Available online at www.sciencedirect.com

SciVerse ScienceDirect

Energy Procedia 37 (2013) 4765 – 4773

Energy Procedia

GHGT-11

Quantification of Risk Profiles and Impacts of Uncertainties as part of US DOE's National Risk Assessment Partnership (NRAP)

Rajesh Pawar[a]*, Grant Bromhal[b], Robert Dilmore[b], Bill Foxall[c], Edwin Jones[c], Curtis Oldenburg[d], Philip Stauffer[a], Stephen Unwin[e], George Guthrie[b]

[a]*Los Alamos National Laboratory, Los Alamos, NM-87545, USA*
[b]*National Energy Technology Laboratory, Pittsburgh, PA-15236, USA*
[c]*Lawrence Livermore National Laboratory, Livermore, CA-94550, USA*
[d]*Lawrence Berkeley National Laboratory, Berkeley, CA-94720, USA*
[e]*Pacific Northwest National Laboratory, Richland, WA-99352, USA*

Abstract

The National Risk Assessment Partnership (NRAP) is a US-Department of Energy (US-DOE) effort focused on developing a science-based methodology for quantifying risk profiles at geologic CO_2 sequestration sites. Risk profiles are calculated using an integrated assessment modelling (IAM) approach which treats a geologic CO_2 storage site as a system and uses a system modelling approach to predict time-dependent behaviour of the storage site. We have developed first generation risk profiles associated with a few key potential impacts due to CO_2 leakage from a sequestration reservoir, including change in groundwater quality in a shallow aquifer and return of CO_2 to the atmosphere.

Keywords: NRAP; Risk Profiles; Risk Quantification; System Modeling; Integrated Assessment Model

1. Introduction

Ensuring that large-scale CO_2 storage is safe and effective requires predicting the long-term integrity of storage sites through a comprehensive consideration of potential site-specific risks. Risk assessment is an

* Corresponding author. Tel.: +1-505-665-6929; fax: +1-505-665-8737.
E-mail address: rajesh@lanl.gov.

1876-6102 © 2013 The Authors. Published by Elsevier Ltd.
Selection and/or peer-review under responsibility of GHGT
doi:10.1016/j.egypro.2013.06.386

integral part of risk management strategy that uses risk quantification results for designing monitoring and mitigation strategies to minimize risks. Risk assessment for CO_2 storage is an area of active investigation. Most efforts to date have relied on qualitative assessment of risks based on FEPs analysis, which relies on a catalogue of ***F***eatures of an engineered geologic system that impact its behaviour, discrete ***E***vents that can impact behaviour, and other ***P***rocesses that can influence its behaviour [1, 2, 3]. Quintessa has developed a detailed database of FEPs which has been adapted for geologic storage of CO_2 [4, 5]. The FEPs approach has also been the primary method for risk assessment used in most of the initial CO_2 storage efforts, such as Sleipner in Norway, Weyburn in Canada, In Salah in Algeria, Quest in Canada and many of the US Regional Carbon Sequestration Partnership efforts such as the Decatur Project in the Illinois basin.

Quantitative risk assessment goes beyond FEPs analysis to predict the long-term behaviour of a CO_2 storage site. FEPs analysis can be incorporated as part of a multi-step approach to integrate simulation and risk assessment:

- Develop site-specific conceptual models based on prioritized set of FEPs that can be used for identifying critical scenarios;
- Develop predictive models for the critical scenarios for simulations of the storage site response based on fundamental physical and chemical phenomena;
- Assessment of potential consequences resulting from the critical scenarios, which can include various health/safety/environment (HSE) risks as well as various non-HSE risks.

Above approach has been used in quantitative risk assessments of other applications including environmental applications. Predictive models can range from the process level numerical reservoir simulators to the system level models such as CO_2-PENS [6]. For both types of approaches, accurate quantification of the parameters and process models that describe the engineered geologic system is fundamental to the quality of the simulation and prediction. For geologic systems, the parameters describing a system have uncertainty associated with them. Consequently, uncertainty quantification (UQ) is a critical element of environmental risk assessments. Refsgaard, van der Sluijs, and coworkers [7, 8, 9] present detailed assessments of uncertainties and methodologies for natural systems. Many efforts are underway internationally to develop various components of these risk assessment tools for CO_2. Many of these efforts are actively engaged in the International Energy Agency Greenhouse Gas Programme's (IEA-GHG) Risk Assessment Network, which is an international forum for scientific experts to identify technical needs related to CO_2 risk assessment.

The concept of risk profiles for using risk assessment to quantify potential long-term liabilities was introduced by Benson [10]. Risk profiles provide a time evolution of the probability of a particular risk, thereby allowing an assessment of the risk integrated over a period of time (for example, post closure). Benson noted that potential risks associated with CO_2 storage will be time dependent, largely tracking the evolution of reservoir pressure in response to injection and post-injection recovery and trapping mechanisms. Consequently, Benson predicted that environmental risks will peak with injection and decline as the sequestration reservoir pressures recover and various near-term and long-term trapping mechanisms come into play. The risk-profile concept has proven very useful in conveying the predicted qualitative evolution of risks. However, the validity of these profiles across a wide range of sites has yet to be confirmed. Quantification of risk profiles is a necessary component in the context of a technical basis for long-term liability. However, no defensible, robust methodology has been developed for quantification of risk profiles for CO_2 storage.

1.1. NRAP

The National Risk Assessment Partnership (NRAP) is a US-Department of Energy (US-DOE) effort focused on developing a defensible methodology quantifying risks at geologic CO_2 sequestration sites. NRAP is made up of five US-DOE national laboratories including Los Alamos National Laboratory (LANL), Lawrence Berkeley National Laboratory (LBL), Lawrence Livermore National Laboratory (LLNL), National Energy Technology Laboratory (NETL) and Pacific Northwest National Laboratory (PNNL). NRAP is developing a science-based methodology for quantifying risks at storage sites and demonstrating it through calculation of risk profiles.

There is broad international consensus on the main types of risks and adverse impacts that could be associated with the long-term storage of CO_2. NRAP is initially focusing on risk profiles associated with several key potential impacts, including,

- Return of CO_2 to the atmosphere,
- Groundwater quality, and
- Reservoir stress that could have adverse impacts on the geosphere.

In general, NRAP is relying on the use of an Integrated-Assessment-Model (IAM) approach, whereby, the site's behaviour is predicted stochastically at the system level but these predictions are based on detailed physical and chemical descriptions of key subsystems at the site using a variety of process-level simulators and/or analytical expressions that represent abstractions (when appropriate). This approach provides the necessary science-basis to the risk quantification approach. The IAM is used to assess long-term performance of a sequestration system in order to predict the potential for a specific event or condition to occur, which can then be coupled with a quantification of the event's consequence/impact to derive the risk. While NRAP is focusing on multiple risk profiles as mentioned above, this paper is primarily focused on risk profile related to return of CO_2 to the atmosphere.

2. Integrated Assessment Model (IAM)

Development of science-based predictive tools for risk assessment is challenging given the scale and complexity of storage sites. An individual storage site may have a footprint on the order of 100s of km^2, and the need to consider the behavior of the site's system from the sequestration reservoir to potential receptors results in a large volume ($>10^3$ km^3) that must be addressed in the predictions that may depend on processes occurring at the nano-scale. Given this scale its challenging to use a single model to predict site-scale behavior based on key processes even at the continuum-scale. Additionally, predicting behaviour of multiple heterogeneous natural systems based on a single, site-scale deterministic model is not possible.

Consequently, a standard approach in quantitative environmental risk assessment is to treat the overall site as a group of coupled subsystems, each of which embodies a unique set of physical and chemical characteristics and processes. This approach assumes that these subsystems can be treated without implicit coupling (i.e., they can be treated independently, addressing subsystem coupling explicitly by integrated assessment model). Such models are analogous to predicting the behavior of an industrial facility by independently predicting the behavior of individual components that are linked via an engineering system model. For quantifying risk profiles, NRAP is exploiting an integrated-assessment-modeling approach based on breaking the storage site into subsystems as illustrated in Figure 1: storage reservoir; potential release mechanisms through wellbores or natural seals; potential receptors (or impact categories).

We are using the CO_2-PENS model [6], developed with the Goldsim® software package, for building the IAM. GoldSim is a commercially available system modeling package which has been tailored with the unique needs of engineered geologic systems in mind, particularly, uncertainty and heterogeneity. Various approaches can be used to build and implement models for system components using Goldsim.

These include analytical expressions, lookup tables, and dynamic link libraries (DLLs) for external executables including process-level models.

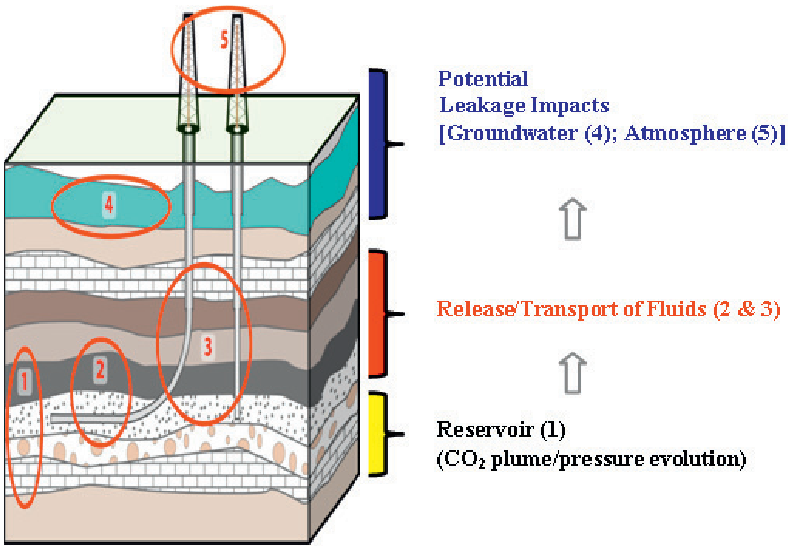

Fig. 1. Sub-systems within IAM structure being developed by NRAP.

The system component models can be executed within a Goldsim model using parameters that are sampled randomly from pre-defined distributions. Within an IAM, the system components are connected so as to capture the various inter-component interactions at a CO_2 storage site. For example, the component model for the sequestration reservoir is connected to the component model for a wellbore and the component model for the wellbore is connected to the one for the shallow aquifer, and so on. The inter-component connections are used to capture the mass transfer or pressure transfer between components.

As noted above, in this paper we are focused on the release of CO_2 to the atmosphere. However, the underpinning IAM for this is also used to assess other potential risks due to leakage, including those due to movement of CO_2 and/or brines out of the reservoir. Quantification of these risks requires an IAM that can be used to predict CO_2/brine movement at a sequestration site over a time period of interest which can be potentially of the order of 100s of years. We used various approaches to build models to describe behavior of storage site sub-system components mentioned above, including, sequestration reservoir, wellbores and aquifers. Our approach to this IAM is briefly described below.

2.1. IAM Component models

The objective of developing the component models is to capture the physical and chemical interactions that will take place as a result of CO_2 injection or migration within the components. In an IAM these models are used to predict how the individual component will behave over a time period of interest. Various approaches can be used to develop component models ranging from abstractions based on detailed process-level simulations to direct incorporation of process simulation results. Our approaches to develop these component models are described below.

- Sequestration reservoir: The IAM reservoir model is used to predict time-dependent changes in reservoir pressure and saturation as the result of CO_2 injection. We used a look-up table approach in which results of detailed reservoir simulations were directly linked as look-up tables. The reservoir simulation model was based on the Kimberlina reservoir in southern San Joaquin basin in California. It is a saline aquifer that is currently being studied as a potential carbon sequestration site. The target reservoir is a sandstone formation. A detailed geologic model was developed for the reservoir and was subsequently used to build a numerical simulation model in LBL's TOUGH2 reservoir simulator. The numerical model was used to perform multiple simulations of large-scale CO_2 injection for 50 years at a rate of 5 million tons/year. Each of the simulation runs was performed for 200 years including 150 years of post-injection relaxation. In all 300 simulation runs were performed to capture the effect of variability in three reservoir parameters including porosity and permeability of target reservoir and permeability of caprock. Sensitivity analysis on these parameters was used to further reduce the 300 runs in 54 representative runs that captured the effect of variability in the reservoir parameters. The time and space-dependent reservoir pressure and saturation results for these 54 runs were brought in the IAM as look-up tables. Each one of the runs was associated with the representative reservoir permeability and porosity and caprock permeability values, such that during the Monte-Carlo calculations a reservoir simulation run can be selected based on a set of the values of uncertain parameters selected for a realization.
- Wellbores: The IAM wellbore model is used to calculate the CO_2/brine flow rate through wellbores as a function of the wellbore properties and the pressure and saturation at the reservoir-wellbore boundary. For cemented wellbores, we used LANL's FEHM simulator to measure CO_2 and brine flow rate up a10-cm diameter wellbore, initially containing 100% brine, for 1500 cases with varying wellbore depth, wellbore cement permeability, pressure and saturation at the reservoir-wellbore interface. We assumed that wellbore cement extended over the entire length of wellbore. Input parameter distributions were generated using a Latin Hypercube Sampling (LHS) scheme in LLNL's PSUADE (Problem Solving environment for Uncertainty Analysis and Design Exploration). The results of 1500 FEHM leakage simulation runs were used in PSUADE to generate higher resolution response surfaces for CO_2 and brine leak rate using a MARS (multi-variate adaptive regression spline) fitting scheme. The response surfaces were converted into a multi-dimensional lookup table for IAM. For open wellbores, we used the drift-flux model in LBL's TOUGH2 simulator to perform simulations of CO_2 leakage through open wellbores. In all, 250 simulation runs were performed by varying wellbore-reservoir boundary pressure, saturation and wellbore depth. The simulated CO_2 and brine leak rates from these runs were converted into a 3-dimensional lookup table for IAM. It should be noted that both the FEHM and TOUGH2 simulations took into account the complexities of CO_2 phase change during leakage from deeper reservoirs (where CO_2 typically exists in super-critical state) to shallow aquifer or atmosphere (where CO_2 typically exists in gaseous state).
- Shallow aquifers: The IAM shallow aquifer model is used to calculate changes in the pH and concentration of total dissolved solids (TDS) in shallow aquifer due to CO_2 and brine leakage. We developed reduced order models (ROMs) using LLNL's PSUADE package coupled with results of detailed simulations using process-level models including LANL's FEHM, LLNL's NUFT and PNNL's STOMP. We developed two reduced-order-models, one for a confined sandstone aquifer and

the second for an unconfined carbonate aquifer. For the sandstone aquifer, a numerical simulation model based on the data for High Plains Aquifer in United States was developed using LLNL's NUFT simulator. For the carbonate aquifers, numerical simulation models based on the data for Edwards' Aquifer in United States were developed using LANL's FEHM and PNNL's STOMP simulators. These numerical models were used to simulate changes in the pH and TDS in the aquifers due to CO_2 and brine leakage in the aquifers. A set of Monte-Carlo runs were performed by varying values of multiple uncertain parameters, including, aquifer hydraulic properties and geochemical properties. Results of the Monte-Carlo simulations were used to develop ROMs for various quantities of interest using LLNL's PSUADE package. These included dimensions of pH and TDS plumes in shallow aquifer and CO_2 leakage rate out of the aquifer. The ROMs had forms of higher-order polynomial functions of the uncertain parameters. These ROMs were linked using DLLs that can plug in to to the IAM developed in Goldsim.

The component models described above were incorporated in the IAM and the IAM was used to calculate risk profiles. While to date we have computed risk profiles for groundwater quality as well as CO_2 return to the atmosphere, for the purpose of this paper only the for the later are provided.

3. Risk Profile Calculations and Results

The risk profiles were calculated using the IAM to perform Monte-Carlo simulations of CO_2 release to the atmosphere. We assumed a hypothetical CO_2 sequestration site with a target reservoir similar to the Kimberlina reservoir but using a set of leakage pathways that are not applicable to the real site. Specifically, our primary leakage scenario included leakage through hypothetical cemented wellbores that penetrated the storage reservoir, using various numbers, distributions, and permeabilities of the wellbores that represented a range of potential storage site scenarios. Each of the Monte-Carlo realizations simulated performance of a CO_2 storage site over 200 years, which included 50 years of CO_2 injection at 5 million tons/year followed by 150 years post-injection relaxation. Each Monte-Carlo run included 750–1000 realizations, sampling a number of uncertain parameters including:

- Sequestration reservoir permeability and porosity, caprock permeability
- Wellbore cement permeability, wellbore location, wellbore spatial density

We used multiple different distributions of wellbore cement permeabilities. These distributions were generated based on various sources of data including the sustained casing vent flow and sustained casing pressure data reported for wells in Alberta and Gulf of Mexico, and two permeability distributions based on the low and high wellbore leakage probabilities used in the Environmental Impact Statement (EIS) for FutureGen application [11]. For each of the distributions we performed a separate set of Monte-Carlo runs. The wellbore spatial density was varied between the densities observed at typical oil/gas fields (~ 6–10 wells/km^2) to a density consistent with a saline formation in an area where no prior oil/gas production activity has taken place (1well/100 km^2).

Figure 2 shows the example results for calculated CO_2 leak rates for several individual realizations in one of the Monte Carlo simulations. The scenario includes wellbores with cement permeabilities sampled from a distribution derived from ranges reported in the EIS developed for a potential storage site for FutureGen and wellbore spatial density similar to that of a mature oil/gas field (10 wells/km^2). The results show that the CO_2 leak rate is dominated by leak characteristics from individual wells, with rate increasing as the reservoir plume intersects a well either during injection or following injection. The net effect is an average probabilistic stochastic leak rate that rises during the injection period and levels off (at least through the 150 years of relaxation that is considered in the simulations. Results of the Monte-Carlo simulations were used to calculate the risk profiles by calculating the probability that the cumulative leak rate exceeds certain cutoffs which will result in failing various CO_2 retention goals such as the IPCC storage goal.

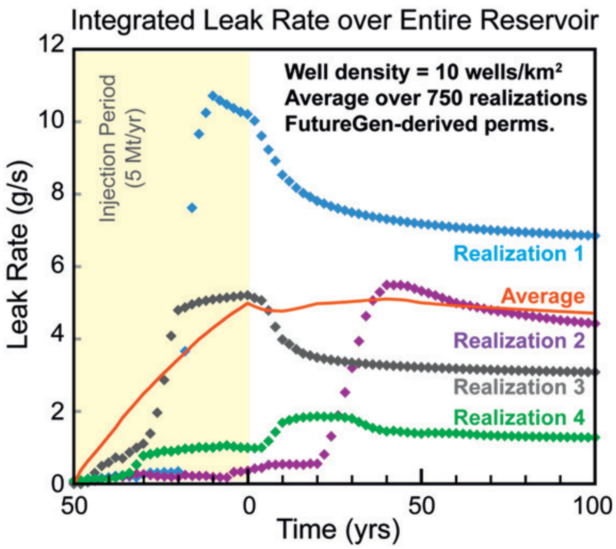

Fig. 2. Example leak rate curves computed using the IAM during a Monte-Carlo calculation.

Figure 3 shows an example of the utility of the computed risk profiles. The example demonstrates effect of wellbore spatial density on the percent of CO_2 retained in a sequestration reservoir over 100 years. The wellbore spatial density was varied between that for typical mature oil/gas fields and very low spatial density. The figure also shows the IPCC storage goal of 99% retention for reference. In addition, the figure shows result of the calculation of 1 year of leakage through an open well for reference. (It should be noted that the open well calculation was performed using a different wellbore model that is applicable to the flow conditions in a non-cemented well.) A continuously leaking open well for one year is an unlikely scenario because it could be readily detected and repaired. However, the data point is shown to provide a comparison to an extreme, end-member scenario; further, the calculations are expected to represent a worst-case, in that the reservoir model did not account for trapping mechanisms (which would limit flow over time). Results on Figure 3 demonstrate that for the type of sequestration system considered in our computation it is possible to meet the storage retention goals over the type of time period considered.

3.1. Uncertainty quantification calculations

We performed uncertainty analysis for the atmospheric CO_2 leak rate. Our ultimate goal for uncertainty analysis is to identify what uncertain parameters have most influence on the various risks and use the results for developing strategies to minimize uncertainties and mitigate risks. As mentioned above, the uncertain variables in calculations for risks of CO_2 leakage to atmosphere included reservoir parameters (reservoir sand permeability, sand porosity and caprock permeability) and wellbore cement permeability. We used multi-variate analysis to determine how the uncertain variables impact the atmospheric CO_2 leak rate. Table 1 shows the computed correlation coefficients through multi-variate analysis.

Table 1. Correlation coefficients for uncertainty analysis of atmospheric CO_2 leak rate.

Variable	Correlation coefficient
Wellbore cement permeability	0.869
Caprock permeability	-0.020
Sequestration reservoir porosity	-0.072
Sequestration reservoir permeability	-0.104

As can be seen from the Table, wellbore cement permeability has a strong influence on the CO_2 leak rate for the sites considered. This is not a surprising result, given that the primary leakage pathway is wellbore and the leak rate through wellbore is strongly influenced by cement permeability. It should also be noted that we assumed that the wellbores are directly connected between sequestration reservoir and the atmosphere and there are no other intermediate formations where leaked CO_2 can be retained preventing it from going to the atmosphere.

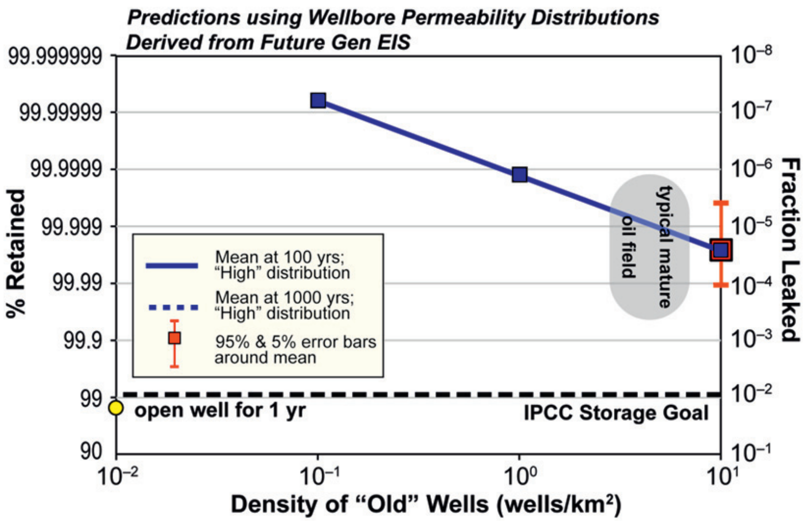

Fig. 3.Effect of wellbore spatial density on amount of CO_2 retained and fraction of CO_2 leaked out of sequestration reservoir.

4. Conclusions and Future Work

As part of the National Risk Assessment Partnership (NRAP) we are developing a science-based approach that can be used for quantitative risk assessment. We are using this approach to compute and validate risk profiles for CO_2 storage sites. We have computed first generation of risk profiles for risks associated with CO_2 leakage. While the risk profiles computed to date are limited in that they do not capture all the underlying processes at a sequestration site, our efforts are helping us identify steps necessary to compute the comprehensive risk profiles. We are using the risk profiles computed to date to address some of the important questions about long-term effectiveness of CO_2 storage sites. In future we will be increasing the comprehensiveness of risk profiles, by incorporating most of the important processes and parameters in our computations. We will demonstrate the comprehensiveness of our approach through application to a wide range of sequestration sites.

Acknowledgements

This work was completed as part of National Risk Assessment Partnership (NRAP) project. Support for this project came from the Crosscutting Research program of the Office of Fossil Energy in the U.S. Department of Energy.

References

[1] Cranwell RM, Guzowski RV. Risk methodology for geologic disposal of radioactive waste: scenario selection procedure. Report of US Nuclear Regulatory Commission NUREG/CR-1667 (SAND80-1429), NRC Washington DC, 1982.

[2] Chapman NA, Andersson J, Robinson P. Systems analysis, scenario construction and consequence analysis definition for SITE-94. Swedish Nuclear Power Inspectorate Report No. 95:26, Stockholm, Sweden, 1995.

[3] Nirex. Overview of the FEP analysis approach to model development. UK Nirex Report S/98/009, 1998.

[4] Savage D, Maul PR, Benbow S, Walke RC. A generic FEP database for the assessment of long-term performance and safety of the geological storage of CO_2. Quintessa Report QRS-1060A-1, 2004, 73 p. (www.co2captureandstorage.info/docs/QuintessaReportIEA.pdf).

[5] Maul PR, Savage D, Benbow SJ, Walke RC, Bruin R. Development of a FEP database for the geological storage of carbon dioxide. In: Wilson, M., Morris, T., Gale, J., Thambimithu, K. (Eds.), Proceedings of the Seventh International Conference on Greenhouse Gas Control Technologies; 2005, Vancouver, Canada, p. 701–710.

[6] Stauffer PH, Viswanathan HS, Pawar RJ, Guthrie GD. A system model for geologic sequestration of carbon dioxide. *Environmental Science & Technology* 2009; **43 (3)**: 565-570.

[7] van der Sluijs. Uncertainty and precaution in environmental management: Insights from the UPEM conference. *Environmental Modelling & Software* 2007; **22**:590–598.

[8] Refsgaard JC, van der Sluijs JP, Brown J, and van der Keur P. A framework for dealing with uncertainty due to model structure error. *Advances in Water Resources* 2006; **29**:1586–1597.

[9] Refsgaard JC, van der Sluijs JP, Hojberg AL, Vanrolleghem PA. Uncertainty in the environmental modelling process—A framework and guidance. Environmental Modelling & Software 2007; **22**:1543–1556.

[10] Benson S. Addressing Long-term Liability of Carbon Dioxide Capture and Geological Sequestration. World Resource Institute (WRI) Long-term liability Workshop, June 7th, 2007. Washington D.C. available: http://www.iepa.com/ETAAC/ETAAC Handouts 8-8-07/2007 June 5 liability workshop summary final K Davis.pdf

[11] Futuregen Project Final Impact Statement, DOE/EIS-0394. available: http://www.netl.doe.gov/technologies/coal/power/futuregen/eis