Development of real time geophysical data acquisition and processing toolbox to monitor flood performance

Quarterly Progress Report

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Disclaimer

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Executive Summary

Sky Research , Inc. is engaged in a project funded by the National Energy Technology Laboratory, Strategic Center for Natural Gas and Oil in the U.S. Department of Energy to develop and validate novel non-invasive methods to monitor and quantify CO2 EOR flood performance.

The project is divided into three research phases corresponding to the three budget periods. The emphasis in Phase I (Budget Period: February 1, 2011 through February 1, 2012) is on site selection, numerical modeling of CO2 EOR flooring and associated expected geophysical signatures for a number of different geophysical sensing modalities for selected sites, and on sensing modality selection. The emphasis in Phase II (Budget period: February 1, 2012 through February 1, 2013) will be on sensing system assembly and testing and on inverse method development. The emphasis in Phase III (Budget period: February 1, 2013 through February 1, 2014) will be on the system field deployment on a selected site and on the interpretation of the field data. This report covers the second quarter of Phase II

A literature review comparing the potential approaches for in situ geophysical monitoring was completed in Phase I of this project. This review will be thoroughly updated by December 15, 2012 to provide detailed technical justification for the choice of an EM monitoring system.

A conference call with DOE in mid December 2012, will be initiated by SKY, to discuss completion of 2 Decision Points and the updated literature review findings as discussed above. There are two decision points at the end of Phase 2 that will be successfully completed before proceeding with Phase 3 proposed work. These decision points will ensure that the project team has demonstrated the technical readiness to proceed to Phase 3 monitoring and evaluating of CO2 flood performance at Yates field in Texas. The two decision points are:

- ***Decision point 1***: This is a decision point at which SKY will decide whether the SKY acquisition hardware provides sufficient data quality and whether they can process this data. If they conclude this is not the case, they shall confer with the DOE program manager on how to re-scope their effort or whether to terminate the project.
    - **Status: Go/No Go:** In Jan 2013 the prototype instrument construction and testing will be completed.
- ***Decision point 2:*** This is a decision point at which point SKY will decide whether they can process and interpret any useable field data at the sites available to us. Based on this decision they may postpone or cancel field efforts until a better candidate site comes along.
    - **Status: Go/No Go:** Numerical studies of the Yates site indicate that they will be able to interpret borehole-borehole data for reservoir imaging. Flow modeling and EM imaging have produced good results.

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1 Introduction

1.1 Background

Sky Research, Inc. is engaged in a project funded by the National Energy Technology Laboratory, Strategic Center for Natural Gas and Oil in the U.S. Department of Energy to develop and validate novel non invasive methods to monitor and quantify CO2 EOR flood performance.

The motivation for this project is the need for next generation imaging capabilities of CO2 EOR floods. Specifically, such imaging capabilities should allow companies involved in CO2 EOR the capability to obtain timely and actionable information about CO2 EOR floods which would allow for the optimization of such floods through injection parameter tuning. The ability to optimize floods is expected to increase the number of sites at which CO2 EOR can be economically applied, and thus result in increases in (and reduction in the cost of) tertiary oil production.

1.2 Scope of Work

The scope of the project is the design, development and validation of a CO2 mapping and monitoring system consisting of a geophysical sensing system and a suite of advanced data analysis algorithms. Specifically, Sky will deliver:

- **A field-tested, cross-borehole, time-domain electromagnetic system employing vector component receivers to measure all components of induced secondary magnetic fields.** The additional vector components produce more informative data that allow for more advanced data interpretation techniques, resulting in more accurate mapping and imaging.
- **Advanced EM data interpretation and imaging techniques.** SKY will test algorithms that directly couple the estimation of three-dimensional electrical conductivity and CO2 saturation

This EM system will map and monitor the injection of CO_2 in a reservoir during enhanced oil recovery (EOR). The output of the data processing (changes in physical properties estimated via the geophysical inversion) will be coupled to multi-phase flow models to provide for estimates of CO_2 flooding performance.

There are three phases of research in this project: Phase 1 (system design), Phase 2 (system construction) and Phase 3 (system field testing). These phases generally correspond to the three years of the project. The project started on February 1, 2011, and this report covers the second quarter of phase 2.

2 Progress of work

2.1 Site selection

Partnerships were discussed academia and industry to explore the potential of monitoring at sites where

CO2 EOR is either ongoing or planned. Sites included SACROC, the Citronella field in Alabama, Chaparral Energy's North Burbank Unit site (NE OK) and multiple sites in the Permian Basin. Several of these operators are interested in the technology.

An agreement was obtained in September 2011 with Kinder Morgan under which Kinder Morgan provided data on two fields (Katz and Yates) where CO2 EOR is occurring. This data was used by the project team in the modeling effort. Based on the numerical analyses described in section 2.3, the Yates field was selected for the pilot study to be conducted in Phase III.

The Yates field has produced more than one billion barrels of oil, with estimated recoverable reserves still approximately one billion barrels (approximately 50% of the original oil in place). Starting 1.5 years ago, CO_2 injection activities in the central, eastern, and northern parts of the field has substantially improved oil production. The reservoir is relatively shallow (~ 500 ft depth) and so represents an easily accessible target for the system. Deeper fields were also considered (e.g. the Katz field at ~3000 ft) but deployment of borehole instruments at these depths is a prohibitive expense at this initial stage.
The field is operated by Kinder Morgan Inc. (KM) and CO_2 EOR operations are ongoing. A 4x4 km area has been identified in collaboration with KM for the pilot study. Figure 1 shows a map of the region with lateral wells used for both injection and production. Open vertical wells are available for sensor placement, and a small number have been identified by KM as “high cased” wells without metallic casing at depth.

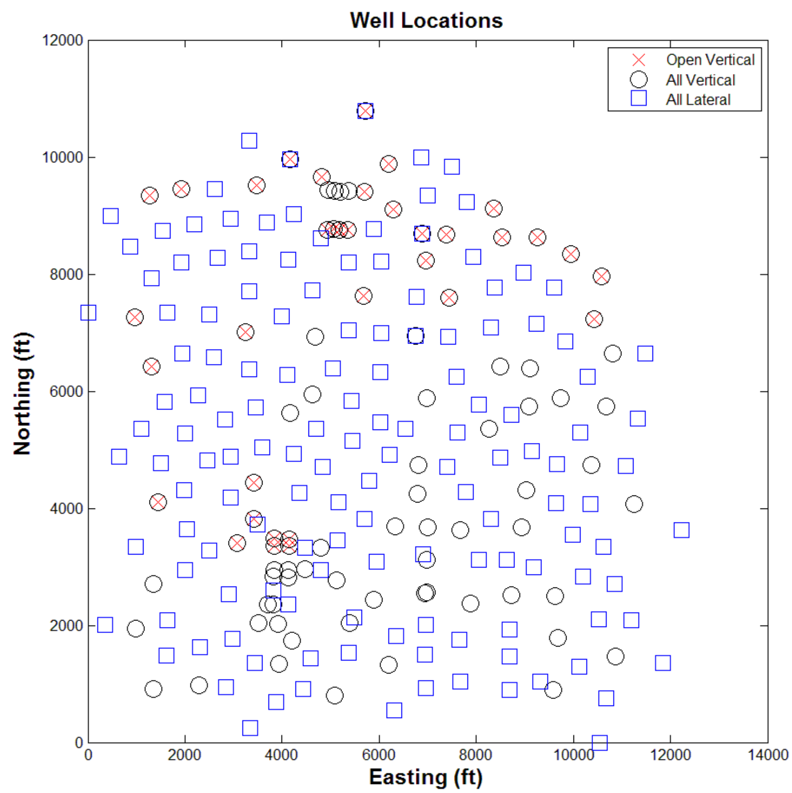

Figure 1. Spatial distribution of vertical and lateral wells within Yates field study area.

For the field trial SKY plan calls for three deployments, each of approximately two weeks. The timescale of CO2 flooding extends over months, so analysis of data acquired over each two week field experiment will yield a static condition for conductivity and saturation. The original proposal for this project envisioned a permanent deployment of the array with remote, “semi-autonomous” operation. Unfortunately, the infrastructure and maintenance required for such an advanced system cannot realistically be realized with the remaining funding. Instead, SKY will remove their sensors after each field deployment, process the data from their measurements, and return several months later to repeat the experiment. The final data products will then be estimated three-dimensional conductivity and saturation models at three stages of CO_2 injection at the Yates field.

Discussions with Kinder Morgan are ongoing to determine the exact number, location and spatial extent of injectors that will be monitored. Once the survey area is established, SKY will carry out a series of measurements using transmitter/receiver well pairs that will provide equivalent information to what would be obtained with a measurement array that is permanently deployed in multiple wells.

2.2 Literature review

A literature review comparing the potential approaches for in situ geophysical monitoring was completed in Phase I of this project. This review will be thoroughly updated by December 15, 2012 to provide detailed technical justification for the choice of an EM monitoring system.

A number of sensing modalities have been considered for this application. At present, seismic methods are primarily used by the petroleum industry. While seismic imaging can provide a high resolution image of the subsurface, the relevant physical properties (impedance. velocity, and density) are relatively insensitive to CO_2 saturation. In contrast, electrical conductivity ranges over several orders of magnitude and laboratory measurements have demonstrated that fluid conductivity is significantly reduced in the presence of CO_2. Consequently, electromagnetic (EM) methods have the potential to more accurately image the time-varying distribution of saturation in the subsurface during CO_2 injection than other potential geophysical techniques (seismic, gravity, magnetic, electrical).

A study carried out for DOE by Lawrence Livermore National Lab (LLNL) in 2002 demonstrated detectable changes in conductivity associated with CO_2 saturation. However, the LNLL study was conducted on a very small scale (approximately 30 m separation between monitoring wells) using cross-borehole frequency domain EM measurements. Our work will significantly advance the state of EOR monitoring by demonstrating the viability of time-domain EM monitoring on a larger scale (~200 m between monitoring wells) and in an active oil field. The LLNL work produced only two-dimensional conductivity models, SKY processing will yield coupled three-dimensional models of conductivity and saturation

2.3 Modeling

The propagation of electromagnetic fields in the time-domain is governed by Maxwell’s equations

$$\nabla \times \mathbf{E} + \mu \frac{\partial \mathbf{H}}{\partial t} = 0$$

$$\nabla \times \mathbf{H} \text{-} \sigma\, \mathbf{E} - \epsilon \frac{\partial \mathbf{E}}{\partial t} = \boldsymbol{s}(t)$$

where E and H are the electric and magnetic fields, respectively. In geophysical applications of electromagnetic sensing, the effect of dielectric permittivity ε is usually negligible in comparison to the electric conductivity σ, with magnetic permeability μ often treated as constant. Analytical solutions to these expressions only exist for relatively simple cases, for arbitrary distributions of electrical conductivity computation of predicted electric and magnetic fields must be handled numerically. We will use a finite volume approach: the subsurface is divided into a mesh of polygonal cells, with each cell assigned a conductivity value (figure 2) .

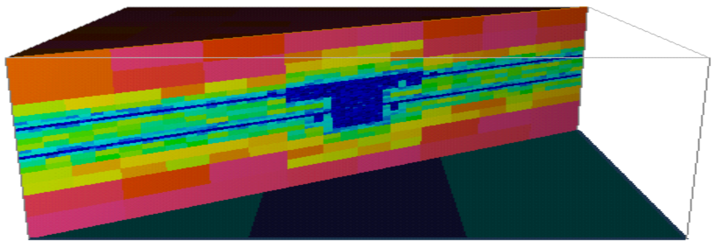

Figure 2. Discretized earth model for reservoir modeling. Two layers of smaller volume (blue) cells delineate air-ground interface and a thin reservoir. Central, vertical core is the region where borehole measurements are simulated.

Similarly, we discretize the time dependence of the fields by computing our numerical solution a number of time steps. The result is a (very large) system of equations for the predicted electric and magnetic fields for a given subsurface distribution of electrical conductivity. Recent numerical implementations employ efficient parallel solvers and have reduced typical solution times by approximately an order of magnitude (from tens of hours to less than one hour).

In practice, we must take the measured electromagnetic fields and infer a conductivity model that can predict these observed data. We solve an inverse problem that minimizes the difference between observed data and the data predicted by our conductivity model. Unfortunately, the inverse problem in this formulation is ill-posed (non-unique and ill-conditioned). This implies that there an infinite number of conductivity models that can fit the data to an arbitrary degree. This difficulty is addressed via Tikhonov regularization: we augment the misfit to the data with an additional term that prescribes the properties of the model which we wish to recover. In the simplest case, we might require the model to be smooth by penalizing large differences in conductivity between adjacent cells in our discretized model. Regularizing the inversion in this way makes the problem well-posed and is a proven method for recovering geologically informative models of the subsurface that are consistent with field measurements.

For the particular application of EOR monitoring with EM sensors, additional regularization of the inverse problem is afforded by the ability to couple the electromagnetic modeling with a multi-phase flow simulation. The governing equations for saturation (s) and pressure (q) are

$$-\nabla \cdot \left((\lambda_o(s) + \lambda_w(s)) K \vec{\nabla} \Psi_w \right) = \nabla \cdot \left(\lambda_o(s) K \Psi_c'(s) \vec{\nabla} s \right) + q$$
$$\phi \frac{\partial s}{\partial t} - \nabla \cdot \left(\lambda_w(s) K \vec{\nabla} \Psi_w \right) = q_w$$

These equations require a similar numerical solution as the EM forward modeling described above. A number of academic and commercial packages are used for simulation of miscible and immiscible CO_2 floods (e.g. STOMP, GEM). However, these codes cannot be readily coupled to an EM forward modeling code as grid conventions and outputs are generally incompatible. We therefore use a multi-phase flow solver developed at UBC that is consistent with the EM modeling codes developed by the same research group. This makes coupling the codes - previously a major obstacle - trivial. This code has been validated using permeability models of candidate reservoirs provided to us by Kinder Morgan.

One possibility to couple EM and flow modeling is to use an assumed petrophysical transform that maps between saturation/pressure and electrical conductivity. This transform can be derived from laboratory measurements (for example, see the LLNL approach). However, this approach relies on limited samples and may not accurately capture the potentially complex relationships between these properties that will be encountered at depth in an actual reservoir. Recent work by the UBC group obviates the need for a defined mapping between hydrologic and geophysical parameters. We use the three-dimensional shape of the predicted saturation anomaly as a constraint during the EM inversion. The result of the EM inversion can then be fed back into the flow model to correct for flow predictions that are inconsistent with the observed electromagnetic data. This predictor-corrector approach has been successfully tested on similar multi-physics problems.

The end result of this modeling and inversion will be a series of three-dimensional, time-lapse models showing the changes in conductivity in the reservoir associated with CO2 saturation. Coupled models of CO2 saturation will also be generated. Together these models will help petroleum engineers understand and optimize CO2 floods for EOR.

2.4 Sensor system design and layout

Electromagnetic systems transmit a time-varying primary magnetic field that illuminates conductive targets in the earth. The variation of this primary field induces currents in the ground that, in turn, radiate a secondary magnetic field that can be measured by receivers deployed at the surface, or in boreholes. In the time-domain mode of operation, the transmitter field is terminated and the decay of induced secondary fields is measured during the off-time.

To obtain data with sufficient signal to noise ratio to support subsequent modeling and inversion, transmitters and receivers must be inductively coupled to the imaged target. Numerical simulations using reservoir models corresponding to candidate test sites indicated that placing the system on the surface would not produce a measurable response from the reservoir. In addition, in active oil fields there is significant electromagnetic noise from infrastructure on the surface. Deployment of both transmitters and receivers down-hole allows us to image the reservoir and isolates the system from noise sources. Figure 3 shows a schematic of the system design.

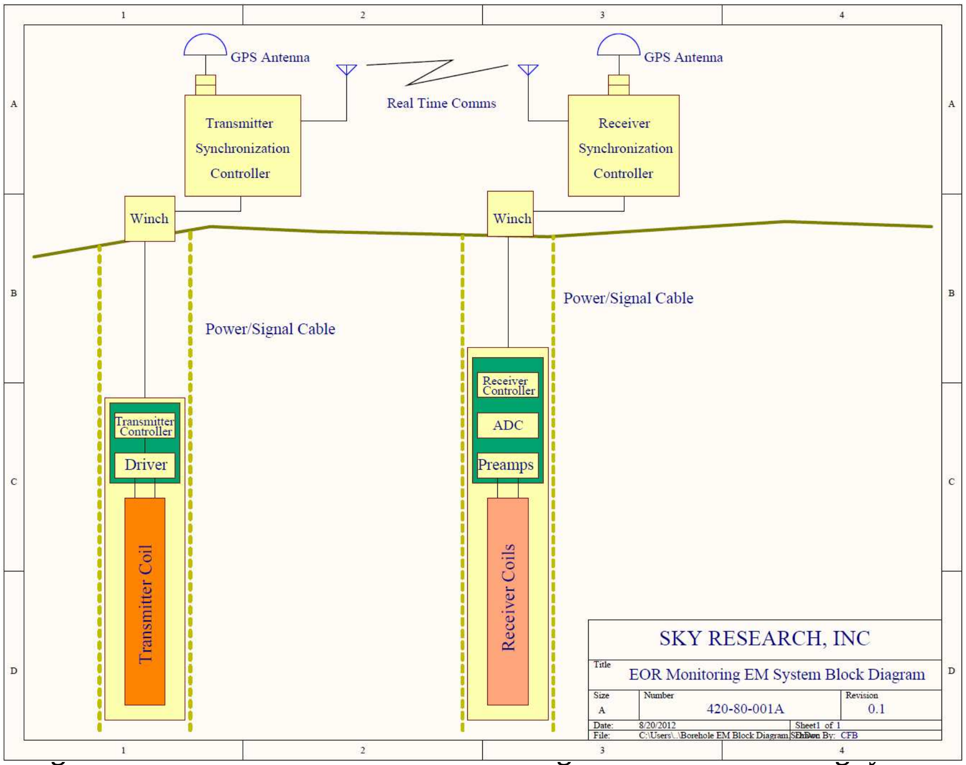

Figure 3 Schematic of downhole electromagnetic EOR monitoring system

Deployment in boreholes introduces additional constraints on system design, with observation wells ranging from 5”-8” in diameter. To meet this requirement, we will use 10 cm vector receiver cubes, as shown in Figure 4. These cubes measure orthogonal components of the secondary field and have successfully been used by Sky Research in a number of environmental applications.

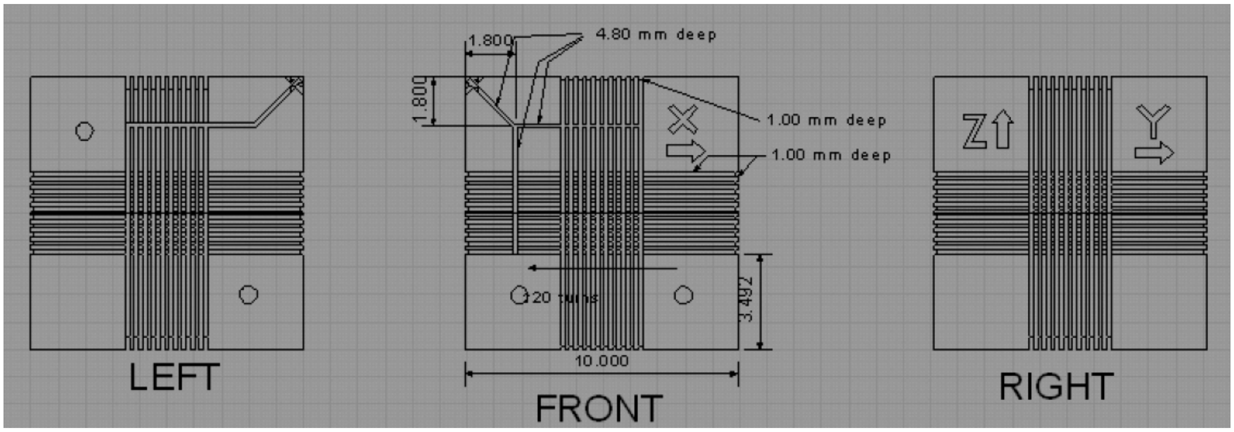

Figure 4. Design of vector receiver cubes used for downhole EM measurements

An additional complication in the deployment of a down-hole EM system is the presence of metal casing that attenuates the transmission of electromagnetic fields. Ideally, we will use wells without metal casing, but the effects of casing on the data can be corrected if necessary.

2.5 Field Deployment

Sky Research will deploy its time-domain electromagnetic EOR monitoring system at the Yates Field, TX. For the field trial we will deploy our transmitters and receivers in available observation wells immediately adjacent to an injection well. Initial flow simulations using a reservoir model provided by Kinder Morgan will help guide the placement of sensors in wells. In addition, experimental survey design methods developed by Dr. Haber's group can be used to obtain a survey with maximal sensitivity to changes in CO2 saturation. The methods use an ensemble of representative reservoir models to optimize the placement of transmitters and receivers, such that the recovered three-dimensional model has maximal resolution of anomalous conductivity structures associated with CO2 saturation.

We will map the area by deploying our system in two wells at a time: one for the transmitter array and one for the receiver array. These arrays will be rotated in all available combinations of observation wells to image flooding in the reservoir. Measurements will also be made at a range of depths (approximately 20 m intervals down to the maximal depth available in each well) for both transmitter and receivers. Given the relative scarcity of vertical wells in Figure 1, we will also try to exploit inactive injection wells, though this will require a correction for shielding by well casings.

For the field trial we plan for three deployments, each of approximately two weeks. The timescale of CO2 flooding extends over months, so analysis of data acquired over each two week field experiment will yield a static condition for conductivity and saturation. The original proposal for this project envisioned a permanent deployment of the array with remote, "semi-autonomous" operation. Unfortunately, the infrastructure and maintenance required for such an advanced system cannot realistically be realized with the remaining funding. Instead, we will remove our sensors after each field deployment, process the data from our measurements, and return several months later to repeat the experiment. The final data products will then be estimated three-dimensional conductivity and saturation models at three stages of CO_2 injection at the Yates field.

With a successful demonstration of this approach, Sky will work to build a ruggedized commercial product that can be permanently deployed for EOR monitoring.

3 Milestone status

3.1 Milestone description

The project is divided into three research phases corresponding to the three budget periods. The emphasis in Phase I (Budget Period: February 1, 2011 through February 1, 2012) is on site selection, numerical modeling of CO2 EOR flooring and associated expected geophysical signatures for a number of different geophysical sensing modalities for selected sites, and on sensing modality selection. The emphasis in Phase II (Budget period: February 1, 2012 through February 1, 2013) will be on sensing system assembly and testing and on inverse method development. The emphasis in Phase III (Budget period: February 1, 2013 through February 1, 2014) will be on the system field deployment on a selected site and on the interpretation of the field data. Table ... summarizes the project task and milestone schedule.

		Year1				Year 2				Year 3			
Task	Task title	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
1	**Project Management and Planning**												
2	**Test site selection, sensitivity and Cost/Benefit Studies and Sensing Modality Selection**												
2.1	Test site commitment	M1											
2.2	Literature Study								M2				
2.3	CO2 EOR Model Development												
2.4	Geophysical Forward Model coupling to CO2 induced changes in physical properties								M3				
2.5	Sensing Modality and Geometry Selection								M4				
3	**System Prototype Construction**												
3.1	System Design												
3.2	System Construction and Testing									M5			
4	**Processing Flow Development and Linking with CO_2-EOR Models**												
4.1	TDEM Processing Code Development								M6				
4.2	Geophysical Processing Framework Development												
4.3	CO_2-EOR Model Linking with Geophysical Framework Output									M7			

5	**Field testing**												
5.1	Final Site selection												
5.2	System Deployment and Data Collection								M8				
5.3	Data processing												
6	**Data Analysis**												M9
7	**Technology Transfer**												
	DECISION POINTS								1,2				

3.2 Milestone status

1: Test site commitment

This milestone consists of obtaining commitment letters to allow for field deployment of the geophysical monitoring system from one or more sites where CO2 EOR is being done. Meeting of this milestone will be demonstrated by providing these letters to the DOE program office.

Status: COMPLETED 4/1/11.

2: Literature study

This milestone consists of completion of a literature study about the use of geophysical characterization and monitoring of CO2 EOR. Meeting of this milestone will be demonstrated by providing this literature study to the DOE program office.

Status: COMPLETED 5/1/11. After review with program office, revisions will be made to the literature review to include additional information. Will determine if/when original PI will be able to make additions to the literature review. expected completion date - 12/1/12

3: Forward Model coupling

This milestone consists of the coupling of the PNNL developed GS 3 model for CO2 injection with Sky Research developed geophysical forward models such that the coupled models can predict the geophysical signal associated with CO2 EOR efforts. Meeting of this milestone will be demonstrated by performing a series of numerical simulations which the coupled models. The results of the simulations will be documented in a letter report which will be provided to the DOE program office

Status: PHASE 1 MILESTONE - Coupled modeling code completed, with numerical simulations carried out. Tests on Yates and Katz field carried out. Report on simulations will be submitted to DOE program office following completion of Phase III continuation application presentation on 8/22/12. expected completion date - 10/15/12

4: Modality selection

This milestone consists of selection of the sensors and configuration of these sensors which will be used in the field demonstration. This milestone will be demonstrated by a report describing the sensor selection and providing the theoretical, field and numerical data supporting the sensor selection. This report will be provided to the DOE program office.

Status: PHASE 1 MILESTONE - Downhole sensor modality selected based on modeling studies. Modeling details will be reported to DOE program office following completion of Phase III continuation application presentation on 8/22/12. expected completion date - 10/15/12

5: Prototype completion

This milestone consists of the completion of the initial prototype sensor system (note that several of these will be constructed for deployment, but this milestone concerns the construction of the initial one). This milestone will be demonstrated by documenting the prototype design specifications, physical assembly (both component and system level) and test data resulting from the prototype. The documents will be provided to the DOE program office.

Status: PHASE 1 MILESTONE - Receiver components purchased and tested. Transmitter design and assemply in progress. Partnership with company specializing in downhole instrumentation has been agreed upon. - expected completion date 1/30/13

6: TDEM (Time Domain Electro Magnetic) inverse code

This milestone consists of the completion of a TDEM inverse code which can estimate changes in subsurface conductivity from TDEM data. This milestone will be demonstrated by processing a number of synthetic (and possibly field) TDEM datasets and demonstrating that the code can obtain realistic estimated of changes in subsurface conductivity from this data.

Status: PHASE 2 MILESTONE - UBC data inversion code applied to synthetic models based on Yates and Katz reservoirs. - expected completion date - 10/15/12

7: Model linking

This milestone consists of the linking of the GS3 model with the geophysical codes to allow for inverse property estimation. This milestone will be demonstrated by executing a number of scenarios on synthetic data to show the coupling and property estimation. A document summarizing the results of these scenarios will be provided to the DOE program office.

Status: PHASE 3 MILESTONE - In Progress. to be completed in 2013

8: System deployment

This milestone consists of the deployment to the field site of the monitoring hardware and the start of data collection. This milestone will be demonstrated by documenting field deployment activities and data collection progress (which will be accessible through a password protected interface). A document summarizing field site deployment and a password/username allowing access to the data portal will be provided to the DOE program office.

Status: PHASE 3 MILESTONE - to be completed in 2013

9: Data analysis completion

This milestone consists of the completion of the data analysis and processing of the field data collected in the field demonstration. This milestone will be demonstrated by a data analysis report which will document field data and processing results. This document will be provided to the DOE program office.

Status: PHASE 3 MILESTONE -To be completed in 2014

3.3 Any changes in approach or aims and reasons for change.

The project objectives will primarily remain unchanged. However, the implementation of cyber infrastructure task will not be pursued within this project. The resources (time and cost) to complete this aspect of the project are not sufficient to implement the necessary infrastructure in an effective manner.

3.4 Actual or anticipated problems or delays and actions taken or planned to resolve them.

We do not anticipate any delays in project execution for the remainder of Phase II and III.

3.5 Any absences or changes of key personnel or changes in consortium/team arrangement.

- Dr. Beran and Dr. Pasion will add the role of Co-Principal Investigators responsible for project management and coordination to their ongoing work on electromagnetic (EM) modeling and inversion. Drs. Beran and Pasion are applied geophysicists specializing in the field of EM data processing. Both have PI experience in electromagnetic data processing research projects funded by SERDP and ESTCP.
- Dr. Eldad Haber will be the project's technical lead. Dr. Haber is an associate professor in the Department of Mathematics and the Department of Earth and Ocean Sciences at the University of British Columbia. Dr. Haber holds a UBC Industrial Research Chair in Computational Geoscience and is a past winner of a DOE Career Award. His research emphasis focuses on efficient and novel solutions of multi-physics problems, including electromagnetic forward modeling and inversion and multi-phase flow. His past research includes the design of a borehole monitoring system with Berkeley National Laboratory.
- Mr. Chet Bassani will continue leading the EM system design and construction.

This project team represents a change from the original team that included Dr. Roelof Versteeg (formerly of Sky Research Inc) as PI and Dr. Alain Bonneville and Dr. Signe White of Pacific Northwest National Lab (PNNL). PNNL were tasked to carry reservoir modeling using the STOMP software developed by PNNL. Earlier in the project, PNNL informed Dr. Versteeg that they were unable to use the STOMP code to model multi-phase flow at the Kinder Morgan sites. A decision was made by Dr. Versteeg and PNNL to utilize the commercial GEM modeling package. For the Phase II continuation presentation, PNNL produced a synthetic, half-space simulation of CO2 injection on a coarse grid that did not include representative geology. A conference call with Sky Research and PNNL scientists was held on August 16. This call included Drs. Beran, Pasion, Bonneville and White. During this call Drs. Bonneville and White provided an update on the progress of the PNNL reservoir modeling effort. This update established that there was no modeling progress beyond the previously described half-space simulation. In particular, flow models for neither the Yates nor Katz reservoirs were completed. Drs. Bonneville and White noted that, while they were still interested in the modeling aspects of the project, there schedule would not allow them to commit significant time to the project over the next few weeks.

In order to have the flow modeling capability necessary for reservoir imaging, Drs. Beran and Pasion contacted Dr. Haber. As part of his UBC research, Dr. Haber had developed a multi-phase flow solver suitable for reservoir modeling. In addition, the package can easily handle data and model formats from commonly used commercial packages (in particular, GEM). Within days of receiving the Kinder Morgan's GEM files that provided the spatial distribution of geologic and hydraulic properties of the

Yates field, Dr. Haber's team was able to produce flow modeling results for a CO2 injection flood. An important aspect of the modeling process is the linkage between the flow models and electromagnetic models. Using the UBC flow modeling and electromagnetic modeling software makes the linking trivial as the software modules utilize the same subsurface meshing conventions. The electromagnetic modeling software – a commercial code for numerical solutions of Maxwell's equations – was used to produce Yates and Katz field CO2 injection imaging results for the Phase III continuation meeting.

4 Appendix A. Statement of Project Objectives

4.1 PROJECT OBJECTIVE

The objective of the project is to design, develop and validate a real time, semi- autonomous geophysical data acquisition and processing system to monitor CO_2-EOR flood performance.

4.2 SCOPE OF WORK

The goals of the project are threefold. First, to design the components of the monitoring system based on a combination of a literature study and numerical modeling of CO2 EOR evolution and associated geophysical signatures. Second, to construct and verify performance of this monitoring system, and to develop the required processing framework allowing for the processing of the data from this system, and third to field test this system at an actual CO2 EOR site and to process the collected data to show the ability to monitor CO2 EOR performance

Expected results: The expected results of this work are fieldable systems (combination of hardware an software) for CO2 EOR floods monitoring. These systems would provide economically affordable monitoring of CO2 EOR floods, and thus could be used to optimize these floods. This would potentially increase production and

4.3 TASKS TO BE PERFORMED

The detailed schedule for all tasks for each funded year is shown in table B1-B3 at the end of the PMP. This shows the detailed breakdown of project staff for each year and each task and subtask. The narrative below describes concisely the approach or methods which will be used to achieve the objectives of each task and subtask

<u>Phase I</u>

Task 1.0 – Project Management and Planning

The Recipient shall execute the project in accordance with the approved Project Management Plan (PMP) covering the entire project period. The Recipient shall manage and control project activities in accordance with their established processes and procedures to ensure subtasks and tasks are completed within schedule and budget constraints defined by the Project Management Plan. This includes tracking and reporting progress and project risks to DOE and other stakeholders.

The Recipient shall work with the DOE Project Officer to modify and update the PMP submitted as part

of the original application package, as necessary. The revised PMP shall be submitted within 30 days of the award. The DOE Project Officer shall have 20 calendar days from receipt of the Project Management Plan to review and provide comments to the Recipient. Within 15 calendar days after receipt of the DOE's comments, the Recipient shall submit a final Project Management Plan to the DOE Project Officer for review and approval.
This task shall include all work elements required to maintain and revise the Project Management Plan, and to manage and report on activities in accordance with the plan. The Recipient shall review, update, and amend the Project Management Plan (upon request of the DOE Project Officer) at key points in the program, notably at each Budget Period transition or GO/NO-GO decision point (if required) and upon schedule variances of more than three (3) months and cost variances of more than 15%.

It shall also include the necessary activities to ensure coordination and planning of the project with DOE/NETL and other project participants. These shall include, but are not limited to, the submission and approval of required National Environmental Policy Act (NEPA) documentation.

The Applicant is restricted from using Federal funds to take any action that would have an adverse affect on the environment or limit the choice of reasonable alternatives prior to DOE providing final NEPA decision regarding this project.

Task 2.0 – Test site selection, sensitivity and Cost/Benefit Studies and Sensing Modality Selection

The recipient shall secure commitments from CO_2 EOR site operators for the system deployment associated with task 5 (field testing). The recipient shall perform a literature study to identify potential sensing modalities. The recipient shall assess the sensitivity of each potential geophysical sensing modality to changes in physical properties associated with CO_2-EOR and the cost/benefit provided by each sensing modality in terms of information (both alone and in conjunction with other sensing data). From the results of this sensitivity study the recipient shall select the specific sensing modalities for the system as well as the performance characteristics (e.g. acquisition lengths, sensitivities, number of units required, spacing between units). This task shall also include an analysis of the optimal deployment configuration of sensors. This task shall include a modeling study to determine the physical changes associated with EOR which will be coupled to geophysical forward modeling studies performed by the recipient (Subtask 2.3 – Geophysical forward model development).

Subtask 2.1 – Test site commitment

The recipient shall obtain commitment letters from at least one but preferably multiple CO_2 EOR site operators to serve as system testing sites for the effort to be performed under task 5 (field testing). The commitment letter shall include information on site location, required site access and resource needs (e.g. space required, power requirements and so on) and length of site access, as well as auxiliary data which will be required by the project and provided by the operator. The recipient shall provide the results of subtask 2.1 (including the sites considered, general site properties, and test site commitment letters) and a preliminary ranking of potential test sites to the DOE Project Officer.

Subtask 2.2 – Literature Study

The recipient shall evaluate the CO_2 Measurement, Monitoring and Validation (MMV) literature (including both reports from specialized workshops and meetings, as well as literature from SEG, SPE, AGU and EAEG and other relevant geophysical and geological societies) to evaluate all different potential sensing modalities and monitoring approaches. This study shall inform and guide the efforts under task 2.3 -2.5. A comprehensive topical report shall be submitted by the recipient at the end of this subtask. This shall have a bibliography and a description of the literature sources used for the report

Subtask 2.3 – CO2 EOR Model Development

The recipient shall develop and implement a forward model that allows the simulation of changes in physical properties (electrical, electromagnetic, density and acoustic properties) associated with the injection of CO_2 for typical EOR field applications. This model will be used as input into subtask 2.4

Subtask 2.4 – Geophysical Forward Model coupling to CO2 induced changes in physical properties

The recipient shall execute forward geophysical modeling tools to map the changes in physical properties provided by subtask 2.2 to calculate observable changes in geophysical measurements for a number of sensing modalities and instrument configurations, including electrical, electromagnetic, active and passive seismic and gravity measurements in surface, single borehole, borehole to borehole and borehole to surface configurations as well as other potentially possible modalities and configurations. This task shall include a detailed numerical sensitivity analysis listed under Task 2.0 which shall quantify the relative and absolute changes in each sensing modality and the expected noise signatures for each sensing modality, and from this the likely probability of detection by the sensing modality/configuration combination

Subtask 2.5 – Sensing Modality and Geometry Selection

The recipient shall select the final combination of sensing modalities, sensor specifications and deployment geometries for the system based on the results of subtask 2.2-2.4.

<u>Phase 2</u>

Task 3.0 – System Prototype Construction

The recipient shall construct a prototype acquisition system that includes both commercial sensors as well as a recipient developed Time domain Electromagnetic TDEM receiver (if selected as an appropriate sensing methodology in task 2). Data from these sensors shall be acquired by data acquisition software and hardware based on recipient-developed geophysical acquisition systems used for high quality geophysical surveys. This system shall be designed to be fully autonomous and environmentally rugged capable of collecting continuous data under expected testing field conditions (changes in temperature, rain, etcetera).

Subtask 3.1 – System Design

The recipient shall design the system (power requirements, form factor, auxiliary components, and sensor placements). This design shall be supported by field tests to minimize noise and component interference. It shall also include the selection of specific geophysical sensors for the sensing modalities selected under task 2 which meet or exceed the sensitivity requirements.

Subtask 3.1 – System Design

The recipient shall design the field data acquisition system which shall has as objective to collect the data as identified as a result of task 2. This system shall consist of an environmental enclosure (which will contain data acquisition hardware, power distribution system, a dedicated system control unit and internal geophysical sensors) and external geophysical sensors. The system components are described under the following subtasks

Subtask 3.1a: Environmental enclosure: The recipient shall design an environmental enclosure: this enclosure shall enclose all the data acquisition elements and be watertight against expected field conditions (including extreme events). The environmental enclosure shall provide industry standard, watertight connectors for system power (either DC or AC power) and wired ethernet connectivity and required connectors to the external geophysical sensors. The recipient shall provide for wireless internet connectivity which shall be integrated in the environmental enclosure. The environmental enclosure shall be designed so that the temperatures in the enclosure will be in the range provided by component manufacturers.

Subtask 3.1b: External geophysical sensors: The recipient shall decide on the number, placement and orientation of external geophysical sensors based on the results of task 2. Each external sensor shall be provided in an environmentally tight enclosure designed for the appropriate environment (e.g. surface mounting or placement in well) with appropriate mounting and orientation capabilities. Each external geophysical sensor shall be connected to the data acquisition hardware in the environmental enclosure through a wired connection which shall meet all applicable site safety requirements.

Subtask 3.1c: Internal geophysical sensors: The recipient shall decide on the number, placement and orientation of internal geophysical sensors based on the results of task 2. The internal geophysical sensors shall be permanently mounted in the environmental enclosure and be connected to the data acquisition hardware through a wired connection which shall meet all applicable site safety requirements. The internal sensor placement shall be optimized to minimize noise and cross sensor interference.

Subtask 3.1d: Power distribution system: The recipient shall decide on the power requirements of the field data acquisition system. Based on these, the recipient shall design a power distribution system which shall receive its power from the external source. The power distribution system shall be able to automatically accommodate a broad range of voltages and currents and fluctuations therein and shall provide clean power to all of the system components. The power distribution system shall be equipped with surge protection capabilities which shall be easily resettable from the outside of the environmental enclosure.

Subtask 3.1e: Data acquisition hardware: The recipient shall provide for data acquisition hardware which will record and store the data from the internal and external geophysical sensors. The data acquisition parameter shall be derived from task 2.

Subtask 3.1f: System control unit: The recipient shall provide for a system control unit which shall control and monitor overall system behavior. This system control unit shall control and monitor the data acquisition hardware, power output and environmental conditions in the environmental enclosure (temperature and humidity) and transmit data collected by the data acquisition hardware systems.

Subtask 3.2 – System Construction and Testing

The recipient shall construct and test the system. This shall include deployment of the prototype system for at least two weeks under field conditions representative of the planned field test site (task 5) to assess system stability and performance in agreement with the design specifications. During the test, geophysical data from each of the selected sensors as well as data describing system health and conditions (power, temperature and humidity) shall be acquired and saved and transmitted continuously. Data assessment shall include but not be limited to data quality, sensor drift, system noise, effect of environmental conditions and the ability to detect specific known changes in the subsurface. For this test the system shall be located at a well- instrumented site where such changes are known from auxiliary observations.

Task 4.0 – Processing Flow Development and Linking with CO_2-EOR Models

The recipient shall develop a processing flow for all geophysical data selected under task 2, which were integrated in the system developed under task 3. The result of the processing flow will be linked with the CO_2-EOR modeling framework. This processing flow shall map the geophysical field data to changes in physical properties which can be ingested by the CO2 EOR modeling framework. The recipient shall integrate the results of all these processing flows into a geophysical processing framework and link the results with a CO2 EOR model

Subtask 4.1: Geophysical Processing Flow Development

The recipient shall design, develop and implement a processing for all the selected geophysical and acquired sensing modalities. This processing flow shall exist of a number of well described data processing steps (data receiving from the field units, QA/QC, data storage in relational database, preprocessing, inversion and finally delivery of a spatiotemporal map of physical properties with associated resolution and confidence matrixes).

Subtask 4.2 – Geophysical Processing Framework Development and linking with CO_2-EOR Model

The recipient shall develop a geophysical processing framework which will utilize the individual processing flows developed under task 4.1 to provide the CO2 EOR model timelapse values of changes in physical properties. This data shall be used by the CO2 EOR model to provide estimates of flood performance.

Phase 3

Task 5.0 – Field Testing

The recipient shall test the system performance by deploying multiple units at a selected field site and collecting and processing data autonomously for a period of 3-6 months. The number and relative placement of units and length of data acquisition shall be based on a numerical modeling effort as well as on programmatic constraints.

Subtask 5.1 – Final Site Selection

The recipient shall select one appropriate site for the system test out of the sites which have committed to serve as potential test sites (task 2.1). Criteria for final test site selection shall include existing infrastructure, favorable conditions in terms of expected geophysical data, ability to collect base line data before and during CO_2-EOR, availability of auxiliary data and the ability to model the underlying system. The recipient shall provide information relative to the selected site, design criteria, and planned testing duration to the DOE Project Officer for approval prior to commencement of testing.

Subtask 5.2 System Deployment and Data Collection
The recipient shall deploy the data acquisition system at the selected site and collect data for approximately 3-6 months. Initial data acquisition length shall be based on the modeling effort. Actual data acquisition length and termination of the field test shall be based both on project constraints and the success full acquisition, processing and interpretation of timelapse geophysical data associated with CO2 EOR. During the field deployment the recipient shall frequently brief the DOE program manager on testing progress and results.

Subtask 5.3 Data Processing
The recipient shall apply the geophysical data processing described under Task 4 to the collected data.

Task 6. Data Analysis
The recipient shall analyze the overall system developed under this effort (both acquisition hardware and processing framework). The recipient shall evaluate the success and limitations of the developed methodology. This shall include both the predicted and actual performance of the data acquisition system, the performance of the data processing flow from both a numerical, computational and result perspective, the match between results obtained from this system and data provided by the site operator, as well as the merit of the resulting data as assessed by the site operator, and the potential benefits of such data to other sites.

Task 7: Technology Transfer
The Recipient shall disseminate the findings of this project, including advances in theory, modeling, processing, and imaging. The mechanisms for transferring these results shall include the development of a project website to report results, presentations at annual SEG and AGU meetings or at other appropriate conferences, at least 1 paper per year in relevant journals, and organization of a workshop or research forum at the appropriate annual meeting of a national organization (e.g., SEG, AAPG, SPE) or in conjunction with PTTC.

5 Cost/Plan Status

Budget	2011	2012	2013	Total
DOE requested funds	$247,158	$247,158	$247,158	$741,474
Sky Research	$172,158	$132,158	$162,158	$466,474
Pacific Northwest National Laboratory	$75,000	$15,000		$90,000
Computational Geophysics Inc.		$100,000	$85,000	$185,000
Non federal matching funds				
Sky Research	$61,789	$61,788	$61,789	$185,366
Totals	$308,947	$308,946	$308,947	$926,840

February 1, 2011 to January 31, 2012	Sky				
Phase I: Task Elements	Roelof Versteeg	Erik Russell	Leonard Pasion	Sam Segal	Jon Miller
Task 1 Project Management and Planning	120	100			
Task 2.Test site selection, sensitivity and Cost/Benefit Studies and Sensing Modality Selection					
Task 2.1 Test site commitment	40				
Task 2.2 Literature Study	100				100
Task 2.3 CO2 EOR Model Development					
Task 2.4 Geophysical Forward Model coupling to CO2 induced changes in physical properties	100		225	50	100
Task 2.5 Sensing Modality and Geometry Selection	140			50	50
Task 3 System Prototype Construction					
Task 3.1 System Design				150	150
Subtotals (hours)	500	100	225	250	400
Subtotals (approximate months)	3.1	0.6	1.4	1.6	2.5

Table B1. Detailed task breakdown associated with project in year 1.

September 1, 2012 - December 31, 2012			
Phase II: Task Elements	Elliot Holtham	Eldad Haber	Livia Mahler
Task 1 Project Management and Planning	50	50	10
Task 2.Test site selection, sensitivity and Cost/Benefit Studies and Sensing Modality Selection	10	40	
Task 2.1 Test site commitment	20	20	5
Task 2.2 Literature Study	25		

Task 2.3 CO2 EOR Model Development	50	100	
Task 2.4 Geophysical Forward Model coupling to CO2 induced changes in physical properties	200	260	
Task 2.5 Sensing Modality and Geometry Selection	20	60	
Task 3 System Prototype Construction			
Task 3.1 System Design	40	40	
Subtotals (hours)	390	595	15
Subtotals (approximate months)	2.4	3.72	0.09

Table B2. Detailed task breakdown associated with project in year 2 for Computational Geosciences, Inc.

February 1, 2012 to January 31, 2013	Sky					
Phase I: Task Elements	RV	ER	LP	CB	JM	LB
Task 1 Project Management and Planning	50	40	50			50
Task 2.Test site selection, sensitivity and Cost/Benefit Studies and Sensing Modality Selection	10					
Task 2.1 Test site commitment	20		5			5
Task 2.2 Literature Study	25					
Task 2.3 CO2 EOR Model Development	50		50			50
Task 2.4 Geophysical Forward Model coupling to CO2 induced changes in physical properties	50		40			40
Task 2.5 Sensing Modality and Geometry Selection	20					
Task 3 System Prototype Construction						
Task 3.2 System Construction and Testing				200	160	
Task 4. Processing Flow Development and Linking with CO_2-EOR Models						
Task 4.1 TDEM Processing Code Development			40			40
Task 4.2 Geophysical Processing Framework Development	20		20			20
Task 4.3 CO_2-EOR Model Linking with Geophysical Framework Output	20		40			40
Task 5. Field testing						
Task 5.1 Final Site selection	20		10			10
Task 5.2 System Deployment and Data Collection						
Task 7. Technology Transfer			20			20
Subtotals (hours)	285	40	275	200	160	275
Subtotals (approximate months)	1.8	0.25	1.7	1.25	1	1.7

Table B3. Detailed task breakdown associated with project in year 2 for Sky. RV = Roelof Versteeg. ER = Erik Russell. LP = Len pasion. CB = Chet Bassani. JM = Jon Miller. LB = Laurens Beran.

February 1, 2012 to January 31, 2013	PNNL			
Phase I: Task Elements	Alain Bonneville	Charlotte Sullivan	Debbie Fagan	Signe Wurstner
Task 1 Project Management and Planning	40			
Task 3 System Prototype Construction				
Task 3.2 System Construction and Testing				
Task 4. Processing Flow Development and Linking with CO_2-EOR Models				
Task 4.1 TDEM Processing Code Development				
Task 4.2 Geophysical Processing Framework Development				
Task 4.3 CO_2-EOR Model Linking with Geophysical Framework Output	40			80
Task 5. Field testing				
Task 5.1 Final Site selection				
Task 5.2 System Deployment and Data Collection				
Task 7. Technology Transfer				
Subtotals (hours)	60			80
Subtotals (approximate months)	0.9			0.5

Table B4. Detailed task breakdown associated with project in year 2 for PNNL.

February 1, 2013 to January 31, 2014	Sky				CGI		
Phase I: Task Elements	Pasion	Beran	Bassani	Segal	Holtham	Haber	Mahler
Task 1 Project Management and Planning	80	80			40	40	20
Task 5. Field testing							
Task 5.2 System Deployment and Data Collection			300	300	80	40	
Task 6. Data analysis			200	200	240	240	
Task 7. Technology Transfer	20	20					
Subtotals (hours)	100	100	500	500	360	320	20
Subtotals (approximate months)	0.6	0.6	3.1	3.1	2.25	2.0	0.13

Table B5. Detailed task breakdown associated with project in year 3.