

Development of a framework for long-term performance assessment of geologic CO₂ sequestration sites

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Abstract

Long-term performance and risk assessment related to geologic CO₂ storage needs a robust and reliable framework. We have used the science based prediction approach to develop such a framework. The approach couples the fundamental physical and chemical processes to a systems level model. The coupling is achieved by developing probability functions through integration of laboratory/field experiments, numerical simulations and field observations. The framework, known as CO₂-PENS, provides a consistent platform to make decisions during site selection, implementation and post-closure stages of any geologic CO₂ storage operation.

Keywords: CO₂, sequestration, risk, performance assessment, systems model

Introduction

Large-scale implementation of geologic storage of CO₂ will require a large number of suitable storage sites (reservoirs). There is a need for a robust and reliable decision-making framework for evaluating the suitability of specific sites to ensure that they will perform up to required goals as well as to determine the risks associated with long-term storage of CO₂. The method needs to take into account the fundamental physical and chemical interactions resulting due to presence of CO₂ at multiple length and time scales (Figure 1).

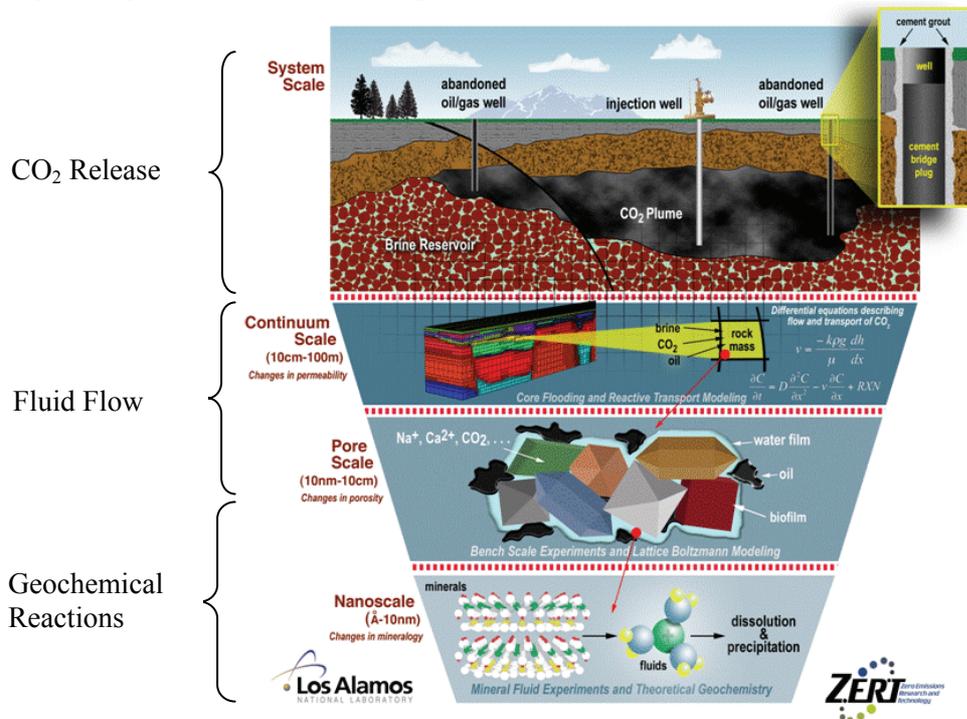


Figure 1. A schematic diagram showing the multiple length scales spanned by processes that control fate of CO₂ in geologic sequestration sites.

The method has to be capable of addressing uncertainties in the reservoir properties and the fundamental processes. In addition, it must link fundamental scientific inputs to decisions based on a required performance goal. The method will need to be both robust and efficient in order to evaluate multiple sites in a timely manner. The former requirement means that the method must be readily adaptable to each considered site and must be capable of addressing *all potential factors* that determine long-term fate of CO₂. The latter requirement means that a valid systematic approach will be required to limit site-specific evaluations to only the *critical factors* for the site (as opposed to all potential factors). As part of the Zero Emissions Research and Technology (ZERT) project at the Los Alamos National Laboratory (LANL), we have developed a framework and a coupled process-systems model based on the framework that can be used to study long-term performance of a wide range of geologic CO₂ storage sites. Both the framework and systems model, known as CO₂-PENS, are developed utilizing the concept of *science-based prediction* to couple process level models to systems models. The CO₂-PENS framework described here is still in preliminary stages of development.

Science based predictions

Science-based prediction links high level systems models, on which decisions can be based, to detailed models of physical and chemical processes by integrating theory, observation, experiment, and simulation [1]. The foundation of predictions is built upon fundamental experimental (laboratory and field), theoretical and computational research into the behavior of individual subsystems and, as appropriate, the coupling between them. For some subsystems, the necessary information can be obtained from experimental data, but most of the complex subsystems involve an iterative approach among experiment, observation, theory and computation. Once an adequate understanding of the important subsystems is gained, the information is synthesized and simplified, accounting for uncertainties, and built into a systems model. The systems model accounts for all the couplings between subsystems and their uncertainties, and produces a probabilistic prediction of the system behavior that can be used for decision-making. The key to the approach is how the transition is made between sub-systems level models and systems level models. For engineered geologic sites, this is done through probability functions that are developed explicitly or implicitly on detailed physics and chemistry. Site specificity is addressed by ensuring that the coupling of all possible performance controlling factors is included while recognizing that site particulars permit only a subset of all possible processes to be investigated in detail. This winnowing of processes is done systematically, providing confidence that the prediction for a site's performance has been comprehensive.

A comprehensive framework

Figure 2 shows an example high level systems model for a CO₂ sequestration project.

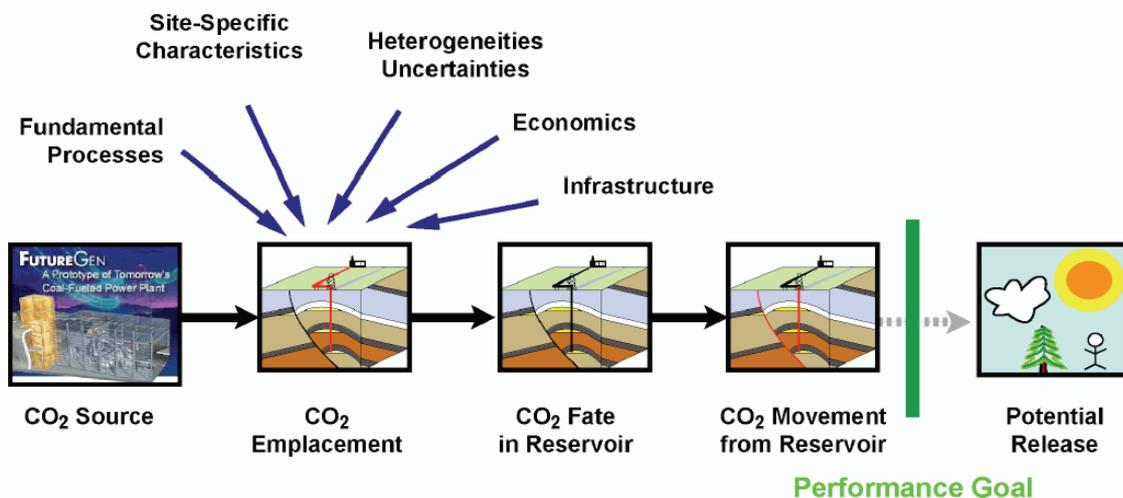


Figure 2. Schematic diagram showing a high level systems model for any CO₂ sequestration project.

A comprehensive model for any CO₂ sequestration project would include all the sub-systems, from the source for CO₂ such as a FutureGen power plant, to the sub-systems affected by potential release of CO₂ such as the terrestrial environment near a geologic repository. Such a model can be used to analyze performance of any site based on any desired metric ranging from economics to health and safety. The sub-systems that make up the model shown in Figure 2 are themselves comprised of sub-systems. These lower level sub-systems can be further sub-divided until the process levels are reached.

The sub-systems which follow the “CO₂ Source” sub-system in Figure 2 represent the geologic repository and the environment in its vicinity. This is the main area of interest for long-term performance and risk assessment. The framework that can be used to study and analyze this area of interest is shown in further details in Figure 3. The main components of this framework include storage reservoirs, seals, potential release mechanisms, CO₂ transport beyond primary storage reservoir and CO₂ release at surface.

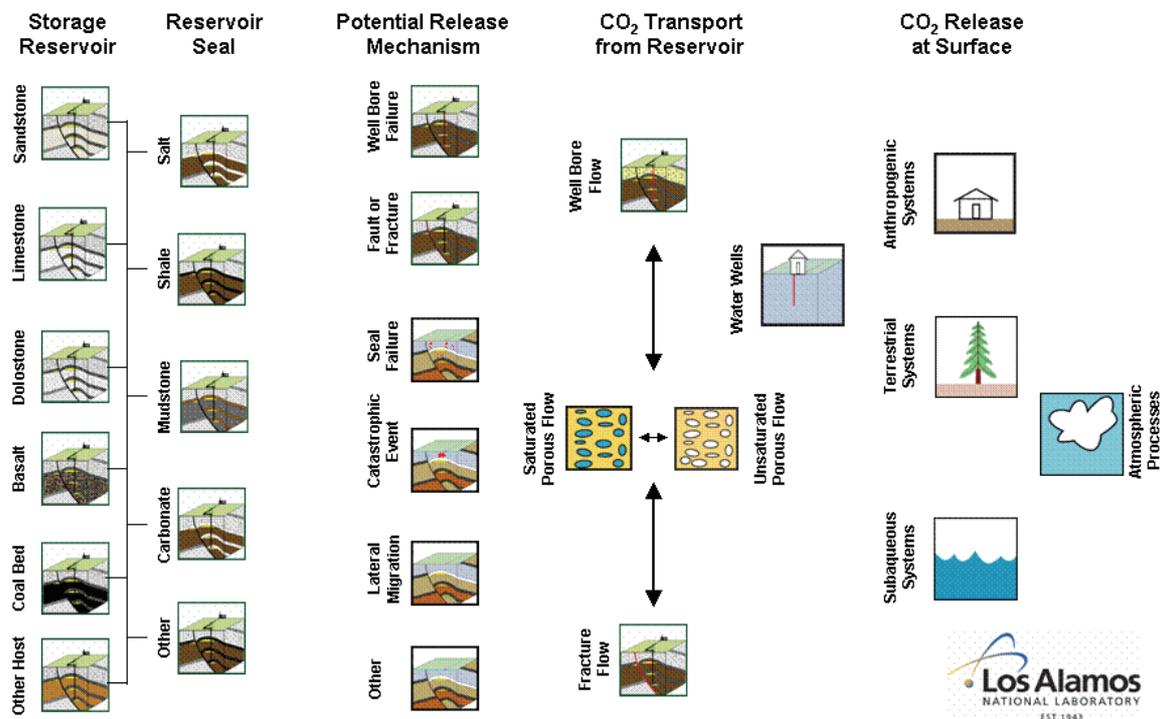


Figure 3. Preliminary framework for assessment of performance of an engineered geologic CO₂ storage site.

The framework shown in Figure 3 can be adapted to take into account different lithologies. The primary storage reservoirs could be sandstone, limestone, dolostone, basalt, or coal beds. The primary seals could be of different lithologies as well, including shale, salt, mudstone, or carbonates. The potential release mechanisms for CO₂ from the primary reservoir include wellbore failure, faults, seal failure, lateral migration or other mechanisms. CO₂ released from the primary storage reservoir could potentially migrate and access different environments including terrestrial and atmospheric systems as well as fresh water aquifers. The approach shown in Figure 3 helps to identify various possible end member sub-systems and the coupling between them. The couplings between the end member sub-systems essentially represent flow between sub-systems. The flow can be flow of CO₂ as well as other fluids or species of interest. This approach is effectively a graphical approach to the features/events/process (FEPs) method that has been demonstrated to be effective in addressing other engineered geologic systems.

The framework described here can be used to predict fate of CO₂ in the reservoir. It can also be

used to determine fate of CO₂ outside the primary reservoir in case of potential release from the reservoir. This provides the flexibility to perform both performance assessment and risk assessment calculations. The framework can be used to answer questions such as what is the ultimate sequestration capacity of the reservoir and what is the total injectivity of the reservoir. It can also be used to answer questions such as what is the probability of a wellbore failure at the sequestration site and in case of failure what are the consequences.

An example of couplings for CO₂ pathways

Figure 4 shows an example of types of couplings that can be established to understand CO₂ flow. The example shown is that for CO₂ flow as a result of a wellbore failure.

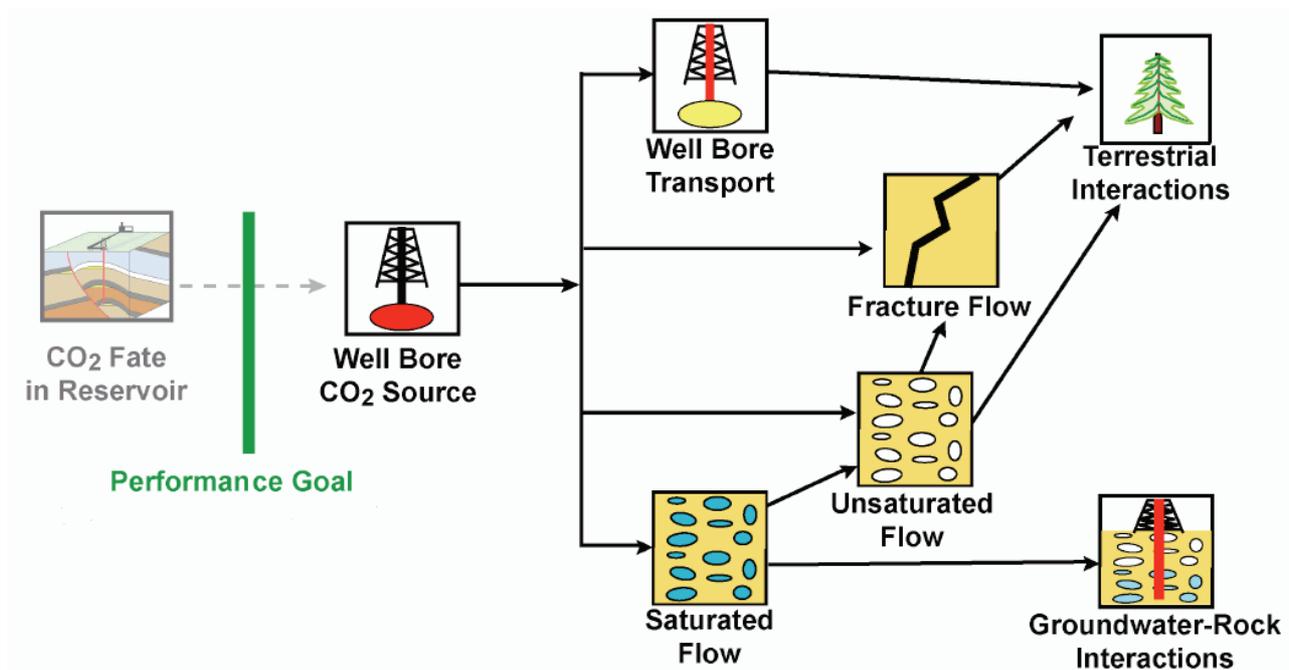


Figure 4. A schematic diagram of a subset of process models underneath high level system models.

Released CO₂ can escape through multiple pathways as demonstrated in the figure. CO₂ can either escape directly through the wellbore to the surface (*wellbore transport*) or it can get to the surface indirectly (*fracture flow*, *saturated flow* or *unsaturated flow*). Ultimately CO₂ can migrate to the terrestrial environment resulting in *terrestrial interactions* or a fresh water aquifer resulting in *groundwater-rock interactions*. These pathways involve many processes, each of which could provide additional levels of containment by inhibiting CO₂ flow. These processes involve linkages that require understanding the many physical and chemical phenomena as a result of CO₂ interaction. These phenomena can be described theoretically, characterized experimentally, and predicted computationally.

Integration to understand fundamental processes

We provide an example of the integration described above, with our on-going research related to cement-CO₂ interactions. In the example shown in Figure 4, the triggering event for CO₂ release is well bore failure. The failure could result as a consequence of various processes, one of which is cement degradation. In order to predict the probability of a well bore failure due to cement degradation it is necessary to characterize interactions between cement and CO₂. We are performing laboratory experiments where cement cores are exposed to CO₂ under different thermodynamic and fluid flow conditions. We are also studying cement samples collected from a well that has been exposed to CO₂ [2]. These samples were collected at one of the CO₂ enhanced oil recovery fields in the Permian basin. The field, SACROC (currently operated by KinderMorgan CO₂ company), is the oldest CO₂ enhanced oil recovery operation in US. These samples are being analyzed using various

analytical techniques to determine possible CO₂-cement interactions at reservoir conditions. Finally, we are also performing detailed reactive transport simulations to match the laboratory experiment results and observations from the field samples. Ultimately, the results of laboratory experiments, analyses of field samples and computational predictions will be used to develop detailed process information for cement-CO₂ interactions. This detailed process information will be linked directly to systems models through probability functions.

Such type of integration can be used to represent all the sub-systems that are part of CO₂-PENS. The systems model resulting from these sub-systems allows a quantitative assessment of the many factors that underpin a decision on a specific engineered geologic site, such as performance, risk, cost, and uncertainties. The science-basis for assessment is addressed by ensuring a direct tie between each of the process modules and fundamental theory and observations as described above. Most current approaches to CO₂ have been focused at either the systems level or the process level, but the coupling between systems level and process level is a critical distinguishing component of CO₂-PENS.

A computational model

Using the framework described above, we have developed a computational model using GoldSim. GoldSim is a commercially available systems modeling package which has been tailored with the unique needs of engineered geologic systems in mind, particularly, uncertainty and heterogeneity. It can be linked directly to process level models such as reactive-transport codes. Figure 5 shows the current version of the systems model developed using GoldSim. Stauffer et al. [3] provides further details about the computational model development process.

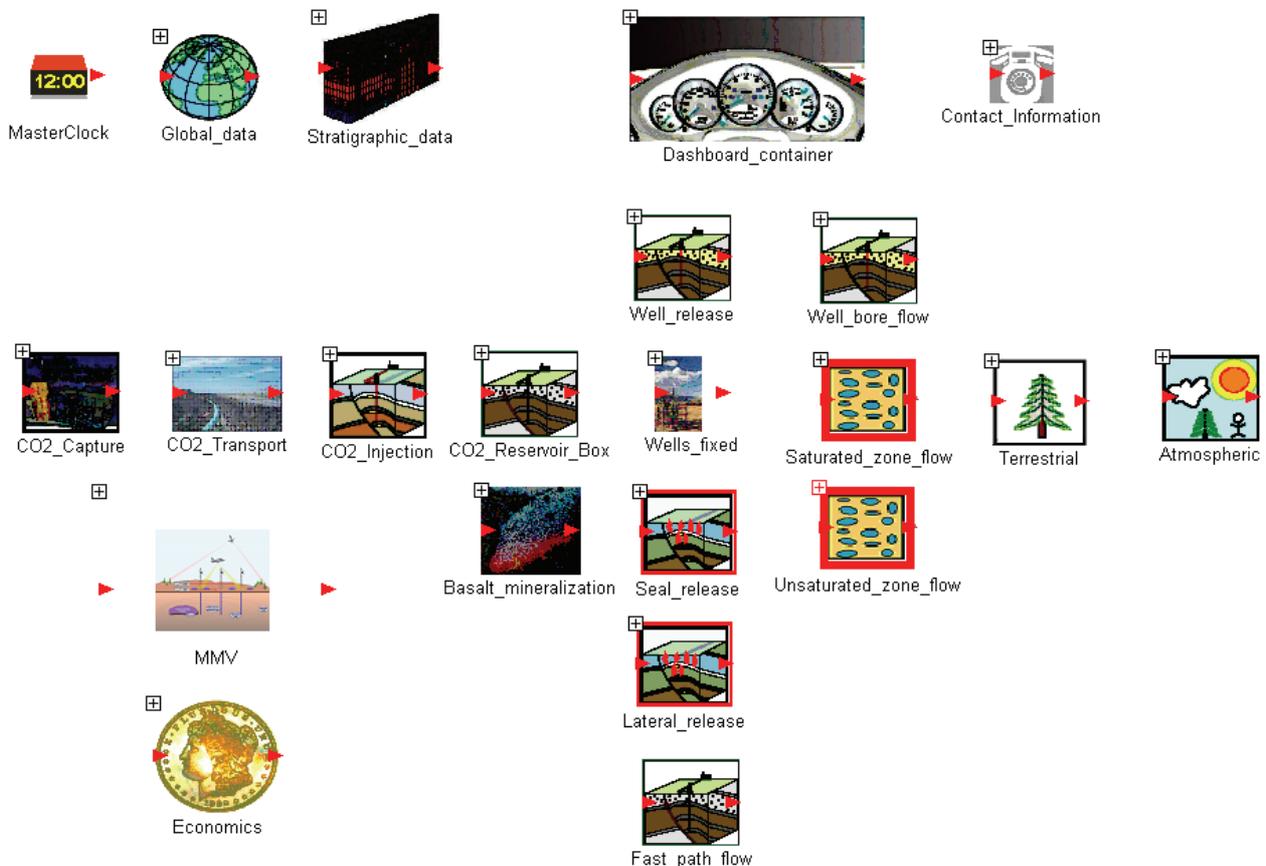


Figure 5. Current version of the GoldSim systems model, CO₂-PENS, developed at LANL.

The various boxes in the model represent various sub-systems shown in Figure 3. As described

earlier the process level details are abstracted within individual boxes either through experimental observations, theoretical models or numerical simulations. Information on parameters including heterogeneity and uncertainty can be input using statistical distributions. This provides the systems model the ability to perform probabilistic predictions.

Measurement/Monitoring/Verification (MMV) and Risk Mitigation

CO₂-PENS framework can easily be used to identify MMV needs as well as applicability of MMV technologies. For example, the analysis of potential CO₂ flow pathways as a result of wellbore failure described earlier can be used to determine where MMV technologies need to be deployed as well as what types of MMV technologies should be deployed for efficient detection. The same analysis can also be used to determine necessity and applicability of various leak mitigation techniques.

Conclusions

We have developed a systems level model that can be used to evaluate suitability of specific geologic sites for long-term storage of CO₂. The model is based on a framework, which is being developed using science based prediction approach. This approach couples systems level models to the physical and chemical processes by integrating theory, observations, experiments and simulations. The model can be applied to evaluate performance of a storage site against any required metrics. It can be applied to answer site operation-specific questions such as total sequestration capacity, injectivity as well as risk-specific questions such as consequences of CO₂ release due to wellbore failure.

Acknowledgements

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