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Final Report for Phase I Northern California CO2 Reduction Project

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Final Report

for

Phase I

Northern California CO_2 Reduction Project

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Introduction

On June 8, 2009, the U. S. Department of Energy's National Energy Technology Laboratory released a Funding Opportunity Announcement (DE-FOA 0000015) with the title, *Recovery Act: Carbon Capture and Sequestration from Industrial Sources and Innovative Concepts for Beneficial CO2 Use*.

C6 Resources (C6), an affiliate of Shell Oil Company, responded with a proposal for Technology Area 1: Large-scale industrial carbon capture and sequestration (CCS) projects from industrial sources. As DOE Federally Funded Research and Development Center (FFRDC) Contractors, Lawrence Livermore National Laboratory (LBNL) and Lawrence Berkeley National Laboratory (LLNL) proposed to collaborate with C6 and perform technical tasks, which C6 included in the C6 proposal, titled the *Northern California CO_2 Reduction Project*. The proposal was accepted for Phase I funding and C6 received DOE Award DE-FE0002042. LLNL and LBNL each received Phase I funding of $200,000, directly from DOE.

The essential task of Phase I was to prepare a proposal for Phase II, which would be a five-year, detailed technical proposal, budget, and schedule for a complete carbon capture, transportation, and geologic storage project, with the objective of starting the injection of 1 million tons per year of industrial CO_2 by the end of FY2015. LLNL and LBNL developed technical proposals (and DOE Field Work Proposals [FWPs]) for many aspects of the geologic testing and CO_2 monitoring that were included in the C6 Phase II proposal, which C6 submitted by the deadline of April 16, 2010.

This document is the Final Report for LLNL's Phase I efforts and is presented in two parts:

Part 1 is the complete text of the technical proposal provided to C6 by LLNL and LBNL for inclusion in the C6 Phase II proposal. Because of space limitations, however, C6 may not have included all of this information in their proposal. In addition to developing the proposal presented below, LLNL's Bill Foxall and Laura Chiarmonte, in collaboration with LBNL, undertook preliminary technical work evaluating the potential for induced seismicity in Solano County.

Part 2 presents technical work preformed during Phase I in the development of a preliminary Certification Framework: Leakage Risk Assessment for CO_2 Injection at the Montezuma Hills Site, Solano County, California, co-authored by LLNL and LBNL collaborators.

Part 1

Technical Tasks Proposed by Lawrence Livermore National Laboratory and Lawrence Berkeley National Laboratory for Phase II of the Northern California CO_2 Reduction Project

The following Table of Contents is from the Project Narrative section of the C6 Resources Phase II proposal for the Northern California CO2 Reduction Project. LLNL and LBNL submitted to C6 Resources for inclusion in their proposal, the technical task descriptions for sections shown in ***bold italics***, which are included in this document. The proposed technical task descriptions were prepared by the following earth scientists at Lawrence livermore National Laboratory and Lawrence Berkeley National Laboratory:

LLNL:
Elizabeth Burton William Foxall Jeff Wagoner Laura Chiaramonte

LBNL:
Jonathan Ajo-Franklin Preston Jordan Curtis Oldenburg John Henry Beyer Mack Kennedy Karsten Pruess Jens Birkholzer Kevin Knauss Jonny Rutqvist John Christensen Tim Kneafsey Eric Sonnenthal Mark Conrad Jennifer Lewicki Nic Spycher Tom Daley Alberto Mazzoldi Donald Vasco Barry Freifeld Seiji Nakagawa Quanlin Zhou

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Technical Task Descriptions

1 SITE CHARACTERIZATION

1.2 Modeling for Capacity, Injectivity, and Containment

1.2.6 Regional Geologic Model

The regional geologic model will be used to study the large-scale pressure response and brine migration issues. It will also be used, as appropriate, in the seismic risk assessment.

A three-dimensional (3D) geomodel is requisite to establishing a framework for any dynamic modeling. Fundamental to geologic characterization is the integration of spatial geologic information, such as stratigraphy, lithology, structure, and rock physical properties. Historically, geoscientists have generally relied on two-dimensional (2D) visualizations for analyzing geological data, but because of the complexity of spatial relationships, a digital 3D model is better suited for integrating different types of data and providing a more realistic geologic characterization of a site. Being able to easily manipulate a large, complex data set provides the geoscientist with the opportunity to detect and visually analyze the spatially correlated data, which leads to an increased understanding of the subsurface.

3D geologic models can be regional in scale, covering thousands of square kilometers, or local. Regional-scale models remain somewhat limited in their development, due in part to the challenges presented by construction of high-resolution grids that are based on sparse structural, lithologic, and stratigraphic data. Smaller, site-specific 3D models can be well constrained in areas where seismic and borehole data are available. Digital models can be continuously revised and updated as new data are acquired or as the interpretative understanding of the geology evolves.

Map-derived data, along with geophysical, borehole and other data, will be assembled into a realistic 3D model as a set of surfaces, with the volumes defined by those surfaces. Faults are represented by 2D grids, which intersect and displace the volumes. This type of geologic framework is critical to the understanding and identification of faults, fracture zones, and facies changes in the caprock, reservoir, and time-equivalent deposits in the surrounding basin.

There are two important types of geologic model that will be developed to characterize the CO2 sequestration site. For the initial model a framework of time-stratigraphic layers will be constructed. These stratigraphic units are generally “named” formations, many of which can be laterally extensive across entire basins. The second type of model will be the lithofacies model, in which lithologies are modeled within the stratigraphic framework. Detailed lithologic analysis is done by interpretation of downhole geophysical logs. These models are particularly important because the lithology of the major stratigraphic units can vary significantly, and it is the lithology that generally determines the physical properties of the rock. These geologic framework and lithofacies models will provide a realistic basis for subsequent subsurface flow simulations.

The process of building a model involves a number of steps. The first step is to define the node structure to create a topographic surface. The free surface is generally based on a 10-30 m lateral resolution DEM, which is converted to a 2D grid within Earthvision. Stratigraphic tops for all of the major stratigraphic units are collected and digitized. These data are then converted to elevation, and 2D grids are generated for the top of each mappable unit. Finally, the fault traces are digitized from hardcopy maps. Using an assumed dip and the digitized trace, a 2D grid (xyz) is generated for each fault surface.

The regional geologic model will support the dynamic modeling described below, and relevant aspects of the risk assessment and risk management plan. The size of the model must be fit for purpose. Based on prior research (Birkholzer and Zhou, 2009; Zhou et al., 2010), Lawrence Berkeley National Laboratory (LBNL) suggests that the static geomodel required for evaluation of large-scale pressure response and brine displacement may range out to tens of kilometers from the injection point. The black rectangle in Figure 1.2.6-1 shows the range of such a model (66 x 82 km). The regional model will include all of the data from outcrops of the reservoir rocks. These are located to the west and to the south of the injection point. The model will extend at least east of the Midland Fault, while the northern extent will depend to some extent on what is learned about geologic trends and other uses of the subsurface as the geomodel model is developed.

To create a model of this size, we will leverage not only the work done by C6 Resources, but also other 3D models generated for the San Francisco Bay Area (LLNL, USGS, etc.). Much of the geologic information integrated into this model will be defined by borehole contacts from the oil and gas industry, available from the California Division of Oil and Gas and Geothermal Resources and C6 Resources. Geologic information is available primarily for the oil and gas fields and from wildcat exploration wells that were drilled prior to 1980. C6 Resources will provide some of the technical data for this modeling effort, including well locations, tops of stratigraphic units, fault locations, geophysical logs, and detailed interpretations of legacy 2D seismic lines. C6 Resources also will provide access to their smaller range geologic model that has been constructed using Petrel software. C6 Resources personnel have also offered to peer-review and collaborate on the regional model.

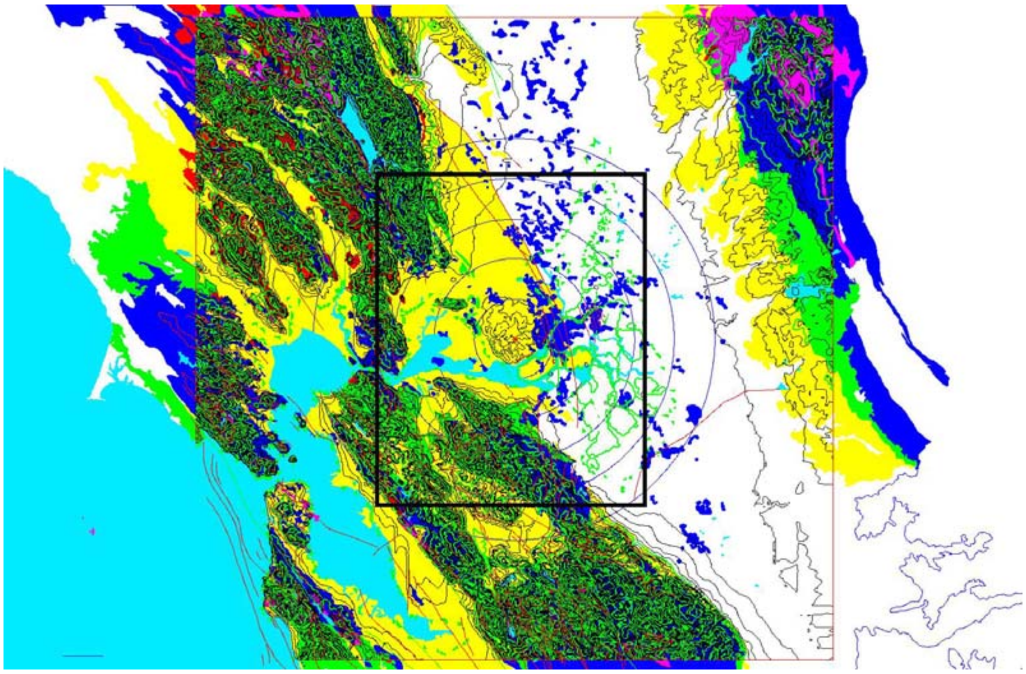

Figure 1.2.6-1. Geologic map centered on the project site. Rectangle is 66 x 82 km, the approximate size of the initial large-scale geologic model. Circles increase in radius by 10 km.

Map key: white and yellow = alluvium/basin fill
various colors = Tertiary through Paleozoic rocks
pink = granitic basement

1.2.7 Regional Hydrogeologic Dynamic Model

Objective

Using a regional 3d geologic model developed by LLNL, LBNL will develop a high-performance regional-scale simulation model, complemented by a suite of specialized “detailed process models”, to conduct predictive simulations of CO2 flow, pressure propagation, and brine migration in response to CO2 injection at the Montezuma Hills site. The purpose of these models is to (1) determine the distribution, migration, and long term fate of the CO2 plume and (2) evaluate the pressure perturbation and brine migration effect in the surrounding area at the basin scale. The regional-scale model will provide the framework for integrated analysis of various sets of data as they are acquired, and will be updated, expanded, and refined on an ongoing basis throughout the project duration. The model will also form the basis for developing a coupled hydro-geomechanical model addressing induced seismicity concerns (Section 1.2.9) as well as a coupled hydro-geochemical (reactive transport) model assessing the geochemical behavior of the natural system (Section 1.2.8), CO2 plume migration, and hypothetical CO2 leak scenarios potentially affecting shallow groundwater. LBNL will integrate in this model all geologic and hydrologic site data made available by C6 Resources (near-field geomodel and data assessment in the Montezuma Hills area) and the Lawrence Livermore National Laboratory (LLNL) large-scale geomodel and data assessment (Section 1.2.6). LBNL will also review additional data sources, such as from the WESTCARB Phase II Pilot test, nearby gas storage operations, groundwater pumping, and naturally occurring events (groundwater recharge and gas trapping), and include in the model setup, if useful.

In addition to the regional-scale 3D model, LBNL will develop a flexible “tool box” of specialized “detailed process models” (DPMs) for near-field aspects, for which the regional-scale model would provide adequate boundary conditions. These DPMs will feature increased resolution over limited spatial scale and include coupling between different process aspects. Together, high-performance regional-scale model and the detailed process models will be utilized over a wide range of scales, from the near-field area (up to 5 miles radius) for detailed CO2 plume behavior and reservoir performance analysis, to the far-field area (up to 30 miles radius) for pressure perturbation and potential seismicity/groundwater impacts.

Motivation for Developing a Regional-Scale Hydrogeologic Model

Industrial-scale injection of CO2 into saline formations in sedimentary basins will cause significant fluid pressurization and migration of native brines. Such pressure changes may induce seismicity (Section 1.2.9) may affect oil and gas operations, and may have environmental impact on shallow groundwater resources. These impacts may limit the storage capacity of the suitable sandstone formations for geologic sequestration. It is critical to understand the large-scale pressurization in a faulted, compartmentalized system for project design and operation. Existing faults near the injection location include the Kirby Hills Fault and the Midland Fault; these are likely sealing faults.

Shallow groundwater resources may be affected by displaced brine if, for example, high-permeability pathways such as conductive faults provide conduits for brine flow into overlying formations. Groundwater resources may also be affected if injection occurs in the deep portion of a reservoir that forms a freshwater aquifer further up dip. This is the case for some of the deep sands considered for CO2 injection, as evidenced by outcrops of the Domengine and Hamilton sands about 10-15 miles away from the injection site. The area affected by pressure propagation can be extremely large, as shown by Birkholzer and Zhou (2009) and Zhou et al. (2010) for a CO2 storage scenario in the Illinois Basin. However, the faulted, compartmentalized geology of the Sacramento Basin will likely confine pressure effects to a much smaller area than in the expansive Illinois Basin.

Other examples of areas that could be affected include the Rio Vista Gas Field to the east and the Kirby Hills Gas Storage Field to the west. The potential Montezuma Hills CO2 injection well lies within ten miles of the Rio Vista Gas Field (largest onshore natural gas field in California) and other significant gas reservoirs. Primary production in the Rio Vista Gas Field has been from the Domengine at depths of 4,500 feet (1,400 m), but there has been production from sands below this to depths of 7,000-10,000 feet (2,100-3,000 m). Gas production for over 60 years has left the Rio Vista reservoirs highly depleted. The target reservoir formation is the Anderson Sandstone at a depth of about 11,000 feet (3350 m) at the proposed well site. However, the synclinal structure and related normal faulting results in the Anderson Sand occurring at depths as shallow as 6,000 feet (1,800 m) at the Rio Vista Gas Field. Given the large volumes of CO2 that may be injected and the potential hydraulic connectivity of the Anderson and other sands between the injection location and the Rio Vista Gas Field, it is of interest to investigate impacts to the gas reservoirs at Rio Vista resulting from large-scale CO2 injection approximately ten miles away.

The regional-scale model will be utilized to evaluate the various issues discussed above during the project development phase (FY11 through FY15) prior to the operational phase (starting FY16). Modeling results will help the design of the Northern California CO2 Reduction Project in terms of storage capacity (for 30 year industrial-scale CO2 injection) which may be limited by various constraints. These results will also inform the design of a large-scale monitoring program, and may provide the technical basis for interactions with regulators and the public. Keeping in mind that the several other capture opportunities within a 20-miles-radius from the Shell Martinez refinery, the model will be built such that it can evaluate and optimize the combined impact of other potential storage projects in the area.

Motivation for Conducting Detailed Process Modeling

The regional-scale dynamic 3D model is the overarching framework that will integrate and focus many of the other activities in the project. However, using the regional-scale model for near-field (CO2 plume-related) processes would be computationally burdensome, and for some process aspects would likely entail significant compromise in accuracy, even with locally refined gridding. Therefore we will develop a “tool box” of additional “detailed process models” (DPMs). These models will feature increased resolution over limited spatial scale and include various types of coupling. DPMs will honor geologic features of the regional-scale model, and an array of different DPMs will be developed that are tailored towards different objectives. Objectives driving the development of DPMs include the following:

-hydrologic site characterization prior to CO2 injection (permeability-thickness, storativity, properties of faults);

-high-resolution modeling of CO2 plume migration, in support of design and placement of monitoring wells and non-invasive monitoring methods;

-design and analysis of tests (including single- and two-phase pressure transients tests, and tracer tests using natural and artificial phase-partitioning tracers and isotopes);
-coupling of processes across multiple scales (such as convectively-enhanced dissolution);

-analysis of coupled geomechanical processes, including potential for inducing movement along faults and associated microseismicity ;

-analysis of chemical interactions between fluids and rocks, including potential for mobilization of contaminants.

Specialized sub-models can minimize numerical errors from coarse gridding and can provide a more effective and accurate representation of multi-scale processes. Such models are needed in connection with hydrologic testing for site characterization, and also in support of monitoring during the early period of CO2 injection, during which CO2 will be confined within relatively small distances from the injection well(s).

The regional-scale model will provide the overall structure and specific boundary conditions for smaller-scale DPMs. While the large-scale 3D model starts from geology and moves towards flow simulation, the development of DPMs will move in the opposite direction. Process modeling will start from smaller-scale and highly spatially-resolved but simplified geometric descriptions, and will emphasize issues of fluid dynamics, and test design and analysis. Geometry and gridding of the local models will be based on the regional-scale model, and geologic detail will be introduced in stepwise fashion as needed to address important questions of system performance.

Parameterization of the models will use information from nearby analog sites, from hydrologic testing, and from core flood experiments. We envision a process of iterative refinements where model calibrations would be “traded” between local and regional models in both directions (up-scaling: small scale to large, and downscaling: large scale to small).

An important issue in the proposed CO2 injection project is the potential compartmentalization of the reservoir. Pressurization effects from large-scale CO2 injection may strongly depend on the transmissivity of nearby faults. Such pressurization effects would determine the likelihood of inducing movement along the faults, with a potential for microseismic activity and leakage. Because of the great practical importance of these issues, we propose a campaign of pressure-transient testing to resolve issues of fault transmissivity. The tests will involve water injection at time-varying rates over periods of a few days, with pressure monitoring at the injection well and also at laterally offset observation wells. Test designs will be developed and optimized through detailed process modeling, taking into account known parameters and conditions at the site, as well as uncertainties.

Another objective with DPM is to adequately resolve process aspects that within a large-scale 3D model can only be addressed in a very approximate way. These include (1) plume geometry and utilization of subsurface space, (2) potential for CO2 migration along localized preferential pathways and into caprocks, (3) convectively enhanced dissolution of CO2, (4) hysteretic behavior of relative permeabilities and capillary pressures, and (5) behavior of natural and artificial tracers. Items (1) through (4) involve strong coupling across scales, requiring multi-resolution approaches to modeling. In (5), phase-partitioning of tracers can produce sharp concentration gradients. For example, when gases of lower aqueous solubility are co-injected with CO2, their concentrations are expected to increase to large values at the leading tip of the CO2 plume. In the Frio test, less soluble noble gases were indeed seen to break through at the observation well more rapidly than less soluble ones.

The information gained through DPM will be transferred back into the large-scale 3D model. This may occur in a number of different ways, including (1) establishing scale dependence of model parameters and making appropriate parameter adjustments, (2) incorporating sub-gridscale models for processes not modeled explicitly, and (3) local grid refinement for an explicit representation of process detail.

Scope of Work

Model Development Phase Model development will be conducted in close collaboration with C6 Resources and LLNL. With input provided by C6 Resources and LLNL, LBNL will review all available geologic field data and other relevant model parameters for the simulation models. Based on preliminary literature and data review and scoping simulations, LBNL, LLNL and C6 Resources will determine the appropriate domain size of the regional-scale simulation model. The preliminary data review will include a lateral extent as much as 30 miles from injection center.

> -For the chosen domain size, develop a detailed static geomodel incorporating the sequence of stratigraphic layers based on existing well data and seismic surveys (LLNL is expected to play a key role in developing this geomodel).
>
> -Include in the geomodel, aquifer salinity throughout, and gas-reservoir fluid composition and pressure for areas of natural gas production, as well as temperature variation.
>
> -Develop a high-performance large-scale simulation model with adequate far-field boundary conditions and appropriate refinement around the projected plume area and known faults.
>
> -Parameterize the model based on existing well data and other geologic and hydrologic information.

-Develop smaller-scale high-resolution DPMs as needed.

-Analyze the system response observed for existing geo-activities (e.g., gas storage and production) and naturally occurring events (groundwater recharge and water compositions) to infer the nature of sealing or leakage of individual faults and across-formation hydraulic communication at a large scale. This will help understand to what degree the system is compartmentalized by faulting.

-Explore and test high-performance computational options available at the super-computer center at LBNL (NERSC).

-Perform preliminary simulations to explore the fate of CO2 in the storage formation and to predict pressure response and brine migration.

-Use the preliminary models to inform the MVA plan development.

-Feed the preliminary models and results into the coupled hydro-geochemical and coupled hydro-geomechanical models

<u>Model Refinement and Calibration Phase</u> The large-scale and detailed process models will be updated, expanded, and refined on an ongoing basis throughout the project duration as various sets of data become available. In 2011, site-specific data will be available from the WESTCARB pilot project: two deep wells with cores from multiple sandstones and shales, logs, water and CO2 injection results, U-tube samples of formation fluids and CO2, cross-well and VSP seismic, surface seismic monitoring, and core flooding experiments. Up to four more wells may be drilled during the last two years of the project for coring, logging, water sampling, and water injection. Results from the small-scale WESTCARB pilot injection will be extremely useful for calibrating the near-field properties of the model, but will not inform the far-field aspects relevant for pressure perturbation and potential seismicity/groundwater impacts. Other calibration options will be explored, such as water injection tests and pressure monitoring, or evaluation of pressure response due to nearby gas storage field activity.

References

Birkholzer, J. T., Zhou, Q., 2009, Basin-scale hydrogeologic impacts of CO2 storage: Capacity and regulatory implications, *International Journal of Greenhouse Gas Control* 3 (6), 745–756.

Zhou, Q., J.T. Birkholzer, E. Mehnert, Y.F. Lin, K. Zhang, 2010. Modeling basin- and plume-scale processes of CO2 storage for full-scale deployment, *Ground Water*, DOI: 10.1111/j.1745-6584.2009.00657.x (in press)

1.2.10 Seismic Wave Propagation Risk Assessment

The proposed C6 Resources carbon storage site is located within the Pacific-North American tectonic plate boundary zone, a region of high seismic activity. Therefore, the site is exposed to significant hazard from naturally-occurring tectonic earthquakes, to which may be added a potential hazard from earthquakes induced by CO2 injection itself. Hazard in this context is defined as the exposure of the site to seismic shaking, expressed as the annual probability of exceeding a given level of ground motion (acceleration or velocity). Seismic risk includes the consequences of the ground shaking, given the hazard. Fault rupture hazard is similarly defined.

Site-specific probabilistic seismic hazard analysis (PSHA) is used to estimate the exceedance probabilities by combining the frequencies of occurrence of earthquakes in the magnitude range that can be generated by faults in the vicinity of the site with relationships that describe the attenuation of ground motion with distance from the source.

The probability of well-designed and properly monitored injection activities inducing damaging (say M>5) earthquakes is generally considered to be very low, but cannot be neglected in a full risk analysis. Public perception of the risks from induced earthquakes, however, is of particular concern to the planning and operation of a CCS facility. Small (M<4) induced events occurring at typical reservoir depths of 1-3 km can be felt over a limited area on the Earth's surface. This can be both annoying and alarming to local residents, but such events usually do not contribute to the overall seismic hazard. This is because the ground motion from a shallow, small event is concentrated in a sharp acceleration spike, the frequency content of which is well above the frequencies (typically ~1-10 Hz) that cause damage to structures.

In collaboration with LBNL, LLNL will develop risk assessment approaches to include induced earthquakes for the project site. This will provide estimates of the total induced seismicity hazard to the facility and the surrounding area, while enabling the contributions from naturally occurring and induced earthquakes to be separated. Therefore, it will be possible to estimate the extent to which induced seismicity changes the overall hazard. Development of the PSHA method will leverage work already in progress under DOE's CCS National Risk Assessment Program and the DOE Geothermal program.

The PSHA method will combine empirical and physics-based approaches. The empirical component will examine existing research results and new microseismic data from CO2 projects and injection operations in geothermal and oil and gas fields to develop frequency-magnitude relationships for induced events in analogous geological and tectonic settings. These relationships can be incorporated in conventional PSHA formulations directly. It may also be possible to constrain more specific time-dependent behavior, in which case recently developed time-dependent PSHA approaches can be modified to include the induced contribution.

The physics-based component will be based on coupled fluid flow and geomechanical simulations carried out by LLNL within the field-scale geological model in collaboration with LBNL. The simulations will model the evolution of pore pressure within active and potentially active fault zones and perturbations to the *in situ* tectonic stress field. The resulting effective confining (normal) and shear stresses on faults will then be used in a frictional constitutive model to simulate the triggering of fault slip events. Frequency distributions of earthquake magnitude and seismic moment for input to PSHA will be generated by simulating the dynamic fault rupture of each of the triggered events to calculate rupture area and stress drop.

Deterministic ground motions at the site and throughout the surrounding area will be estimated by propagating the seismic waves generated by the dynamic rupture simulations through the field-scale and regional geologic models using LLNL's finite difference seismic wave propagation code, WPP. Ground motions will also be calculated from prescribed larger magnitude scenario events placed on the local faults. These finite difference calculations can be used both in physics-based hazard estimation and to calibrate the ground motion relations used in conventional PSHA for specific source-site path conditions.

LLNL will use microseismic monitoring carried out by LBNL to evaluate growth of the pressure front and the evolution of stress conditions within and surrounding the reservoir. The coupled geomechanical, dynamic rupture, and wave propagation modeling described above will also be used to facilitate interpretation of the recorded microseismic data by detailed investigation of the locations and mechanics of the events and the causative stress conditions.

The results of this work will then be used to determine if a physics-based and/or empirical time-dependent PSHA can be used to develop a seismic mitigation strategy based on the frequency-magnitude characteristics and locations (with respect to active and potentially active faults) of recorded earthquakes.

1.2.11 Certification Framework for Leakage Risk Assessment

Because geological carbon sequestration (GCS) is not widely carried out either in the U.S. or abroad, there is very little experience upon which to base estimates of performance of GCS systems. In the absence of a long track record, leakage risk assessment methods are needed to address concerns by the various stakeholders about the effectiveness of CO2 trapping and the environmental impacts resulting from CO2 injection. For the last two years, investigators at LBNL, The University of Texas at Austin, and the Texas Bureau of Economic Geology have been developing a framework called the Certification Framework (CF) for estimating CO2 and brine leakage risk for GCS sites (Oldenburg et al., 2009). Risk assessment methods such as the CF rely on site characterization, predictive models, and various methods of addressing uncertainty that is inherent in subsurface systems. LLNL has co-authored the following report:

Oldenburg, C. M., Jordan, P., Mazzoldi, A., Wagoner, J. L., Bryant, S. L., and Nicot, J-P., Certification Framework – Leakage risk assessment for CO2 injection at the Montezuma Hills site, Solano County, California, May 26, 2010.