AADE-23-NTCE-SPP-09

Evaluating Cement as a Containment Barrier for Underground Hydrogen Storage

Athar Hussain, Hossein Emadi, Sugan Raj Thiyagarajan, and Diana Maury Fernandez; Texas Tech University

Abstract

Encouraging the use of renewable energy is crucial for meeting our energy needs, but it requires bulk storage to be practical. One potential solution is underground hydrogen storage, which could provide a consistent supply of clean energy for the world. Depleted hydrocarbon reservoirs may be a viable storage option for this purpose, given their existing infrastructure. However, ensuring wellbore integrity is a major challenge when storing hydrogen in such reservoirs. To test the feasibility of this approach, a core holder to replicate wellbore conditions having a 12” long, 4” diameter core sample that has a concentric two-inch drilled hole is used in this study. A one-inch perforated pipe, as the casing, is placed inside the 2” hole, and the cement will be placed between the pipe and the core. 72 hours after pouring the cement between the core and the pipe, hydrogen is injected into the sandstone from the casing through the cement. A CT scanner was then used to detect any leakage channels or cracks in the cement that could compromise the integrity of the storage system. This new method could offer a promising alternative for underground hydrogen storage in depleted hydrocarbon reservoirs.

Introduction

There is a need for an energy transition toward a more sustainable and low-carbon energy system. This involves transitioning from fossil fuels to renewable energy sources like solar, wind, and hydroelectric power. By reducing greenhouse gas emissions and promoting a more sustainable energy system, we can help to mitigate the negative impacts of climate change and protect the environment for future generations (Canbaz et al., 2021). Additionally, an energy transition can also bring economic benefits and promote energy independence and security. Figure 1 demonstrates the Global primary energy consumption by source.

Hydrogen is considered a valuable energy carrier because it can be produced using renewable energy sources (Figure 2)and can be used in various applications, including transportation, electricity generation, heating, and industrial processes.

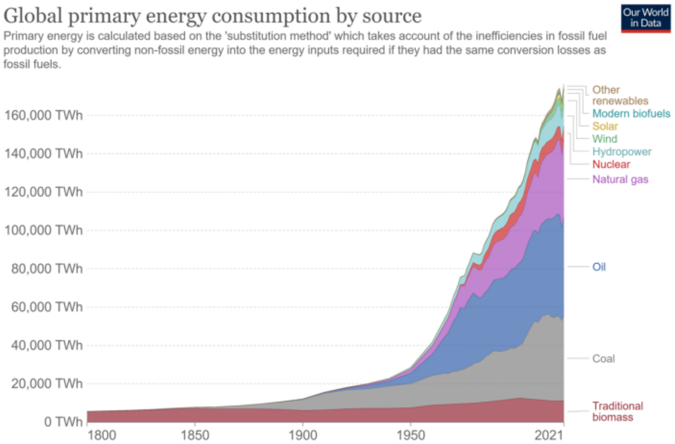

Figure 1 Global Primary Energy Consumption by Source (BP Statistical Review of Energy)

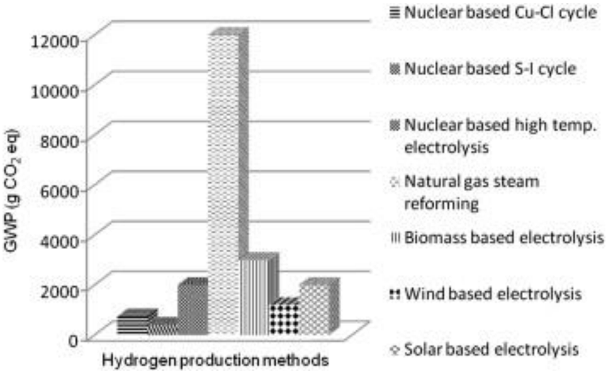

Figure 2 Hydrogen Production Methods (Ozbilen et al., 2011)

Hydrogen can also be stored for long periods of time, making it a useful energy storage medium for intermittent renewable energy sources like solar and wind power. Depleted hydrocarbon reservoirs are a promising option for hydrogen storage because they can be repurposed for hydrogen use, and existing gas infrastructure can be utilized (Figure 3). However, there are potential challenges associated with using these reservoirs. For example, residual oil or gas left in the reservoir could contaminate the hydrogen, reducing its purity. Additionally, the presence of residual oil could cause chemical reactions that could affect the storage capacity of the reservoir(Thiyagarajan et al., 2022).

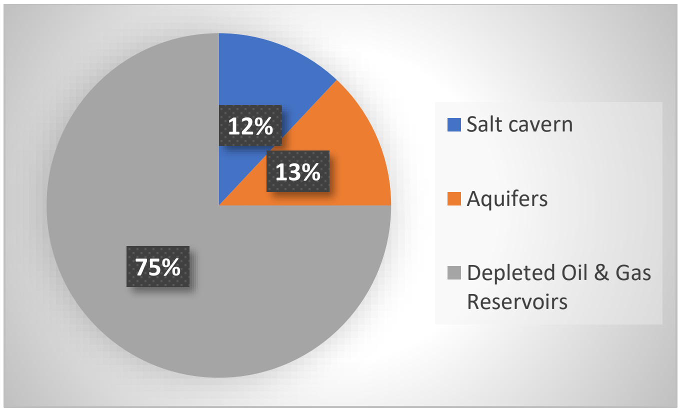

Figure 3 Share of Underground Hydrogen Storage by its Type (Hussain et al., 2022)

Another potential challenge is the risk of hydrogen leakage due to channels in wells or faults in geological formations. Hydrogen is a lightweight molecule, and if it escapes from storage facilities, it can quickly dissipate into the atmosphere. The unsuitability of drilled wells and other materials used in oil and gas production for subterranean hydrogen storage, as well as potential channels in the geologic formation that could allow hydrogen to flow, can also contribute to hydrogen leakage(Al-Hadrami et al., 2022).

Ensuring the integrity of production and injection wells is crucial for effective hydrogen retrieval and storage, as well as for avoiding environmental consequences. For example, unused plugged and abandoned legacy wells can potentially leak hydrogen, leading to safety hazards and costly environmental consequences(Bechara et al., 2022).

Figure 4 illustrates the potential pathways for hydrogen leakage, highlighting the importance of careful planning and maintenance of hydrogen storage facilities to minimize the risks associated with hydrogen storage in depleted hydrocarbon reservoirs.

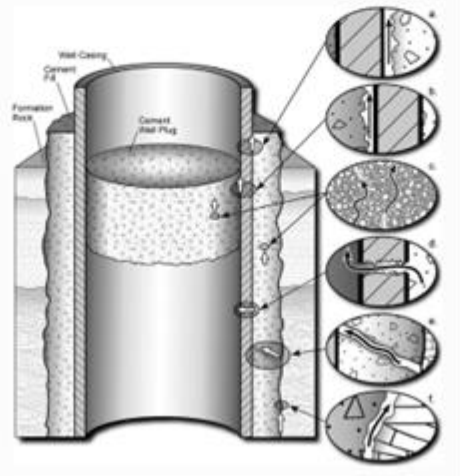

Figure 4 Potential Hydrogen Leakage Paths(Gasda et al., 2011)

Maintaining the integrity of the wellbore is crucial to prevent the uncontrolled release of hydrogen into permeable formations or to the surface. The redox process of H_2/H_2O is not very active at low temperatures, but factors such as water saturation, formation rock salinity, temperature, pH value, oxygen presence, and concentration, and the presence of siderite, dolomite, or calcite can affect the sealing properties and solubility of the cement barrier(Hussain et al., 2022).

One way that hydrogen can leak is through the cemented annulus, where cracks can form in the cement during the well's life cycle. There are three types of potential defects that can occur in the cemented annulus. The first type is disk-shaped cracks that occur perpendicular to the well axis at certain depths due to cement hydration-induced shrinkage. These cracks are always present and connect the formation and the casing/cement interfaces at multiple depths. The second type of defect is radial cracks, which are caused by over-pressurization of the wellbore or an increase in the wellbore temperature. The vertical extent of these cracks is mostly controlled by heterogeneities along the wellbore axis, and they are rarely observed on advanced cement evaluation logs. The third type of defect is micro-annulus, which results from the debonding of the inner (casing/cement) or outer (formation/cement) interface. Such debonding can occur due to a decrease in wellbore pressure or temperature, or an increase in the pressure at the interface(Lecampion et al., 2011). Figure 5 provides a schematic of the different types of cement sheath failures.

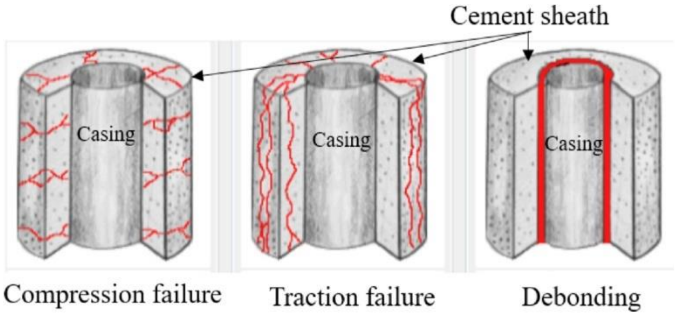

Figure 5 Cement Sheath Failures (Li et al., 2020)

Previous research has shown that the interface between cement and casing in oil and gas wells is particularly vulnerable to damage, as compared to other parts of the wellbore(Sault et al., 1984)(Bois et al., 2013). Tests such as shear tests and hydraulic tests are conducted to measure the bonding strength of the interface, with some researchers suggesting that a pushout test is better suited for characterizing the interface tensile strength. Recently, computed tomography (CT) imaging has been increasingly used to study the behavior of cement in wellbores, enabling visualization and quantification of annular seal damage and relating the zonal isolation performance of the cement sheath to the physical properties of the wellbore components(Anya et al., 2023). CT imaging can also reveal potential areas of weakness, aiding in the optimization of cement formulations to improve wellbore integrity. Previous studies have used CT imaging to study the evolution of cement sheaths under thermal cycling, highlighting the importance of optimizing cement formulations to ensure wellbore integrity(Anya et al., 2020).

The current study aims to evaluate the cement's ability to restrict the leakage of hydrogen from a wellbore integrity perspective. The experiments will analyze if the cement is sealing the wellbore to prevent leakage which can lead to sustained casing pressure.

Lessons Learnt from Carbon Capture and Storage

In recent reviews, it was found that some laboratory tests conducted by researchers on Portland-based cement may have led to claims of poor CO_2 resistance due to several reasons. Some of these tests failed to recognize large boundary effects or ignored them completely. Autoclave tests were used without applying confining stress, which is an inferior method compared to dynamic tests conducted in Hassler cells by the Oil and Gas industry. No pressure/flow confining stresses were applied to simulate the forces in rock and casing, which could lead to inaccurate results. CO_2 paths for the least flow resistance in rock versus cement were not tested, and there was no justification for "accelerating" carbonation layers artificially. In some cases, artificial methods were used to report that carbonated layers were "dissolving," with no benchmarks or criteria established to justify the artificial removal of carbonated layers. This is counterintuitive since carbonated layers have been shown to protect cement against degradation. Other factors such as ultra-slow diffusion rates in cement, skin damage in the surrounding rock of the annulus, unrealistic cement surface areas, rock and cement pore plugging by precipitates, carbonated cement pore collapse by overburden rock's confining pressure, and simulated rock and connate water compositions were not tested. Moreover, molecular CO_2 dispersion versus hydrated/ionized CO_2 (H_2CO_3) was not measured or controlled, and pH versus time and location was not measured or controlled to match reservoir conditions. There was no pH increase by conversion back to solvated molecular CO_2 and buffering by rock and dissolved minerals were not simulated, which significantly limits pH decreases by CO_2. Instead, the tests made pH unrealistically low with de-ionized water at high temperatures. The application of electricity to cement curing water in the laboratory equipment caused the water to acidify itself more than the CO_2 would alone in underground reservoirs, and strong acids were used to simulate weak carbonic acid in the cement curing water. Furthermore, temperatures and pressures did not match the plume's pressure front, and effects on P and T induced by injection/production were not simulated. Finally, there were no attempts to match pH in curing water to predictions from geochemical reservoir models(Santra & Sweatman, 2011).

Experimental Methodology

A precise batch of Class H slurry was produced in accordance with the API-RP-10B-2 regulations (API, 1997), with a slurry density of 15.5 lbs./gal (1.87g/cm^3). Lab-scale wellbore for the cement mixture was created (Figure 6). The equipment used for the experiments is a pressure vessel made primarily of lightweight aluminum alloy, which is reinforced with carbon fiber for high-pressure applications. The vessel can hold a wellbore that measures up to 304 mm in height and 101 mm in diameter.

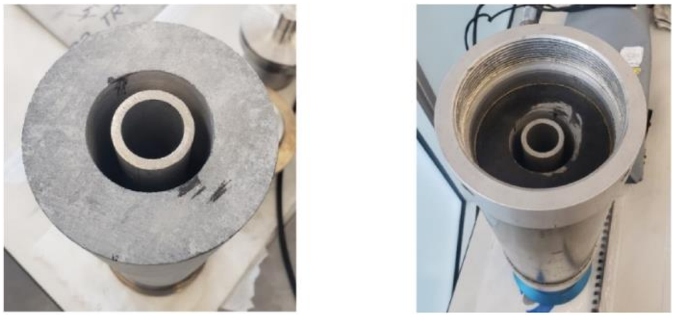

Figure 6 Wellbore Model for cement placement

To apply heat to the wellbore, a flexible heating jacket is wrapped around the pressure vessel, and pressure transducers are attached to the outlet ports for pressure detection. The wellbore used in the tests consists of a 304 mm high Berea Sandstone core with an internal diameter of 50.8 mm and an outer diameter of 101 mm. The casing is made of Grade 304 stainless steel pipe with an outer diameter of around 33 mm and an inner diameter of 24 mm(Figure 7).

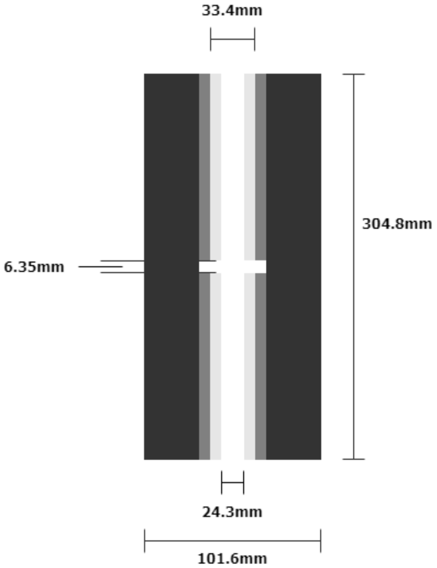

Figure 7 Wellbore Model Schematic

To simulate a perforation, a 6.35 mm rubber plug is inserted through holes drilled into the steel pipe and cement, which allows for the observation of fluid-driven phenomena relevant to cement integrity around the perforation zone. This technique is unique compared to other techniques described in the introduction.

To obtain images, a Ceretom® NL3000 scanner with a maximum slice thickness of 1.25 mm was used, and for hydrogen injection tests (Figure 8), an Ametek Chandler Engineering 2-cylinder Quizix pump was used. The CT scanner has 8 detector rows that can simultaneously acquire 8 image slices during a full rotation. The scanner operates at tube voltages between 100 to 140 kV and current values from 1 to 7 mA, with a rotation time range of 2 to 6 seconds and a maximum scanning range of 64 cm. Each image slice has a thickness of 1.25 mm. Figure 9 shows the 3D volume image of the wellbore model generated by the CT Scanner.

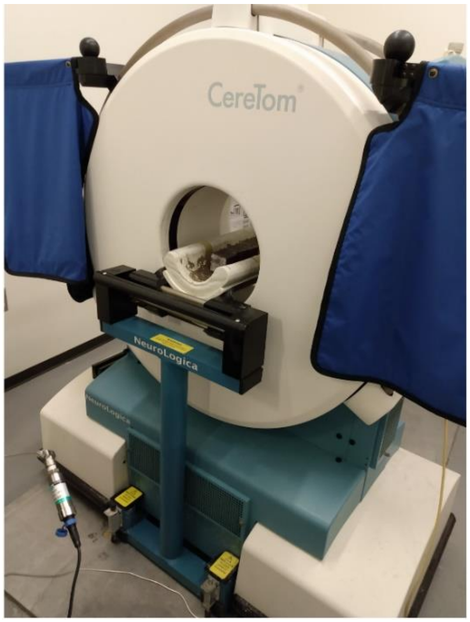

Figure 8 Ceretom CT Scanner

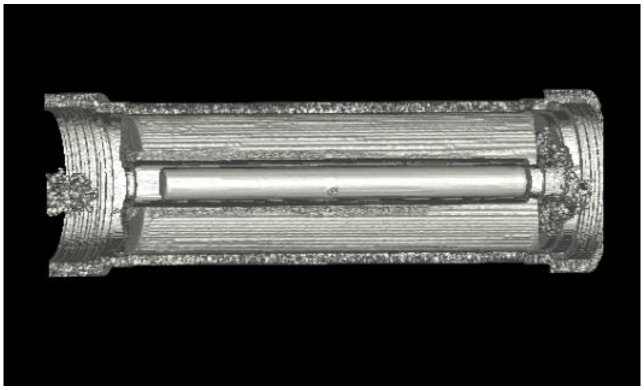

Figure 9 3D Volume image of the wellbore model.

To conduct the study, the cement was poured into the space between the casing and sandstone, and the vessel was sealed. A heating jacket was used to maintain a temperature of 120°F for a three-day curing period, and after that, the simulated perforation was exposed by removing the rubber plug from the pipe, and the vessel was resealed. A CT scan was taken before hydrogen injection to evaluate the initial quality of the annular cement for the hydrogen injection tests. The cement annulus was equipped with pressure transducers at one end, and hydrogen was injected into the annulus at a rate of 62.5 psi per hour for 24 hours using a Quizix pump (Figure 10). The pressure changes in the annulus were continuously monitored using a data acquisition system.

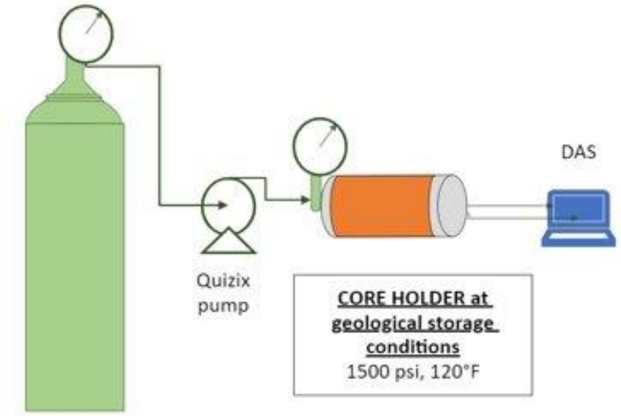

Figure 10 Experimental Setup

Results

The study found that when hydrogen was injected into the wellbore model using a Quizix pump, the pressure was immediately detected by the data acquisition system. This suggests that the cement was unable to act as a seal for the hydrogen injected. Figure 11 demonstrates the pressure from the quizix pump and the pressure transducer readings.

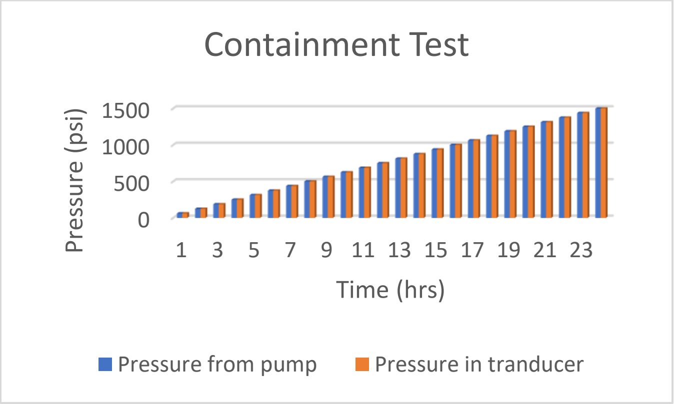

Figure 11 Containment Injection Test of Hydrogen

The pressure readings observed on the Data Acquisition System were consistent with the amount of hydrogen that was injected using the pumps (there was no lag time). This indicates that the cement was inefficient in providing an effective seal to prevent the leakage of hydrogen to the surface. To further investigate the reason for the leakage, CT-scanned images were analyzed which demonstrated that debonding at the cement/casing interface could have formed the flow channel for hydrogen leakage (Figure 12).

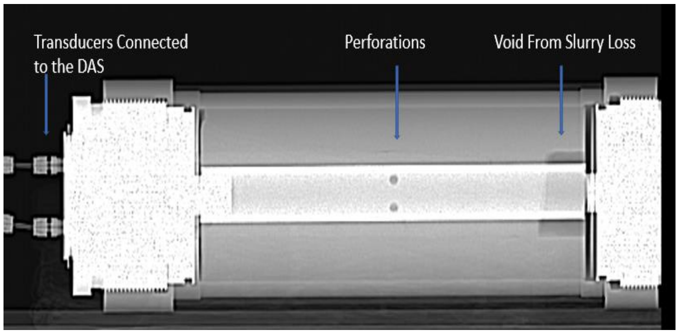

Figure 12 CT scan of the Wellbore Model

Inadequate bonding between the cement and the casing or formation rock can occur if there is insufficient mechanical interlock or chemical adhesion between the cement and the surfaces it is meant to bond with. This can result in the formation of gaps or voids that allow fluid migration or gas leakage through the wellbore, which can compromise the integrity of the well and lead to environmental or safety risks. Figure 13, Figure 14, and Figure 15 demonstrate the debonding at the cement/casing interface.

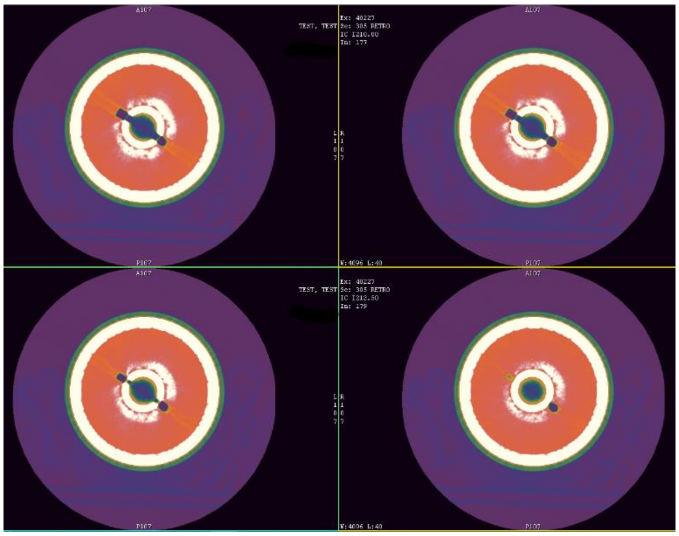

Figure 13 CT Scan images showing debonding

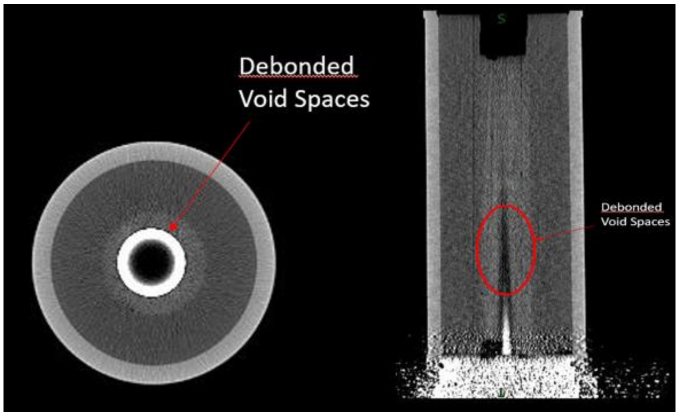

Figure 14 Debonding in the casing cement interface from Transverse and Coronal Plane

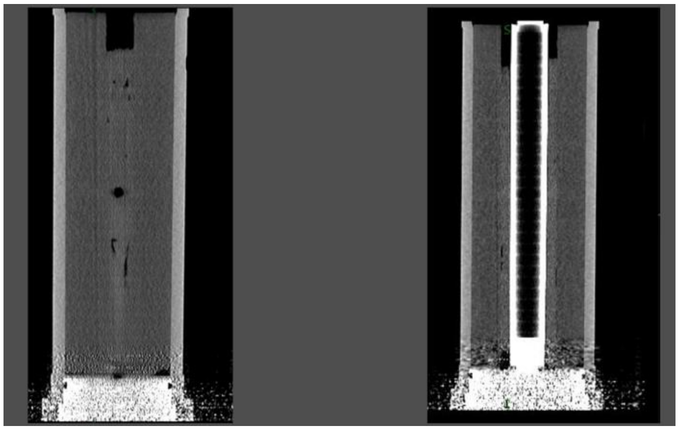

Figure 15 Debonding of the cement/casing interface from the Sagittal plane

Moreover, exposure to high temperatures, pressures, and chemical reactions can cause the cement to degrade and lose its structural integrity over time, leading to debonding. For instance, exposure to high temperatures (more than 230^{0}F)can cause the cement to lose its compressive strength and become brittle, while exposure to certain chemicals can cause it to corrode or dissolve.

Overall, cement debonding in oil wells is a complex phenomenon that can result from a range of factors, including inadequate bonding, poor cement quality, and exposure to harsh downhole conditions. It is important to monitor the integrity of cement barriers in oil wells regularly and to take appropriate measures to address any issues that may arise to ensure the safe and efficient operation of the well.

Conclusions

The study aimed to investigate the efficiency of hydrogen injection in a lab-scale wellbore model and its potential impact on the success of the subsurface hydrogen storage operation.

This study illustrates that inadequate bonding between the cement and the casing or formation rock can occur if there is insufficient mechanical interlock or chemical adhesion between the cement and the surfaces it is meant to bond with. This can lead to the formation of gaps or voids that allow fluid migration or gas leakage through the wellbore, which can compromise the integrity of the well and lead to environmental or safety risks.

By using the hydrogen injection test, a novel method to evaluate any potential debonding or leakage through the cement was demonstrated. The pressure readings observed during the test were consistent with the amount of hydrogen that was injected using the pumps, indicating that the Neat Class H cement will not be able to contain hydrogen and leakage will occur if a depleted oil and gas reservoir is used for an underground hydrogen storage site prior to remedial cement jobs.

Therefore, the study suggests that the hydrogen injection test can be a useful tool in detecting any potential debonding or leakage through the cement, which can help to ensure the integrity of the well and reduce environmental and safety risks.

References

Al-Hadrami, H., Emadi, H. & Hussain, A. (2022). Investigating the Effects of Hydrogen on Wet Cement for Underground Hydrogen Storage Applications in Oil and Gas Wells. *International Journal of Structural and Construction Engineering*, *16*. https://publications.waset.org/10012725/investigating-the-effects-of-hydrogen-on-wet-cement-for-underground-hydrogen-storage-applications-in-oil-and-gas-wells

Anya, A., Emadi, H. & Watson, M. (2020). Computed Tomography Study of Annular Cement Mechanical Response Under Cyclic Hydraulic Stress. *Proceedings of the 8th Unconventional Resources Technology Conference*. https://doi.org/10.15530/urtec-2020-3263

Anya, A., Emadi, H. & Watson, M. (2023). A novel apparatus and method for lab-scale study of wellbore integrity using CT imaging and analysis. *Journal of Petroleum Science and Engineering*, *220*, 111209. https://doi.org/10.1016/j.petrol.2022.111209

API, A. P. I. (1997). *API RP 10B - Recommended Practice for Testing Well Cements* (22nd Edition).

Bechara, E., Gamadi, T., Hussain, A. & Emadibaladehi, H. (2022, June 20). Effect of hydrogen exposure on shale reservoir properties and evaluation of hydrogen storage possibility in depleted unconventional formations. *Unconventional Resources Technology Conference*. https://doi.org/https://doi.org/10.15530/urtec-2022-3723858

Bois, A.-P., Vu, M.-H., Ghabezloo, S., Sulem, J., Garnier, A. & Laudet, J.-B. (2013). Cement Sheath Integrity for CO2 Storage – An Integrated Perspective. *Energy Procedia*, *37*, 5628–5641. https://doi.org/10.1016/j.egypro.2013.06.485

Canbaz, C. H., Aydin, H., Canbaz, E., Akberov, I., Aksahan, F., Hussain, A., Emadi, H. & Temizel, C. (2021). A Comprehensive Review and Status of Renewable Resources and Oil & Gas Under the Supply and Demand Dynamics in the World. *Day 4 Thu, October 21, 2021*. https://doi.org/10.2118/205116-ms

Gasda, S. E., Wang, J. Z. & Celia, M. A. (2011). Analysis of in-situ wellbore integrity data for existing wells with long-term exposure to CO2. *Energy Procedia*, *4*, 5406–5413. https://doi.org/10.1016/j.egypro.2011.02.525

Hussain, A., Al-Hadrami, H., Emadi, H., Altawati, F., Thiyagarajan, S. R. & Watson, M. (2022). Experimental Investigation of Wellbore Integrity of Depleted Oil and Gas Reservoirs for Underground Hydrogen Storage. *Day 2 Tue, May 03, 2022*. https://doi.org/10.4043/32003-ms

Lecampion, B., Quesada, D., Loizzo, M., Bunger, A., Kear, J., Deremble, L. & Desroches, J. (2011). Interface debonding as a controlling mechanism for loss of well integrity: Importance for CO2 injector wells. *Energy Procedia*, *4*, 5219–5226. https://doi.org/10.1016/j.egypro.2011.02.500

Li, C., Guan, Z., Zhao, X., Yan, Y., Zhang, B., Wang, Q. & Sheng, Y. (2020). A new method to protect the cementing sealing integrity of carbon dioxide geological storage well: An experiment and mechanism study. *Engineering Fracture Mechanics*, *236*, 107213. https://doi.org/10.1016/j.engfracmech.2020.107213

Ozbilen, A., Dincer, I. & Rosen, M. A. (2011). A comparative life cycle analysis of hydrogen production via thermochemical water splitting using a Cu–Cl cycle. *International Journal of Hydrogen Energy*, *36*(17), 11321–11327. https://doi.org/10.1016/j.ijhydene.2010.12.035

Santra, A. & Sweatman, R. (2011). Understanding the long-term chemical and mechanical integrity of cement in a CCS environment. *Energy Procedia*, *4*, 5243–5250. https://doi.org/10.1016/j.egypro.2011.02.503

Sault, P. A. P., P. H., Parcevaux, P. A. & Sault, P. H. (1984). SPE 13176 Cement Shrinkage and Elasticity: A New Approach for a Good Zonal Isolation. *SPE Annual Technical Conference and Exhibition*. https://doi.org/https://doi.org/10.2118/13176-MS

Thiyagarajan, S. R., Emadi, H., Hussain, A., Patange, P. & Watson, M. (2022). A comprehensive review of the mechanisms and efficiency of underground hydrogen storage. *Journal of Energy Storage*, *51*, 104490. https://doi.org/10.1016/j.est.2022.104490