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

F. Burcu Gorucu, SPE, National Energy Technology Laboratory/US Department of Energy/Pennsylvania State University; Sinisha A. Jikich, SPE, National Energy Technology Laboratory/Parsons; Grant S. Bromhal, National Energy Technology Laboratory/US Department of Energy; W. Neal Sams, National Energy Technology Laboratory/EG&G; Turgay Ertekin, SPE, Pennsylvania State University; and Duane H. Smith, National Energy Technology Laboratory/US Department of Energy

Summary

Increases in carbon dioxide (CO₂) levels in the atmosphere and their contributions to global climate change are a major concern. CO₂ sequestration in unmineable coals may be a very attractive option, for economic as well as environmental reasons, if a combination of enhanced-coalbed-methane (ECBM) production and tax incentives becomes sufficiently favorable compared to the costs of capture, transport, and injection of CO₂.

Darcy flow through cleats is an important transport mechanism in coal. Cleat compression and permeability changes caused by 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 CO₂-induced swelling on permeabilities and injectivities has received little (if any) detailed attention.

CO₂ and methane (CH₄) have different swelling effects on coal. In this work, the Palmer-Mansoor model for coal shrinkage and permeability increases during primary methane production was rewritten to also account for coal swelling caused by CO₂ sorption. The generalized model was added to a compositional, dual-porosity coalbed-methane reservoir simulator for primary (CBM) and ECBM production. A standard five-spot of vertical wells and representative coal properties for Appalachian coals was used (Rogers 1994). 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, cleat porosity, and injection pressure. The economic variables included CH₄ price, CO₂ cost, CO₂ credit, water disposal cost, and interest rate. Net-present-value (NPV) analyses of the simulation results included profits resulting from CH₄ production and potential incentives for sequestered CO₂. This work shows that for some coal seams, the combination of compressibility, cleat porosity, and shrinkage/swelling of the coal may have a significant impact on project economics.

Introduction

In recent years, primary production of natural gas from coal seams has become an important source of energy in the United States. Proven CBM reserves have been estimated at 18.5 Tscf, representing 10% of the total natural-gas reserves in the United States. CBM production started in the early 1980s as a small, high-cost operation but reached 1.6 Tscf in 2002. This was more than 8% of the total US natural-gas production that year (Kuuskraa 2003).

The production of CBM reservoirs begins with the pumping of significant volumes of water to lower reservoir pressure and to allow CH₄ desorption and flow (Stevens et al. 1998). 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 and 60% of the original gas in place, so that considerable amounts of gas are left behind (Gale and Freund 2001; Stevens et al. 1999; Van Bergen et al. 2001). Because of this, and because of concerns about global warming caused by accumulations of CO₂ in the atmosphere (National Energy Technology Laboratory 2003, 2004), new technologies for ECBM production based on the injection of carbon are being investigated in the US, Europe, China, and Japan (Coal-Seq Forum 2004, 2006).

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; CH₄ diffuses from the matrix into the cleats, through which it flows to production wells (Sams et al. 2005). The injection of CO₂ into coalbeds has many potential advantages: It sequesters CO₂, it reduces the production time for CBM, and it increases reserves by improving the recovery of CBM. However, the improved CH₄ recovery is accompanied by an increase in costs for CO₂ supply, additional drilling, and well and surface equipment. Thus, CO₂-ECBM and sequestration are accompanied not only by promised benefits but also by new technical challenges and financial risks.

There are more than 70 active CO₂ enhanced-oil-recovery (EOR) projects; hence, the economics of the process are well documented (Moritis 2000; Jarrell et al. 2002; Taber 1990). However, because there has been so little commercial or field experience of any type for injection of CO₂ into coal (Reeves and浦东 2005), at this time, economic studies [especially those designed to explore the effects of different values of the most important parameters (Bromhal et al. 2004a; Jikich et al. 2004)] must depend mostly on reservoir-engineering projections of field behavior and estimates of economic variables. Nevertheless, economic projections are needed for several important reasons:

- For public policy and private investment decisions, the need for informed projections about the costs and benefits of CO₂-ECBM
- For the public and private sectors, the need for similar information about sequestration in coal relative to other sequestration options
- For the design of applied R&D programs, the need to know not only the engineering effects (Bromhal et al. 2005) 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) (Laxminarayan et al. 2004). It is believed [on the basis of good experimental evidence (Seidle and Huitj 1995; Seidle et al. 1992; Harpalani and Chen 1997; Harpalani 2002)] 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 CBM 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 (Coal-Seq 2004, 2006; Laxminarayana et al. 2004).

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 (Kuuskraa 2003, 2004). Another recent approach has been to analyze the very limited number of field data (Reeves and Oudinot 2005). These studies were for vertical wells. Recently, as suggested by the field project under way in northern West Virginia (Cairns 2003), we have studied the economics of horizontal wells for CO₂-ECBM/sequestration projects (Bromhal et al. 2004a; Jikich et al. 2004). Engineering impacts of CO₂-induced swelling on horizontal-well projects also have been studied (Bromhal et al. 2004b). 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 “prototypical” CO₂-ECBM/sequestration project using vertical injection and production wells in a coalbed 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 CBM simulator, PSU-COALCOMP (Manik 1999; Manik et al. 2002), 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 (Gunter et al. 2005). Several somewhat similar models have been proposed for sorption (desorption)-induced swelling (shrinkage) of coals (Palmer and Mansoori 1998; Sawyer et al. 1990; Pekot and Reeves 2003). These equations were developed originally for primary CBM production and thus treat only a single sorbed compound (i.e., CH₄). However, it is well established that different fluids have different sorption isotherms and induce different amounts of coal swelling (Laxminarayana et al. 2004). In the present work, a Palmer-Mansoori type equation (Palmer and Mansoori 1998) was used but was modified to accommodate the effects of both sorption of CO₂ and desorption of CH₄. However, the Northern Appalachian basin (located in West Virginia, Pennsylvania, and Ohio) is considered one of the largest CBM resources in the US, with reserves estimated at 61 Tscf. Coals in this basin are mostly bituminous or higher in rank (Byrer et al. 1987). 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 ft; sometimes, the seams are broken into thinner seams, presenting a unique problem for development (Patchen et al. 1991).

**Engineering Computations**

We use PSU-COALCOMP, a two-phase, multidimensional, compositional CBM reservoir simulator (Manik et al. 2002), which has been validated against similar codes (Gunter et al. 2005). The code treats the multicomponent sorption that takes place within the coal matrix. For this study, the code was modified to account for shrinkage and/or swelling, which can occur because of fluid sorption and/or desorption.

The gas/water flow within the coal system is simulated by the standard two-phase Darcy model based on relative permeabilities. Straight-line relative permeability curves are used, with endpoints as shown in Table 1. During water production, the average reservoir pressure decreases, allowing CH₄ to be desorbed and increasing its saturation within the cleats. In general, desorption increases cleat apertures and their absolute permeabilities. In addition, by shifting the location of the system on the relative permeability curves to higher gas saturation, the desorption also increases the gas fractional flow. However, the relative permeability curves used in the code are not changed by CH₄ desorption. Conversely, CO₂ sorption tends to decrease cleat apertures, absolute permeabilities, gas saturations, and fractional flows, but (as for CH₄ desorption) does not change the relative permeability curves used.

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, τ. As seen from the following equation, the value of the sorption time constant is closely related to cleat spacing in coal:

\[
\tau = \frac{1}{D_{mi} \times a} \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \qu
(f) is taken as the cleat spacing in the above equations. For smaller values of \( \tau \), 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. Unlike the situation in conventional gas reservoirs (where the CH\(_4\) occurs in gaseous form within the matrix pores), in coal seams virtually all of the CH\(_4\) exists in sorbed form. Hence, the matrix porosity is of relatively little significance in coal, and the matrix porosity and effects of shrinkage/swelling on the matrix porosity are not included in the PSU-COALCOMP formulation.

The multicomponent sorption model uses ideal adsorbate solution (IAS) theory to calculate the isotherms for two-component fluids from the isotherms for each of the single-components and using the Peng-Robinson equation of state (Peng and Robinson 1976) for the required thermodynamic functions. Three different models are provided for the sorption isotherms within the code: Langmuir, Toth, and UNILAN. In this study, only the Langmuir model may eventually prove desirable (Siriwardane et al. 2006a, 2006b), only extension of the model from a single component to two components (CH\(_4\) and CO\(_2\)) was required for the present study.

Various laboratory studies have shown that (under most conditions) coal swells when it absorbs a fluid and shrinks when desorption of a gas occurs (Laxminarayana et al. 2004; Seidle and Huitt 1995; Seidle et al. 1992; Harpalani and Chen 1997; Harpalani 2002). Moreover, not only does the amount of the strain depend on the particular coal, but it is also different for each gas component (Laxminarayana et al. 2004). In fact, even if CO\(_2\) and CH\(_4\) had the same effect on the strain quantitatively, shrinkage near CH\(_4\)-production wells could occur simultaneously with swelling near wells being used for CO\(_2\) injection. 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 model for primary CBM production (Palmer and Mansoori 1998). 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 undergoing deformation. A perfectly incompressible material has a Poisson’s ratio of \( \frac{1}{2} \). Poisson’s ratio must be greater than \(-1\) and less than or equal to \( \frac{1}{2} \); however, Poisson’s ratio is positive for most materials of engineering interest. While various modifications (e.g., from linear to 3D) of the Palmer-Mansoori model may eventually prove desirable (Siriwardane et al. 2006a, 2006b), only extension of the model from a single component (CH\(_4\)) to two components (CH\(_4\) and CO\(_2\)) was required for the present study.

In the work presented here, the original equation for the cleat porosity given by Palmer and Mansoori has been modified to account for multiple gas components:

\[
\phi = \phi_0^c + c_m p + \left( \frac{K}{M} - 1 \right) \sum_j s_{m,j} \mu_j. \tag{3}
\]

Here, \( \phi \) is the cleat porosity, and \( c_m \) is a mechanical property of coal that is generally a function of Young’s modulus, Poisson’s ratio, and grain compressibility. For the cases studied in this paper, \( c_m \) is equal to \( 1/M \), \( p \) is the gas pressure, \( K \) is the bulk modulus, \( M \)

### Table 2—Coal-SEAM and Operational Parameters That Were VaryED In the Simulations

<table>
<thead>
<tr>
<th>Young’s Modulus (million psia)</th>
<th>Injection Pressure (psia)</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>

Note: Bolded numbers represent the base-case values.

\[
NPV = \sum_{n=0}^{N} \frac{R_n - C_n}{(1 + i)^n}, \tag{4}
\]

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 Eq. 4 is described as the yearly economic evaluation.

NPVs were used as a basis for comparison between CO\(_2\)-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

**Economic Evaluation**

Rather than using \( s_m \), Palmer and Mansoori use the \( c_m/b \) ratio, where \( b \) is the inverse of the Langmuir volume constant for each gas and \( c_m = \rho_m / \mu \) (Langmuir pressure constant).
NPV. NPV seems to be a more appropriate method of comparison than the rate of return method, when one deals with incremental revenues (Balen et al. 1988).

Table 3 lists the investments and operating costs used in the economic analysis. Capital expenditures are generally considered as investments (Thompson and Wright 1985). Capital expenditures found in oil and gas property evaluations include drilling and well-development costs, as well as the 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 (Pagnier et al. 1999).

Actual drilling costs for the Appalachian basin were estimated using cost data from drilling companies operating in northern West Virginia.* 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.

Surface facilities for CBM primary production contain a pump or a gas lift system, water/gas separators, and compressors. CO₂ 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 (Pautz et al. 1992). Those costs were escalated at 4% per annum to obtain 2005 costs. Operation and maintenance costs have been estimated in a similar fashion (Jarrell et al. 2002). 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 et al. (2002) cited CO₂ prices of USD 1/Mscf (supercritical, at injection pressure) from an ethanol plant in Kansas. West Texas prices are approximately USD 0.75/Mscf, delivered. Recently, Kuuskraa (2003) listed a market price for CO₂ of USD 0.75/Mscf. The lowest delivered price for CO₂, in our literature search was that of Stevens et al. (1999), between USD 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. Because every time the CO₂ cost terms were found in the analysis, they appeared in the form of a net cost (cost minus credit), only the net cost was used. Table 4 shows the different costs and credits that were used to determine the net cost in each case. 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 Tables 3 and 4. In the analysis, costs were discounted on a yearly basis. For each simulation, yearly quantities of CH₄ 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 3 shows the CH₄ and CO₂ prices considered. CH₄ prices between USD 3 and USD 5/Mscf, and CO₂ costs of USD 0.53 to USD 2.63/Mscf, in USD 0.53/Mscf increments, were used. Various CO₂ credits were also considered; values from USD 0 to USD 1.05/Mscf, in USD 0.26/Mscf increments, were used.

### Methodology

We simulated sequestration into a coal seam with the properties that typically may be found in Appalachian coal. Those properties are listed in Tables 1 and 2.

The hypothetical reservoir had an area of 9 sq miles, subdivided into 36 160-acre inverted five-spot patterns. Each five-spot pattern

### Table 3—Economic Parameters That Were Varied in the Analysis

<table>
<thead>
<tr>
<th>CH₄ Price (USD/Mscf)</th>
<th>CO₂ Cost (USD/Mscf)</th>
<th>CO₂ Credit (USD/Mscf)</th>
<th>Water-Disposal Cost (USD/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></td>
<td>0.12</td>
</tr>
<tr>
<td>2.1</td>
<td>0.79</td>
<td></td>
<td></td>
<td>0.15</td>
</tr>
<tr>
<td>2.63</td>
<td>1.05</td>
<td></td>
<td></td>
<td>0.18</td>
</tr>
</tbody>
</table>

Note: Bolded numbers represent the base-case values.

* Personal communication with M. Coomb, Halliburton (2004); personal communication with D. Javis, Javis Drilling (2004).
had one CO2 injector in the middle of the pattern and four producing wells in the corners of the pattern. The simulations were performed on a quarter of a five-spot pattern, a 1320 × 1320 ft area. A 44 × 44 × 1 grid was used, with the gridblocks measuring 30 ft on a side. The total original gas in place was 0.51 Bscf per pattern for a coal thickness of 6.6 ft. Because of 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 CH4 was continued for a period of 6 months. At the end of primary production, the central well in each pattern was shut in for 1 day and converted to an injector. The CO2 then was injected in the central wells until project termination. The CO2 injection pressures used are listed in Table 2. 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 because of economic considerations.

Results

The average injectivity for a single five-spot pattern with the properties listed in Table 1 and marked in bold lettering in Table 2 was 23,040 Mscf/D (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 different values of Young’s modulus and Poisson’s ratio can be seen in Table 5. When the coal studied had a Young’s modulus of 1.45 × 10⁶ psia and a Poisson’s ratio of 0.4, the injectivity decreased to 10,224 Mscf/D. Of the parameter combinations used with coal swelling, this one gave the highest injectivity. However, the average injection rate for this swelling case was still 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 ν, representing a more elastic coal, the calculated injection rate was 360 Mscf/D, which was only 1.5% of the injection rate predicted without considering swelling (23,040 Mscf/D).

Production-rate curves were plotted to illustrate the effects of the coal-swelling phenomena on an ECBM process. Fig. 1 shows the production-rate curves during CO2 injection. The time scale begins when CO2 injection is 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 (0.145×10⁶ 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 caused by pore-pressure falloff. Therefore, soon after the start of primary production, the permeability around the production wells had decreased to less than one-half its initial value. Moreover, as soon as CO2 injection started, the permeability around the injection wells was reduced to ~1 md. After this sudden decrease, the permeability tended to stay constant (~1 md) 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 decreased significantly. 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 (0.725×10⁶ or 1.45×10⁶ psia) 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 CH4 productivity caused by coal swelling can be a cause for economic concerns about ECBM processes. To illustrate the effects of coal swelling on the economics of a project, NPVs were calculated for various representative coal-seam elastic properties (Young’s modulus and

| Table 5—Average Injection Rate (Mscf/D) for the Various Young’s Modulus and Poisson’s Ratios Simulated |
|---|---|---|---|
| E (× 10⁶ psia) | 0.145 | 0.725 | 1.45 |
| ν | | | |
| 0.2 | 360 (1.5) | 1,584 (6.9) | 6,336 (27.5) |
| 0.3 | 1,382 (6.0) | 3,744 (16.3) | 10,080 (43.8) |
| 0.4 | 1,728 (7.5) | 4,320 (18.8) | 10,224 (44.4) |

Note: 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/D.

Fig. 1—CH4 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.
Poisson’s ratio and porosity values (see Table 2). Fig. 2 is a 3D 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 cleat porosity on the economic outcome of a project. The negative effect of coal swelling on coal permeability and, consequently, on injectivity and the economics of the project was larger for the smaller values of porosity. The surface representing NPV values for coal with 0.5% cleat porosity was as much as USD 24 million when \( E = 1.5 \times 10^6 \) psia and \( v = 0.4 \) (less elastic coal), while for the most elastic coals considered, the NPV was approximately USD 0.

The large dependence of NPV on Young’s modulus and Poisson’s ratio were not seen for larger values of the cleat porosity because there was less permeability reduction for the same amount of swelling. It may be noted that when coal-swelling effects were not included, the NPV for the coal with 0.5% porosity was USD 36.6 million, 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.

To examine the possible effects of coal swelling on seams of Pittsburgh coal, we replotted a cross section of Fig. 2 (Young’s modulus = 0.725×10⁶ psia, representative of Pittsburgh coal) in Fig. 3a. The latter figure illustrates the effects of Poisson’s ratio on NPV for different cleat-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 Fig. 2 is plotted in Fig. 3b; the latter figure illustrates the effects of Young’s modulus on the NPV for different porosity values and a Poisson’s ratio of 0.3 (also representative for Pittsburgh coals). In this figure, the more pronounced effect of coal swelling for smaller Young’s moduli can be seen easily. In summary, for coal-swelling phenomena, Young’s modulus seems to be more important than Poisson’s ratio.

As illustrated by Fig. 4, when the computations for Fig. 2 were recalculated with a net (purchase price minus credit) CO₂ cost of USD 1.05/Mcf CO₂, some of the relationships changed. First, the cost of CO₂ caused two competing financial effects; producing more CH₄ by displacing it with CO₂ gave an economic benefit, while injecting CO₂ caused a cost. In this case, the effects of porosity on NPV were heightened; the NPV for the smallest porosity (0.5%) was as much as twice the NPV calculated for the highest porosity value (2%) and small Poisson’s ratio. This was likely because a smaller volume of (costly) CO₂ was required to
displace the CH$_4$. However, because of coal swelling, the decrease in permeability was more pronounced for smaller porosities; this was especially true for smaller values of Young’s modulus and Poisson’s ratio, when the injection rate (Table 5) was reduced by almost 100 times. Therefore, lower-cleat-porosity cases with little swelling (i.e., higher $E$ and $v$) were more competitive in cost, while lower-cleat-porosity cases with more swelling (i.e., lower $E$ and $v$) were much less competitive. This effect became important when a significant positive net cost of CO$_2$ was included in the study.

Fig. 5 illustrates cross sections of Fig. 4 for fixed values of Young’s modulus and Poisson’s ratio that are representative of Pittsburgh coal. In Fig. 5, as in Fig. 3, the effect of Young’s modulus is again seen to be more significant than that of Poisson’s ratio. The difference between positive net CO$_2$ cost and no-cost scenarios, as described above, can be seen more clearly in Fig. 5b, where a low-Young’s-modulus, low-cleat-porosity coal gives a negative NPV, while a high-Young’s-modulus, low-cleat-porosity coal gives the highest NPV. Because of the complex interplay between fluid costs and coal-seam properties in the presence of coal swelling, comparisons of different NPVs may be misleading if the circumstances and causes for the differences are not considered.

A 3D plot also was constructed to show the combined effects of CH$_4$ price and CO$_2$ net cost on the NPV for different porosity values (Fig. 6). The coal-seam properties and operational pressure for Fig. 6 are listed in Tables 1 and 2. When the CO$_2$ net cost was less than USD 0.53/Mcf, the NPVs for coals with larger cleat porosities were larger, with both the cumulative CO$_2$ injected and CH$_4$ produced also larger. However, higher cumulative injection of CO$_2$ reduced the NPV as the net CO$_2$ cost increased. This effect shifted the NPV surface in Fig. 6 for 0.5% porosity upward, thus making the NPV larger for the coals with smaller porosities.
trend also can be seen in Fig. 7, in which NPV is plotted for different CH$_4$ price and porosity values at a constant net CO$_2$ cost of USD 1.05/Mcf. Moreover, this figure illustrates the positive effect of CH$_4$ price on the NPV more clearly. Not surprisingly, as CH$_4$ price increased, NPV also increased.

The effect of CH$_4$ price is further illustrated in Fig. 8, in which results for different Young’s moduli (and a constant cleat porosity of 0.5%) are plotted. As can be seen, the NPV for the case in which the coal-swelling effect was neglected was less than that for the case of swelling of a coal with a relatively large Young’s modulus. In the latter case, reduction of the cumulative CO$_2$ 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 CH$_4$ production caused the NPV to decrease.

In Fig. 9, the CO$_2$ 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 Fig. 9, the NPV depends mostly on cumulative CH$_4$ produced, so that higher production results in higher NPV values.

The effect of net CO$_2$ cost on NPV for different values of Young’s modulus is plotted in Fig. 10. In this plot, cleat porosity and Poisson’s ratio are 0.5% and 0.3, respectively. As discussed earlier, cumulative CH$_4$ production and CO$_2$ sequestration were much larger when coal swelling was neglected. These differences were reflected in the NPVs, which were much larger for smaller net CO$_2$ costs and larger cumulative CH$_4$ production. On the other hand, as the cost of CO$_2$ increased because of the larger cumulative CO$_2$ injection costs, NPVs for the no-swelling cases decreased.

Fig. 6—NPV as a function of CH$_4$ price and net CO$_2$ cost. All other physical and economic parameters are for the base case: highest surface at low CO$_2$ cost, 2% cleat porosity; lowest surface at low CO$_2$ cost, 0.5% cleat porosity.

Fig. 7—NPV vs. CH$_4$ price for different porosities at a net CO$_2$ cost of USD 1.05/Mcf.
below the NPVs calculated when swelling was included. Moreover, for the smallest Young’s modulus \((0.145 \times 10^6\text{ psia})\), the NPV curve was much lower than the NPV curves for the larger, more-realistic Young’s modulus. The small NPVs 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 nonswelling case is different from the shapes of the other curves. The slope of the NPV curve in the range of USD \(-0.52\) to \(0.79/\text{Mscf}\) was much steeper than for higher net CO\(_2\) cost values. This is, in part, because the project lifetime for the lower net CO\(_2\) costs was much longer than for the higher net CO\(_2\) costs.

Conclusions

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

1. Injectivity of CO\(_2\) decreases when swelling occurs; coal swelling can have significant effects on injection and production rates and, hence, profitability.

2. Profits from a project may be affected positively or negatively by swelling and shrinkage effects; the net CO\(_2\) cost will help to determine if swelling contributes positively or negatively to NPV.

3. Therefore, 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.

4. 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.

5. 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 CO\(_2\)). This can have public policy implications for designing the proper economic incentives for sequestration.

6. Because of the potential impacts, accurate values of Young’s modulus and Poisson’s ratio are necessary to make reliable predictions.

7. 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 \(j\)
\(c_m\) = a parameter equal to \(1/M\) in this study
\(C_n\) = annual costs for year \(n\)
\(E\) = Young’s modulus
\(i\) = discount rate
\(j\) = gas-component index
\(J\) = number of gas components
\(K\) = bulk modulus
\(M\) = constrained axial modulus
\(n\) = yearly index for summation of annual revenues
\(N\) = number of project years
\(p\) = gas pressure
$R_a =$ annual incremental revenue for the nth year

$s_{m,j} =$ matrix swelling coefficient for sorbed gas j

$\nu =$ Poisson’s ratio

$\phi =$ cleat porosity

$\phi_{r,s} =$ cleat porosity at the reference gas pressure (0.0 psia)

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**References**


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**SI Metric Conversion Factors**

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*Conversion factor is exact.

Fatma Burcu Gorucu is currently working for Advanced Resources International as a reservoir modeler. Her main interest areas are carbon sequestration, natural gas production from coal seams, and reservoir simulation. Gorucu did her MS thesis research at the National Energy Technology Laboratory, where she was involved in CO2 sequestration in unmineable coal seams. She holds a BS degree from the Middle East Technical University and an MS degree from Pennsylvania State University, both in petroleum and natural gas engineering.

Sinisha (Jay) Jikich is a senior engineer at the National Energy Technology Laboratory/Parsons. His research interests include improved oil and gas recovery, reservoir characterization, and geologic sequestration. Jikich holds an MS degree in polymer physics from the University of Bucharest, Romania, and MS and PhD degrees in petroleum engineering from the University of Wyoming. He serves as a Technical Editor for SPE/EE; he is also the recipient of an Outstanding Technical Editor Award from SPE and two Fulbright grants to teach geologic sequestration at the University of Miskolc, Hungary, and the University of Belgrade, Serbia.

Grant S. Bromhal currently works for the US Department of Energy at the National Energy Technology Laboratory in Morgantown, West Virginia, where he previously was a National Research Council post-doctoral student. His current research focuses on modeling of environmental and energy systems, particularly related to carbon sequestration. Bromhal holds bachelors’ degrees in civil engineering and mathematics from West Virginia University, as well as a master’s degree in civil and environmental engineering and a PhD degree in environmental engineering, both from Carnegie Mellon University.

W. Neal Sams is a scientist with EG&G Technical Services in Morgantown, West Virginia, where he designs reservoir simulators and performs simulation studies. Sams joined EG&G in 1987 and has performed a number of simulation studies of carbon sequestration/ECBM production. He is the author of MASTER, a miscible flood simulator, and NFFLOW, a discrete fracture gas reservoir simulator. Sams holds BS and PhD degrees from the University of Houston.

Duane H. Smith is a senior scientist at the National Energy Technology Laboratory and an adjunct professor of physics at West Virginia University. He has more than 20 years of experience in the industrial, academic, and government sectors, performing R&D on oil and gas production, and is the coauthor of more than 250 contributions to the technical literature. Smith holds an undergraduate degree from Carnegie Mellon University and MS and PhD degrees from the University of Chicago.

T. Ertekin is Professor and Chairman of Petroleum and Natural Gas Engineering at Pennsylvania State University, where he is also holder of the George E. Trimbble Chair in Earth and Mineral Sciences. His principal research areas are fluid-flow dynamics in porous media, reservoir simulation, well-test analysis, unconventional gas reservoirs, and artificial intelligence. Ertekin holds BSc, MSc, and PhD degrees in petroleum engineering. He is the recipient of several awards from Penn State; in addition, he is the 1998 recipient of the SPE Distinguished Faculty Achievement Award and the 2001 SPE Lester C. Uren Award. Ertekin was named an SPE Distinguished Member in 2001.