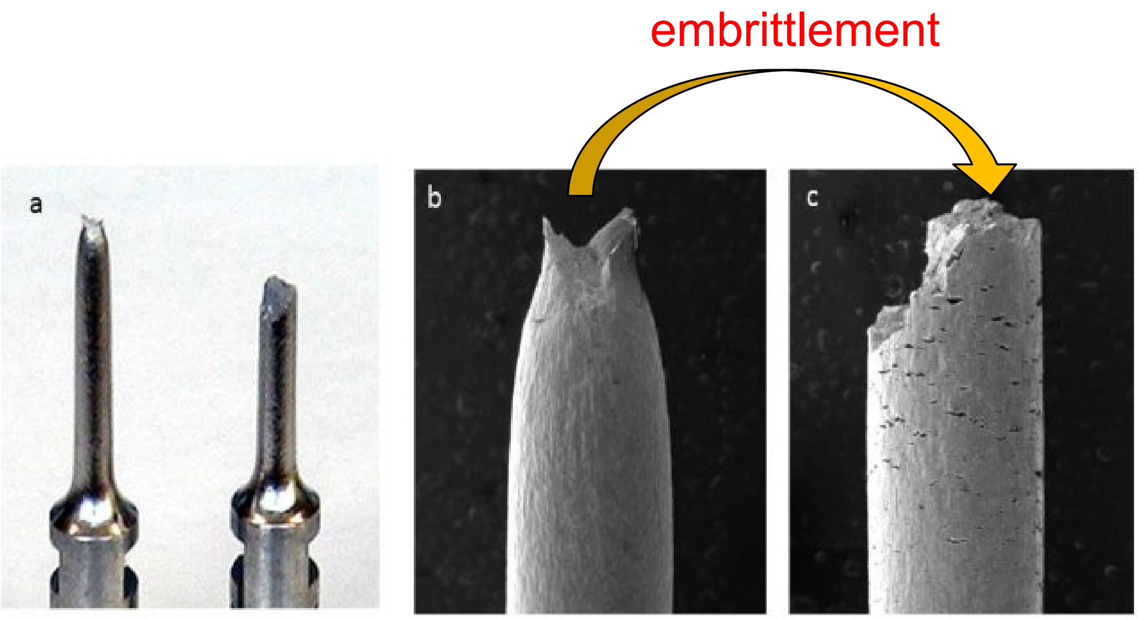
- The casing steel used in casing, when exposed to high-pressure hydrogen continuously, is damaged by multiple mechanism.
- The cement integrity failure occurs when the sheath fails to provide zonal isolation, casing corrosion protection, or formation/casing structural support, resulting in leakage pathways.

5. Wellbore material design objectives

Well components	Design objectives	Material characteristics
Casing and Tubing	Resist HE	Alloys with a high Nickel Equivalent (often ≥27%) exhibit no HE.
	Resist Corrosion	Use of Corrosion-Resistant Alloys or specialized corrosion inhibitors
Cement Sheath	Ensure Hydraulic Barrier	Use of pure cement slurry, or casing-cement (High Magnesium Resistant) composites
	Accommodate Thermal/Pressure Cycles	The cement with ductile behavior (difficult to achieve), and high Young's Modulus and Poisson's ratio

The steel components must be selected to actively resist Hydrogen Embrittlement and Hydrogen Blistering. Moreover, the primary goal for cement is to minimize the pore structure to prevent H2 migration and maintain mechanical integrity.

5. INITIAL FINDINGS



The image of the specimen after fracture (a) whole image (b) specimen without hydrogen (c)specimen with hydrogen[1)]

Hydrogen embrittlement susceptibility[2)]

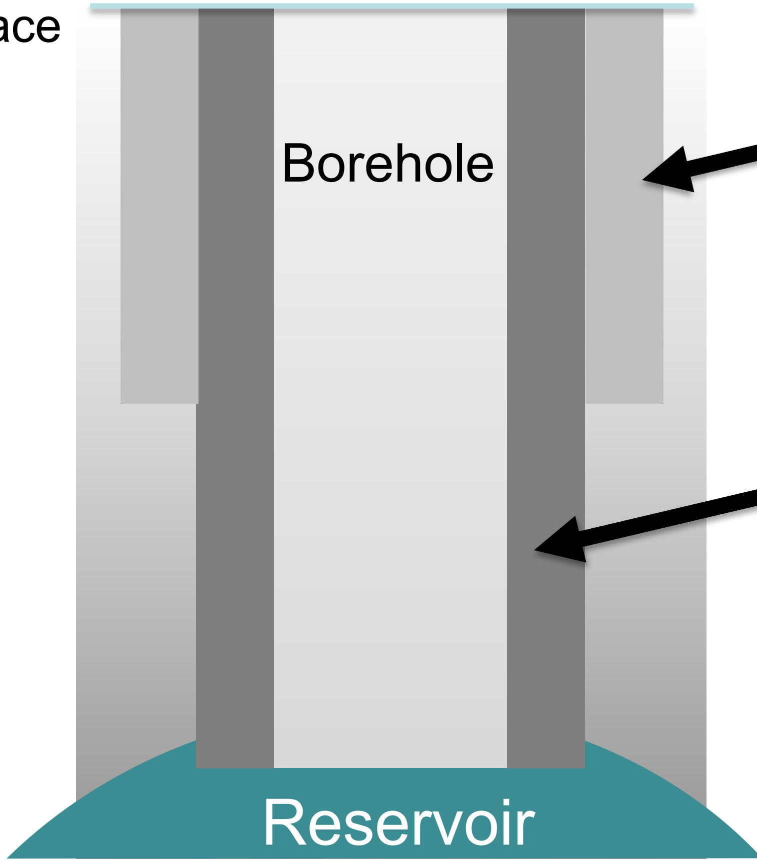
	Hydrogen embrittlement susceptibility
1042 Steel	Extremely embrittled
Titanium	Slightly embrittled
6061-T6 Aluminum	Negligibly embrittled

- Hydrogen cause the material to become brittle (hydrogen embrittlement)
- Hydrogen embrittlement susceptibility varies depending on the material: appropriate material selection is crucial

1) The High Pressure Gas Safety Institute of Japan, https://www.khk.or.jp/hydrogen/erosion.html
2) NASA, SAFETY STANDARD FOR HYDROGEN AND HYDROGEN SYSTEMS, Guidelines for Hydrogen System Design, Materials Selection, Operations, Storage, and Transportation (2005).

5. INITIAL FINDINGS

The surface



Outside casing: J55 steel

→limited hydrogen embrittlement[1)]

Inner casing: N80-Q steel

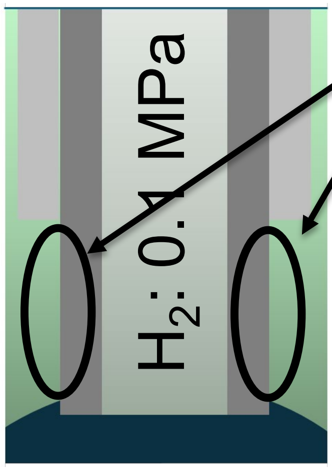
→ It consists of a martensitic phase (susceptible to hydrogen embrittlement)

The schematic illustration of certain wellbores in Japan.

- The wellbore casing consists of a two-layer concentric cylindrical configuration.
- The material used in the inner casing consists of a martensitic phase and is therefore susceptible to hydrogen embrittlement.

1) B. Loder, *et al*, *AMPP Annual Conference + Expo*, 2023

5. INITIAL FINDINGS



The analysis domain

The schematic illustration of a certain wellbore and H_2 gas pressure.

The size of casing and the coefficient of hydrogen permeation

The diameter of the inner casing	244.5 mm
The thickness of the inner casing, *t*	10.03 mm
The coefficient of hydrogen permeation (The room temperature[1]) φ	2.4×10^{-14} mol/(msPa$^{-1/2}$)

The permeation flux, *J*

$$J = \frac{\varphi \Delta \sqrt{p}}{t} = 7.7 \times 10^{-10}\ \mathrm{mol/(m^2 s)}$$

The leakage rate per unit time, *C*

$$C = \frac{\frac{pV}{RT}}{JA} = 3.4 \times 10^{-8}\ \%/\mathrm{s}$$

p: H_2 gas pressure, V: The internal volume of the casing
R: Gas constant, T: Temperature, A: The inner surface area of the casing

- The amount of hydrogen permeation in the lower part of the casing is 3.4×10^{-8} %/s: hydrogen leakage into the subsurface is limited.

1) H. G. Nelson, *et al*, NASA TN D-265, *1973*

6. Future works

- Experimental tests on assessing the geochemical interaction between hydrogen and wellbore cement.
- After exposing samples to hydrogen, mechanical properties of the well cement (class G) will be investigated and compared with ordinary cement (class A).
- Investigation of the hydrogen effect on cement sheath and evaluate the degree of degradation.
- Combine the findings of the effect on well casing and cement sealing, then form a comprehensive study results.