

Ensuring long-term caprock integrity in carbon capture, utilisation and storage: a comprehensive review of geo-mechanical and monitoring approaches

Mohd Sadiq^{1,2}, Ravi Sharma^{1,*}, Beer Singh Bisht² and Manisha Chaudhary¹

¹Department of Earth Sciences, Indian Institute of Technology Roorkee, Roorkee 247 667, India

²Geodata Processing and Interpretation Centre (GEOPIC), Oil and Natural Gas Corporation Limited, Kaulagarh Road, Dehradun 248 195, India

Caprock integrity is essential for the successful implementation of carbon capture utilisation and storage (CCUS) technologies, which are pivotal for reducing atmospheric carbon dioxide (CO₂) levels and mitigating climate change. The present study examines the role of caprock in preventing CO₂ leakage, methods for assessing and ensuring its integrity and the techniques for monitoring its long-term stability. Caprock, typically composed of low-permeability materials such as shale and/or anhydrite, acts as a barrier to prevent the upward migration of CO₂ from the underlying storage reservoirs. The effectiveness of caprock in preventing the leakage is determined by its physical and mechanical properties, including high porosity, low permeability, high mechanical strength and geochemical stability. Case studies from projects like Sleipner and In Salah demonstrate that effective caprock can secure CO₂ for extended periods without significant leakage.

Different methods are employed to ensure caprock integrity. They include laboratory testing, field experiments and geo-mechanical modelling. Core sampling and laboratory tests provide the data on caprock properties, whereas *in situ* stress tests and hydraulic fracturing experiments offer insights into the stress distribution and mechanical behaviour of the caprock formations. Numerical models coupled with fluid flow and mechanical deformation simulations predict the impact of CO₂ injection on caprock stability. Risk assessment and mitigation strategies, such as optimising injection pressures and using chemical sealants, are essential for reinforcing the caprock integrity.

The long-term stability of caprock is critical to the sustainability of CCUS projects. Geochemical models simulate CO₂-brine-rock interactions, assessing the impact of geochemical reactions on caprock properties. Advanced monitoring technologies, including seismic surveys, interferometric synthetic aperture radar (InSAR) and fibre optic sensors, provide real-time data on the mechanical and chemical behaviour of caprock. Integrated monitoring programmes from projects like Weyburn-Midale and Otway highlight the

importance of comprehensive monitoring and adaptive management strategies.

Future research should prioritise the development of advanced models that incorporate complex geo-mechanical and geochemical interactions and enhance real-time monitoring technologies. Policy development should emphasise comprehensive risk assessments, continuous monitoring and international collaboration to ensure the safety and effectiveness of CCUS projects globally.

Keywords: Climate change, carbon capture utilisation and storage, caprock integrity, environmental impact, geomechanics.

CLIMATE change poses a considerable threat to the global environment and thus, effective mitigation strategies must be developed and implemented. Carbon capture utilisation and storage (CCUS) technology is one of the most important technologies as it aims at reducing the level of atmospheric carbon dioxide (CO₂). CCUS technology helps to mitigate the adverse effects of greenhouse gases on the climate by capturing CO₂ emissions from industrial sources and safely storing them in geological formations. Secure storage is necessary to ensure that the captured CO₂ does not escape and re-enter the atmosphere. In particular, the success and credibility of CCUS technology as a solution to climate change are strongly dependent on the integration of site-specific, dynamic geomechanical monitoring to secure long-term caprock integrity¹.

One of the secure storage approaches implies the use of distributed fibre optic strain sensing for geo-mechanical monitoring. It guarantees the ability to track subsurface and surface deformation in real-time and is cost-effective, since it involves high-resolution data². Coupled numerical simulations that account for the interactions among compositional, geochemical and geo-mechanical processes are critical. These simulations should be employed to assess the risk of caprock failure during

*For correspondence, (e-mail: ravisharmafes@iitr.ac.in)