Verification of the Performance of Integrated Assessment Model’s (NRAP-IAM) Component Reduced-Order Models

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**Cover Illustration:** A schematic showing the various subsystems included in the National Risk Assessment Partnership-Integrated Assessment Model-Carbon Storage (NRAP-IAM-CS).


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https://edx.netl.doe.gov/nrap
Verification of the Performance of Integrated Assessment Model’s (NRAP-IAM) Component Reduced-Order Models

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<th>Term</th>
<th>Description</th>
</tr>
</thead>
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<tr>
<td>CO₂</td>
<td>Carbon dioxide</td>
</tr>
<tr>
<td>CO₂-PENS</td>
<td>CO₂ – Predicting Engineered Natural Systems</td>
</tr>
<tr>
<td>DLL</td>
<td>Dynamic link library</td>
</tr>
<tr>
<td>DOE</td>
<td>U.S. Department of Energy</td>
</tr>
<tr>
<td>FEHM</td>
<td>Finite Element Heat &amp; Mass</td>
</tr>
<tr>
<td>IAM</td>
<td>Integrated assessment model</td>
</tr>
<tr>
<td>LANL</td>
<td>Los Alamos National Laboratory</td>
</tr>
<tr>
<td>LBNL</td>
<td>Lawrence Berkeley National Laboratory</td>
</tr>
<tr>
<td>LHS</td>
<td>Latin Hypercube Sample</td>
</tr>
<tr>
<td>MARS</td>
<td>Multi-variate Adaptive Regression Spline</td>
</tr>
<tr>
<td>NRAP</td>
<td>National Risk Assessment Partnership</td>
</tr>
<tr>
<td>ROM</td>
<td>Reduced-order model</td>
</tr>
<tr>
<td>TDS</td>
<td>Total dissolved solids</td>
</tr>
<tr>
<td>USDW</td>
<td>United States Drinking Water</td>
</tr>
</tbody>
</table>
Acknowledgments

This work was completed as part of the National Risk Assessment Partnership (NRAP) project. Support for this project came from the U.S. Department of Energy’s (DOE) Office of Fossil Energy’s Crosscutting Research program. The authors wish to acknowledge Traci Rodosta (Carbon Storage Technology Manager), Kanwal Mahajan (Carbon Storage Division Director), M. Kylee Rice (Carbon Storage Division Project Manager), Mark Ackiewicz (Division of CCS Research Program Manager), Darin Damiani (Carbon Storage Program Manager), Robert Romanosky (NETL Crosscutting Research, Office of Strategic Planning), and Regis Conrad (DOE Office of Fossil Energy) for programmatic guidance, direction, and support.
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EXECUTIVE SUMMARY

The National Risk Assessment Partnership (NRAP) consists of five U.S. Department of Energy national laboratories collaborating to develop a framework for quantifying the long-term risks associated with geologic carbon dioxide (CO₂) storage. The approach taken by NRAP for quantifying the risks involves using integrated assessment models (IAMs) to predict long-term performance of a geologic CO₂ storage site. An IAM is developed with a systems modeling approach that uses reduced-order models (ROMs) to predict long-term behavior of system components, including injection target reservoirs, wellbores, natural pathways including faults and fractures, groundwater, and the atmosphere. In the case of NRAP, individual ROMs are developed using detailed, high-fidelity numerical simulations.

This report summarizes the process and results of verifying the performance of wellbore and aquifer ROMs incorporated in the IAM. The ROMs have been incorporated as DLLs (dynamic link libraries). The verification process involved exercising the DLLs through execution of the IAM and comparing the predicted results against the results of executing the ROMs independently (outside of IAM) with same set of inputs. Excellent matches were obtained between the two sets of results ensuring that the individual component ROMs have been correctly incorporated in the IAM and are performing as expected.
1. INTRODUCTION

The National Risk Assessment Partnership (NRAP) is developing a defensible methodology for quantifying long-term risks at geologic carbon dioxide (CO2) storage sites. NRAP has been utilizing a “science-based predictions” approach for simulating long-term performance of CO2 storage sites and computing risks. The science basis is ensured by taking into account the physical and chemical interactions within the key parts of the storage site while performing long-term predictions. NRAP uses a system modeling approach to predict long-term performance of the CO2 storage site with integrated assessment models (IAMS). IAMS are mechanistic computational models of processes that occur within and among various components of the system, e.g., from wellbore to reservoir to leaky well, and up the well to shallow aquifer (USDW) and/or the atmosphere. IAMS model the couplings of processes from the point of injection through to the impact that any leaking CO2 or brine may have on shallow aquifer or the atmosphere. The approach of coupling complex models involves significant computational cost. Meanwhile, uncertainty in subsurface systems demands that a large number (often many thousands) of realizations of the systems be modeled to bracket and quantify the uncertainty associated with impacts, likelihoods, and therefore risk.

To meet both the requirements of modeling coupled processes and carrying out possibly thousands of realizations to capture uncertainty in model and input parameters, NRAP is developing and using reduced-order models (ROMs) which are computationally efficient versions of the complex full model that capture the key underlying physical/chemical interactions in the system while being much more efficient to compute. To calculate the impact or consequences part of the risk equation, NRAP uses what are referred to as risk proxies to avoid unnecessary ambiguity and complexity in risk assessment. The leakage risk proxies currently used by NRAP are as follows: (1) pH in the aquifer (a direct function of dissolved CO2 concentration); (2) total dissolved solids (TDS), (a direct function of brine and CO2 concentration); (3) concentration of heavy metals and organics, including Arsenic, Lead, Cadmium, Benzene, Phenol, and Napthalene; and (4) flux of CO2 into the atmosphere through a leakage pathway such as a leaky well.

1.1 INTEGRATED ASSESSMENT MODEL

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 hundreds of square kilometers (km²) and the need to consider the behavior of the entire site from the sequestration reservoir to potential receptors results in a large volume (>10³ km³) that should be taken into consideration during the long-term performance predictions. Given this scale, its challenging to use a single model to predict long-term site-scale behavior based on key processes even at the continuum-scale (~m). Additionally, predicting behavior 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 linked together with one-way coupling (i.e., they can be treated independently, addressing subsystem coupling explicitly by an integrated 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 risks, NRAP is
utilizing the integrated assessment modeling approach based on breaking the storage site into subsystems as illustrated in Figure 1: storage reservoir; potential release pathways such as wellbores or faults and fractures; and potential receptors (or impact categories). Within the IAM, the system components are connected to capture the various inter-component interactions at a CO₂ 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 assuming there is no feedback.

The NRAP IAM is built upon the CO₂-PENS model (Stauffer et al., 2009), developed with the GoldSim® software package. 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.

1.1.1 IAM Component Models

The objective of developing the component models is to capture the physical and chemical interactions that take place as a result of CO₂ 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. ROMs were developed for each of the system components. Various approaches can be used to develop component ROMs ranging from abstractions based on
detailed process-level simulations to direct incorporation of process simulation results. The approaches used to develop the component ROMs are described below.

• **CO₂ Storage Reservoir**: The reservoir ROM is used to predict time-dependent changes in reservoir pressure and saturation as the result of CO₂ injection. The ROM is a look-up table approach in which results of detailed reservoir simulations are directly linked as look-up tables. The reservoir simulation model was based on the Kimberlina reservoir in the southern San Joaquin basin in California. It is a saline reservoir 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 LBNL’s TOUGH2 reservoir simulator. The numerical model was used to perform multiple simulations of large-scale CO₂ 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 the porosity and permeability of the target reservoir and the permeability of the 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 three reservoir parameters. Each one of the runs was associated with its representative reservoir permeability, reservoir porosity and caprock permeability values, such that during a stochastic simulation a reservoir simulation run can be selected based on a set of the values of uncertain parameters selected for a realization. Further details of the ROM are provided in (Stauffer et al., 2016).

• **Wellbores**: The wellbore ROM is used to calculate the CO₂/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, numerical simulations were performed using Los Alamos National Laboratory’s (LANL)’s Finite Element Heat & Mass (FEHM) model to calculate CO₂ and brine leakage through a wellbore. The problem setup included not only the CO₂ storage reservoir but also an intermediate permeable reservoir and a shallow aquifer. The CO₂ and brine flow rate up a 10-cm diameter wellbore, initially containing 100% brine, was computed for 1,500 cases with varying wellbore depth, wellbore cement permeability, intermediate reservoir depth, intermediate reservoir permeability, pressure, and saturation at the primary storage reservoir-wellbore interface. It was assumed that wellbore cement extended over the entire length of the wellbore. Input parameter distributions were generated using a Latin Hypercube Sampling (LHS) scheme with the R statistical software package. Results of ~1,500 leakage simulation runs were used to generate higher resolution response surfaces for CO₂ and brine leak rates into intermediate aquifer, groundwater aquifer and atmosphere using a MARS (Multi-variate Adaptive Regression Spline) fitting scheme. For open wellbores, numerical simulations of CO₂ leakage through open wellbores were performed using the drift-flux model in LBNL’s TOUGH2 simulator. In all, 7,200 simulation runs were performed by varying wellbore-reservoir boundary pressure, saturation and wellbore depth. The simulated CO₂ and brine leak rates from these runs were converted into a three-dimensional lookup table for IAM. It should be noted that both the FEHM and TOUGH2 simulations took into account the complexities of CO₂ phase change during leakage from deeper reservoirs (where CO₂ typically exists in super-critical state) to the shallow aquifer or atmosphere (where CO₂ typically exists in gaseous state). Further details of the cemented wellbore ROM are provided in Harp et al. (2016) and those for open
wellbore ROM are provided in Pan and Oldenburg (2014). These ROMs were converted into a DLL and linked to the IAM.

- **Shallow Aquifer:** The shallow aquifer ROMs are used to calculate changes in the pH and concentration of TDS due to CO$_2$ and brine leakage. The ROMs are based on two sites: the confined, reducing sandstone High Plains aquifer, which extends between South Dakota and Texas, and a portion of the unconfined, oxidizing carbonate Edwards Aquifer of south-central Texas. A combined hydrogeology/geochemical ROM has been developed for each aquifer. High-fidelity numerical models were used to simulate changes in the groundwater aquifers due to CO$_2$ and brine leakage. 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 parameter ranges of interest. These included volumes of pH and TDS plumes in shallow aquifer, volumes of heavy metal plumes, volumes of organics plumes, and CO$_2$ flux out of the aquifer. The ROMs were developed using the MARS fitting scheme and had forms of higher-order polynomial functions of the uncertain parameters. Similar to the wellbore ROM, the aquifer ROM was converted into a DLL and linked to the IAM.

The performance of each of the component ROMs mentioned above was verified against the high-fidelity models used to develop them. Details of these verifications have been provided in the Stauffer et al. (2016) for the reservoir ROM, Harp et al. (2016) for the wellbore ROM, and Keating et al. (2016) for the aquifer ROM.

The component ROMs were successfully incorporated in the IAM as DLLs. In order to assure that the individual component models are performing as expected as part of the IAM, a verification exercise was performed in which the predictions of the ROMs when executed as part of the IAM were compared against those where the ROMs were exercised independently with the same set of inputs.
2. METHODS

As part of the verification process for the wellbore and aquifer ROM, the IAM was exercised to simulate two separate scenarios. Next, the individual ROMs for cemented wellbore and aquifer were exercised independently (outside the IAM) with the same set of inputs as the ones received by their respective DLLs within the IAM. The outputs computed by the DLLs as part of the IAM were compared with the outputs from the ROMs exercised outside the IAM. For open wellbore, multiple IAM runs were performed to simulate the scenario of CO₂ leakage through an open wellbore. The predicted leakage rate was compared against the lookup table values. Further details are provided in the sections below.

2.1 CEMENTED WELLBORE DLL & ROM PERFORMANCE COMPARISON

The scenario of leakage of CO₂ through a cemented wellbore was simulated with the IAM to verify the performance of the wellbore DLL. The problem setup included a primary storage reservoir, an intermediate reservoir, a shallow groundwater aquifer, and a single cemented wellbore whose location is assumed to be known a-priori. The storage reservoir model was based on the lookup table approach described in Section 1. The cemented wellbore was placed at 37,500 m (X) and 49,000 m (Y). At this location, the wellbore depth was 5,263 m. The wellbore cement permeability was assumed to be 1 Darcy (1.0 e⁻¹² m²). The details of the problem setup are shown in Figures 2–7 below through multiple IAM input dashboards used to define the problem.

Figure 2: The “Scenario Type and Inputs” dashboard for cemented wellbore DLL performance verification problem setup.
Figure 3: The “Site Data” dashboard for cemented wellbore DLL performance verification problem setup.

Figure 4: The “Sequestration Reservoir” dashboard for cemented wellbore DLL performance verification problem setup.
Figure 5: The “Legacy Wells” dashboard for cemented wellbore DLL performance verification problem setup.
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**Figure 6:** The “Shallow Aquifer and Intermediate Reservoir Physical Parameters” dashboard for cemented wellbore DLL performance verification problem setup.

**Figure 7:** The “Land Surface” dashboard for cemented wellbore DLL performance verification problem setup.
The IAM was run to simulate 200 years of storage site performance. The CO₂ flow rates into intermediate reservoir, shallow aquifer, and atmosphere as predicted by the wellbore ROM DLL within the IAM were compared with the wellbore ROM run independently. The inputs to the independent wellbore ROM included wellbore depth, wellbore cement permeability, intermediate reservoir depth, intermediate reservoir permeability, and time-dependent pressure and CO₂ saturation at the intersection of the wellbore and the CO₂ storage reservoir.

2.2 OPEN WELLBORE DLL & ROM PERFORMANCE COMPARISON

The scenario of leakage of CO₂ through an open wellbore was simulated with the IAM to verify the performance of the open wellbore DLL. The problem setup included primary storage reservoir, and a single open wellbore whose location is assumed to be known a-priori. The storage reservoir model was based on the built-in simple reservoir model. The reservoir spatial extent was assumed to be 10 km x 10 km. Values of reservoir geologic parameters used for the simulation runs are shown in Table 1 below.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reservoir thickness</td>
<td>20 m</td>
</tr>
<tr>
<td>Reservoir permeability</td>
<td>3 Darcy</td>
</tr>
<tr>
<td>Reservoir porosity</td>
<td>0.2</td>
</tr>
<tr>
<td>Residual water saturation</td>
<td>0.1</td>
</tr>
<tr>
<td>Residual CO₂ saturation</td>
<td>0.2</td>
</tr>
</tbody>
</table>

The open wellbore was placed at 7,000 m (X) and 5,000 m (Y). The CO₂ injection well was placed at 5,000 m (X) and 5,000 m (Y). The details of the problem setup are shown in Figures 8–13 below through multiple IAM input dashboards used to define the problem.
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Figure 9: The “Site Data” dashboard for open wellbore DLL performance verification problem setup.

Figure 10: The “Sequestration Reservoir” dashboard for open wellbore DLL performance verification problem setup.
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Figure 11: The “Simple Reservoir Characteristics” dashboard for open wellbore DLL performance verification problem setup.

Figure 12: The “Legacy Wells” dashboard for open wellbore DLL performance verification problem setup.
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Multiple simulation runs were performed by varying the reservoir depth (2,000 m, 3,000 m, 4,000 m) and CO₂ injection rates (200 tons/day, 500 tons/day, 1,000 tons/day, 2,000 tons/day). Each of the runs simulated 50 years of site performance. The CO₂ flow rate predicted by the IAM was compared against the values provided by Pan and Oldenburg (2014).

2.3 AQUIFER DLL & ROM PERFORMANCE COMPARISON

The scenario CO₂ and brine leakage into a shallow aquifer through a cemented wellbore was simulated with the IAM to verify the performance of the aquifer ROM DLL. Similar to the wellbore test setup, the problem setup included primary storage reservoir, an intermediate reservoir, a shallow aquifer and a single cemented wellbore whose location is known a-priori. The storage reservoir model was based on the lookup table approach described in Section 1. The cemented wellbore was placed at 36,500 m (X) and 49,000 m (Y). The wellbore cement permeability was assumed to be 10 Darcy (1.0 e⁻¹¹ m²). The details of the problem setup are shown in Figures 14–20 below through multiple IAM input dashboards used to define the problem.
Figure 14: The “Scenario Type and Inputs” dashboard for aquifer DLL performance verification problem setup.

Figure 15: The “Site Data” dashboard for aquifer DLL performance verification problem setup.
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**Figure 16:** The “Sequestration Reservoir” dashboard for aquifer DLL performance verification problem setup.

**Figure 17:** The “Legacy Wells” dashboard for aquifer DLL performance verification problem setup.
Figure 18: The “Shallow Aquifer and Intermediate Reservoir Physical Parameters” dashboard for aquifer DLL performance verification problem setup.
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Shallow Aquifer Hydrologic & Geochemical Parameters

<table>
<thead>
<tr>
<th>Hydrologic</th>
<th>Single</th>
<th>Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Permeability (Darcy)</td>
<td>☑</td>
<td>✔️ Uniform</td>
</tr>
<tr>
<td>Permeability Variance</td>
<td>☑</td>
<td>✔️ Uniform</td>
</tr>
<tr>
<td>Permeability Correlation Length (km)</td>
<td>☑</td>
<td>✔️ Uniform</td>
</tr>
<tr>
<td>Permeability Anisotropy (Kx/Kz)</td>
<td>☑</td>
<td>✔️ Uniform</td>
</tr>
<tr>
<td>Aquifer Thickness (m)</td>
<td>☑</td>
<td>✔️ Uniform</td>
</tr>
<tr>
<td>Horizontal Hydraulic Gradient</td>
<td>☑</td>
<td>✔️ Uniform</td>
</tr>
</tbody>
</table>

| Geochemical                                      |       |             |
| Calcite Surface Area (m²/gm)                     | ☑      | ✔️ Uniform | Mean: 5.005, Std. Dev: 0.003, Min: 0, Max: 0.01 |
| Organic Carbon Volume Fraction                   | ☑      | ✔️ Uniform | Mean: 0.005, Std. Dev: 0.02, Min: 0, Max: 0.01 |
| Benzene Kd (log(Kd))                             | ☑      | ✔️ Uniform | Mean: 1.61, Std. Dev: 0.022, Min: 1.49, Max: 1.73 |
| Benzene Decay Constant (Days)                    | ☑      | ✔️ Uniform | Mean: 914, Std. Dev: 11.38, Min: 1.16, Max: 2.04 |
| Pah Kd (log(Kd))                                 | ☑      | ✔️ Uniform | Mean: 2.98, Std. Dev: 0.12, Min: 2.98, Max: 3.16 |
| Pah Decay Constant (Days)                        | ☑      | ✔️ Uniform | Mean: 0.586, Std. Dev: 0.9, Min: 0.43, Max: 2.94 |
| Phenol Kd (log(Kd))                              | ☑      | ✔️ Uniform | Mean: 1.345, Std. Dev: 0.18, Min: 1.21, Max: 1.45 |
| Phenol Decay Constant (Days)                     | ☑      | ✔️ Uniform | Mean: 0.42, Std. Dev: 1, Min: 0.3, Max: 2.96 |
| Seq. Reservoir Brine Molality                    | ☑      | ✔️ Uniform | Mean: 7.67, Std. Dev: 0.001, Min: 7.8 |

Figure 19: The “Shallow Aquifer Hydrologic and Geochemical Parameters” dashboard for aquifer DLL performance verification problem setup.
The IAM was run to simulate 200 years of storage site performance. The volumes of pH and TDS plumes as predicted by the ROM DLL within the IAM were compared with the aquifer ROM run independently. The inputs to the independent aquifer ROM included shallow aquifer hydrologic and geochemical parameters and time-dependent CO2 and brine leakage rate in the shallow aquifer.
3. **RESULTS/OBSERVATIONS**

In order to verify the performance of the DLLs, DLL predictions for quantities of interest were compared with the predictions by respective ROMs.

3.1 **CEMENTED WELLBORE DLL/ROM COMPARISONS**

Figures 21–23 show comparisons of the predicted CO$_2$ flow rates into an intermediate reservoir, a groundwater aquifer, and to the atmosphere. There are slight differences in the results of stand-alone ROM and the DLL predictions. These differences are primarily due to the differences in the numerical precisions of the programs used for testing and are unavoidable. While there are differences in some of the individual values the overall trends in data are very similar.

![Figure 21: Comparison between CO$_2$ flow rate (kg/s) through a cemented wellbore into an intermediate reservoir predicted by the wellbore model DLL and the ROM.](image)
Verification of the Performance of Integrated Assessment Model’s (NRAP-IAM) Component ROMs

Figure 22: Comparison between CO$_2$ flow rate (kg/s) through a cemented wellbore into groundwater aquifer predicted by wellbore model DLL and ROM.

Figure 23: Comparison between CO$_2$ flow rate (kg/s) through a cemented wellbore to the atmosphere predicted by wellbore model DLL and ROM.
3.2 OPEN WELLBORE DLL PREDICTIONS COMPARISON

Figures 24–26 show comparisons of the IAM predicted CO$_2$ flow rate to the atmosphere against the overpressure for reservoir depths of 2,000 m, 3,000 m, and 4,000 m respectively. Each figure shows predictions for various injection rates. The IAM predictions are plotted against the values calculated by Pan and Oldenburg (2014) which are stored as look-up tables.

![Figure 24: Comparison between CO$_2$ flow rate (kg/s) through an open wellbore to the atmosphere predicted by the wellbore model DLL and Pan and Oldenburg (2014) predictions. Results for a reservoir depth of 2,000 m.](image)
Figure 25: Comparison between CO₂ flow rate (kg/s) through an open wellbore to the atmosphere predicted by the wellbore model DLL and Pan and Oldenburg (2014) predictions. Results for reservoir depth 3,000 m.

Figure 26: Comparison between CO₂ flow rate (kg/s) through an open wellbore to the atmosphere predicted by the wellbore model DLL and Pan and Oldenburg (2014) predictions. Results for reservoir depth 4,000 m.
### 3.3 AQUIFER DLL/ROM PREDICTIONS COMPARISON

Figures 27–31 show comparisons of the predicted pH & TDS plume volumes, the pH plume length and widths, and the CO₂ flow to atmosphere through the vadose zone.

**Figure 27:** Comparison between pH plume volume predicted by aquifer model DLL and ROM.

**Figure 28:** Comparison between TDS plume volume predicted by aquifer model DLL and ROM.
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Figure 29: Comparison between pH plume length predicted by aquifer model DLL and ROM.

Figure 30: Comparison between pH plume width predicted by aquifer model DLL and ROM.
Figure 31: Comparison between CO$_2$ flow rate through vadose zone predicted by aquifer model DLL and ROM.
4. **DISCUSSION**

Figures 21–31 show excellent matches for various quantities predicted by the DLLs against either the look-up-table (open wellbore) or independent ROMs (cemented wellbore and aquifer). The results show that the DLLs for wellbore and aquifer reduced order models as implemented in the IAM are performing as expected.
5. **CONCLUSIONS**

The verification tests demonstrate that the wellbore and aquifer ROMs have been implemented successfully in the IAM. It should be noted that only a single test was performed to verify performance of each DLL and the successful results do not ensure that the DLL will perform as expected under any possible scenario. Nonetheless, it indicates that basic connections between the models is working correctly. More thorough and comprehensive testing is planned for the future to include a wide range of scenarios and parameter values. Results of these future verification tests will be reported through another study.
6. REFERENCES


Pan, L.; Oldenburg, C. M. *NRAP ROM for Leakage through an Open Wellbore from the Reservoir due to CO\textsubscript{2} Injection*; LBNL Deliverable to the National Risk Assessment Partnership: Milestone Report; February 3, 2014.


NRAP is an initiative within DOE’s Office of Fossil Energy and is led by the National Energy Technology Laboratory (NETL). It is a multi-national-lab effort that leverages broad technical capabilities across the DOE complex to develop an integrated science base that can be applied to risk assessment for long-term storage of carbon dioxide (CO₂). NRAP involves five DOE national laboratories: NETL, Lawrence Berkeley National Laboratory (LBNL), Lawrence Livermore National Laboratory (LLNL), Los Alamos National Laboratory (LANL), and Pacific Northwest National Laboratory (PNNL).

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