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Stochastic leakage estimates from a carbon storage reservoir using NRAP-Open-IAM

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Abstract

Definition of permanent carbon sequestration varies among different regulating agencies around the world. In California, one requirement to obtain the California Air Resource Board's (CARB) Certificate of Permanence for a carbon sequestration project is to demonstrate that with greater than 90% probability, more than 99% of the sequestered carbon dioxide (CO_2) will remain sequestered for 100 years after the end of the injection phase.

This paper demonstrates how the U.S. Department of Energy’s (DOE) National Risk Assessment Partnership’s (NRAP) Open-source Integrated Assessment model (NRAP-Open-IAM) can be used to demonstrate permanence. NRAP-Open-IAM is an open-source software product developed by a consortium of five national laboratories (National Energy Technology Laboratory (NETL), Los Alamos National Laboratory, Lawrence Berkely National Laboratory, Lawrence Livermore National Laboratory, and Pacific Northwest National Laboratory). It is free, fast, and contains modules that can model most leak paths. This work only addresses the multisegmented wellbore component of NRAP-Open-IAM.

One concern with running Monte Carlo simulations to assess geological carbon storage risk is whether the methodology is fast enough to be practical. The NRAP-Open-IAM framework/methodology is sufficiently fast to allow for Monte Carlo simulations to quantify uncertainty for the purpose of demonstrating containment per CARB requirements.

The proposed methodology is as follows. Using a detailed simulation model, full field simulation of the injection phase and 100 years post-injection phase of the project is initially performed. From the results, a representative well is selected and the pressure and saturation profile at the location are extracted. These profiles are then used as inputs to NRAP-Open-IAM’s multisegmented wellbore component. NRAP-Open-IAM is used to generate many realizations of a typical abandoned well. A supplemental Monte Carlo

simulation is run to scale up the type well to full field. Statistics obtained from the Monte Carlo simulation are used to demonstrate whether CARB's Certificate of Permanence requirement is met.

Introduction

In carbon capture and storage (CCS) projects involving prior artificial penetrations into the storage reservoir, assessing confinement risk posed by existing (legacy) wells is a major consideration. Confinement risk assessment and the definition of permanent sequestration of CO_2 in CCS projects varies among different regulating agencies around the world. However, most U.S. state and foreign regulatory frameworks do not require the quantification of a project's containment risk. One exception is the California Air Resources Board (CARB). To qualify for California's Low Carbon Fuel Standard (LCFS) credit, the CCS project must obtain a Certificate of Permanence from CARB. To qualify for a Certificate of Permanence, the project needs to demonstrate that the fraction of CO_2 retained in the storage complex is very likely (greater than 90% probability of occurrence) to exceed 99% over 100 years post-injection.

Demonstrating that a CCS project meets the Certificate of Permanence criterion can be challenging due to uncertainty in the values of some parameters. Large numbers of sensitivity simulations need to be performed to account for data uncertainty and availability. Detailed simulation models are impractical when stochastic analyses are required.

National Risk Assessment Partnership (NRAP),[1] a consortium of five U.S. national laboratories, created NRAP-Open-IAM, an open-source software product that enables quantification of containment effectiveness at storage sites in the context of system uncertainties and variability. NRAP-Open-IAM represents the next-generation in a line of systems-based computational models developed for quantitative geological carbon storage (GCS) risk assessment. As stated by NRAP, the model comprises a set of reduced-order and analytical models of various components of the GCS system, potential leakage pathways, receptors of concern including impact to groundwater resources and the atmosphere, a framework to support stochastic simulation, time stepping, uncertainty quantification, other analytical functionality for scenario and risk-performance evaluation, and a basic graphical user interface to support scenario development, data input simulation definition, and basic post-processing and results display.

One of the key advantages of NRAP-Open-IAM is that it is fast and computationally efficient. Its strengths include its in-built modules for modeling CO_2 injection into aquifers and wellbore models, which enables users to analyze containment risk and the risk to underground sources of drinking water (USDW) and quantify any resulting contamination. The product has certain limitations if a project concerns injection into stacked storage reservoirs, when modeling injection below depleted oil and gas reservoirs, and when analyzing the risk of atmospheric leakage, however, all of these can be overcome.

In this paper, we discuss a methodology for performing a quantitative risk assessment for a CCS project using NRAP-Open-IAM. To overcome limitations of the NRAP-Open-IAM tool, simplified, conservative approximations are applied. Similarly, with this methodology, the number of stochastic variables can be reduced by assuming conservative data values. For example, the pressure throughout a sequestration reservoir can be assumed to be equal to the maximum pressure seen by the legacy well set and the reservoir fluid at maximum gas saturation. If the CCS site meets the permanence criteria with these conservative assumptions, the analysis can be considered sufficient. The potential consequence of this expedient approach is that it may over-estimate the leakage risk. If the estimated risk to containment is above the acceptable limit, it will be necessary to refine the conservative assumptions to be closer to actual field conditions. For instance, the actual evolution of CO_2 saturation and pressure with time at the location of the

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[1] The National Risk Assessment Partnership (NRAP) is a multi-national laboratory collaborative research effort leveraging broad technical capabilities across the DOE complex to develop the integrated science base, computational tools, and protocols required to quantitatively assess and manage environmental risks at geologic carbon storage sites. NRAP involves five DOE national laboratories: NETL, Los Alamos National Laboratory (LANL), Lawrence Berkeley National Laboratory (LBNL), Lawrence Livermore National Laboratory (LLNL), and Pacific Northwest National Laboratory (PNNL).

applicable wells will have to be considered. Thief zones and effective leak path permeability distributions will need to be refined. A reduced order model for a hydrocarbon dissipation layer may need to be introduced. The rest of this paper illustrates how this methodology can be applied to NRAP-Open-IAM to determine whether a CCS site meets CARB's containment criteria for qualifying for a Certificate of Permanence. The results shown are for illustrative purposes for a hypothetical reservoir.

Risk Assessment Paths

A risk assessment begins with identifying the potential leak paths. A path is defined as any continuous path connecting the source (sequestration zone) to the sink (USDW or atmosphere). Potential contributors to a leak path include the following:

- Caprock fractures or faults that may open to allow CO_2 to escape the complex. This is unlikely so long as injection projects will be operated below fracture pressures with safety margins and sites with thick caprocks will be selected for storage.
- Earthquakes may cause faults to reopen and casings to fail, leading to leakage of CO_2 from the complex. This risk is best addressed with a well thought out contingency plan and periodic drills. For sites with low seismicity and no active faults, this should not be a concern.
- Another group of potential paths is associated with the project wells and operations. The risk associated with operational issues (blow-out, equipment failures, accidents, etc.) are addressed through robust operation and mitigation plans.
- CO_2 may leak up the interior of the casing. It will be assumed that internal barrier elements (cement plugs) are properly placed inside the casing or remediated so that leakage up the interior of the casing is negligible. This path is excluded from the assessment.
- CO_2 may leak up the annulus formed by the formation and the casing, through de-bonded or cracked cement, or due to the absence of cement. This is the path that will be assessed in this work.

Using NRAP-Open-IAM for a CCS site risk assessment

NRAP-Open-IAM is a collection of modules built by a consortium of five U.S. national laboratories to improve quantitative containment risk analysis. These modules are correlations, reduced order models, table lookups, and analytical solutions calibrated to detailed simulations and data from basins in Alberta, Canada, and the Gulf of Mexico and the FutureGen 2.0 site. The model considers stratigraphic and structural trapping and disregards long-term sequestration effects such as mineralization/solubility trapping. This approach to modeling is reasonable because it is conservative and the period of investigation spans 100 years post-injection, during which long-term trapping mechanisms do not contribute to confinement.

It warrants note that unlike detailed simulation models, NRAP-Open-IAM's improved runtime efficiency makes it practical for use with Monte Carlo simulations and stochastic analyses. Moreover, this improved runtime is achieved without compromise to the accuracy of the risk assessment. It should not be assumed that detailed simulation models are superior because they are more complex, as the data values required to realize the benefit of such complexity are generally not known with the requisite degree of accuracy.

The NRAP-Open-IAM user guide (Vasylkivska, et al., 2022) provides an overview and list of the inputs and outputs of each of the available modules in NRAP-Open-IAM. Each of the modules cites additional references that go into greater detail. For further details on a module (e.g., underlying algorithms), users can refer to NRAP-Open-IAM's source code.

Each of the NRAP-Open-IAM modules have a set of requirements. For example, the Multisegmented Wellbore module used to demonstrate the application of the methodology for purposes of this paper requires all sands to be aquifers. For NRAP-Open-IAM to integrate all these modules, it forces all NRAP-Open-IAM models to meet certain requirements even if the module that needs these requirements is not being used. The following is a partial list:

- Alternating shale/sand sequence
- A minimum of three sets of shale/sand sequence with the deepest sand being the "reservoir," where the CO_2 is injected
- All sands are aquifers
- The pressure at the top of the topmost shale is 11.6 to 40 psia

Sands are layers that can sequester CO_2 and shales are layers that can confine CO_2. Figure 1 below depicts the minimum configuration assumed by NRAP-Open-IAM.

NRAP-Open-IAM in the LHS (Latin Hypercube Sampling) mode accepts input data as a statistical distribution. It efficiently samples the input variable space to generate many possible realizations that honor the statistical distribution of the input variables. The LHS mode is used for this stochastic analysis methodology.

For assessing containment risk, only the Multisegmented Wellbore module is needed. For this module, the cement is assumed to span the entire shale layer as depicted in Figure 1. The wellbore is assumed to be an open hole.

The Multisegmented Wellbore module solves a one-dimensional Darcy's flow equation in the vertical direction. This module also calculates the flow between the aquifer and the wellbore using Theis' equation. Theis' equation is invalid for sands that are depleted reservoirs.

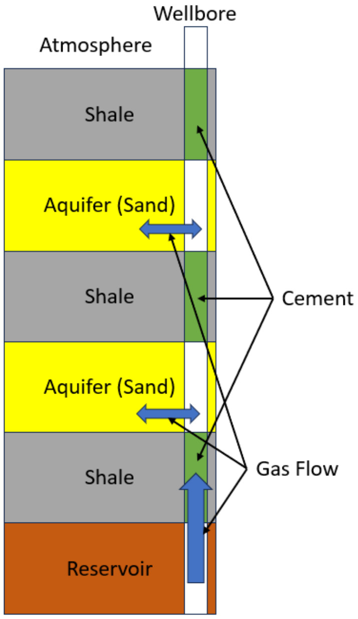

Figure 1. Open-IAM minimum configuration

Figure 2 shows the simplified and conservative stratigraphic column for a hypothetical CCS site. The sands are depleted reservoirs and there are only two shale layers. The required third shale layer at the top of the stack is missing as it is an unconfined shallow aquifer. The task is to convert the problem shown in Figure 2 into the problem shown in Figure 1 which can be solved by NRAP-Open-IAM using some conservative assumptions.

The first conservative assumption is to count any CO_2 above the reservoir as having escaped the CCS complex.

The second conservative assumption is to neglect the cement above the Upper Confining shale. This is done by assigning high permeability values to it. With these two conservative assumptions, the analysis is reduced to assessing flow at the Upper confining zone interphase, which is what is required to assess confinement. A one-meter-thick layer of shale can be added to the top of the stratigraphic column without affecting the problem. The problem depicted in Figure 2 can thus be transformed into the form required by NRAP-Open-IAM. Because the layers above the caprock are irrelevant to the analyses and therefore ignored, their properties are unimportant. Any reasonable values that pass NRAP-Open-IAM data validation can be used.

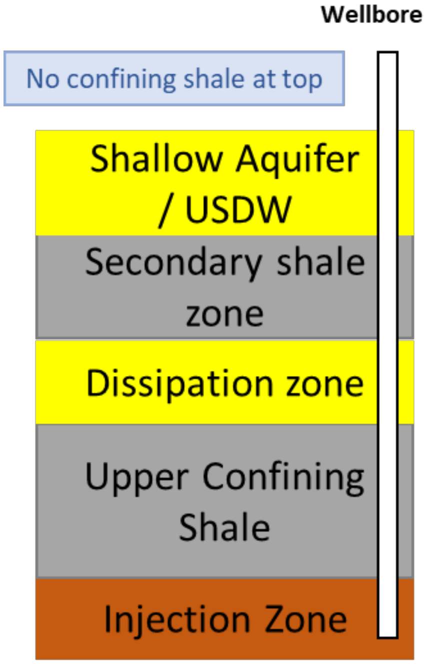

Figure 2. Simplified stratigraphic column for a hypothetical CCS site

The next step is to gather the data needed by NRAP-Open-IAM and its Multisegmented Wellbore model:

- The reservoir pressure and saturation over the injection period and 100 years after end of injection
- The thickness of the layers
- The CO_2 and brine PVT properties
- Fraction of the cement sheath in the caprock with good Cement Bond Log (CBL)
- The effective permeability of the cement sheath

NRAP-Open-IAM allows a few different ways to incorporate reservoir saturation and pressure into the Multisegmented Wellbore model. Typically, in early risk assessment, a flat maximum pressure and saturation can be assumed. Another option is to use one of NRAP-Open-IAM's reservoir modules. An advantage of NRAP-Open-IAM is that it can also take the pressure and saturation results from a detailed dynamic simulation as the input to the Multisegmented Wellbore module and would be the recommended option for this methodology. To reduce the stochastic variables, the maximum pressure and saturation seen among the legacy wellbore set in the detailed dynamic simulation can be used as the input to the NRAP-Open-IAM model.

The thickness of the layers can vary from well to well, so the statistical distribution of the thickness is input to the model.

NRAP-Open-IAM uses a constant CO_2 and Brine density and viscosity. The program allows stochastic input for properties, but to be conservative, the density and viscosity at reservoir temperature and pressure can be used.

The effective permeability of the cement sheath used is based on literature (Carey, et al., 2007) (Crow, Williams, Carey, Celia, & Gasda, 2009).

Carey, et al. examined the condition of the cement and casing in a well in an EOR field after exposure to CO_2 for 30 years. The Cement Bond Log (CBL) showed good cement bond. Carey et al. found that the casing in the reservoir showed no signs of corrosion or metal loss. The cement in the reservoir showed signs of CO_2 damage near the cement-formation interface but it remained intact and still provided hydraulic seal and protection for the casing.

Crow, et al. investigated a well in a CO_2 producing reservoir. It had also been exposed to CO_2 for 30 years similar to the Carey, et al. study. This well used CO_2 resistant cement. The cement as expected showed little degradation. Its permeability ranged from several 10s of micro Darcies to several micro Darcies. The casing also showed no corrosion or metal loss. The CBL showed good cement bond. They also performed a vertical interference test to measure in situ the effective permeability of the cement sheath. They estimated the effective permeability to be between 1 and 10 mD, for a well with good cement bond.

For this methodology, a lognormal distribution with a range between 1 and 10 mD and a more conservative assumption of a range between 1 and 100 mD can be examined for the containment risk assessment. Because the geometry of the well that Crow, et al. investigated may be different from the wells in for the CCS site, the permeability should be scaled to preserve the transmissibility.

NRAP-Open-IAM assumes that the entire length of the caprock along the wellbore is protected with a cement sheath with good cement bond. This is not necessarily true, however, the length of cement with a good bond is not an input parameter to NRAP-Open-IAM. This length is accounted for by adjusting the effective permeability. The transmissibility in the Darcy law depends on the ratio of the effective permeability to the length of the cement with good CBL. Reducing the length is equivalent to increasing the permeability. For a specific CCS site, the statistical distribution of the fraction of good cement sheath is obtained by analyzing the available CBL data. Wells without CBL can be incorporated by discounting their cement estimates by 50%, thus assuming a higher permeability distribution.

With all the needed input data, NRAP-Open-IAM is used to generate 2,000 realizations from a "representative well". To scale up to a CCS site with N wells, a supplemental Monte Carlo simulation is run. The supplemental Monte Carlo simulation is performed using custom code and is not a feature of NRAP-Open-IAM. In this second Monte Carlos simulation, N realizations from the pool of 2,000 realizations that NRAP-Open-IAM generated are randomly selected (with replacement). The output from these N realizations is summed to generate one possible realization. This is repeated 5,000 times to generate 5,000 possible realizations. Using these realizations, a histogram of possible outcomes is generated, and the cumulative probability distribution is created. From the cumulative distribution we can determine whether the permanence criteria are met.

Results

Figure 3 shows an example of the end result of such an analysis, as described in the previous section for a hypothetical CCS site. The green histogram is the normalized histogram of the percentage of the injected CO_2 leaked. The blue curve is the cumulative distribution. The vertical red line is 1% of the injected CO_2. The horizontal red line is the 90% probability. To satisfy the permanence criterion, the vertical line must intersect the blue cumulative probability distribution curve above the horizontal 90% probability line. Alternatively, the horizontal red line must intersect the blue curve to the left of the vertical 1% of injected CO_2 line. If you draw a vertical line from where the horizontal 90% line intersects the blue cumulative distribution curve, the point at which the vertical line intersects the X-axis is the estimated percentage of the injected CO_2 leaked with greater than 90% confidence. For this case, the leaked amount of CO_2, with greater than 90% confidence, is 0.348% of the total sequestered volume.

Because of the conservative assumptions made, this is an upper bound of the potential leakage and thus this assessment meets CARB's permanence criterion.

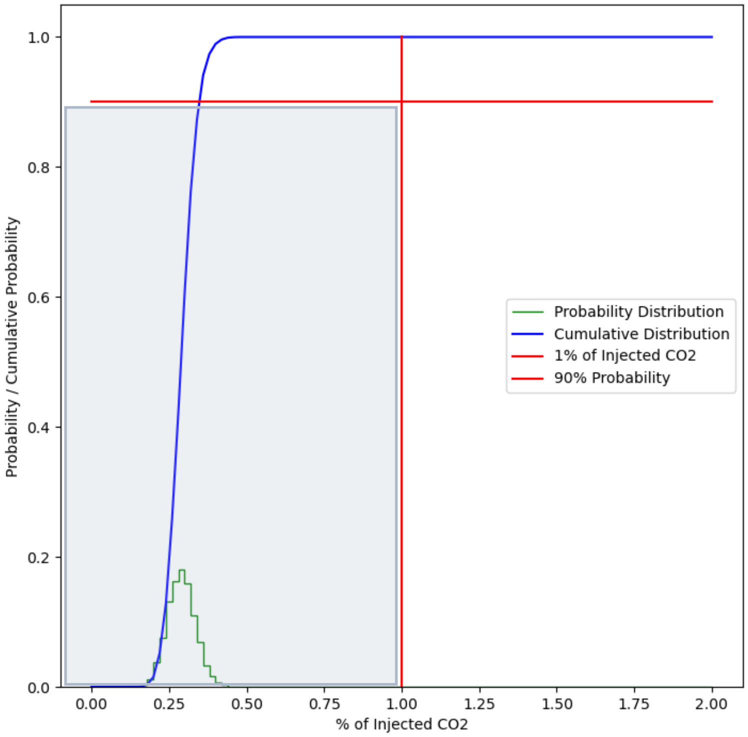

Figure 3. Example of results of the leak risk analysis

Discussion

Additional sensitivities can be run to assess the robustness of the results and to identify the important parameters, but the above illustration shows that NRAP-Open-IAM can be used to obtain quantitative results for risk assessment.

There are other methods for quantitatively estimating containment risk. For example, Alcalde, et al., 2018 performed a study on percent leakage of CO_2 for onshore and offshore wells and poorly and well-regulated oil and gas fields. The Alcalde study included longer time period trapping mechanisms and other pathways other than along the cement sheath. The main difference between this methodology and Alcalde, et al.'s approach, however, is that this methodology makes use of information specific to the field and not generic data. Also, Alcalde et al. considered immobilization trapping mechanisms as their window of investigation extended to 10,000 years, the point at which such effects become significant.

The methods described in this paper can also be used to examine single legacy "leaky wells" that may be considered problematic, with the results used to guide the decision for remediation. The assessment of the applicable well can then be updated with the outcome of the remediation campaign. Finally, monitoring well data can be used to calibrate the model to a given CCS project during its operating and post-injection life.

Conclusions

This paper demonstrates how to use NRAP's open-source software, NRAP-Open-IAM, to assess and quantify containment risk through abandoned wellbores. NRAP-Open-IAM is not as complex or flexible as detailed simulation models, however, it allows for fast Monte Carlo simulations for stochastic analysis and the ability to incorporate the results from detailed simulation models. Moreover, its reduced complexity, and thereby its speed, are achieved without compromising the integrity of the risk assessment. Because the data required by detailed simulation models are often unknown or uncertain, and NRAP-Open-IAM allows inclusion of such uncertainties in stochastic parameters, NRAP-Open-IAM offers a practical approach to probabilistically assess containment risk for CCS projects. The open architecture, which allows modification of the in-built models to suit specific field conditions is an additional advantage of NRAP-Open-IAM.

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