Matrix Shrinkage and Swelling Effects on Economics of Enhanced Coalbed Methane Production and CO₂ Sequestration in Coal


Abstract

Increases in CO₂ levels in the atmosphere and their contributions to global climate change have been a major concern. It has been shown that CO₂ injection can enhance the methane recovery from coal. Accordingly, sequestration costs can be partially offset by the value added product. Indeed, coal seam sequestration may be profitable, particularly with the introduction of incentives for CO₂ sequestration. Hence, carbon dioxide sequestration in unmineable coals is a very attractive option, not only for environmental reasons, but also for possible economic benefits.

Darcy flow through cleats is an important transport mechanism in coal. Cleat compression and permeability changes due to gas sorption desorption, changes of effective stress, and matrix swelling and shrinkage introduce a high level of complexity into the feasibility of a coal sequestration project. The economic effects of carbon dioxide-induced swelling on permeabilities and injectivities has received little (if any) detailed attention.

Carbon dioxide and methane have different swelling effects on coal. In this work, the Palmer-Mansoori model for coal shrinkage and permeability increases during primary methane production was re-written to also account for coal swelling caused by carbon dioxide sorption. The generalized model was added to PSU-COALCOMP, a dual porosity reservoir simulator for primary and enhanced coalbed methane production. A standard five-spot of vertical wells and representative coal properties for Appalachian coals were used. Simulations and sensitivity analyses were performed with the modified simulator for nine different parameters, including coal seam and operational parameters and economic criteria. The coal properties and operating parameters that were varied included Young’s modulus, Poisson’s ratio, the cleat porosity, and the injection pressure. The economic variables included CH₄ price, CO₂ cost, CO₂ credit, water disposal cost, and interest rate. Net present value analyses of the simulation results included profits due to methane production, and potential incentives for CO₂ sequestered. This work shows that for some coal-property values, the compressibility and cleat porosity of coal may be more important than more purely economic criteria.

Introduction

In recent years primary production of natural gas from coal seams has become an important source of energy in the United States. Proven coalbed methane reserves have been estimated at 18.5Tcf, representing 10% of the total natural gas reserves in U.S. Coalbed methane (CBM) production started in early 1980’s as small, high cost operations, but reached 1.6Tcf in 2002. This was more than 8% of total U.S. natural gas production that year.²

The production of CBM reservoirs begins with the pumping of significant volumes of water to lower reservoir pressure and to allow methane desorption and flow.³ The fraction of the original gas-in-place typically produced by primary depletion seems to be somewhat controversial. However, according to recent publications, recoveries are often between 20-60% of the original gas-in-place, so that considerable amounts of gas are left behind.⁴, ⁵, ⁶ Because of this, and because of concerns about global warming due to accumulations of carbon dioxide in the atmosphere,⁷, ⁸ new technologies for enhanced coalbed methane (ECBM) production based on the injection of carbon are being investigated in the United States, Europe, China, and Japan.⁹

In the CO₂-ECBM/sequestration process, injected CO₂ flows through the cleats in the coal by Darcy flow, diffuses into the coal matrix, and is sorbed by it; methane diffuses from the matrix into the cleats, through which it flows to production wells.¹⁰ The injection of CO₂ into coalbeds has many potential advantages: (1) it sequesters CO₂; (2) it reduces the production time for CBM; and, (3) it increases reserves by improving the recovery of CBM. However, the improved methane recovery is accompanied by an increase in costs for CO₂ supply, additional drilling, and well and surface

Box 833836, Richardson, TX 75083-3836, U.S.A., fax 01-972-952-9435.
equipment. Thus CO₂-ECBM and sequestration is accompanied not only by promised benefits, but also new technical challenges and financial risks.

There are more then 70 active CO₂ enhanced oil recovery (EOR) projects; hence, the economics of the process are well documented. However, because there has been so little commercial or field experience of any type for injection of CO₂ into coal, at this time economic studies especially those designed to explore the effects of different values of the most important parameters must depend mostly on reservoir engineering projections of field behavior and estimates of economic variables. Nevertheless, economic projections are needed for several important reasons. Among these reasons are (1) for public policy and private investment decisions, the need for informed projections about the costs and benefits of CO₂-ECBM; (2) for the public and private sectors the need for similar information about sequestration in coal relative to other sequestration options; and (3) for the design of applied R&D programs, the need to know not only the engineering effects, but also the potential economic impacts of what are believed to be the most important physicochemical effects and uncertainties for injection of CO₂ into coal. When a fluid, such as CO₂ or CH₄ is sorbed (or desorbed) by coal, the coal swells (or shrinks). It is believed (on the basis of good experimental evidence) that, as a result of the swelling (or shrinkage) of the matrix, the cleat apertures and permeabilities decrease (or increase). Thus, this effect may increase permeabilities during primary production of coalbed methane, but decrease injectivities and permeabilities for CO₂. At present, there are major, widespread technical concerns about the effects of CO₂-induced swelling on CO2 injectivity and gas flows.

Previous economic studies of CO₂-ECBM/sequestration have considered the economics of sequestration in coal vs. those of sequestration in brine-saturated formations, depleted oil fields, or depleted gas fields. Another recent approach has been to analyze the very-limited number of field data. These studies were for vertical wells. Recently, as suggested by the field project underway in northern West Virginia, we have studied the economics of horizontal wells for CO₂-ECBM/sequestration projects. Engineering impacts of CO₂-induced swelling on horizontal-well projects have also been studied. However, to our knowledge no study has addressed the potential economic impacts of CO₂-induced coal swelling and the relative importance of such coal-seam properties as Young’s modulus and Poisson’s ratio (which affect the degree of swelling) and cleat porosity (which helps determine the effect of the swelling on the cleat permeability).

In this paper we present an economic evaluation of a “typical” CO₂-ECBM/sequestration project using vertical injection and production wells in a coal bed with properties similar to those found in the Northern Appalachian basin. To account accurately for the physical phenomena during the injection and production we use a three dimensional, dual porosity, compositional simulator, which has been validated in a comparison study using both artificial and field data against most of the other leading coal-seam simulators in the world. Several, somewhat similar, models have been proposed for sorption (desorption)-induced swelling (shrinkage) of coals. These equations were developed originally for primary coal-bed methane production, and thus treat only a single sorbed compound (i.e., methane). However, it is well-established that different fluids have different sorption isotherms and induce different amounts of coal swelling.

In the present work a Palmer-Mansoori type equation was used, but modified to accommodate the effects of both sorption of CO₂ and desorption of CH₄.

**Background**

Coal bed methane development in the eastern United States (U.S.) is focused mainly on Northern Appalachian, Central Appalachian, and Warrior basins. Currently, the Warrior basin is the largest producer. However, the Northern Appalachian basin located in West Virginia, Pennsylvania and Ohio is considered one of the largest CBM resources in the U.S., with reserves estimated at 61 Tcf. Coals in this basin are mostly bituminous or higher in rank. The economic analyses described in this paper are representative for this basin. The main target coals are Waynesburg, Pittsburgh, Bakerstown, Freeport, Pocahontas #3, and Kittanning. The Pittsburgh coals have drawn the most attention, because of wide areal distribution, thickness, and gas content. The Appalachian coal seam thicknesses range from a few feet to 25 feet; and sometimes the seams are broken into thinner seams, presenting a unique problem for development.

**Engineering Computations**

We use PSU-COALCOMP, a two-phase, multi-dimensional, dual porosity compositional coalbed methane reservoir simulator, which has been validated against similar codes. The code treats the multi-component sorption that takes place within the coal matrix. The multi-component sorption model uses the Peng-Robinson equation of state, and the ideal adsorbate solution (IAS) theory to calculate the required thermodynamic functions. Three different models are provided for the sorption isotherms within the code: Langmuir, Toth, and UNILAN. The gas/water flow within the cleat system is simulated by the standard two-phase Darcy model based on relative permeabilities.

The flow within the coal matrix, as well as the sorption/desorption dynamics, is represented by a lumped-parameter system that characterizes the process with a sorption time constant, . The value of the sorption time constant is closely related to cleat spacing in coal. It characterizes the rate at which gas exchanges between the micropores and the cleat system. For smaller values of , the exchange of material between the micropores and the cleats is rapid, and equilibrium between the micropores and the cleats is more easily maintained during a production and/or injection process. Equilibrium is not maintained when the time constant becomes a sizeable fraction of the characteristic time of the injection process.
The simulator has a number of options for controlling the wells within a simulation. Wells may be opened to flow, shut in, or converted according to a number of criteria selected by the user. These features facilitate the use of the simulator to study coalbed methane reservoirs undergoing either primary production or sequestration and enhanced recovery schemes. The details of the mathematical formulations for both the fluid flow model and the multi-component sorption model, before addition of the equations for swelling and shrinkage, may be found elsewhere. 27

The model used in PSU-COALCOMP to account for coal swelling in the presence of sorbed components is a modified version of the Palmer-Mansoori 29. This model describes the deformation of the coal matrix by a linear elasticity model characterized by two parameters: Young’s modulus and Poisson’s ratio. Young’s modulus is the ratio of stress to strain on a specified surface in a direction normal to the surface. Thus, Young’s modulus is a measure of a material’s stiffness or its resistance to deformation. Poisson’s ratio is the ratio of lateral strain and longitudinal strain. It is a measure of the volume change of a material under going deformation. A perfectly incompressible material has a Poisson’s ratio of ½. Poisson’s ratio must be greater than -1 and less than or equal to ½; however, Poisson’s ratio is positive for most materials of engineering interest. For the simulations herein, Young’s modulus was varied between 0.145 Mpsia to 1.45 Mpsia (add refs). Poisson’s ratio was varied between 0.2 and 0.4 (add refs).

The original equation for the cleat porosity given by Palmer and Mansoori has been modified to account for multiple gas components:

$$
\phi = \phi_o^* + c_m P \left( \frac{K}{M} - 1 \right) \sum s_{m,j} a_i
$$

(1)

where $\phi$ is the cleat porosity, $c_m$ is the matrix compressibility (a mechanical property of coal that is generally a function of Young’s modulus, Poisson’s ratio and grain compressibility, and is equal to $1/M$ for the cases studied in this paper), $P$ is the gas pressure, $K$ is the bulk modulus, $M$ is the constrained axial modulus, $s_{m,j}$ is the matrix swelling coefficient (volumetric strain over quantity of sorbed gas) for sorbed gas $j$, $a_i$ is the mass of gas $j$ sorbed, $J$ is the number of gas components, the subscript $j$ corresponds to each gas component. More detailed descriptions of most of these parameters may be found in Palmer and Mansoori. The symbol $\phi_o^*$ is for the porosity at the 0.0 psi reference pressure (when it is assumed that no gas is sorbed to the coal). This equation accounts for what Pekot and Reeves call differential swelling, 31 which means that the coal swells more in the presence of some sorbed components than for others. Once the pressure and composition dependence of the porosity has been calculated, the cleat permeability is obtained from the cubic law. A more complete description of the swelling model used in the simulator can be found elsewhere. 17

Mechanical properties of coal have been correlated with rank, a measure of the quality and thermal maturity of the organic matter, and especially with the carbon content, measured on a dry, ash-free (daf) basis. 36 Berkowitz summarized experimental data from a number of sources for coals with different coal ranks and carbon contents. 37 In his summary, Young’s modulus ranged from less than 145,000 psi to greater than 2,030,000 psi. However, the largest values of Young’s modulus appear to be relatively insensitive to coal rank for smaller carbon contents, which includes most bituminous coals. 36 According to Berkowitz, 37 the best data for coals with 81.5% to 89.0% daf carbon content had an average Young’s modulus of about 696,000 psi; for 92.5% carbon content the value was 753,000 psi. Therefore, a value of 725,000 psi was chosen to represent the Young’s modulus of many Eastern coals.

The initial permeability of the coal seam was set at 10 mD. The coal physical properties and operational parameters that were varied for sensitivity studies, all of which influenced the economic outcome of the project, are listed in Table 4.

### Economic Evaluation

Net Present Values (NPV) were used as a basis for comparison between CO2-ECBM/sequestration scenarios, which consider the effects of different operating procedures, coal properties, swelling, and economic variables on process economics. NPV is defined by an equation of the form

$$
NPV = \sum_{n=0}^{N} \frac{R_n - C_n}{(1+i)^n}
$$

(2)

where NPV is the net present value, $R_n$ is the annual incremental revenue for the $n$th year, $C_n$ is the annual operating and capital costs for the $n$th year, $N$ is the number of project years, and $i$ is the discount rate. The term summed in Equation 2 is described as the yearly NPV. Net present value seems to be more appropriate method of comparison than the Rate of Return (ROR) method, when one deals with incremental revenues. 38

Table 1 lists the investments and operating costs used in the economic analysis. Capital expenditures are generally considered as investments. 39 Capital expenditures found in oil and gas property evaluations include drilling and well-development costs, as well as cost of surface equipment.

The cost of drilling and developing the wells includes casing, tubing, drilling mud and cement, logging, and completion costs. The cost of surface equipment includes tanks, separators, compression equipment, pumps, flowlines, metering equipment, and labor to install surface equipment. 40 Actual drilling costs for the Appalachian basin were estimated using cost data from drilling companies operating in Northern West Virginia. 41, 42 In this work we consider that all the wells were previously drilled, and the wells were put in production at the start of economic evaluation.

---

1 Rather than using $s_{m,j}$ Palmer and Mansoori use the $c_j/b$ ratio, where $b$ is the inverse of the Langmuir volume constant for each gas, and where $c_j = s_m * \frac{\lambda_p}{P}$ (Langmuir pressure constant).
Surface facilities for coalbed methane primary production contain a pump or a gas lift system, water-gas separators, and compressors. Carbon dioxide sequestration requires additional surface installations for CO2 injection such as injection skids, automation, and wellheads. The cost of additional downhole equipment was added to the surface equipment cost. The surface costs were estimated from averaging costs for CO2 tertiary oil-recovery projects in West Virginia. Those costs were escalated at 4% per annum to obtain 2005 costs. Operation and maintenance costs have been estimated in a similar fashion. Cost values for individual sequestration projects will vary, depending on the particular conditions of the project and locality.

CO2 sequestration economics are very sensitive to the CO2 injection and separation costs. Power plant flue gas should be one of the most important sources of CO2 for sequestration. Dubois cited CO2 prices of $1.00/mscf (supercritical, at injection pressure) from an ethanol plant in Kansas. West Texas prices are around $0.75/mscf, delivered. Recently, Kuuskrää listed a market price for CO2 of $0.75/mscf. The lowest delivered price for CO2 in our literature search was that of Stevens, between $0.25 and 0.35/mscf. One possible incentive for CO2 sequestration is a credit given per ton of CO2 sequestered, whether it is received from a government entity or obtained on the open market through a trading scheme. In this study different CO2 costs and sequestration credits were considered. These were lumped into a single parameter, CO2 cost minus credit per unit of CO2 sequestered, or net CO2 cost.

The costs used in the economic calculations are shown in Table 1. In the analysis costs were discounted on a yearly basis. For each simulation, yearly quantities of methane produced and CO2 sequestered were calculated, the values and costs were summed for that year, and the total was discounted to the present using a determined discount rate. Discount rates between 6% and 18% were used, in 3% increments. Summing the NPV for each year gave an NPV dollar value for the entire project. This NPV dollar value allows for direct comparison among all of the different scenarios studied. In this study all NPV calculations were done before taxes.

Table 4 shows the economic parameters. Methane prices between $3/mscf and $5/mscf, and CO2 costs of $0.53/mscf to $2.63/mscf, in $0.53/mscf increments, were used. Various CO2 credits were also considered; values from $0.0/mscf to $1.05/mscf, in $0.26/mscf increments, were used.

Methodology

We simulated sequestration into a coal seam with the properties that may typically be found in Appalachian coal. Those properties are listed in Table 2.

The hypothetical reservoir had an area of 9 square miles, subdivided into 36, 160 acre inverted five spot patterns. Each five spot pattern had one CO2 injector in the middle of the pattern and four producing wells in the corners of the pattern. The total original gas in place (OGIP) was 0.51 Bscf per pattern for a coal thickness of 6.6 ft. Due to the relatively thin pay zone, we considered only one layer for the simulation grid.

During each simulation, all wells were produced to reduce the water content of the coal. The primary production of methane was continued for a period of six months. At the end of primary production, the central well in each pattern was shut in for one day and converted to an injector. The CO2 was then injected in the central wells until project termination. The project was terminated when the produced gas was 10% or more CO2, except when the yearly NPV was less than or equal to zero, in which case the project was terminated early due to economic considerations.

The coal physical properties and operational parameters that were varied, all of which influenced the economic outcome of the project, are listed in Table 3. The CO2 injection pressure was set at 725 psi, 870 psi, or 1015 psi.

Results

The average injectivity for the coal reservoir with the properties listed in Table 2 and marked in bold lettering in Table 3 was 23,040 mscf/day (for a porosity of 0.5%, where coal swelling is neglected). However, the injectivity was significantly smaller when coal swelling was included in the simulations. The decreases in the average injection rate for a single five-spot pattern and different values of Young’s modulus and Poisson’s ratio can be seen in Table 5. When the coal studied was less elastic with a higher Young’s modulus (1.45*10^6 psia) and a larger Poisson’s ratio (0.4), the injectivity decreased to 10,224 mscf/day. The average injection rate for this swelling case was less than one-half the rate for the case when coal swelling was neglected. The injectivity decrease was even more pronounced when the elasticity of the coal was large. For the smallest values of E and v, representing a more elastic coal, the calculated injection rate was 360 mscf/day, which was only 1.5% of the injection rate (23,040 mscf/day).

Production rate curves were plotted to illustrate the effects of the coal swelling phenomena on an ECBM process. Figure 1 shows the production rate curves during CO2 injection. The time scale begins when CO2 injection was begun at 180 days after the start of primary production. The four curves illustrate that the decrease in the production rate is significant when the coal elasticity is large. The curve for the smallest Young’s modulus (0.145*10^6 psia) and Poisson’s ratio (0.2) is significantly below the curve that represents production rate when the coal swelling effect is not included. When coal with such low values of Young’s modulus was simulated, the coal cleats experienced significant closure due to pore pressure falloff. Therefore, soon after the start of the primary production, the permeability around the production wells had decreased to less than one half of its initial value. Moreover, as soon as CO2 injection started, the permeability around the injection wells was reduced to ca. 1md. After this sudden decrease, the permeability tended to stay constant (~1md) for the rest of the project life. Accordingly, as a result of both the effective stress and matrix swelling effects on coals with a small Young’s modulus, the productivity was significantly decreased. On the other hand, the permeability
decrease around the production wells was not noticeable when the coal had larger (and probably more realistic) values of Young’s modulus (725*10^6 psi or 1.45*10^6 psi), and a larger Poisson’s ratio (0.3 or 0.4). However, the production rates calculated for these less elastic coal seams were still less than the rate obtained when no coal swelling effect was included in the simulations, because of the 70% reduction in permeability around the injection wells produced by the swelling effects.

The decreases in the CO2 injectivity and methane productivity caused by coal swelling can be a cause for economic concerns about ECBM processes. To illustrate effects of coal swelling on the economics of a project, net present values were calculated for various representative coal seam elastic properties (Young’s modulus and Poisson’s ratio) and porosity values (see Table 3). Figure 2 is a three-dimensional plot of NPV vs. Young’s modulus and Poisson’s ratio; this surface is shown for three different values of the cleat porosity. The values of CH4 price, interest rate, and water disposal rate used for the NPV calculations are listed in bold numbers) in Table 4. The net cost for CO2 injection (purchase price minus sequestration tax credit) was taken as zero for these “base case” computations. One of the major effects suggested by this figure is a pronounced effect of porosity on the economic outcome of a project. The negative effect of coal swelling on coal permeability, and consequently on productivity and the economics of the project, was larger for the smaller values of porosity. The dependence of NPV on Young’s modulus and Poisson’s ratio were not seen for larger values of the porosity. It may also be noted that when coal swelling effect was not included, the NPV for the coal with 0.5% porosity was as much as $24M when coal was considered as less elastic by assigning bigger values for elastic properties, while for the more elastic coals the NPV could be negative. The large dependence of NPV on Young’s modulus and Poisson’s ratio were not seen for larger values of the porosity. It may also be noted that when coal swelling effect was not included, the NPV for the coal with 0.5% porosity was $36.6 M, but this was reduced to less than half when coal swelling was included in the simulations. Neglect of coal swelling effects may overestimate the economics of a project, especially for coals with smaller porosities and values of Young’s modulus.

In order to examine possible effects of coal swelling on seams of Pittsburgh coal, we replotted a cross section of Figure 2 (Young’s modulus = 0.725*10^6 psi, representative of Pittsburgh coal) in Figure 3a. The latter figure illustrates effects of Poisson’s ratio on NPV for different porosity values. The effect of coal swelling was somewhat smaller for the larger values of Poisson’s ratio, but not significantly. Similarly, another cross section of Figure 2 is plotted in Figure 3b; the latter figure illustrates effects of Young’s modulus on the NPV for different porosity values and Poisson’s ratio 0.3 (also representative for Pittsburgh coals). In this figure, the more pronounced effect of coal swelling for smaller Young’s moduli can be easily seen. In summary, for coal swelling phenomena Young’s modulus seems to be more important than Poisson’s ratio.

As illustrated by Figure 4, when the computations for Figure 2 were recalculated with a net (purchase price minus credit) CO2 cost of $1.05/mcf CO2, the NPV values for the smallest porosity (0.5%) were as much as twice the NPV calculated for the the highest porosity value (2%) and small Poisson’s ratio. This result would be surprising if obtained for negligible coal swelling; (in that case an increase in the NPV with greater pore volume would be expected). However, when swelling effects were included, the decrease in permeability was more pronounced for smaller porosities; thus the injection rate (Table 5) was reduced by almost 100 times. Therefore, as the porosity decreased, the cumulative CO2 sequestered decreased more for smaller values of Young’s modulus, Poisson’s ratio, and porosity. This effect was noticeable when the net CO2 cost was included in the study, which produced larger NPV results for smaller porosities as the cumulative injection decreased significantly.

Figure 5 illustrates cross sections of Figure 4 for fixed values of Young’s modulus and Poisson’s ratio that are representative of Pittsburgh coal. In Figure 5, as in Figure 3, the effect of Young’s modulus is seen to be more significant than that of Poisson’s ratio. The difference between the two plots becomes evident when one compares effects of porosity on NPV for non-zero net CO2 costs. When the net CO2 cost is relatively large, the NPV numbers can be larger for coals with smaller porosities, because the amounts of cumulative CO2 sequestered are smaller, which reduces the CO2 expense for the project. In situations such as this, comparisons of different net present values may be misleading if the circumstances and causes for the differences are not considered.

A three-dimensional plot also was constructed to show the combined effects of CH4 price and CO2 net cost on the NPV for different porosity values (Figure 6). The coal seam properties and operational pressure for Figure 6 are listed in Table 2. When the CO2 net cost was less than $0.53/mcf, the net present values for coals with larger porosities were larger, with both the cumulative CO2 injected and methane produced also larger. However, higher cumulative injection of CO2 reduced the NPV as the net CO2 cost increased. This effect shifted the NPV surface in Figure 6 for 0.5% porosity upwards, thus making the NPV larger for the coals with smaller porosities. This trend also can be seen in Figure 7, in which NPV is plotted for different CH4 price and porosity values at constant net CO2 cost of $1.05/mcf. Moreover, this figure illustrates the positive effect of CH4 price on the NPV more clearly. Not surprisingly, as CH4 price increased, NPV increased also.

The effect of CH4 price is further illustrated in Figure 8, in which results for different Young’s moduli but constant porosity of 0.5% are plotted. As can be seen, the NPV for the case in which coal swelling effect was neglected was less than that for the case of swelling of a coal with relatively large Young’s modulus. In the latter case reduction of the cumulative CO2 injected decreased the expenses of the project, thus making the NPV larger. On the other hand, when Young’s modulus was small, the significant reduction in CH4 production caused the NPV to decrease.

In Figure 9 the CO2 net cost was zero. In this case the NPV calculated for the no-swelling case was larger than the NPV value for any other value of Young’s modulus. In Figure 9 the NPV depends mostly on cumulative CH4
produced, so that higher production results in higher NPV values.

The effect of net CO₂ cost on NPV for different values of Young’s modulus is plotted in Figure 10. In this plot porosity and Poisson’s ratio are 0.5% and 0.3, respectively. As discussed earlier, cumulative CH₄ production and CO₂ sequestration were much larger when coal swelling was neglected. These differences were reflected in the NPV values, which were much larger for smaller net CO₂ costs and larger cumulative CH₄ production. On the other hand, as the cost of CO₂ increased, due to the larger cumulative CO₂ injection costs, net present values for the no-swelling cases decreased below the net present values calculated when swelling was included. Moreover, for the smallest Young’s modulus (0.145*10⁶ psia) the NPV curve was much lower than the NPV curves for larger, more-realistic of Young’s modulus. The small net present values for the smallest Young’s modulus were caused by significant reductions in production rates. It should be noted that the behavior of the NPV curve for the no-coal swelling case is different from the shapes of the other curves. The slope of the NPV curve in the range of - $0.52/mmcf to $0.79/mmcf was much steeper than for higher net CO₂ costs. This is, in part, because the project lifetime for the lower net CO₂ costs was much longer than for the higher net CO₂ costs.

Conclusions

On the basis of the models and data of this study, the following tentative conclusions may be reached:

- Injectivity of CO₂ decreases when swelling occurs; coal swelling can have significant effects on injection and production rates, and hence profitability.
- Profits from a project may be affected positively or negatively by swelling and shrinkage effects; the net CO₂ cost will help to determine if swelling contributes positively or negatively to NPV.
- Hence, cleat porosity, Young’s modulus, and Poisson’s ratio often will be critical parameters in determining a project’s value, although the Poisson’s ratio often has a significantly smaller effect than the other two.
- The effects of swelling and shrinkage are not limited to the injection wells; production wells can see a permeability increase, or even—for certain values of the critical parameters—a permeability decrease.
- NPV project analyses for sequestration purposes may lead to misleading conclusions; i.e., a project may have a higher NPV simply because it sequesters less CO₂. This can have public policy implications for designing the proper economic incentives for sequestration.
- Because of the potential impacts, accurate values of Young’s modulus and Poisson’s ratio are necessary in order to make reliable predictions.
- Swelling models need to be validated with both laboratory and field data; chemically and/or geomechanically advanced models may be needed.

Nomenclature

- $a_j$ -- mass of sorbed gas $j$
- $c_m$ -- matrix compressibility
- $C_n$ -- annual costs for year $n$
- $i$ -- discount rate
- $j$ -- gas component index
- $J$ -- number of gas components
- $K$ -- bulk modulus
- $M$ -- constrained axial modulus
- $P$ -- gas pressure
- $n$ -- yearly index for summation of annual revenues
- $N$ -- number of project years
- $NPV$ -- net present value
- $R_n$ -- annual incremental revenue for the $n$th year
- $s_m,j$ -- matrix swelling coefficient for sorbed gas $j$
- $\phi$ -- cleat porosity
- $\phi_o$ -- cleat porosity at the reference gas pressure (0.0 psi)

Bscf = $10^9$ standard cubic feet
mscf = $10^3$ standard cubic feet
Acre = 43560 square feet
$SM = 10^6$ $
Mpsia = 10^6$ psia

Acknowledgements

This work was funded entirely by the Office of Fossil Energy, U.S. Department of Energy.

References


Table 1. Capital and operational costs.

<table>
<thead>
<tr>
<th>Cost Types</th>
<th>Cost per well ($k)</th>
<th>Total Cost ($k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start Up Costs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drilling (85 wells)</td>
<td>94</td>
<td>7,990</td>
</tr>
<tr>
<td>Surface Equipment (85 wells)</td>
<td>19</td>
<td>1,615</td>
</tr>
<tr>
<td>Downhole Equipment (85 wells)</td>
<td>8</td>
<td>680</td>
</tr>
<tr>
<td>Pipeline costs</td>
<td>N/A</td>
<td>150</td>
</tr>
<tr>
<td>MMV capital costs (@10%)</td>
<td>N/A</td>
<td>1,045</td>
</tr>
<tr>
<td><strong>Total Start-up</strong></td>
<td></td>
<td><strong>11,480</strong></td>
</tr>
<tr>
<td>Yearly Costs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operations and Maintenance</td>
<td></td>
<td>3,060</td>
</tr>
<tr>
<td>MMV Maintenance (@10%)</td>
<td></td>
<td>305</td>
</tr>
<tr>
<td><strong>Total Yearly Costs</strong></td>
<td></td>
<td><strong>3,365</strong></td>
</tr>
</tbody>
</table>

Table 2. Reservoir properties used in all simulations.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reservoir Thickness</td>
<td>6.6 ft</td>
</tr>
<tr>
<td>Critical Gas Saturation</td>
<td>0.0%</td>
</tr>
<tr>
<td>Depth</td>
<td>1400 ft</td>
</tr>
<tr>
<td>Critical Water Saturation</td>
<td>10.0%</td>
</tr>
<tr>
<td>Lateral Permeability</td>
<td>10 md</td>
</tr>
<tr>
<td>Initial Water Saturation</td>
<td>40%</td>
</tr>
<tr>
<td>Skin</td>
<td>0.0</td>
</tr>
<tr>
<td>Reservoir Temperature</td>
<td>113°F</td>
</tr>
<tr>
<td>Sorption Volume Constant (CH₄, CO₂)</td>
<td>262 scf/ton, 1570 scf/ton</td>
</tr>
<tr>
<td>Initial Mole Fraction of Gas (CH₄, CO₂)</td>
<td>100%, 0%</td>
</tr>
<tr>
<td>Sorption Pressure Constant (CH₄, CO₂)</td>
<td>725 psi, 290 psi</td>
</tr>
<tr>
<td>Reservoir Drainage Area</td>
<td>3 mi x 3 mi (36 x 160 acres)</td>
</tr>
<tr>
<td>Rock Density</td>
<td>87.4 lb/ft³</td>
</tr>
<tr>
<td>Wellbore Radius</td>
<td>0.3 ft</td>
</tr>
<tr>
<td>Initial Reservoir Pressure</td>
<td>696 psi</td>
</tr>
<tr>
<td>Coalface Pressure at Producers</td>
<td>100 psi</td>
</tr>
<tr>
<td>Matrix Swelling Coefficient (CH₄, CO₂)</td>
<td>0.0105 ton/mscf, 0.00703 ton/mscf</td>
</tr>
<tr>
<td>Sorption Time Constant</td>
<td>5.7 days</td>
</tr>
</tbody>
</table>
Table 3. Coal seam and operational parameters that were varied in the simulations. Bolded numbers represent the base case values.

<table>
<thead>
<tr>
<th>Young's Modulus (Mpsi)</th>
<th>Injection Pressure (psi)</th>
<th>Poisson's Ratio</th>
<th>Porosity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.145</td>
<td>725</td>
<td>0.2</td>
<td>0.5</td>
</tr>
<tr>
<td>0.725</td>
<td>870</td>
<td>0.3</td>
<td>1</td>
</tr>
<tr>
<td>1.45</td>
<td>1,015</td>
<td>0.4</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 4. Economic parameters that were varied in the analysis. Bolded numbers represent the base case values.

<table>
<thead>
<tr>
<th>CH₄ price ($/mcf)</th>
<th>CO₂ cost ($/mcf)</th>
<th>CO₂ credit ($/mcf)</th>
<th>Water Disposal Cost($/stb)</th>
<th>Interest Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>0.53</td>
<td>0</td>
<td>0.4</td>
<td>0.06</td>
</tr>
<tr>
<td>4</td>
<td>1.05</td>
<td>0.26</td>
<td>0.99</td>
<td>0.09</td>
</tr>
<tr>
<td>5</td>
<td>1.58</td>
<td>0.53</td>
<td>0.4</td>
<td>0.12</td>
</tr>
<tr>
<td></td>
<td>2.1</td>
<td>0.79</td>
<td>0.99</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>2.63</td>
<td>1.05</td>
<td>0.4</td>
<td>0.18</td>
</tr>
</tbody>
</table>

Table 5. Average injection rate (mscf/day) for the various Young’s Modulus and Poisson’s Ratios simulated. Other parameters were from the base case scenario. Numbers in parentheses are percent of the injection rate for no shrinkage and swelling, ceteris paribus—23,040 mscf/day.

<table>
<thead>
<tr>
<th>E (*10⁶ psia)</th>
<th>ν</th>
<th>0.145</th>
<th>0.725</th>
<th>1.45</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td></td>
<td>360 (1.5)</td>
<td>1,584 (6.9)</td>
<td>6,336 (27.5)</td>
</tr>
<tr>
<td>0.3</td>
<td></td>
<td>1,382 (6.0)</td>
<td>3,744 (16.3)</td>
<td>10,080 (43.8)</td>
</tr>
<tr>
<td>0.4</td>
<td></td>
<td>1,728 (7.5)</td>
<td>4,320 (18.8)</td>
<td>10,224 (44.4)</td>
</tr>
</tbody>
</table>

Figure 1. Methane production rate as a function of time for different values of Young’s modulus and Poisson’s ratio. Dashed lines are the production rates that would occur if the project were extended past its economic life.
Figure 2. Net present value of each simulated case, as a function of Young’s modulus, Poisson’s ratio, and porosity. Net CO₂ cost is zero. Other physical and economic parameters are as in the base case.

Figure 3. Net present value as a function of a) Poisson’s ratio (at E=0.725*10⁶ psia) and b) Young’s modulus (at v=0.3) for a net CO₂ cost of zero.
Figure 4. Net present value of each simulated case, as a function of Young’s modulus, Poisson’s ratio, and porosity. Net CO₂ cost is $1.05. Other physical and economic parameters are as in the base case.

Figure 5. Net present value as a function of a) Poisson’s ratio (at E=0.725×10⁶ psia) and b) Young’s modulus (at ν=0.3) for a net CO₂ cost of $1.05.
Figure 6. Net present value as a function of methane price and net CO₂ cost. All other physical and economic parameters are for the base case.

Figure 7. Net present value vs. CH₄ price for different porosities at a net CO₂ cost of $1.05/mcf.
Figure 8. Net present value vs. CH₄ price for different Young’s moduli at a net CO₂ cost of $1.05/mcf.

Figure 9. Net present value vs CH₄ price for different Young’s moduli at a zero net CO₂ cost.
Figure 10. Net present value as a function of net CO₂ cost, for several values of Young’s modulus. All other variables are as in the base case.