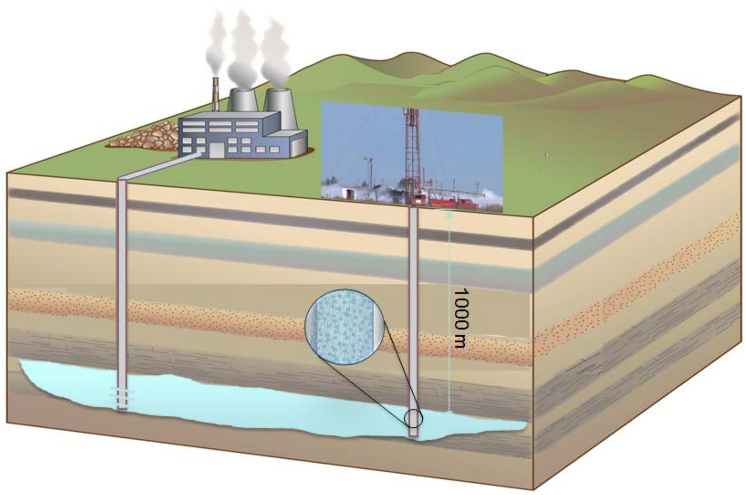
NRAP
National Risk Assessment Partnership



Reduced-Order Model for Leakage Through an Open Wellbore from the Reservoir due to Carbon Dioxide Injection

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Cover Illustration: CO_2 plume encounters leaking water-filled well leading to uncontrolled open wellbore flow of two-phase CO_2 and water mixture.

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Reduced-Order Model for Leakage Through an Open Wellbore from the Reservoir due to Carbon Dioxide Injection

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Acronyms, Abbreviations, and Symbols

Term	Description
CO_2	Carbon dioxide
U.S. DOE	U.S. Department of Energy
GCS	Geologic Carbon Sequestration
NETL	National Energy Technology Laboratory
NRAP	National Risk Assessment Partnership
ROM	Reduced-Order Model

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ABSTRACT

Potential CO_2 leakage through existing open wellbores is one of the most significant hazards that need to be addressed in geologic carbon sequestration (GCS) projects. In the framework of the National Risk Assessment Partnership (NRAP) which requires fast computations for uncertainty analysis, rigorous simulation of the coupled wellbore-reservoir system is not practical. We have developed a 7,200-point look-up table reduced-order model (ROM) for estimating the potential leakage rate up open wellbores in response to CO_2 injection nearby. The ROM is based on coupled simulations using T2Well/ECO2H which was run repeatedly for representative conditions relevant to NRAP to create a look-up table response-surface ROM. The ROM applies to a wellbore that fully penetrates a 20-m thick reservoir that is used for CO_2 storage. The radially symmetric reservoir is assumed to have initially uniform pressure, temperature, gas saturation, and brine salinity, and it is assumed these conditions are held constant at the far-field boundary (100 m away from the wellbore). In such a system, the leakage can quickly reach quasi-steady state. The ROM table can be used to estimate both the free-phase CO_2 and brine leakage rates through an open well as a function of wellbore and reservoir conditions. Results show that injection-induced pressure and reservoir gas saturation play important roles in controlling leakage. Caution must be used in the application of this ROM because well leakage is formally transient and the ROM lookup table was populated using quasi-steady simulation output after 1000 time steps which may correspond to different physical times for the various parameter combinations of the coupled wellbore-reservoir system.

1. INTRODUCTION

Potential CO_2 leakage through existing open wellbores is one of the most significant hazards that need to be addressed in geologic carbon sequestration (GCS) projects. As used in this report on leakage, we define the term wellbore in the broadest sense to refer to either the boring in the rock, the annular space between casing and rock, and/or the open space within the casing of the well. Leakage through a wellbore in response to pressure increase and phase change in the reservoir due to CO_2 injection are complicated processes that involve many, often interacting, geologic and engineering factors. Proper evaluation of the inherently dynamic leakage through a wellbore requires a fully coupled wellbore-reservoir model that is based on full characterization of the target reservoir and operational scenarios. However, in the framework of the National Risk Assessment Partnership (NRAP), such rigorous modeling is not feasible, and a reduced-order model (ROM) is necessary for estimating the potential leakage rate in response to CO_2-induced changes in the reservoir for certain reservoir-wellbore configurations.

Although simplifications are needed, the ROM should not be oversimplified, and the critical processes and factors that control the leakage rate should be included in the ROM. For example, the bottom-hole conditions in a leaking wellbore depend on both the wellbore processes and the reservoir processes. As shown in Figure 1 from a numerical simulation, the pressure at the well bottom decreases quickly from the initial reservoir pressure as the leakage takes place, and the pressure decrease propagates into the deep reservoir with time (Figure 1a). This quick bottom-hole pressure decline occurs mainly because of the decrease in gravity-induced pressure exerted on the well bottom as a result of rapid CO_2 expansion in the leaking wellbore, i.e., the entire weight of the fluid column in the wellbore becomes much lighter when the gas saturation increases to above 0.9 (Figure 1b), even though the gas saturation in the reservoir is still around 0.1. Such expansion of CO_2 in the wellbore also causes a significant drop in wellbore temperature (Figure 1c).

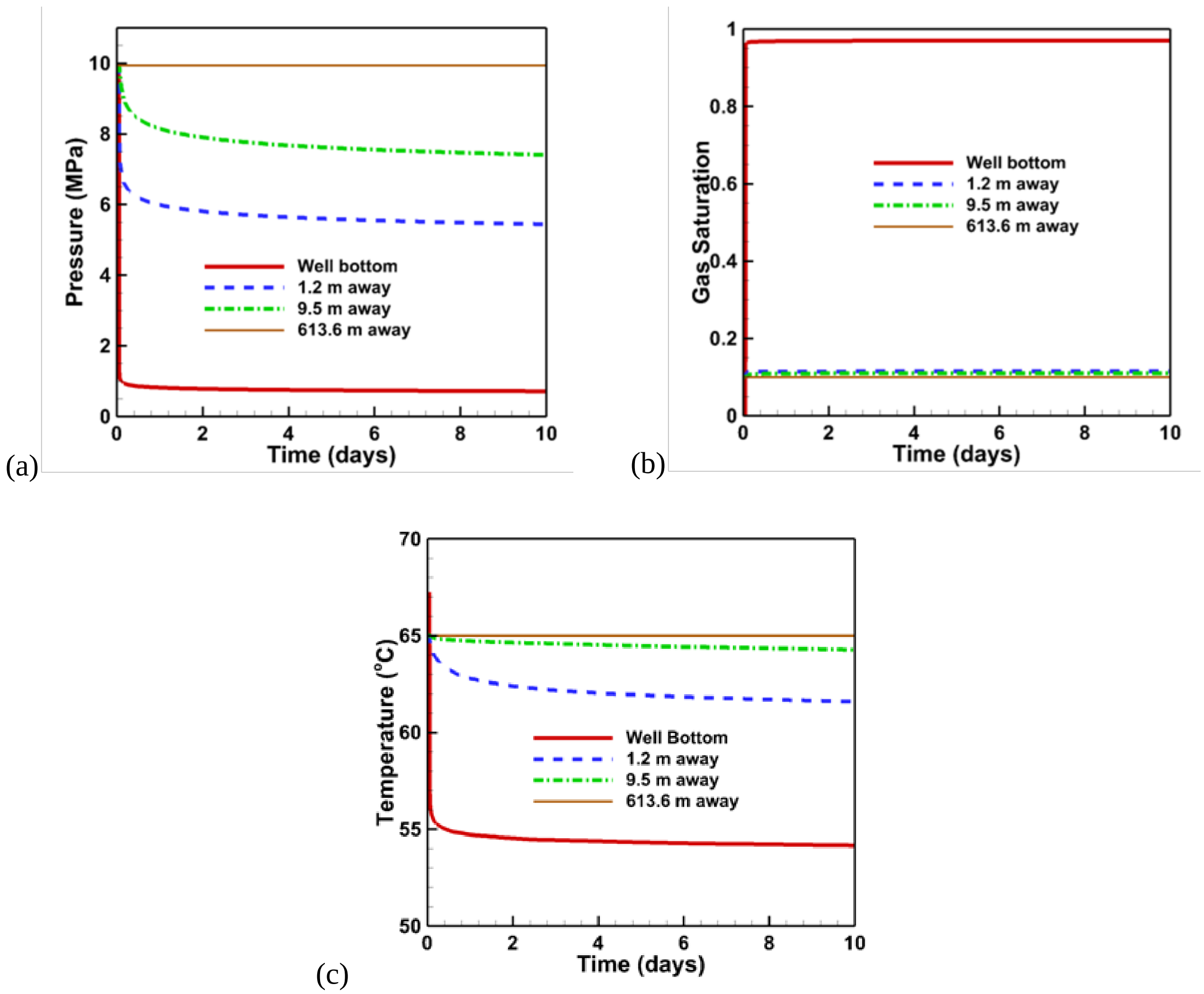

Figure 1: Pressure (a), gas phase saturation (b), and temperature (c) responses at various locations in a leaking wellbore-reservoir system from numerical simulations using T2Well (Pan and Oldenburg, 2014).

These results show clearly that a wellbore-only ROM cannot capture the important and significant deviations in wellbore conditions relative to reservoir conditions that may occur during the process of leakage.

The objective of this work is to develop a ROM that includes the most important controlling factors of wellbore-reservoir coupled processes, but is still efficient for estimating the leakage rates within the NRAP computational framework. The model is a look-up table response-surface model, which can be generally expressed as:

$$q_i = f\left(x_1, x_2, \cdots, x_N\right) \tag{1}$$

where q is the leakage rate of either the CO_2 or the liquid (brine + dissolved CO_2) and x_j is the jth factor (or parameter). The values defining the look-up table were generated by repeated simulations of a fully coupled wellbore-reservoir simulator T2Well (Pan and Oldenburg, 2014).

2. CONCEPTUAL MODEL AND PARAMETER SPACE

This study considered a wellbore fully perforated through a 20-m thick reservoir that is used for CO_2 storage. The radially symmetric reservoir is assumed to have initially uniform pressure, temperature, gas saturation, and brine salinity, and it is assumed these conditions are held constant at the far-field boundary (100 m away from the wellbore). In such a system, the leakage can quickly reach quasi-steady state (Figure 1), so that the calculated leakage rates can be easily interpreted in the NRAP framework for given reservoir conditions estimated by the reservoir ROM. Note that because of this simplified reservoir model (a single model layer), the effect of stratification of CO_2 in the reservoir due to buoyancy, as well as those due to other heterogeneous features or geometric effects (e.g., different perforation length of the wellbore), are ignored. The model must also ensure that possible depletion effects due to leakage are properly considered (e.g., the reservoir conditions are frequently updated by the reservoir ROM considering leakage).

There are many parameters (or factors) that could affect the leakage rates to various degrees. The parameters selected were believed to be important for estimating the leakage rates and also consistent with those used in the reservoir ROM.

Depth of the Reservoir

GCS reservoirs are usually restricted to certain depth ranges for economic and storage efficiency reasons. In this model, the depth of the reservoir will determine the ambient pressure (i.e., the hydrostatic pressure) and temperature in the reservoir, which will greatly affect the behavior of the injected CO_2, the length of the hypothetical wellbore, and the mean permeability of the reservoir. Four depths are selected in this study, namely, 1000, 2000, 3000, and 4000 m below land surface.

Depth of the Wellbore Top

Two depths are used to define the effective top of the well for different leakage scenarios as follows: (1) wellhead at 0 m (open to atmosphere) for surface leakage; and (2) top of well at 500 m below land surface (open to a constant shallow aquifer) for leakage to underground sources of drinking water. Constant-pressure and temperature boundary conditions are used at the top of the model wellbore.

Reservoir Permeability-Thickness Product

The CO_2 storage reservoir may have spatially variable permeability and thickness, which affect the overall resistance to leakage provided by the reservoir. These two parameters can be combined into a single parameter, the permeability-thickness product of the reservoir. Since the reservoir ROM in the integrated risk model uses depth-dependent permeability with an average reservoir thickness of 297 m (Wainwright et al., 2012), a similar depth-dependent reservoir permeability-thickness product is used in this ROM. The reservoir thickness in this model is fixed, so the variation in reservoir permeability-thickness product is realized by varying permeability. For each reservoir depth, three levels of reservoir permeability-thickness product (mean plus one order of magnitude increase or decrease) were modeled.

Brine Salinity

Brine salinity could affect the density of leaking brine and the solubility of CO_2 in the aqueous phase. Three levels of brine salinity were simulated: 0, 0.1, and 0.2 salt mass fraction in the aqueous (liquid) phase.

Reservoir Gas Phase Saturation

Gas- (CO_2-rich) phase saturation is one of the most important factors controlling the leakage rates. Gas saturation decreases from the vicinity of the injection well to the boundary of the plume. A leaking well could intersect quite different gas saturations, even in the same reservoir, depending on well location. Ten levels of gas-phase saturation from 0.01 to 1.0 were simulated.

Injection-Induced Pressure Perturbation

CO_2 injection causes reservoir pressure to increase from its initial ambient pressure. This pressure perturbation is one of the major driving forces for brine and CO_2 leakage through an open wellbore. This study assumed that the initial ambient pressure in the reservoir is at hydrostatic pressure at the given depth with fixed geothermal gradient and no salt. According to the results of the NRAP Reservoir Performance Working Group, the maximum pressure perturbation considered in the integrated risk model is 19.45 MPa. Consequently, ten levels of pressure perturbation from 0.1 to 20 MPa are simulated.

The detailed parameter ranges are summarized in Table 1. In total, leakage was simulated for 7,200 parameter combinations and incorporated into the look-up table.

Table 1: Parameters and their ranges used in generation of the look-up table

Depth of well top (m)	Depth of reservoir (m)	Reservoir permeability-thickness product (10^{-11} m^3)	Reservoir Temperature (°C)	Brine salinity (mass fraction)	Pressure perturbation (MPa)	Gas saturation
0	1,000	40.2 (±1 order)	40	0.0, 0.1, or 0.2	10 levels between 0.1 and 20 MPa	10 levels between 0.01 and 1.0
	2,000	12.1 (±1 order)	65			
	3,000	6.0 (±1 order)	90			
	4,000	5.4 (±1 order)	115			
500	1,000	40.2 (±1 order)	40			
	2,000	12.1 (±1 order)	65			
	3,000	6.0 (±1 order)	90			
	4,000	5.4 (±1 order)	115			

3. THE SIMULATOR (T2WELL/ECO2H) AND NUMERICAL GRID

T2Well/ECO2H is a numerical simulator that can simulate nonisothermal, multiphase, and multicomponent (H_2O, NaCl, CO_2) fluid and energy flow in the integrated wellbore-reservoir system. The code has been verified against analytical and numerical solutions and field CO_2 production testing data, and has been applied to solve various problems involving coupled wellbore-reservoir flow processes (e.g., Pan and Oldenburg, 2014). Simulations were run for 1,000 time steps for each case. The leakage rates at the end time were recorded as the quasi-steady flow rates for the given reservoir conditions and the wellbore geometry.

A one-dimensional grid of 20-m long grid cells is used to represent the wellbore. The deepest grid cell of the well is connected to another one-dimensional (radial) grid that represents the reservoir, whose radial cell width varies from 0.1 m near well to 29 m at the boundary of the model. The reservoir thickness is 20 m with a permeability that matches the given reservoir permeability-thickness product. Examples of T2Well grids can be found in Pan and Oldenburg (2014).

4. RESULTS

As shown in Figure 2a, the CO_2 flow rate through an open wellbore is sensitive to both the reservoir pressure increase due to injection (reservoir pressure minus the hydrostatic pressure at the given depth) and the reservoir gas (CO_2-rich) phase saturation. However, sensitivity to just one of the parameters is dominant in different portions of the parameter space. When the reservoir gas saturation is above about 0.2 (five times the residual gas saturation in the reservoir in these models), the CO_2 flow rate is mainly controlled by the injection-induced pressure increase. Otherwise, the reservoir gas saturation plays a more important role in controlling the CO_2 flow rate, especially for lower gas saturations. Such a nonlinear response pattern is due to nonlinear mobility of the gas phase in the reservoir. As shown in Figure 2d, the gas saturation at the bottom of the well (inside) is above 0.9 if the reservoir gas saturation is above 0.2, which means that the entire leaking well is dominated by the gas phase. This sharp increase in gas saturation in the well occurs because of the large pressure gradient from the formation to the interior of the well and corresponding expansion of gas. We also note that the gas saturation usually increases from the bottom to the top of the well due to decreasing of pressure so that the well as whole should be drier than that showed by the gas saturation at the bottom.

Similar patterns can be seen in terms of the liquid phase (brine) flow rate (Figure 2b). However, the highest flow rate occurs in the region of lower gas saturation and largest pressure increase (the lower-right-hand corner). Furthermore, for the same pressure perturbation, the liquid-phase flow rate becomes smallest near the gas saturation of 0.1, indicating that the strongest gas-phase interference to the liquid-phase flow occurs at this saturation. The drop in both the well-bottom pressure perturbation (Figure 2c) and the well-bottom temperature (Figure 2e) are associated with this region, implying strong CO_2 expansion.

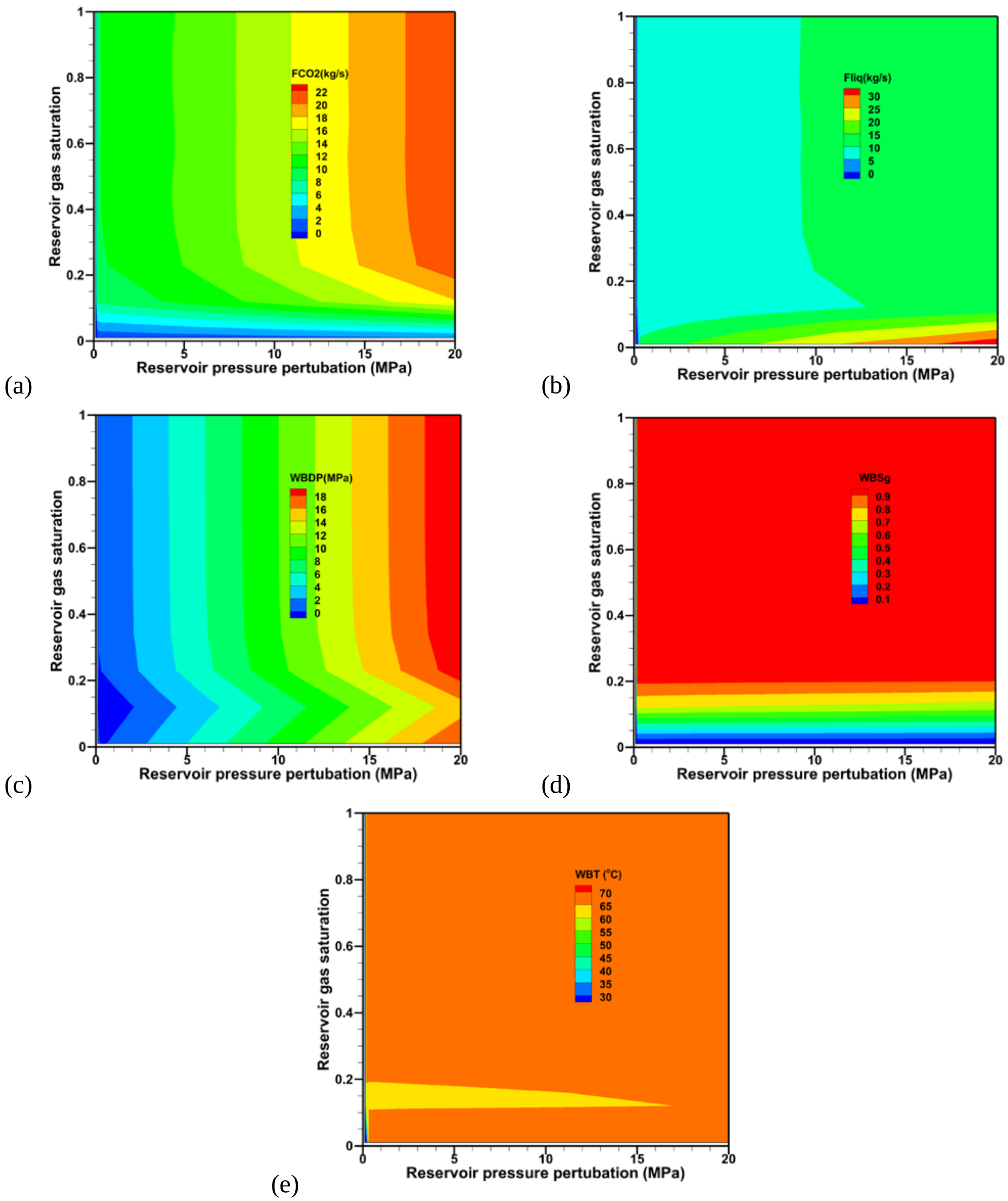

Figure 2: Response surface as a function of the reservoir pressure increase and the reservoir gas saturation in the base case (well top depth = 0, reservoir depth = 2,000 m, reservoir permeability-thickness product = 12.1 × 10^{-11} m^3, salinity = 0). a) Gas phase (CO_2-rich phase) leakage rate, b) brine (H_2O-rich phase) leakage rate, c) pressure increase (pressure minus the hydrostatic pressure) at well bottom, d) gas saturation at well bottom, and e) temperature at well bottom (the ambient reservoir temperature is 65°C).

5. THE LOOK-UP TABLE

The simulation results are stored in an Excel file (NRAP_well_res_ECO2H_Tables.xlsx). The leakage flow rates (CO_2-rich phase and brine) are listed (in sheet "Summary") with the corresponding parameters described in Table 1.

6. DISCUSSION

Leakage of CO_2 and brine through an open wellbore (which is initially filled with brine) from a storage reservoir is fundamentally a nonlinear and transient process. The total flow rate and composition will be generally functions of time. Therefore, describing leakage using CO_2 and brine leakage rates at a single time may not necessarily be adequate for risk-assessment purposes. In the particular case of the look-up table described above, a fixed 1,000th time step was used as the time to report the leakage rates. Because the time-step size could be very different under different reservoir conditions, the actual reporting time varies from a few hundred seconds to many weeks. As a result, caution is needed in applying the above look-up table to compare the leakage rates between different scenarios, especially between systems with different well configurations (e.g., depths of the well top and bottom). Although it is possible to run simulations until some kind of quasi-steady state criteria have been met to gain relatively uniform results, it would require much more effort than has currently been allocated.

Another option is to develop a ROM that is more robust and efficient than the general numerical model. One option in this regard is to extend the previously developed analytical solution for steady-state two-phase wellbore flow (Pan et al., 2011) to include a simplified reservoir (e.g., fixed resistance to each phase) and an empirical wellbore temperature model. However, significant effort is also required to develop an improved ROM.

7. CONCLUSIONS

A 7,200-point look-up table has been created using T2Well/ECO2H. The table can be used to estimate both the free-phase CO_2 and brine leakage rates through an open well as a function of wellbore and reservoir conditions. The parameters are selected to be consistent with the reservoir ROM in the NRAP framework. The model is believed to be more accurate than a wellbore-only model in representing the leakage scenarios.

The stratification effects on the leakage processes due to CO_2 buoyancy in the reservoir and other heterogeneous features or geometric effects were ignored in this ROM. Such effects are expected to be more profound in the case of thicker reservoirs or multiple-layered reservoirs, so that the ROM developed here may be subject to large errors in estimating the open wellbore leakage rates. Further investigations are needed to quantify such errors or to develop a ROM that is applicable to a broad range of reservoir configurations.

Because of the limited project effort allocated for the work, the 1,000th time step was used as the reporting time for all simulations. Consequently, quasi-steady state may not be reached in all cases as assumed. Therefore, care should be taken when comparing the leakage rates between different scenarios, especially between cases with different wellbore configurations. In addition, the model should be used such that the possible depletion effects due to leakage are properly considered (i.e., frequent update of the reservoir conditions).

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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 (CO_2). 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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