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Quantifying the Isolation Performance of Geologic CO_2 Storage Through Technology Integration

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Successful geologic storage of anthropogenic CO_2 requires the ability to match waste-stream and injection-site characteristics such that requisite isolation performance is predicted by advanced reactive transport models. Then, site characteristics, modeling results, and CO_2 imaging/sampling techniques must be matched such that predicted performance can be verified by comprehensive monitoring programs. Here, the injection site is taken to include the target reservoir, seal, localized wellbore environment, and overburden, while its characteristics encompass myriad hydrological, compositional, geomechanical, dimensional, and structural properties. Key waste-stream characteristics include projected incremental and cumulative flux, impurity compositions and concentrations, and the number and spacing of injection wells. "Requisite" isolation performance refers to that which satisfies all operational, economic, and regulatory requirements within acceptable uncertainty bounds. The technology portfolio required to forecast and verify such performance necessarily integrates modeling, monitoring, site characterization, and laboratory experimental elements.

Extending CO_2-flood operations from dedicated EOR to EOR explicitly coupled with CO_2 storage to CO_2 isolation within saline aquifers involves significant paradigm shifts and technical challenges for the oil field services industry. The shifts involve economic blueprint, CO_2 source and recycling, characterization and monitoring responsibility, performance criteria, and uncertainty magnitude. The challenges focus on incorporating into modeling tools explicit account of CO_2 impurities, fluid-rock interactions, and coupled geochemical/geomechanical effects, refining techniques for reservoir and site characterization, developing novel detection methods for CO_2 monitoring, and quantifying prediction and measurement uncertainty.

Reactive transport modeling, an advanced computational method that integrates the operative processes of multiphase flow, geochemical mass transfer, and geomechanical deformation, provides new insights into the four fundamental components of isolation performance: capacity, footprint, containment, and risk, the latter of which denotes uncertainty bounds on the former three. In particular, modeling studies of this kind have been used to illustrate the dependence of incremental capacity (injectivity) and cumulative storage potential on key reservoir properties; to elucidate the dynamics of CO_2 mass partitioning among hydrodynamic, solubility, and mineral trapping mechanisms; to demonstrate the dependence of seal integrity on concomitant geochemical and geomechanical processes; and to delineate characteristic variations in partitioning and seal integrity evolution that distinguish typical EOR and saline aquifer settings. These variations suggest that optimal long-term isolation performance will be obtained in structurally open reservoirs, where the injection-induced pressure perturbation and the ultimate mass ratio of hydrodynamic to chemical/residual trapping are both minimized.

Fundamental challenges to future modeling efforts focus on identifying key screening criteria that will facilitate optimal source/sink matching, and on quantifying and reducing the uncertainties that surround such predictions. To meet these challenges, we must complete rigorous parametric sensitivity studies, construct robust uncertainty propagation algorithms, and develop improved process models, process coupling, site-independent data, and geostatistical site characterization techniques. Next-generation modeling work will exploit advanced stochastic inversion methodologies that facilitate explicit integration and iterative refinement of performance prediction, monitoring, and site characterization efforts.