Geophysical Monitoring of Geologic Sequestration

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Two important reasons for monitoring geological sequestration processes are to assess the efficacy of the injection process and to verify safe containment. Ideally, one would like to not only track subsurface movement of CO_2 but also monitor the integrity of reservoir seals. Moreover, the ability to predict the behavior of monitoring strategies will be important for documenting the "safety case" that will be needed for public acceptance and site permits. In the most general scenario, monitoring will include a combination of direct and indirect methods. The initial targets of our project are the indirect methods of subsurface monitoring. Our objectives are to: (1) assess the available options for geophysical monitoring during CO_2 injection; (2) develop simulators to predict the capabilities and sensitivities of the various monitoring methods; and (3) propose new low-cost methods and strategies for subsurface geophysical monitoring. There are several geophysical methods potentially capable of meeting the subsurface monitoring needs. These range from space-borne radar to surface-based and borehole-based seismic and electromagnetic techniques. Each method has strengths and weaknesses and complexities related to their applicability to specific storage scenarios, site and reservoir location, and of course cost to implement. No doubt a combination or sequence of methods will be needed during the life of a sequestration project. Moreover, it is not yet established that long-term monitoring past closure of the reservoir will be required so we focus initially on monitoring during the injection phase or the early life of the storage project.

The fundamental issues regarding the application of geophysical methods involve changes in the rock and fluid properties associated with the injection process. Each storage scenario (oil/gas reservoirs, saline aquifers, or coalbeds) presents a different situation and must be analyzed and modeled separately. A deliverable from the monitoring research will be a series of modeling tools for simulating the geophysical response(s) due to injected CO_2. We began the project with a study of depleted oil reservoir and aquifers. During the next year we'll add research on coalbeds.

Changes in Fluid and Rock Properties

Changes in fluid saturation and pore pressure may cause significant changes in the physical and geophysical properties of the rocks and fluids of a hydrocarbon reservoir or aquifer undergoing CO_2 injection. We estimate these changes under the assumption that geochemical changes will occur at longer time scales than is of immediate interest to a monitoring activity.

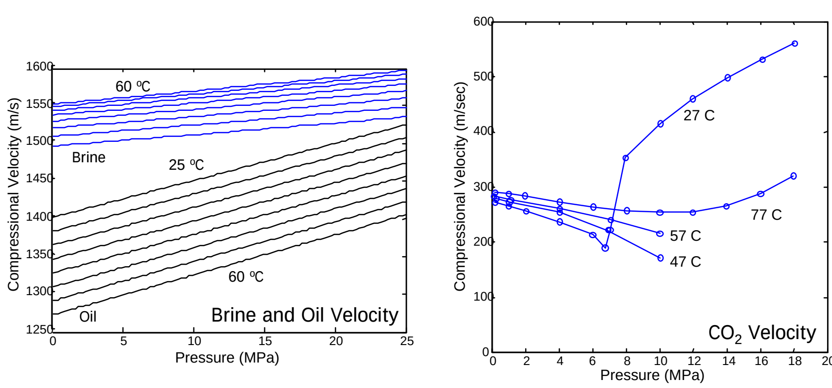
If the CO_2 is injected in a supercritical state, it will have liquid like densities (around 0.5 g/cc) and gas like compressibility and viscosity. We initially assume that mixing of the fluids in the pore space is occurring at isostress and homogeneously at the pore scale. Increasing CO_2 saturation will cause the bulk fluid density and viscosity to decrease, while the effective compressibility will be dramatically increased. Increasing pore pressure changes the stress on grains and grain contacts and may affect cracks and fracture behavior. Changes in density, compressibility, and viscosity may be detectable using seismic and/or gravity measurements. Electrical methods may useful at detecting the differences in electrical conductivity of CO_2 saturated and saline water. Large-scale changes in pressure may be detectable using deformation methods.

Geophysical Models and Simulators

We considered first seismic, electrical, gravitational, and deformation methods for subsurface monitoring of oil and gas reservoirs and saline aquifers. First the properties of the mixed fluid are estimated then the mixed CO_2-saturated fluid is incorporated into a porous rock model, which in most cases depends on the rock type and both overburden and pore pressure. The bulk rock properties model is then incorporated in a reservoir scale model in order to simulate field scale behavior. The first reservoir scale models are intentionally kept simple in order to illustrate first-order behavior and geophysical sensitivity to the changes. The geophysical methods considered first are seismic, electrical, gravitational, and deformation techniques. We provide herein a brief summary of each below.

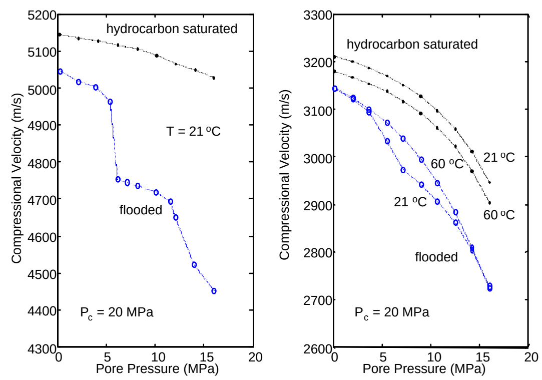
We are developing a suite of numerical models that capture the state-of-the-art in our understanding of porous rock and fluid properties and geophysical simulation of various monitoring strategies. For now, we anticipate linking these geophysical simulators up with the reservoir seal and flow simulators that provide spatial and temporal variations of pressure and saturation. In this way, we can model and/or predict the behavior of the injection process and analyze the injection scenario for the safety and CO_2 containment. Our first version of the geophysical simulator was used to estimate changes in the seismic, electrical, gravity and deformation response of a simple model for a petroleum reservoir.

Seismic methods: Seismic methods are the most popular choice for subsurface imaging. Seismic methods offer a variety of source-detector geometries, frequencies, and imaging strategies that can be adapted to depth and spatial resolution needs (Harris, 1996). The speed of sound in CO_2 is a factor of three or more less than the speed in typical reservoir liquids (Fig. 6). When CO_2 is mixed with reservoir fluids, the mixture becomes more compressible and the density decreases, thus causing the velocity of sound to decrease significantly (Fig. 7a). The velocity of compressional and shear moduli of fluid-saturated porous media can estimated using the Gassmann's model. While the Gassmann model requires some rock frame parameters that are not easily determined, it is nevertheless very useful at estimating the changes in moduli caused by changes in saturation (Fig. 7b). These models must be refined for specific reservoir conditions at a target sequestration site. Seismic methods may be implemented in a variety of geometries and frequencies, thus giving the most flexibility to monitor small and large scale behavior of the injection process.



(a) (b)

Figure 6. The velocities of compressional waves in the component fluids are important for estimating the velocity of a CO_2-saturated mixture: (a) velocity in typical brines and oils; (b) velocity in CO_2 [2].



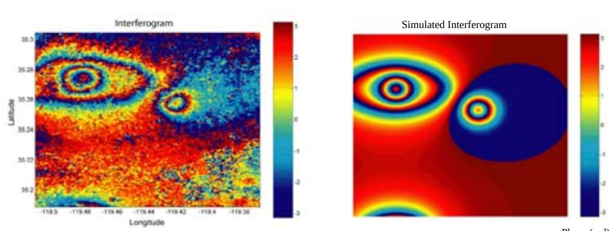
(a) (b)

Figure 7. The velocity of compressional waves in CO_2-saturated sandstone is significantly less than oil-saturated sandstone. (a) measured velocities (Nur and Wang, 1989); (b) modeled velocities calculated from the Gassmann fluid substitution model and a trial pressure dependence. Shear velocities do not change significantly due to saturation changes.

Electrical and electromagnetic methods: EM methods rely on changes in electrical conductivity and dielectric properties of the fluids caused by CO_2. For example, the conductivity of brine-saturated reservoir fluids will decrease when less conductive CO_2 is injected. This decrease may be detectable with EM methods depending on many other operating factors such frequency and source and detector geometry.

Gravitational methods: Gravity methods detect changes in bulk density caused by subsurface density variations. The sensitivity and speed of gravity measurements is such that they my be useful in assessing large-scale changes in mass associated with injection and detecting leaks.

Deformation methods: Displacement of the Earth's surface will occur when pore pressure changes in the subsurface. In a closed reservoir, the pressure changes would be caused by the injection of CO_2. This deformation can be monitored using satellite radar interferometry (InSAR), ground-based GPS, or surface tiltmeters, depending on the magnitude of the deformation and surface conditions. We have used InSAR to image deformation over the Elk Hills oil field in Southern California. Both inflation and subsidence were observed over subsurface reservoir that is undergoing both production and injection (Fig. 8). Such methods may be useful in addressing questions regarding mass balance and CO_2 migration.



[2] Wang, Z., and Nur, A., 1989, Effects of CO2 flooding on wave velocities in rocks with hydrocarbons: Soc. Petr. Eng. Res. Eng., **3**, 429-439.

(a) (b)

Figure 8. InSAR interferograms over a petroleum field in Southern California: (a) measured interferogram; (b) simulated interferogram corresponds to both inflation and subsidence[3].

Future Work:

Future extensions to streamline methodology are varied. Work will continue to represent the effects of gravity and capillarity on multiphase flow and testing to ensure that physics are incorporated accurately. The importance of capillary effects during compositional displacement will also be investigated. Specific work in the area of aquifer sequestration includes development of a phase behavior module accurately honoring the effects of salinity on the solubility of CO_2 in brine, density, and viscosity of brine all as a function of salinity and temperature. Impact of capillary effects on the injection process and the arrangement of CO_2 and brine within the aquifer will also be investigated. Additional work will be done to evaluate computational approaches appropriate to the period after completion of injection. For the relatively slow processes of CO_2 diffusion through brine, the slow gravity overturn that results when dissolved CO_2 increases the density of the brine slightly, and chemical reactions among mineral species, streamline methods are probably not the best choice. A student joining the group in the fall will look at these issues.

We also plan to begin work relevant to sequestration and enhanced gas recovery in coalbeds. One focus area is to continue evaluation of the potential for dual-use enhanced gas recovery and CO_2 sequestration potential in the Powder River basin. This project takes advantage of other Stanford research going on there in collaboration with cooperative operators. Secondly, we have developed an analytical theory for gas injection into coalbeds including adsorption of methane, CO_2, and nitrogen onto coal surfaces[4]. The analytical work will continue and focus on two-phase flow (gas and water) including adsorption and desorption with an arbitrary number of components. This analytical work will lay the underpinnings for future multidimensional streamline calculations. Conceptual and physical models for enhanced gas recovery from coalbeds are incomplete and not well developed. A limited experimental program will be undertaken to complement the analytical calculations. The intent is to provide data to which calculations may be compared. A second aim of the experimental program is to collect data on the mechanical properties of coal as it takes up CO_2. Stress dependent factors, such as permeability and porosity reduction, may be important during CO_2 injection. In this manner, our knowledge of the physics of coalbed methane recovery are expanded.

A comprehensive review of potential depleted oil and gas reservoir in the Gulf of Mexico as potential sites for CO_2 sequestration will begin. This effort will entail development of an appropriate work flow for CO_2 sequestration and engagement of the suite of practical problems that would accompany any effort to evaluate a specific reservoir for this purpose.

In the area of monitoring, we plan to extend the simulation framework began this year and summarized above to incorporate more general models for the pressure dependence of fluid-saturated rock properties. Also, we will add a more accurate model for the complete seismic

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[3]Onn, F., Wynn, D.T., and Zebker, H.A., On the Detectability of Ground Deformation for Monitoring CO2 Sequestration in Underground Reservoirs Using InSAR and GPS: *Eos Trans. AGU, 83*(47), Fall Meet. Suppl., Abstract G61B-0993, 2002.

[4] Zhu, J., K. Jessen, A. R. Kovscek, and F.M. Orr Jr. "Analytical Solutions for Coal-Bed Methane Displacement by Gas Injection, " SPE 75255 Proceedings of the SPE/DOE Thirteenth Symposium on Improved Oil Recovery, Tulsa, OK April 13-17, 2002

response. The other models (electrical, gravity and deformation) will be improved and generalized as well. These improvements will allow a more realistic simulation of the changes associated with CO_2 injection in depleted oil and gas reservoirs and saline aquifers. We plan to develop a rock properties module for the changes in coal properties associated with combined CH_4 production and CO_2 injection. During the upcoming year, we also plan to begin coupled simulation of the combined flow and geophysical responses during injection for various storage scenarios. We will add a statistical description for the saturated rock properties for purposes of estimating uncertainty in simulated responses. We also plan to begin the search for cooperative research activities involving field demonstration of geophysical monitoring methods.

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