Introduction to this special section: Carbon management

Matt Flannery[1], Kurang Mehta[2], and Arpita P. Bathija[3]

https://doi.org/10.1190/tle42110734.1

Carbon capture, utilization, and sequestration/storage (CCUS) might be considered as putting the proverbial genie of carbon dioxide (CO_2) back in the bottle. In brief, we aim to separate CO_2 from industrial combustion exhaust, or directly from the atmosphere, and inject it into subsurface brines (either as a supercritical fluid or dissolved in seawater) with the ultimate goal of permanent mineralization. An ancient alchemist seeking to take the air from fire, add to water, and turn the mixture to rock would be delighted indeed. This is an ambitious goal, but one within our collective reach. The last five years have witnessed a dramatic increase in the number of CCUS projects, investments, and technology advances. These recent developments have been the most sustained progress since CO_2 was first injected into the ground in 1972 or since it was initially sequestered commercially at Sleipnir in 1996.

Since 2021, the number of projects has grown at an interannual rate of 35%. At the time of this writing, some 265 CCUS projects worldwide are in various stages of progress, with only 40 of these in operation. About 80% are in either North America or Europe, with multiple projects in China, Australia, Indonesia, Brazil, the United Arab Emirates, and Malaysia making up the other 20%. The global annual operational storage capacity, currently about 40–50 Mt CO_2/year, will need to maintain a 35% average growth rate for at least a decade to achieve the target of sequestering 1 Gt CO_2/year by 2030. Of the 40 commercial sequestration projects currently operating, only fve facilities inject more than 7 Mt CO_2/year into saline formations. To reach the committed objectives, both the number and size of future projects will have to increase. CCUS alone is insufficient to counter the effect of anthropogenic emissions of greenhouse gases; it is only part of an array of mitigation options, all of which must be pursued if we are to meet net-zero emissions targets and limit average global warming to 1.5°C above preindustrial levels.

The fastest increase in number of CCUS projects has been in the United States since the passing of the Inflation Reduction Act (Sec 13104), Bipartisan Infrastructure Law (2021), and CHIPS and Science Act (2022). At the time of this writing, between the U.S. Environmental Protection Agency, North Dakota, and Wyoming, there are some 140 projects in preconstruction or construction in the United States. Primacy (in which U.S. state governments assume primary authority from the federal level to enforce and implement environmental laws and regulations) for Louisiana is pending, while Texas, Arizona, and West Virginia have also begun this process. Devolution of primacy to the various states is expected to increase the number of geoscientists reviewing the applications, which should help reduce the application timeframes for Class VI well permits. While Canada offers the CCS Investment Tax Credit, and the European Union has a framework to certify carbon removal and provides funding through the Strategic Energy Technology Plan, a comparable combination of grants, loans, and commoditized credits on the scale of the Inflation Reduction Act remains to be emulated outside the United States.

Of the four main potential sequestration projects identified by the United States Geological Survey (CO_2-enhanced oil recovery [EOR], saline aquifers, depleted petroleum reservoirs, and unusable coal seams), the most interest has, unsurprisingly, been in aquifers close to large emitters, EOR, and depleted petroleum reservoirs. Sedimentary basins host the majority of current targets, with siliciclastic projects outnumbering carbonate storage formations. In part, this is due to the lower economic threshold of EOR projects, which tend to be in siliciclastic formations, and the abundance of saline aquifer candidates that are known from petroleum exploration. There has also been some exciting development of CO_2-rich fluid interaction with mafic formations, a development that expands the range of target geologies to include volcanic formations. Even fractured granite prospects are under development where there is evidence of competent overlying confining intervals.

As the volume of projects grows and more approach the final investment decision stage, the requirements for successful characterization have settled into more familiar processes. Among independent and national oil companies alike, the last 18 months have seen a rapid period of restructuring, with dedicated CCUS teams growing from a few individuals into multidisciplinary teams with clear front-end engineering design targets.

In subsurface characterization, novel applications of established subsurface geoscience toward CCUS challenges have been too numerous to track, with industry conferences, forums, and symposia occurring monthly. As a result of these activities, geophysics and other geologic disciplines are enjoying a renaissance, employing advances in digital rock characterization, machine learning, and automation of data processing that were previously impossible. Geoscientists are uniquely positioned to contribute, but we must remember that with experience comes bias, and there are several essential considerations to supporting the various CCUS projects as can be seen in the following examples.

Confining lithology presence and competency. For saline aquifers, geophysical techniques are essential in defining structure and architecture. Time-lapse (4D) seismic monitoring of plume movement has been demonstrated at Sleipnir. However, for early-stage screening of projects, seismic monitoring is best supplemented with geochemical and petrophysical techniques, as subseismic features might easily invalidate a candidate. The absence of a

---

[1] Stratum Reservoir, Houston, Texas, USA. E-mail: matt.flannery@stratumreservoir.com.
[2] Ecopetrol America, Houston, Texas, USA. E-mail: kurang.mehta@ecopetrol-america.com.
[3] Aramco Americas, Houston, Texas, USA. E-mail: arpita.bathija@aramcoamericas.com.

hydrocarbon accumulation means that confining interval competency must be determined by other methods; acquisition and analysis of physical rock samples (ideally whole core) can reduce uncertainties and provide calibration data for remote techniques. More confident decisions are also supported by geochemical characterizations (composition and isotopes) of the formation brines and their native dissolved CO_2, combined with detailed profiling of their pore pressures.

Legacy wells competency. Legacy wells in industrial areas can amount to literally dozens of penetrations through the confining zone and overlying strata. Historically, the casing cement for penetrations through saline aquifers was intended to stabilize the hole and withstand fluid ingress at the local hydrostatic pressure. However, it was not intended to fill the myriad tensile fractures that often surround a well, particularly in brittle lithologies. These fracture networks present potential leakage chimneys to the overlying strata. Plugged wells were also not designed to withstand an increase in formation pressure from CO_2 injection decades after abandonment. In some cases, even the steel casing itself can be expected to be a potential leak pathway upon corrosion, particularly if reached by the CO_2 plume. Consequently, many operators are prioritizing areas peripheral to historical exploration and production activities, close enough to leverage the basin models but far enough from legacy wells. There are more than 123,000 documented legacy "orphaned" onshore wells across the United States. This is estimated to be just 3% of the total number of orphaned wells; hundreds of thousands remain undocumented and therefore pose potentially unrecognized risks to CCUS project operations.

Formation behavior upon pressurization. Even in EOR projects where injection is evaluated, the behavior of reservoir rock upon pressurization is only infrequently measured. Where depleted petroleum reservoirs are the candidates, repressurization of the reservoir may be necessary to raise in-situ pressures above the critical pressure of CO_2. The assessment of stress regimes, ground deformation, fault reactivation, induced seismicity, and crack propagation in rock that has been compacted from decades of production is an area in which, as an industry, we have little operational experience.

Confining interval characterization. Rarely, if ever, are seals characterized with the rigor that we apply to reservoir formations; this presents a potential collective blind spot. From calculating trip speeds out of the hole, to creep tests at representative saturations in CO_2-brine, assessments of the tight confining intervals are frequently underestimated both in complexity and time. Again, data from actual physical samples of the formation, whether conventional whole core or rotary sidewall cores, provide essential constraints to models. Legacy cuttings are an often-overlooked source of information. The analysis of cuttings mineralogy and trapped gases provides insight that is sometimes sufficient to conclude if the formation is competent to gas migration.

Rock-fluid interactions. Typically, petroleum is unreactive with the formation mineralogy at production timescales. Fluid-rock compatibility tends to focus on the drilling and completion fluids, mud cake stability, and clean-up efficiency during unloading. Injectant-rock compatibility is a standard assessment in acid stimulation operations, but these are short-term operations limited to a few hours or days at most. Conversely, injection of CO_2 into sedimentary formations usually results in chemical reactions that can alter rock properties and characteristics. For example, the dissolution of the reactive phases such as plagioclase and calcite can cause an increase in porosity and a decrease in mechanical strength in the near-wellbore region. Precipitation of quartz and calcite phases then follows, but in rock volumes more distal from the injection zone. That precipitation increases the strength and brittleness of the formation and reduces the porosity. These phenomena are readily observed within a few weeks in laboratory experiments at reservoir operation conditions. Geomechanical tests on core plugs while soaking/flooding with CO_2 at reservoir conditions are therefore strongly recommended to constrain the engineering parameters needed. For example, creep tests to bracket wellbore stability over the operational lifetime are critical. Ideally, these should be carried out to capture the upper limits of anticipated conditions during operation and the storage period thereafter.

Accurate modeling of the plume-formation interaction requires the dynamic reservoir model and the reactive transport model to function in sync. The most widely used reservoir models tolerate few, if any, chemical changes while the geochemical models are unable to represent the movement of fluid through a rock of changing porosity and permeability. Progress is being made to integrate these, but this remains an area for expansion, as does the hierarchy of uncertainties for a given development.

Fluid-fluid interaction. If fluid models are to accurately forecast the plume propagation, their underlying equation of state models must capture the whole composition phase behavior. A drop in brine pH can shift the point of mineral solubility equilibrium, initially resulting in dissolution of carbonates and silicates. Over periods of weeks to months, this dissolution buffers the brine pH and progresses to precipitation of carbonate and quartz. Saline brines are also at risk of halite scale upon contact with the injectant plume front. While most projects carry CO_2 as the main component, the confounding actors can actually be the contaminants such as SO_x, NO_x, amines (NR_xH_y), CO, light hydrocarbons, COS, CS_2, H_2S, N_2, O_2, and H_2 in the injectant streams. These contaminants all take up sequestration volume in the pore spaces. The SO_x, NO_x, NR_xH_y, CO, COS, CS_2, and H_2S compounds impact and complicate the rock-fluid interactions. Gases such as N_2, O_2, and H_2 all raise the saturation pressure and commensurate pumping power needed to achieve a supercritical fluid phase. Some projects along the U.S. Gulf Coast are considering as much as 5%–15% non-CO_2 gases.

Monitoring. Offshore seismic monitoring of the storage interval has been in use for more than two decades, while many onshore applications remain untested. Geophysical methods for monitoring plume movement have predictably experienced interest and investment, with each industry conference carrying a larger number of breakthroughs in acquisition, reprocessing, and interpretation. In addition to seismic and microseismic techniques, technologies that have seen renewed innovation and development, both individually and combined, include interferometric synthetic aperture radar and modulated spectroscopic technologies as well as gravity, electromagnetic, and electrical resistivity tomography. As projects mature to operation and field testing becomes more common, no doubt there will be further waves of refinement and optimization of geophysical techniques.

Counterintuitively, perhaps the most challenging strata to monitor are the relatively shallow underground sources of drinking water (USDW). Robust integrated monitoring programs require a confident baseline of conditions in the subsurface prior to injection. Groundwater aquifers are usually influenced by meteoric influx, and baseline compositions can vary seasonally. Consequently, establishment of a robust USDW baseline can require months-long regular sampling prior to operation commencement. For many industry professionals accustomed to deepwater or unconventional operations, a monitoring program of shallow strata for months or years is far from their initial project plans, but this is a critical component of any CCUS project.

In many ways, the worldwide growth in CCUS activity represents a new era of exploration geoscience. As an industry, we are now assessing formations as targets that were previously dismissed. Candidate formations are being considered in regions that have never held potential for mineral extraction activities, such as basins with no mature source rock or valuable ore deposits. Each week there are new examples of combining previously siloed disciplines, with digitization of legacy samples and artificial intelligence-assisted interpretations enabling novel insights. Between the opportunities for sequestration in sedimentary and mafic formations, we are very much at the beginning of the creaming curve for CCUS. As a community of geoscientists, we are confident that our knowledge and experience are extremely valuable in this accelerating field of study, while we also recognize the need to identify and address the potential pitfalls stemming from our preconceptions.

A glimpse at the technical progress made in this regime is presented in this special section through four enlightening articles. To begin, the work done by Osunrinde et al. focuses on how the selection of a geologic site with a specific deposition setting affects its sustainability as a carbon storage site and its storage efficiency. Creation of a robust structural framework was an important factor in revealing that the formation was laterally continuous and structurally controlled, allowing for the CO_2 gas to be distributed uniformly throughout the formation.

Alamsyah et al. perform a preliminary analysis of natural CO_2-saturated gas sands distribution in Indonesia and demonstrate the value of using simple seismic attributes such as sum of negative amplitudes as a linear proxy to sand thickness and CO_2 saturation. Koehn et al. perform a similar case study on CO_2 trapping characteristics of fold-and-thrust belts. Their work focuses on assessing carbon storage potential in the Appalachian Basin and beyond. With this study, they were able to identify that the regions in the Valley and Ridge physiographic province holds complex fold-and-thrust structures that would effectively trap commercial volumes of CO_2.

Understanding the containment and conformance of injected CO_2 requires a time-lapse seismic analysis. This type of work is demonstrated in the article by Pevzner et al., who focus on detection of a CO_2 plume by time-lapse analysis of Rayleigh-wave amplitudes extracted from downhole distributed acoustic sensor recordings of ocean microseisms. It is an interesting learning that time-lapse amplitude changes indicate temporal changes of stiffness of the geologic layers, such as changes in saturation or pressure of the fluid in a porous layer in the vicinity of the borehole. In particular, Rayleigh-wave amplitudes are sensitive to the presence of a CO_2 plume in the wellbore created as a result of a small injection into a thin and porous reservoir layer. TLE

Editors' note: A fully referenced version of this text is available upon request.