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Numerical Investigation of the Storage Efficiency Factor for CO_2 Geological Sequestration in Saline Formations

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Abstract

The CO_2 storage efficiency factor is an important term for calculating the amount of CO_2 storage in deep saline formations. This study investigates the potential effects of formation parameters and injection schemes on the storage capacity calculations and the relationship between the storage efficiency factor and the key parameters for the injection of CO_2 in closed saline formations, using numerical simulations. In this paper, we evaluated the CO_2 storage efficiency factors for a 3D hypothetical reservoir system. The studied parameters include the size of storage domain, heterogeneity of formation permeability, porosity, compressibility. Influence of different well designs and injection schemes on the storage efficiency factor has also been investigated. This work may help in identifying the key factors for increasing the storage efficiency factor.

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Keywords: CO_2 geological sequestration; storage efficiency factor; storage capacity; saline aquifer; numerical simulation.

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1. Introduction

Geological carbon dioxide sequestration in deep formations is a promising measure for mitigating the impact of climate change [1-5]. Deep saline formations are thought to be the greatest potential for CO_2 sequestration due to their large capacity potential. Governments and industries need to know more about CO_2 storage efficiency for achieving a significant and meaningful reduction in CO_2 emissions.

The CO_2 storage efficiency factor is an important term for calculating the amount of CO_2 storage in deep saline formations. It is defined as the volume fraction of the subsurface available space for CO_2 storage and has several components that reflect different physical barriers that inhibit CO_2 from contacting 100 percent of the pore volume of a given basin or region [6]. Storage efficiency is the multiplicative combination of volumetric parameters that reflect the portion of a basin's or region's total pore volume that CO_2 is expected to actually contact [7]. However, evaluation of the CO_2 storage efficiency factor in deep saline aquifers is not a straightforward or simple process. On the one hand, the efficiency factor is a function of the two-phase flow and transport processes, formation geometry, formation heterogeneity, well location, CO_2 injection scheme and formation porosity, etc. On the other hand, various CO_2 trap types and trapping mechanisms that may occur at the different time frames and the different physical states in which the CO_2 might occur [8]. Most of researchers focus on storage capacity estimations. Different investigators employ a variety of approaches and methodologies [6, 8-12], and it is difficult to compare and evaluate. Most of these studies focus on theoretical investigation, analytical solutions, or simple 2D models. In this paper, we combine numerical simulation and analysis method to calculate CO_2 storage efficiency factor based on 3D models, the results indicate that it is an accurate approach which can apply to any complicated CO_2 storage reservoirs.

This study aims at investigating the potential effects of formation parameters and injection schemes on the storage efficiency calculations and the relationship between the storage efficiency factor and several most important parameters for the injection of CO_2 in closed saline formations using numerical simulation method. A three-dimensional (3D) numerical model was developed for the investigation. A variety of study cases are investigated through the models.

2. Methodology

Estimation of CO_2 storage efficiency can be based on analytic techniques as well as numerical simulations. A recent publication for estimating storage efficiency during CO_2 injection with the simple analytical equation is given in Okwen et al. (2010). We can calculate CO_2 storage efficiency factor by either the equation given in Zhou et al. (2008) or the equation by USDOE. CO_2 storage efficiency factors calculated using the two analytic methods are very close. Conversion from CO_2 mass to CO_2 volume is conducted at each time step using the CO_2 density calculated at average pressure conditions.

The USDOE equation used to calculate the CO_2 storage efficiency factor (E_{saline}) for saline formation is:

$$E_{saline} = G_{co_2} / A_t h_g \phi_{tot} \rho \tag{1}$$

Where G_{co_2} [M] is the capacity as mass of CO_2 , G_{co_2} can be determined from the simulation results; A_t [L2] and h_g [L] are the aquifer area and thickness respectively; ϕ_{tot} [L3/L3] is the average porosity of entire saline formation, ρ [M/L3] is the density of CO_2 under aquifer conditions.

The storage efficiency factor $E(t_I)$ for a closed system can be calculated by Zhou et al. (2008):

$$E(t_I) = (\beta_p + \beta_w)\Delta p(t_I) + 0.5(\beta_{ps} + \beta_w)\frac{V_s}{V_f}\Delta p(t_I) + \int_0^{t_I} \frac{Ak_s \Delta p(t)}{\mu_w B_s V_f} dt \quad (2)$$

$$\Delta p(t_i) = \frac{V_{CO_2}(t_i) - Ak_s \Delta t / \mu_w B_S \sum_{j=0}^{i-1} \Delta p(t_j)}{(\beta_p + \beta_w)V_f + 0.5(\beta_{ps} + \beta_w)V_S + Ak_s \Delta t / \mu_w B_S}, \quad i = [1, n] \quad (3)$$

$$V_{CO_2}(t_i) = q_{co_2} t_i / \rho_{co_2}(t_i) \quad (4)$$

Where $\Delta p(t_I)$ is the pressure buildup at time t_I; $\Delta p(t)(t = [0, t_I])$ is the transient pressure buildup from the beginning to the end of injection， which can be discretized into a number (n) of equally spaced time intervals of duration Δt to form a series: $t_0, t_1, \cdots, t_{i-1}, t_i, \cdots, t_{n-1}, t_n$, with $t_0 = 0$ and $t_n = t_I$; $V_{CO_2}(t_i)$ is the total injected CO_2 volume at time t_I; q_{CO_2} is the CO_2 injection rate; $\rho_{co_2}(t_i)$ is the CO_2 density at time t_I; β_p and β_{ps} is the pore compressibility of aquifer and the cap rock, respectively; B_f is thickness of the aquifer; ϕ_f is the porosity of aquifer; $V_f = (\phi_f A B_f)$ is the initial total pore volume; B_s is the thickness of seal; ϕ_s is the porosity of seal; $V_s (= \phi_s A B_s)$ is the total pore volume of seal; β_w is the compressibility of the native brine; μ_w is the viscosity of the native brine; The compressibility and viscosity of brine are calculated according to Mathias et al. (2009); k_s is the permeability of overlying seal.

A 3D model was developed to study the CO_2 storage efficiency factor in response to CO_2 injection into an idealized saline formation. The calculation of CO_2 storage capacity for various study schemes uses the TOUGH2-MP[13] reservoir simulator.

A model domain was chosen to represent a deep saline aquifer underlying a typical aquifer/aquitard (e.g., sandstone/shale) stratigraphy. The model domain is assumed to be a part of the hypothetical basin. The storage formation into which CO_2 is injected, located at a depth of approximately 1200 m below the ground surface, is 20 m thick and bounded at the top by a sealing layer 10 m thick. The bottom of the storage formation is formed by impermeable base rock. Altogether, the model domain includes one storage layer and one sealing layer. The modeled domain with a thickness of 30 m covers an area of 10 km×10 km. The model comprises six model layers (five aquifer sublayers and one aquitard layer) in vertical direction. The entire three-dimensional mesh consists of 43854 gridblocks. The three-dimensional unstructured mesh was designed as shown in a plan view in Figure 1. Carbon dioxide is injected at a constant rate of 1.5 kg/s (47304 t/yr). The vertical injection well is located in the center of model and perforated across the entire thickness of the aquifer. For the ideal situation, CO_2 is expected to occupy the entire aquifer layer.

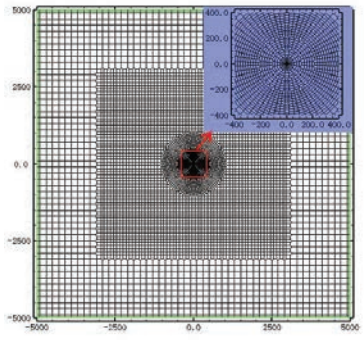

Figure 1 Plan view of the three-dimensional mesh

Initial hydrostatic pressures vary linearly with depth from 120 bar at the top to 122.943 bar at the bottom. There is no lateral variation. Temperature varies linearly with depth from 38.6 ℃ at the top to 39.2 ℃ at the bottom with a geothermal gradient of 20 ℃/km. The groundwater has a salinity of 3%. The system has closed boundaries laterally, and the overlying seal of the aquifer is not perfectly impervious but with the permeability of 10^{-20} m^2 and porosity is 0.1. The properties of the aquifer are typical of sedimentary formations suitable for CO_2 storage, with a permeability of 1.0×10^{-13} m^2 and a porosity of 0.35.

In the closed system, the maximum injection pressure must be less than the measured fracture closure pressure in order to avoid geo-mechanical damage. For comparison, we assume a maximum allowable pressure increase of 6.0 MPa for this study, which corresponds to 50% of the initial hydrostatic pressure at the top of the hypothetical storage formation. To perform CO_2 storage efficiency factor calculations, it is assumed here that the storage efficiency of a reservoir is defined by the percentage of CO_2 occupied space when the maximum pressure buildup is reached. For investigating the potential effects of formation parameters and injection schemes on the CO_2 efficiency factor, the parameters included formation permeability, porosity and compressibility are selected. In addition, the scale of study area, different well locations and injection schemes have been studied.

Formation is heterogeneous in many actual field formations. We studied two different permeability distribution ways, liner distribution and logarithmic distribution, as shown in Figure 2. The distribution of formation permeability is controlled by a random factor m which is permeability modification parameter [14].

$$k' = k \times m \tag{5}$$

where k is intrinsic permeability of grid block, equals to $1.0\times10^{-13}m^2$, k' is revised permeability.

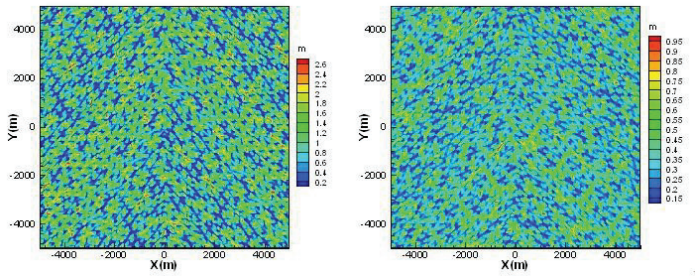

Figure 2 Permeability distributions in plan view (a) linear distribution (b) logarithmic distribution

Based on the above permeability linear stochastic distribution (m is 0 to 2.8) model, the reservoir porosity was selected of 0.15, 0.25, and 0.35 for three different cases. The formation compressibility of 4.5×10^{-9}, 4.5×10^{-10} and 4.5×10^{-11} based on homogeneous model is used for additional three cases.

The relationship between the CO_2 storage efficiency factor and the size of storage reservoir was examined through different size of model domain. The potential effects of model boundaries on the storage efficiency are investigated. We change the model size for a range of 10km×10km, 20km×20km, 30km×30km, 40km×40km in XY direction, respectively.

For investigating the influence of injection schemes on storage efficiency, firstly we stop the injection for 5yrs，20yrs, 50yrs respectively when the maximum pressure buildup (MPB) has reached and then continue to inject until MPB reached again.

In addition, a model using regular rectangular grids in plane with the grid spacing of 100 m was built. The number of wells of 1, 5, 9, 13, 25, 49, and 81 is used for the study. The injection well spacing is 1000 m. The well layouts are shown in Figure 3. Carbon dioxide is injected at a total constant rate of 1.5 kg/s for all well cases. This study aims at investigating the potential effects of the number of injection wells and wells layout on the storage efficiency calculations.

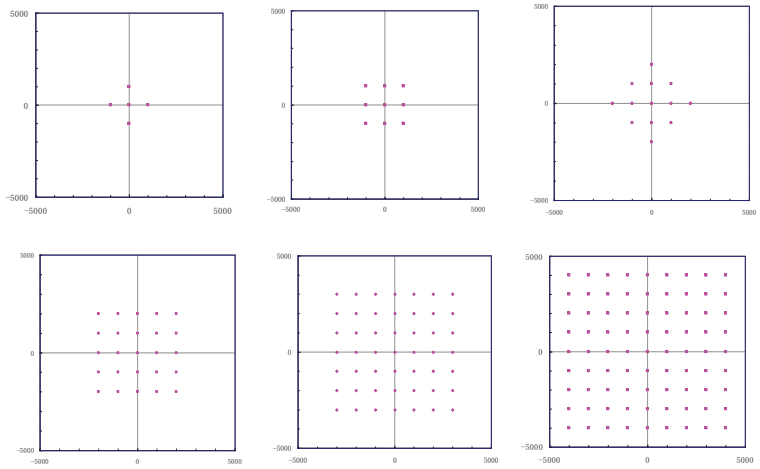

Figure 3 The plan distribution of injection wells (the pink dots represent wells)

3. Results and Discussion

In general, the maximum pressure buildup occurs near wellbore. This is the reason why pressure gradient between wellbore and storage formations is one of the key factors controlling flux distribution in the storage layers. Pressure buildup is the primary limiting factor on CO_2 storage efficiency of a defined system. Changes of the maximum pressure buildup with time for the different cases are shown in Figure 4.

Figure 4 (a) shows maximum pressure buildup for the cases of random distributions of permeability. The maximum pressure buildup increases faster for the two random distribution cases than the homogeneous model. The distribution of permeability is an important factor for storage efficiency calculations. Heterogeneous cases have lower storage efficiency than homogeneous case. This may be because pressure increases too fast nearby the wellbore due to local CO_2 flow was impeded for the permeability random distribution cases. In generally, most of reservoirs are heterogeneous, the storage efficiency factors calculated from homogeneous models are often higher than the actual one. In addition, it is noted from Figure 4 (b) (c) and Figure 5 (b) (c) that large compressibility can improve CO_2 storage efficiency. However larger porosity cannot enhance CO_2 storage efficiency. This may be because larger porosity and compressibility can alleviate increase of the maximum pressure buildup, and more CO_2 can be stored in aquifer at the moment of MPB reached. However, the larger pore volume by increasing porosity causes storage efficiency decrease.

The simulation results shown on Figure 4 (d) indicate the total carbon dioxide stored in entire system increase obviously along with the range of model increase. Extending the range of the model provides more space available for CO_2 storage. However, the storage efficiency factor decreases almost linearly with domain's size increase, as shown on Figure 5 (d). This indicates that the side boundaries of the domain do not significantly influence the arriving time of maximum pressure buildup.

Figure 4 (e) shows that increasing of the number of wells can extend the arrival time of the maximum pressure buildup. Figure 5 (e) indicates that the different number of wells and locations have significant influence on CO_2 storage efficiency of the formations. Simply stated, the larger number of injection wells, the more CO_2 can be stored in the formation. However, the storage efficiency does not show significant improvement when injection wells fully cover the study area. This may be because larger number of wells can alleviate local increase of the maximum pressure buildup and more CO_2 can be stored in aquifer at the moment of MPB reached, but it cannot effectively alleviate the MPB increase if the number of wells is beyond a certain number. The simulation results show that the wells layout is a key factor for the storage efficiency estimations. In the actual injection projects, both storage efficiency and economic significance have to be considered for the layout of the injection wells.

Figure 4 (f) shows that the maximum pressure buildup slightly decreases after the cease of injection and only a small amount of CO_2 can be injected again. This indicates that once the maximum pressure buildup reached, it is very difficult to inject again at the same location within a certain period. Longer cease period of injection may lead to more CO_2 injected again. However, the additional storage amount is quite limited. Short period pause of injection shows very limited improvement on CO_2 storage efficiency.

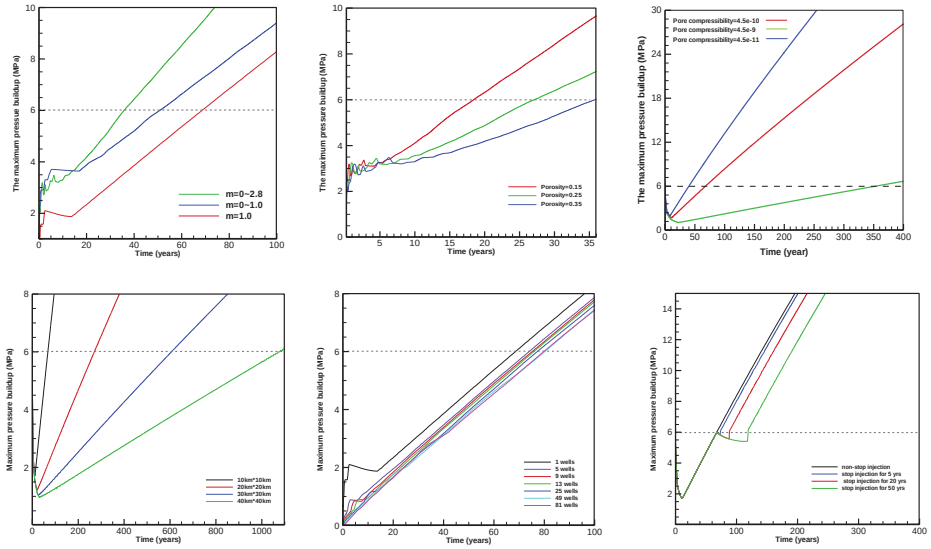

Figure 4 Comparison of maximum pressure buildup (in MPa) of different simulation cases (a) change permeability distribution (b) different porosity,(c) different pore compressibility,(d) change the scale of study area,(e) different number of injection wells,(f) different injection schemes

Figure 6 shows the spatial distributions of CO_2 saturation when the maximum pressure buildup reaches 6.0 MPa and at the time of 100 years. The CO_2 plumes are illustrated using saturation contours for supercritical CO_2. It is noted that carbon dioxide only occupied a small portion of the whole available space. The CO_2 plumes diffusion very slowly. This indicates that even for such a simple aquifer system, fully access of the storage space is impossible.

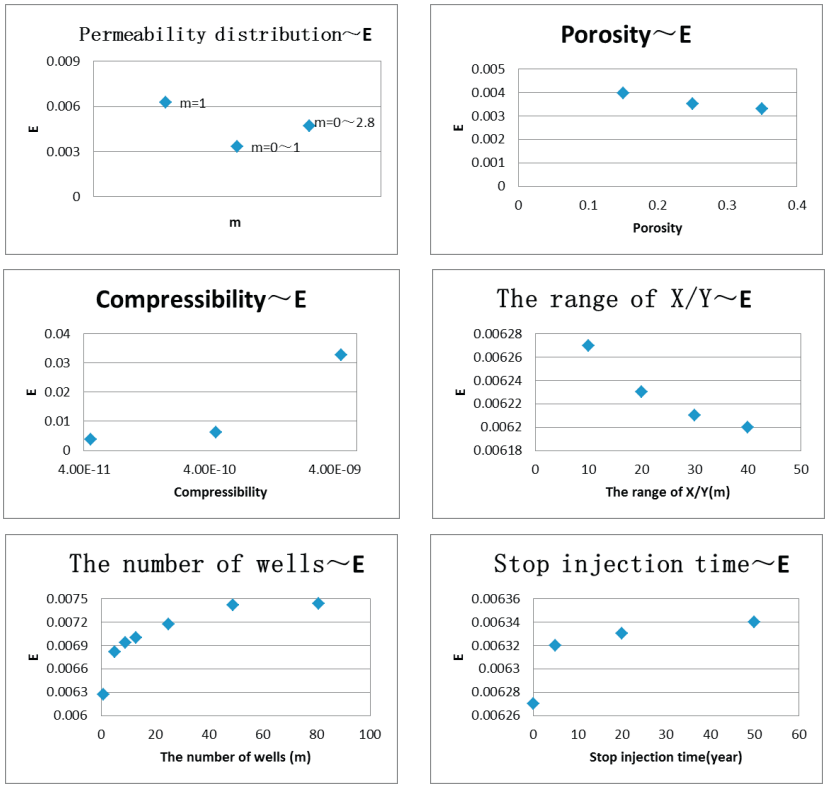

Figure 5 Comparision of CO_2 storage efficiency factor of different simulation cases(a)different permeability distribution schemes, (b)different porosity,(c)different compressibility,(d) change the scale of study area,(e)different number of injection wells,(f) different injection schemes

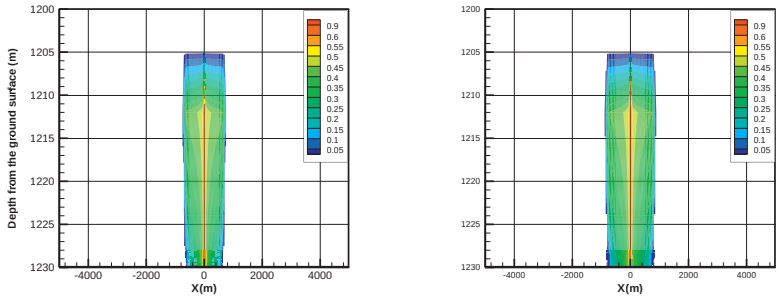

Figure 6 Spatial distributions of CO_2 saturation (a) Maximum pressure buildup reaches 6.0 MPa, (b) at the time of 100 years

4. Conclutions

CO_2 storage efficiency factor can be estimated based on numerical simulations. Simulation results indicate that there is only very small formation porous space occupied by CO_2 in closed systems. In this study, influence of the size of study area, heterogeneity of formation permeability, porosity,

compressibility, well locations and injection schemes on the storage efficiency factor has also been investigated. We may conclude that the storage efficiency factor could be meaningless parameter for storage capacity calculation without considering the reservoir size and injection schemes. Even though this study is based on the simplified aquifer systems, the approach can apply to any complicated CO_2 storage reservoirs. It is a preferred method to estimate the storage efficiency factor through construction of a 3D numerical model for specific storage site by incorporating detailed geological information of the site and injection scheme used. Moreover, simulation results can give information for a more reasonable injection strategy, injection time, and wells layout strategy.

Acknowledgements

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References

[1] Bachu S, Gunter WD, Perkins EH. Aquifer disposal of CO_2: hydrodynamic and mineral trapping. Energy convers. Manage 1994; 44: 3151-3157.

[2] Bachu S. Sequestration of CO_2 in geological media in response to climate change: road map for site selection using the transform of the geological space into the CO_2 phase space. Energy Convers. Manage 2002; 43: 87-102.

[3] Koide H, Tazaki Y, Noguchi Y, Nakayama S, Iijima M, Ito K, Shindo Y. Subterranean containment and long term storage of carbon dioxide in unused aquifers and indepleted natural gas reservoirs. Energy Convers. Manage 1992; 33 (5-8): 619-626.

[4] IPCC : IPCC Special Report on Carbon Dioxide Capture and Storage. New York: Cambridge University Press; 2005.

[5] Van der Meer LGH. Investigations regarding the storage of carbon dioxide in aquifers in the Netherlands. Energy Convers. Manage 1992; 33 (5-8): 611-618.

[6] Goodman A, Hakala A, Bromhal G, Guthrie G, McIntyre D, Kutchko B, Romanov V, Fazio J, Huerta N. U.S.DOE methodology for the development of geologic storage potential for carbon dioxide at the national and regional scale. Int.J. Greenhouse Gas Control 2011; 5: 952-965.

[7] Van der Meer LGH. The CO_2 storage efficiency of aquifers. Energy Convers. Manage 1995; 36 (6-9): 513-518.

[8] Bradshaw J, Bachu S, Bonijoly D, Burruss R, Holloway S, Christensen NP, Mathiassen OM. CO_2 storage capacity estimation: issues and development of standards. Int. J. Greenhouse Gas Control 2007; 1: 62-68.

[9] Doughty C, Pruess K, Benson S, Hovorka S, Knox P, Green C. Capacity investigation of brine-bearing sands of the Frio-Formation for geological sequestration of CO_2. Proceedings of First National Conference on Carbon Sequestration. U.S.Department of Energy, National Energy Technology Laboratory, Berkeley, CA, USA; 2001.

[10] Brennan ST, Burruss RC. Specific storage volumes: a useful tool for CO_2 storage capacity assessment. Natural Resources Research 2006; 15 (3): 165-182.

[11] Bachu S, Bonijoly D, Bradshaw J, Burruss R, Holloway S, Christensen NP, Mathiassen OM. CO_2 storage capacity estimation: methodology and gaps. Int. J. Greenhouse Gas Control 2007; 1: 430-443.

[12] Zhou Q, Birkholzer JT, Tang CF, Rutqvist J. A method for quick assessment of CO_2 storage capacity in closed and semi-closed saline formations. Int.J.Greenhouse Gas Control 2008; 2 (4): 626-639.

[13] Zhang K, Wu YS, Pruess K. User's Guide for TOUGH2-MP- A Massively Parallel Version of the TOUGH2 Code. Report LBNL-315E. Lawrence Berkeley National Laboratory, Berkeley, CA, USA ; 2008.

[14] Pruess K, Oldenburg C, Moridis, G. TOUGH2 user's guide. Report LBNL-43134, Lawrence Berkeley National Laboratory, Berkeley, CA, USA; 1999.