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ScienceDirect

Energy Procedia 63 (2014) 4062 – 4070

Energy Procedia

GHGT-12

FutureGen 2.0 Monitoring Program: An Overview of the Monitoring Approach and Technologies Selected for Implementation

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Abstract

The FutureGen 2.0 Project will design and build a first-of-its-kind, near-zero emissions coal-fueled power plant with carbon capture and storage (CCS). To assess storage site performance and meet the regulatory requirements of the Class VI Underground Injection Control (UIC) Program for CO_2 Geologic Sequestration, the FutureGen 2.0 project will implement a suite of monitoring technologies designed to 1) evaluate CO_2 mass balance and 2) detect any unforeseen loss in CO_2 containment. The monitoring program will include direct monitoring of the injection stream and reservoir, and early-leak-detection monitoring directly above the primary confining zone. It will also implement an adaptive monitoring strategy whereby monitoring results are continually evaluated and the monitoring network is modified as required, including the option to drill additional wells in out-years. Wells will be monitored for changes in CO_2 concentration and formation pressure, and other geochemical/isotopic signatures that provide indication of CO_2 or brine leakage. Indirect geophysical monitoring technologies that were selected for implementation include passive seismic, integrated surface deformation, time-lapse gravity, and pulsed neutron capture logging. Near-surface monitoring approaches that have been initiated include surficial aquifer and surface-water monitoring, soil-gas monitoring, atmospheric monitoring, and hyperspectral data acquisition for assessment of vegetation conditions. Initially, only the collection of baseline data sets is planned; the need for additional near-surface monitoring will be continually evaluated throughout the design and operational phases of the project, and selected approaches may be reinstituted if conditions warrant. Given the current conceptual understanding of the subsurface environment, early and appreciable impacts to near-surface environments are not expected.

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Peer-review under responsibility of the Organizing Committee of GHGT-12
doi:10.1016/j.egypro.2014.11.438

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Keywords: carbon sequestration; carbon capture and storage; monitoring; MVA; leak detection

1. Introduction

The advancement of carbon capture and storage (CCS) technology shows promise for addressing carbon dioxide (CO_2) emissions and global climate change concerns. The objectives of the FutureGen 2.0 project are to demonstrate, at the utility-scale, the technical feasibility of implementing carbon capture and storage in a deep saline reservoir [1, 2]. Implementation of the FutureGen 2.0 project supports these objectives. In cooperation with the U.S. Department of Energy (DOE), the FutureGen 2.0 project partners—the FutureGen Industrial Alliance, Inc. (Alliance)—will repower a previously retired oil-fired power plant in Meredosia, Illinois, with oxy-combustion technology to capture approximately 1.1 million metric tons (MMT) of CO_2 each year, which is more than 90 percent of the plant's carbon emissions. Other emissions, such as sulfur oxides, nitrogen oxides, and mercury, will be reduced to near-zero levels. Using safe and proven pipeline technology, the CO_2 will be transported approximately 45 km to the storage site near Jacksonville, Illinois, and injected into a deep saline reservoir (~ 1,200 m below ground surface) through a network of horizontal injection wells.

To assess storage site performance and meet the regulatory requirements of the Class VI Underground Injection Control (UIC) Program for CO_2Geologic Sequestration, a monitoring program must be designed and implemented that can track and account for the mass of CO_2 injected. This paper provides a summary of the overall monitoring approach adopted by the FutureGen 2.0 project, and the testing and monitoring activities that the Alliance will undertake at its FutureGen 2.0 storage site. All testing and monitoring activities will be performed in accordance with Title 40 of the Code of Federal Regulations (CFR) Sections 146.89, 146.90, and 146.91 (40 CFR §146.89, 146.90, and 146.91) to verify that the storage site is operating as permitted and is not endangering any underground sources of drinking water (USDWs).

2. Monitoring Approach

The primary objective of the monitoring program is to implement a suite of monitoring technologies that are both technically sound and cost-effective, and provide an effective means of 1) monitoring the evolution of the CO_2 plume and pressure front, 2) evaluating CO_2 mass balance, and 3) detecting any unforeseen loss in CO_2 containment. The monitoring program will include injection well testing and monitoring activities, groundwater quality monitoring immediately above the primary confining zone and in the lowermost USDW aquifer, and injection-zone monitoring that will consist of 1) direct pressure monitoring, 2) direct geochemical monitoring, and 3) indirect (i.e., geophysical) monitoring of the CO_2 plume and pressure-front evolution. The monitoring infrastructure will be comprised of a network of deep monitoring wells and a surface-based network of combined passive seismic/surface deformation monitoring stations. The CO_2 injection stream will be continuously monitored as part of the instrumentation and control systems for the FutureGen 2.0 project; injection stream monitoring will also include periodic collection and analysis of grab samples to track CO_2 composition and purity. A summary of the planned monitoring technologies and measurement frequency is provided in Table 1.

Prior to injection of CO_2, background levels of any anticipated hydrogeologic, geochemical, and geophysical parameters will be measured to establish a baseline against which subsequent measurements will be compared. Both direct and indirect measurements will be used collaboratively with numerical models of the injection process to verify that CO_2 is effectively sequestered within the targeted deep geologic formation and that the stored CO_2 mass is accounted for. The approach is based in part on early-detection monitoring wells that target regions of increased leakage potential (e.g., areas of highest pressure buildup containing wells that penetrate the caprock). Leak-detection monitoring can be divided into two distinct modes. The first is "detection" mode, which focuses on detecting a leak at the earliest possible opportunity. Because of its larger areal extent of detectability, this mode will most likely be informed by changes in fluid pressure, although localized changes in aqueous geochemistry in the monitoring interval immediately overlying the caprock might also be detected. If a leak is detected, this

Table 1. Monitoring frequencies by method and project phase.

		DOE Active Phase			Commercial Phase	
Monitoring Category	Monitoring Method	Baseline 3 yr	Injection (startup) ~3 yr	Injection ~2 yr	Injection ~15 yr	Post-Injection 50 yr
CO_2 Injection Stream Sampling and Analysis	Grab sampling and analysis	3 events, during commissioning	Quarterly	Quarterly	Quarterly	NA
CO_2 Injection Stream Monitoring	Continuous monitoring of injection process (injection rate, pressure, and temperature; annulus pressure and volume)	NA	Continuous	Continuous	Continuous	NA
Corrosion Monitoring	Corrosion coupon monitoring of Injection Well Materials	NA	Quarterly	Quarterly	Quarterly	NA
Mechanical Integrity Testing (ACZ/USDW wells excluded)	PNC and temperature logging (frequency shown for injection wells)	Once after well completion	Annual	Annual	Annual	Annual until wells plugged
	Cement-evaluation and casing inspection logs	Once after well completion	During well workovers	During well workovers	During well workovers	NA
	Annular pressure monitoring	NA	Continuous	Continuous	Continuous	NA
Pressure Fall-Off Testing	Injection well pressure fall-off testing	NA	Every 5 yr	Every 5 yr	Every 5 yr	NA
Groundwater Quality Monitoring	Fluid sampling and analysis in ACZ and USDW monitoring wells	3 events	Quarterly	Semi-Annual	Annual	Every 5 yr
	Electronic P/T/SpC probes installed in ACZ and USDW wells	1 yr min	Continuous	Continuous	Continuous	Continuous
Direct CO_2 Plume and Pressure-Front Monitoring	Fluid sample collection and analysis in SLR monitoring wells	3 events	Quarterly	Semi-Annual	Annual	Every 5 yr
	Electronic P/T/SpC probes installed in SLR wells	1 yr min	Continuous	Continuous	Continuous	Continuous

Table 1. (contd)

		DOE Active Phase			Commercial Phase	
Monitoring Category	Monitoring Method	Baseline 3 yr	Injection (startup) ~3 yr	Injection ~2 yr	Injection ~15 yr	Post-Injection 50 yr
Indirect CO_2 Plume and Pressure-Front Monitoring	Passive seismic monitoring	1 yr min	Continuous	Continuous	Continuous	Continuous
	Integrated deformation monitoring	1 yr min	Continuous	Continuous	Continuous	Continuous
	Time-lapse gravity	3 events	Annual	Annual	Annual	NA
	PNC logging of RAT installations	3 events	Quarterly	Quarterly	Annual	Annual

ACZ = above confining zone; NA = not applicable; PNC = pulsed-neutron capture; P/T/Spc = pressure, temperature, and specific conductance; RAT = reservoir access tube; SLR = single-level in-reservoir; USDW = underground source of drinking water.

would trigger a secondary “assessment” mode of monitoring wherein the focus would be on quantifying the rate and extent of the leak. This mode would continue to be informed by pressure data, but characterization of changes in aqueous geochemistry within the early leak-detection monitoring interval would likely play an increased role in the assessment. In this mode, monitoring costs may increase if additional analytes and/or more frequent sample collection are required to adequately characterize the leak. While CCS projects must plan for both modes of leak-detection monitoring, the expectation is that the assessment mode will never be required.

A comprehensive suite of geochemical and isotopic analyses will be performed on fluid samples collected from the reservoir and overlying monitoring intervals. These analytical results will be used to characterize baseline geochemistry and provide a metric for comparison during operational phases of the project. A primary design consideration for “detection” monitoring is minimizing lifecycle cost without sacrificing the ability to detect a leak. As a result, only select parameters measured during the baseline monitoring period will be routinely measured during operational phases of the project when operating in leak-detection mode. Indicator parameters will be used to the extent possible to inform the monitoring program. Once baseline conditions and early CO_2 arrival responses have been established, observed relationships between analytical measurements and indicator parameters will be used to guide less frequent aqueous sample collection in later years.

The monitoring network will address prediction uncertainty by adopting an “adaptive” or “observational” monitoring approach (i.e., the monitoring approach will be adjusted as needed based on observed monitoring and updated modeling results) [3, 4, 5]. This approach will include the option to install additional wells in outyears to verify CO_2 plume and pressure-front evolution and/or evaluate leakage potential.

If a significant CO_2 leakage response is detected, a modeling evaluation will be used to assess the magnitude of containment loss and make bounding predictions regarding the potential for CO_2 migration above the confining zone, including any resulting impacts on shallower intervals, and ultimately, the potential for adverse impacts on USDW aquifers or other ecological receptors. Observed and simulated arrival responses at the early leak-detection wells and shallower monitoring locations will be compared throughout the life of the project and results will be used to calibrate and verify the model, and improve its predictive capability for assessing the long-term environmental impacts of any fugitive CO_2. If deep early-detection monitoring locations indicate that primary confining zone leakage has occurred, a comprehensive near-surface-monitoring program will be evaluated and, if warranted, activated to fully assess environmental impacts relative to previously established baseline conditions.

3. Monitoring Network Summary

The monitoring network design is based on the Alliance's current conceptual understanding of the site and predictive simulations of injected CO_2 fate and transport. The model used in the design analysis was parameterized based on site-specific characterization data collected from the initial stratigraphic borehole and reflection seismic surveys conducted at the FutureGen 2.0 storage site [6]. The network design also considered other available regional data, including the effects of structural dip, regional groundwater flow conditions, and the potential for heterogeneities or horizontal/vertical anisotropy within the injection zone and overburden materials [7]. The monitoring network will be in place and completely functional prior to any CO_2 injection and associated pressure buildup in order to establish the baseline conditions from which to compare and evaluate future injection/post-injection conditions. CO_2 injection will only proceed once baseline levels have been established for all implemented monitoring methods. Active wells (i.e., wells not yet decommissioned) will continue to be monitored for the duration of the project to characterize subsurface pressure and CO_2 migration and guide operational and regulatory decision-making.

3.1 Monitoring Well Network

The monitoring well network, which includes both injection-zone monitoring wells and monitoring wells installed above the primary confining zone, is designed to detect unforeseen leakage from the reservoir as soon after the first occurrence as possible. Two aquifers above the primary confining zone will be monitored, including the aquifer immediately above the confining zone (Ironton Sandstone) and the St. Peter Sandstone, which is separated from the Ironton by several carbonate and sandstone formations and is considered to be the lowermost USDW at the site (see Figure 2). Direct monitoring of the lowermost USDW aquifer is required by the U.S. Environmental Protection Agency's (EPA's) UIC Program for CO_2 geologic sequestration (75 FR 77230) and is a primary objective of this monitoring program. Wells will also be instrumented to detect changes in the stress regime (via pressure in all wells and microseismicity in selected wells) to avoid over-pressurization within the injection or confining zones that could compromise sequestration performance.

The monitoring well network will include two wells (SLR1 and SLR2) within the injection zone (Elmhurst/Mount Simon Sandstones), two wells (ACZ1 and ACZ2) within the first permeable interval immediately above the primary confining zone (Ironton Sandstone), one well (USDW1) within the designated lowermost USDW (St. Peter Sandstone), and three reservoir access tubes (RATs), which will be used to monitor CO_2 saturation in the reservoir and caprock. Well locations are shown in Figure 1 and a hydrogeologic cross section illustrating the relative position and depth interval of the various wells is shown in Figure 2. These wells will be used to continuously and directly monitor for changes in fluid pressure, temperature, and specific conductance (P/T/SpC), and will be routinely sampled to monitor for changes in aqueous chemistry, during the pre-injection, injection, and post-injection monitoring periods. Measurements at these locations will be compared with numerical model predictions and used to calibrate the model as necessary.

In addition to the five planned monitoring wells, there will be three RAT installations used to track the evolution of the CO_2 plume. The RATs are non-perforated, cemented casings used to monitor for CO_2 arrival and quantify saturation levels via downhole PNC (pulsed-neutron capture) geophysical logging across the reservoir and caprock. PNC logging is a proven method for quantifying CO_2 saturation around a borehole. These three monitoring installations are located at increasing distances from the injection site to provide measures of CO_2 saturation at the predicted 1-, 2- and 3- to 4-year arrival times, respectively. The three RAT installations are also distributed across three different azimuthal directions, providing CO_2 arrival information for three of the four predicted lobes of the CO_2 plume. These near-field CO_2 saturation measurements will allow for calibration of the numerical model early in the injection phase of the project and verify whether the CO_2 plume is developing as predicted. The RAT installations will continue to be monitored for the duration of the project to assess the potential for vertical migration of CO_2 into the caprock material.

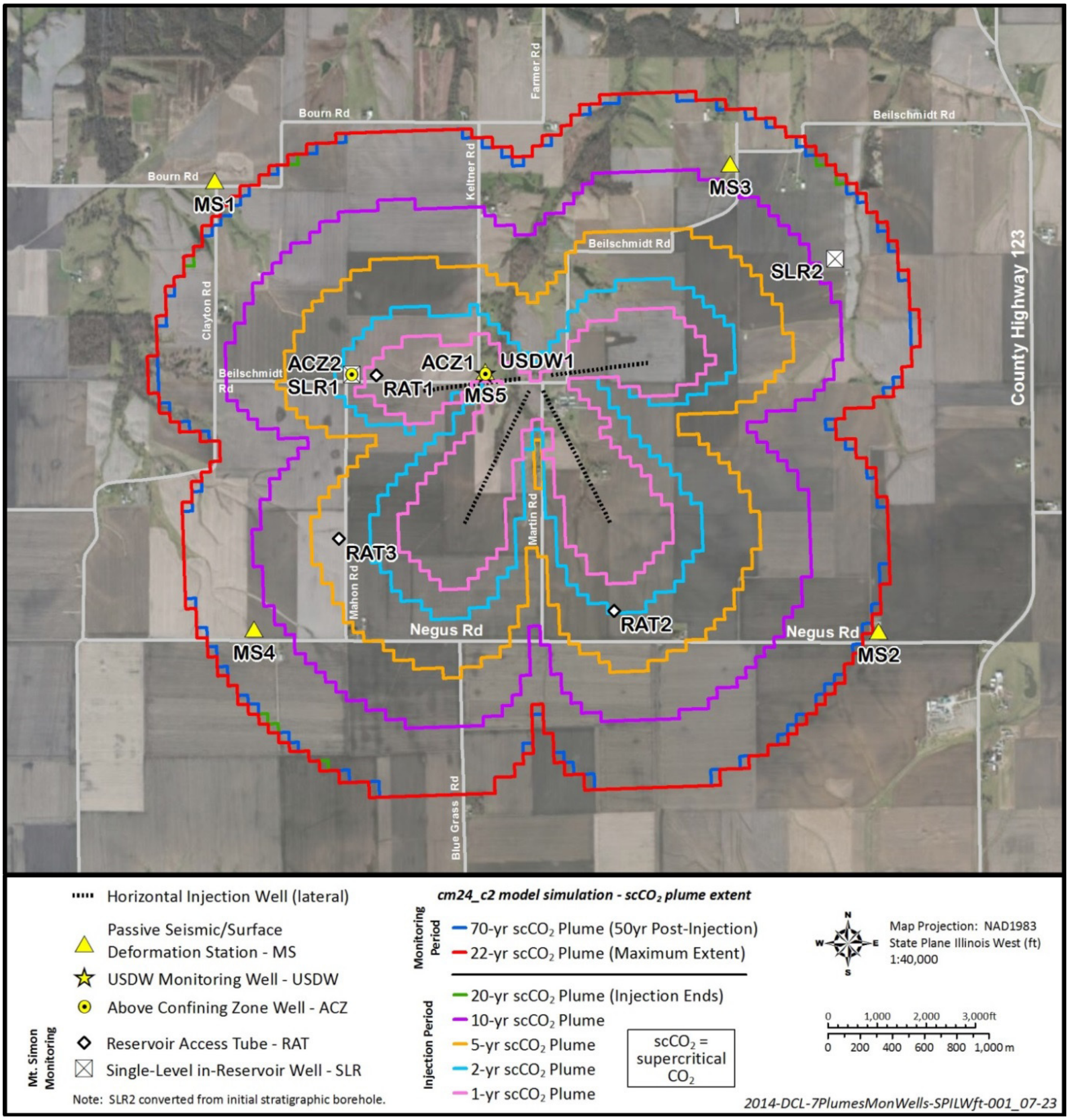

Figure 1. Nominal monitoring network layout and simulated $scCO_2$ plume.

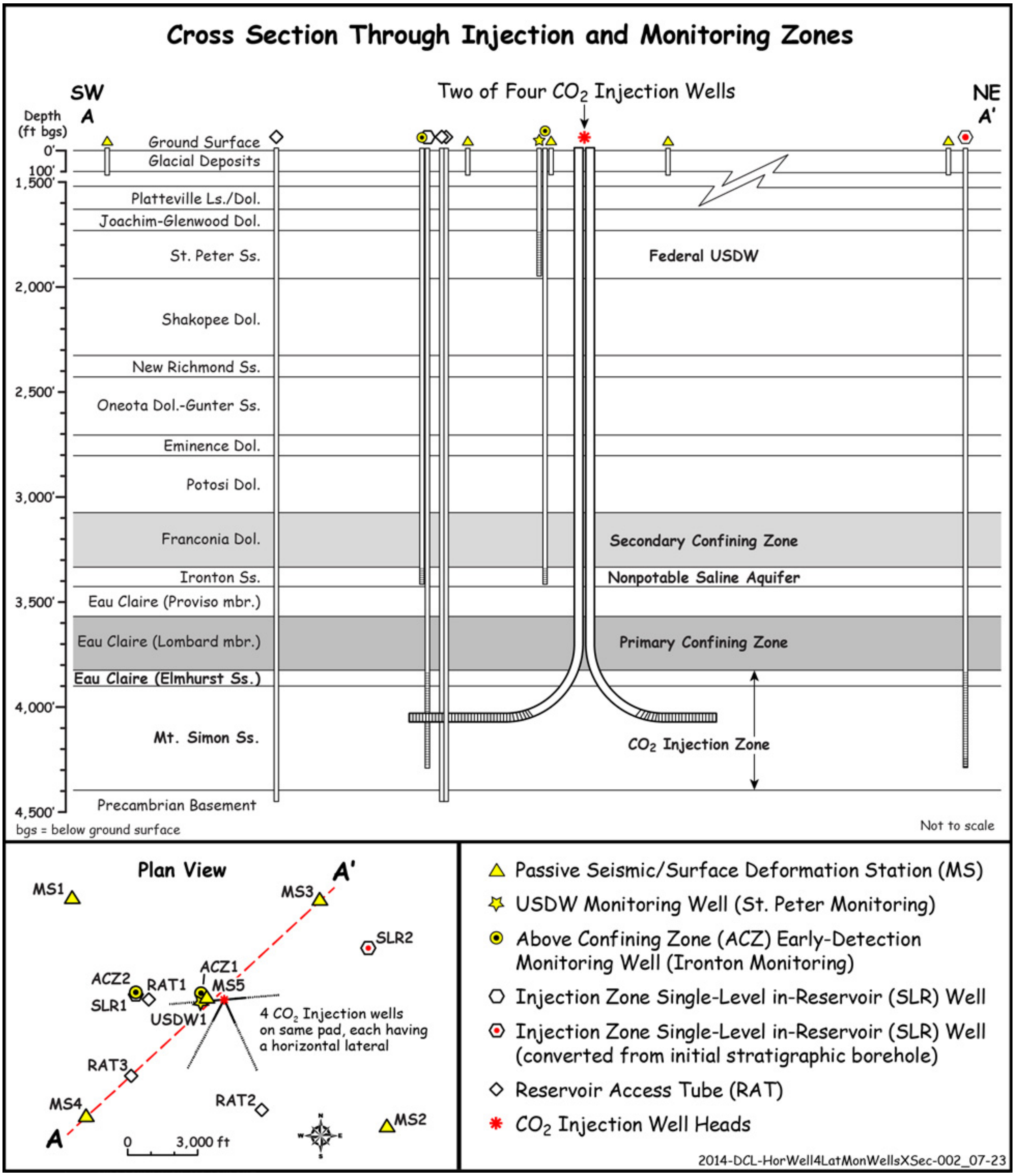

Figure 2. Cross-sectional view of the injection and monitoring well network.

3.2 Geophysical Monitoring Network

Geophysical monitoring methods are sensitive to subsurface conditions that can change as a result of changes in fluid saturation or pressure associated with CO_2 injection. Geophysical monitoring methods considered for the FutureGen 2.0 storage site included electrical resistivity tomography, passive seismic monitoring, two and three-dimensional (2D and 3D) surface seismic surveys, vertical seismic profiling, cross-well seismic imaging, time-lapse gravity, magnetotelluric soundings and controlled source electromagnetics, integrated deformation monitoring, and PNC logging. This comprehensive suite of technologies was evaluated with respect to site-specific conditions and subjected to a screening process; then suitable methodologies were selected for deployment as part of the monitoring program. This selection process considered the level of sensitivity, spatial resolution, the costs to install and operate, and potential interference with other monitoring activities. Technologies that were selected for implementation included passive seismic monitoring, time-lapse gravity, integrated deformation monitoring, and PNC logging.

Integrated deformation monitoring and passive seismic monitoring are two indirect monitoring techniques that will be used to detect and characterize development of the pressure front resulting from injection of CO_2. The objective of the deformation monitoring is to provide a means of detecting asymmetry in the CO_2 plume development and to help guide the adaptive monitoring strategy. The objective of the passive seismic monitoring network is to accurately determine the locations, magnitudes, and focal mechanisms of injection-induced seismic events with the primary goals of

- addressing public and stakeholder concerns related to induced seismicity,
- estimating the spatial extent of the pressure front from the distribution of seismic events, and
- supporting assessments of caprock integrity and the potential for containment loss.

Another indirect monitoring technique—PNC logging—will be the primary means of tracking the advancement and evolution of the CO_2 plume. Time-lapse gravity will provide additional low cost measurements that will supplement the PNC logs and support the assessment of plume evolution.

3.3 Near-Surface Environmental Monitoring Network

At the direction of the UIC Program Director, no surface or near-surface monitoring methodologies are included as a requirement of the Class VI Underground Injection Control permit. Even though near-surface monitoring is not required at the FutureGen 2.0 storage site, the Alliance has initiated several approaches, including surficial groundwater monitoring, surface-water monitoring, soil-gas monitoring, atmospheric monitoring, and an evaluation of spatiotemporal mapping of vegetation and surface conditions through remote sensing. Initially, only the collection of baseline data sets is planned, with the exception of atmospheric monitoring, which may continue throughout the life of the project. The need for additional near-surface monitoring approaches will be continually evaluated throughout the construction and operational phases of the project, and selected monitoring technologies may be reinstituted if conditions warrant. Given our current conceptual understanding of the subsurface environment, early and appreciable impacts on near-surface environments are not expected, so extensive networks of surficial aquifer, surface-water, soil-gas, and atmospheric monitoring stations are not warranted at this time.

4. Summary

The FutureGen 2.0 project has completed initial subsurface design work and is preparing to construct a geologic storage site capable of receiving up to 22 MMT of CO_2 at a rate of 1.1 MMT/yr (i.e., a 20-yr injection period, which will be followed by a 50-yr post-injection monitoring period). Integral to this storage site design is a testing and monitoring program that will be implemented to track and account for the mass of CO_2 injected, and that will protect underground sources of drinking water (USDWs) from storage related impacts. The FutureGen 2.0 project has selected and plans to implement a suite of monitoring technologies that are both technically sound and cost-effective, and provide an effective means of 1) evaluating CO_2 mass balance and 2) detecting any unforeseen containment loss. The monitoring program is comprised of both direct and indirect monitoring methodologies, including: 1) direct monitoring of the injection stream, reservoir, ACZ, and USDW monitoring zones and 2) indirect geophysical monitoring to provide a measure of CO_2 plume evolution/symmetry and to support assessment of the potential for injection related induced seismicity.

Acknowledgements

The FutureGen 2.0 project is supported by a $1 billion commitment in U.S. federal funding from the American Recovery and Reinvestment Act. The program is implemented under Cooperative Agreement DE-FE0001882 between the U.S. Department of Energy and the FutureGen Industrial Alliance, a non-profit membership organization created to benefit the public interest and the interests of science through research, development, and demonstration of near-zero emissions coal technology. Members of the Alliance include some of the largest coal producers, coal users, and coal equipment suppliers in the world. For more information on FutureGen 2.0, please visit www.futuregenalliance.org.

References

[1] Bonneville, A., T. J. Gilmore, E. C. Sullivan, V. R. Vermeul, M. E. Kelley, S. K. White, D. Appriou, B. N. Bjornstad, J. L. Gerst, N. Gupta, J. A. Horner, C. McNeil, M. A. Moody, W. M. Rike, F. A. Spane, P. D. Thorne, E. R. Zeller, Z. F. Zhang, J. Hoffman, and K. K. Humphreys. 2013. Evaluating the Suitability for CO2 Storage at the FutureGen 2.0 Site, Morgan County, Illinois, USA. Energy Procedia, 37, 6125-6132.

[2] Gilmore, T. J., A. H. R. Bonneville, V. R. Vermeul, F. A. Spane, M. E. Kelley, E. C. Sullivan, and J. Hoffman. 2014. Overview of the CO2 Geological Storage Site for the FutureGen Project in Morgan County Illinois, USA, GHGT12, this issue.

[3] Siegrist, Robert L., Michelle Crimi, and Thomas J. Simpkin. 2011. *In Situ Chemical Oxidation for Groundwater Remediation.* Vol. 3, of SERDP ESTCP Environmental Remediation Technology. Springer New York, 2011.

[4] Belcher, David M. and Kurt D. Sichelstiel. 1995. Case Study: the observational approach and fast-track remediation of NSB kings bay. Federal Facilities Environmental Journal, Vol. 6, No. 2, p. 77-90.

[5] Hudak, Paul F. and Hugo A. Loaiciga. 1992. A location Modeling Approach for Groundwater Monitoring Network Augmentation. Water Resources Research, Vol. 28, No. 3, p. 643-649.

[6] Alliance (FutureGen Industrial Alliance, Inc.). 2012. *Borehole Completion and Characterization Summary Report for the Stratigraphic Well, Morgan County, Illinois*. FG-RPT-015 Rev 1, Washington, D.C.

[7] Alliance (FutureGen Industrial Alliance, Inc.). 2013. *Underground Injection Control Permit Applications for FutureGen 2.0 Morgan County Class VI UIC Wells 1, 2, 3, and 4 – SUPPORTING DOCUMENTATION.* FG-RPT-017-Revision 1. Jacksonville, Illinois.