Screening Model for ECBM Recovery and CO_2 Sequestration in Coal

Coal-Seq V1.0

Topical Report

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Anne Taillefert and Scott Reeves

Advanced Resources International
9801 Westheimer, Suite 805
Houston, TX 77042

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Executive Summary

In October 2000, the U.S. Department of Energy, through contractor Advanced Resources International (ARI), launched a three-year government-industry R&D collaboration called the Coal-Seq project. The Coal-Seq project is investigating the feasibility of CO_2 sequestration in deep, unmineable coalseams, by performing detailed reservoir studies of two enhanced coalbed methane recovery (ECBM) field projects in the San Juan basin. The two sites are the Allison Unit, operated by Burlington Resources, and into which CO_2 is being injected, and the Tiffany Unit, operated by BP America, into which N_2 is being injected (the interest in understanding the N_2-ECBM process has important implications for CO_2 sequestration via flue-gas injection). The purposes of the field studies are to understand the reservoir mechanisms of CO_2 and N_2 injection into coalseams, demonstrate the practical effectiveness of the ECBM and sequestration processes, demonstrate an engineering capability to model them, and to evaluate sequestration economics. In support of these efforts, laboratory and theoretical studies are also being performed to understand and model multi-component isotherm behavior, and coal permeability changes due to swelling with CO_2 injection. To facilitate industry realization of the benefits of an improved knowledge of ECBM processes, a screening model has been developed.

The purposes of the model are to:

- Capture the technical findings of the Coal-Seq project in an easy-to-use tool that can predict the results of an ECBM/CO_2-sequestration project under a broad set of conditions and assumptions.
- Put that tool directly in the hands of industry to facilitate project consideration and screening.

The model consists of a database of reservoir simulation cases, which can be retrieved and compared. Results are presented both graphically and in tabular form, and include incremental methane recoveries and CO_2 sequestration volumes. Economic calculations can also be performed. An inherent assumption in the model is that an existing coalbed methane field is being converted to ECBM/carbon-sequestration service; the economics of a grass-roots project, which include the costs associated with production well drilling, are not considered.

ARI's COMET3 simulator was utilized to build the model. Starting with a base-case set of model parameters, the user can then select one of three values for seven different parameters, including permeability, well spacing, depth, coal rank, injection rate, injection gas, and injection timing. In addition, the user can specify any coal thickness.

In total, 1975 simulation runs were performed, out of a total of all possible combinations of 2268 (some runs could not be made due to incompatible reservoir/operating conditions, such as low permeability and high injection rates for example).

The database used is Microsoft Access, and the user interface to facilitate data retrieval and manipulation was built using Microsoft Visual Basic. Microsoft Access 2000 with the latest service packs is required to use the model.

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1.0 Introduction

In October 2000, the U.S. Department of Energy (DOE), through contractor Advanced Resources International (ARI), launched a three-year government-industry R&D collaboration called the Coal-Seq project[1]. The Coal-Seq project is investigating the feasibility of CO_2 sequestration in deep, unmineable coalseams, by performing detailed reservoir studies of two enhanced coalbed methane recovery (ECBM) field projects in the San Juan basin. The two sites are the Allison Unit, operated by Burlington Resources, and into which CO_2 is being injected, and the Tiffany Unit, operated by BP America, into which N_2 is being injected (the interest in understanding the N_2-ECBM process has important implications for CO_2 sequestration via flue-gas injection). The purposes of the field studies are to understand the reservoir mechanisms of CO_2 and N_2 injection into coalseams, demonstrate the practical effectiveness of the ECBM and sequestration processes, demonstrate an engineering capability to model them, and to evaluate sequestration economics. In support of these efforts, laboratory and theoretical studies are also being performed to understand and model multi-component isotherm behavior, and coal permeability changes due to swelling with CO_2 injection. To facilitate industry realization of the benefits of an improved knowledge of ECBM processes resulting from this project, a screening model has been developed.

The purposes of the model are to:

- Capture the technical findings of the Coal-Seq project in an easy-to-use tool that can predict the results of an ECBM/CO_2-sequestration project under a broad set of conditions and assumptions.
- Put that tool directly in the hands of industry to facilitate project consideration and screening.

This report describes the model and also serves as the Users Manual for it.

2.0 Model Construction & Assumptions

2.1 Model Construction

The model consists of a database of reservoir simulation cases, which can be retrieved and compared. Results are presented both graphically and in tabular form, and include incremental methane recoveries and CO_2 sequestration volumes. Economic calculations can also be performed. An inherent assumption in the model is that an existing coalbed methane field is being converted to ECBM/carbon-sequestration service; the economics of a grass-roots project, which include the costs associated with production well drilling, are not considered.

ARI's COMET3 simulator was utilized to build the model. A technical description of the simulator can be found in the references[2]. Starting with a base-case set of model parameters, the user can then select one of three values for seven different parameters, as follows:

- Permeability: 1 mD, 10 mD or 100 mD.
- Spacing: 40 acres, 160 acres or 640 acres.
- Depth: 1,000 ft, 5,000 ft or 10,000 ft.
- Coal Rank: high, medium or low.
- Injection Rate: 10 Mscfd/ft, 50 Mscfd/ft or 100 Mscfd/ft.
- Injection Gas: 100% CO_2, 100% N_2 or 50% CO_2 / 50% N_2.
- Injection Timing: the first 7.5 years, the second 7.5 years or continuous for 15 years.

In total, 1975 simulation runs were performed, out of a total of all possible combinations of 2268 (3^7 runs plus a no-injection scenario for each case) the results of which are stored in the database of this application (some runs could not be made due to incompatible reservoir/operating conditions, such as low permeability and high injection rates for example). In addition, the user can specify any coal thickness; the results from the database (which were all run with a thickness of 10 feet), are automatically scaled up or down according to the input coal thickness.

The database used is Microsoft Access, and the user interface to facilitate data retrieval and manipulation was built using Microsoft Visual Basic. Microsoft Access 2000 with the latest service packs is required to use the model.

2.2 Constants and Assumptions

This section describes the constants and assumptions of the model. It should be noted that all the simulations were run for 15 years.

2.2.1 Initial Conditions

The initial conditions for each simulation were:
- Initial water saturation: S_{wi} = 100%
- Reservoir pressure gradient: 0.43 psi/ft
- Reservoir temperature: 60°F + 2°/100 ft

2.2.2 Geometry

The reservoir geometry was:
- Coals are flat lying.
- Coals are represented by a single layer.
- Any coal thickness can be selected; the model results are up scaled or downscaled accordingly.

2.2.3 Reservoir Properties

The reservoir properties were:
- Permeability anisotropy: 1:1
- Vertical permeability: Kv = 0
- Porosity: ϕ = 0.25%.
- Fracture spacing: FS = 0.5 inches.

2.2.4 Desorption Data

- The initial conditions are always saturated (equilibrium with isotherm) with respect to gas content (100% methane).
- The coal isotherms are shown on Figure 1.
- The Langmuir Volume and Langmuir Pressure constants used are summarized in Table 1. These data were obtained from the literature [3,4,5].
- Sorption time: τ = 10 days (all gases, all coals)
- Coal density basis: ρ_{coal} = 1.8 g/cc

Table 1: Langmuir Constants

Rank	Vro	Nitrogen		Methane		Carbon Dioxide	
		VL (scf/ton)	PL (psi)	VL (scf/ton)	PL (psi)	VL (scf/ton)	PL (psi)
Sub Bit	0.40	45	2125	45	1650	650	725
Hi Vol Bit	0.90	150	1600	250	845	650	300
Med Vol Bit	1.30-1.40	250	1400	450	560	650	240

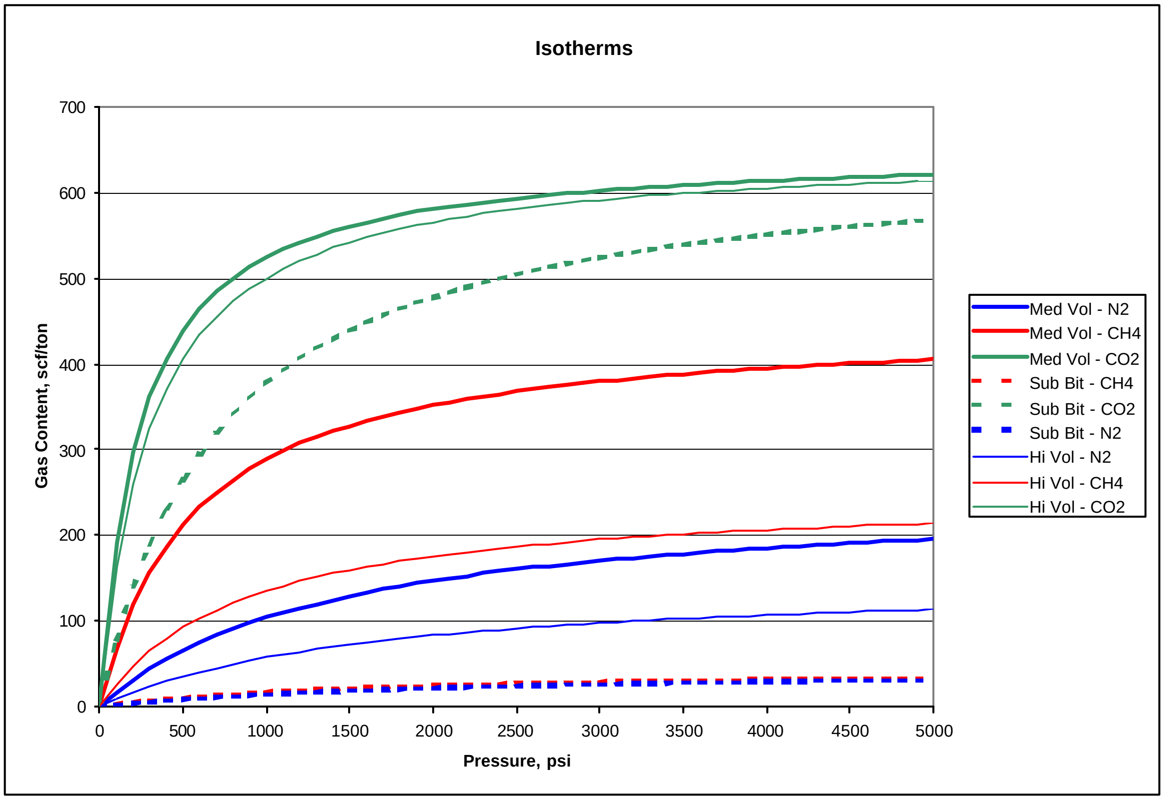


Figure 1: Isotherms

2.2.5 Gas PVT Data

The gas PVT data were:
- Gas gravity = 0.6
- In-situ gas composition: 100% methane
- Water specific gravity: 62.4 lbm/ft^3
- Water viscosity: 0.577414 cp

Gas PVT properties were automatically derived via correlations in the COMET3 model.

2.2.6 Compressibilities

The formation compressibility assumptions were:
- Pore volume compressibility: Cp = 200×10^{-6} psi^{-1}
- Matrix shrinkage compressibility: Cm = 1×10^{-6} psi^{-1}
- Permeability exponent: n = 0

Note: Since n=0, no pressure-dependant permeability or matrix shrinkage/swelling was considered.

2.2.7 Relative Permeability and Capillary Pressure

The relative permeability and capillary pressure assumptions were:
- The relative permeability curves are shown on Figure 2.
- There is no capillary pressure function.

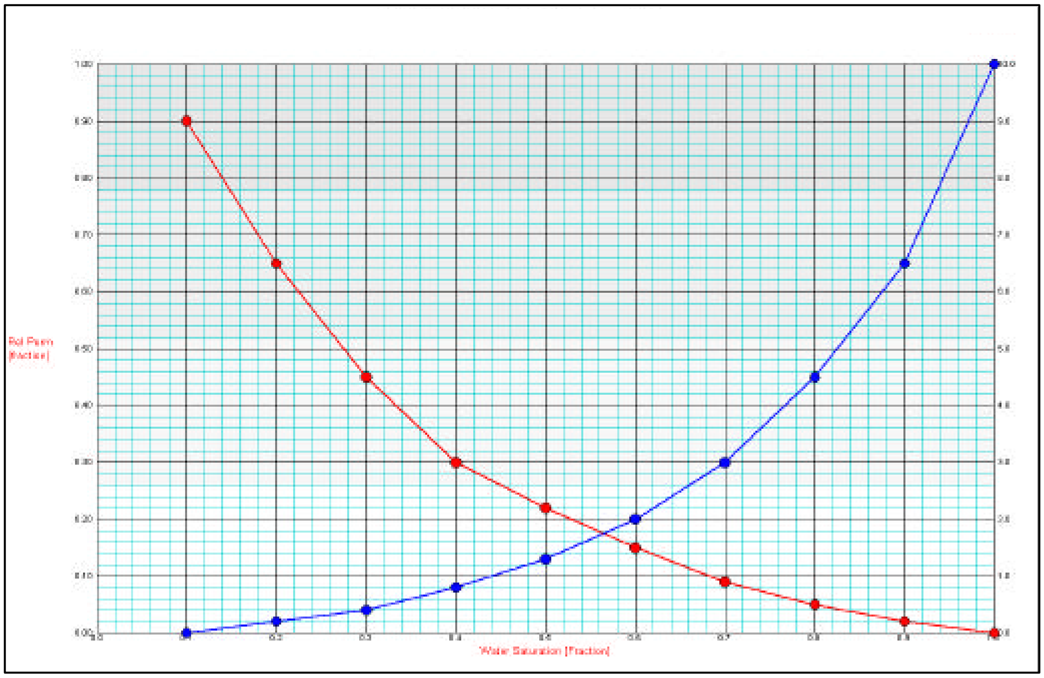


Figure 2: Relative Permeability Curves

2.2.8 Production / Injection Wells

The well control were:
- Flowing bottom hole pressure for the producing wells: FBHP = 50 psi.
- A flowing bottom hole pressure for injection wells was not considered (i.e., injection rates were specified with no constraints on pressure).
- Skin factor for producing wells: s=-2
- Skin factor for injection wells: s=0
- Wellbore radius: r = 0.33 feet (8'' hole)

3.0 Using the Model

3.1 Installation

The installation requires only a few steps.

- Create a folder on the C drive named **CoalSeq** (C:\CoalSeq).
- Copy the executable CoalSeq.exe as well as the folder Database and the manual (Manual.pdf), provided on the CD, in the CoalSeq folder newly created (C:\CoalSeq\CoalSeq.exe, C:\CoalSeq\Database and C:\CoalSeq\Manual.pdf).

The model is now ready to be used.

3.2 Running The Model

This section describes step by step how to use this model, specifically how to select the input data, make plots, export the data, run economic evaluations and print the results.

3.2.1 Plot Input

The user will define first the cases intended to be studied by selecting the simulation's parameters. As CoalSeq provides the user with a graphic picture of the results, some characteristics of the graphic will have to be determined. The user may input the following data (refer to Figure 3).

3.2.1.1 Cases' Selection

➊ Main Case

The main case can only be a non-injection case. Four parameters can be selected:

- Permeability: 1 mD, 10 mD or 100 mD.
- Spacing: 40 acres, 160 acres or 640 acres.
- Depth: 1,000 ft, 5,000 ft or 10,000 ft.
- Coal Rank: high, medium or low.

Once the above parameters have been selected, click the 'Get Data' button to import the corresponding data from the database, as well as each time any parameter is changed, as the database is not automatically updated.

➋ Comparison 1 / 2 / 3

Added to the main case, three other cases can be imported for comparison purposes. Seven parameters can be selected, the same four as for the main case as well as

- Injection Rate: 10 Mscfd/ft, 50 Mscfd/ft or 100 Mscfd/ft.
- Injection Gas: 100 % CO_2, 100 % N_2 or 50% CO_2 / 50% N_2.

- Injection Timing: the first 7.5 years, the second 7.5 years or continuous for 15 years.

The same remark as for the main case applies to import the data.

❸ Coal Thickness

All the simulations have been run using a 10 feet coal thickness. Adjustments to thickness are done on a simple ratio.

3.2.1.2 Plot's Characteristics

❹ Plot Title:

Two lines are available to give a title to the plot. The title will be visible at the top of the plot on the *Chart* tab as well as on the printout.

❺ X Axis

Fourteen different parameters can be selected from the dropdown list for the X-axis. They are the following:

- Time
- CH_4 Production Rate
- Cumulative Produced CH_4
- CO_2 Production Rate
- Cumulative Produced CO_2
- N_2 Production Rate
- Cumulative Produced N_2
- Total Gas Rate
- CO_2 Injection Rate
- Cumulative Injected CO_2
- N_2 Injection Rate
- Cumulative Injected N_2
- % N_2/CO_2
- Net CO_2 Sequestration.

The user has the option to make some modifications to the minimum, maximum and major step of the scale (the major step indicates where the gridlines will be positioned).

❻ Y Axis

The same parameters are available for the Y-axis as for the X-axis. The first time the plot is drawn, the maximum value for the Y-axis is computed as being the maximum value of the selected parameter of the imported cases. The major step is computed as the tenth of the maximum. If the user considers the scale not to be appropriate, the maximum, minimum and major step can be changed.

❼ Plot Characteristics

In order to see a curve on the plot, the 'Normal Line' option has to be checked. The color and line thickness can be changed as the user desires.

❽ <u>Manual</u>

If any help is needed, the manual is automatically accessible through the Manual button. Please note that Adobe Acrobat 5.0 must be installed with the following path: C:\Program Files\Adobe\Acrobat 5.0\Acrobat\Acrobat.exe.

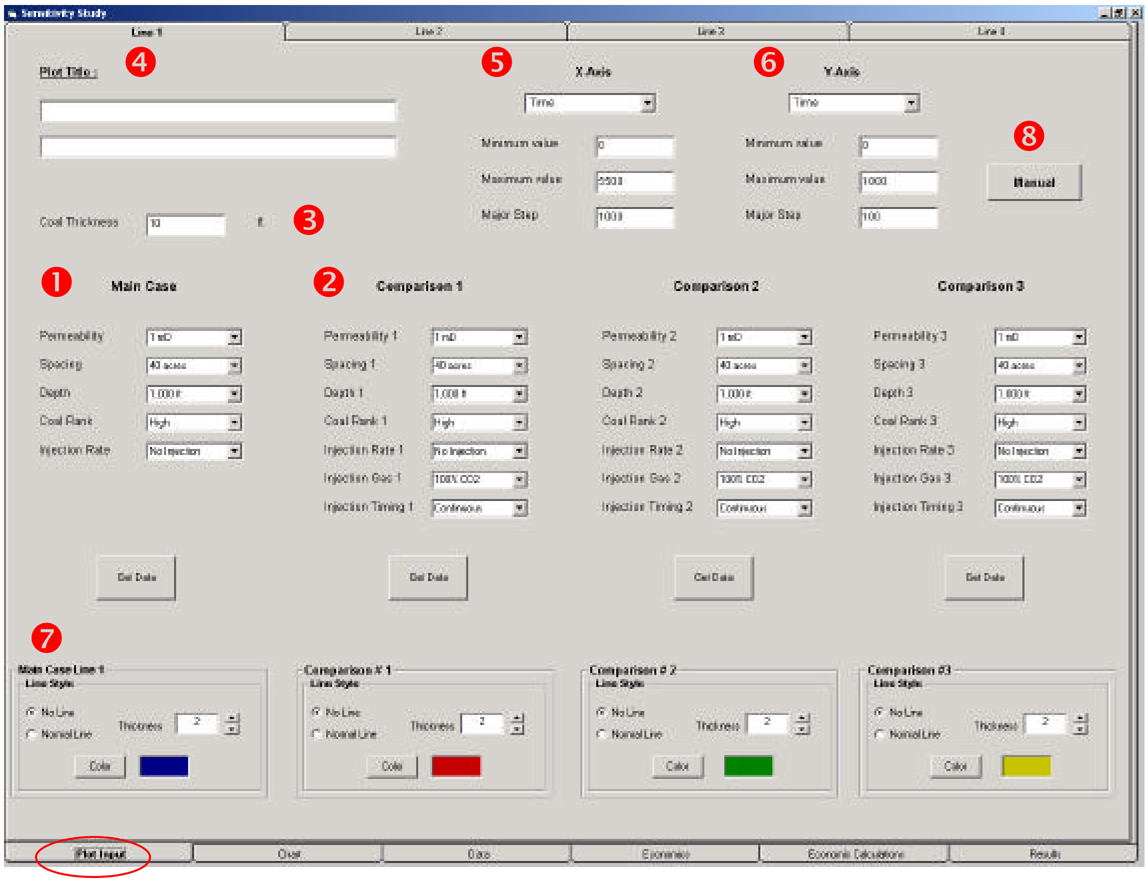


Figure 3: Model Screen Shot *Plot Input (a)*

More than only one parameter can be plotted by selecting new parameters for each axis on the tabs *Line 2*, *Line 3* and *Line 4*. As explained before, fourteen parameters can be selected for the X and Y-axis (Figure 4). A new option, the Line Style is here available (Figure 4). Due to a restriction of Visual Basic, this option only works for a line thickness of 1; any other thickness will automatically draw a solid line.

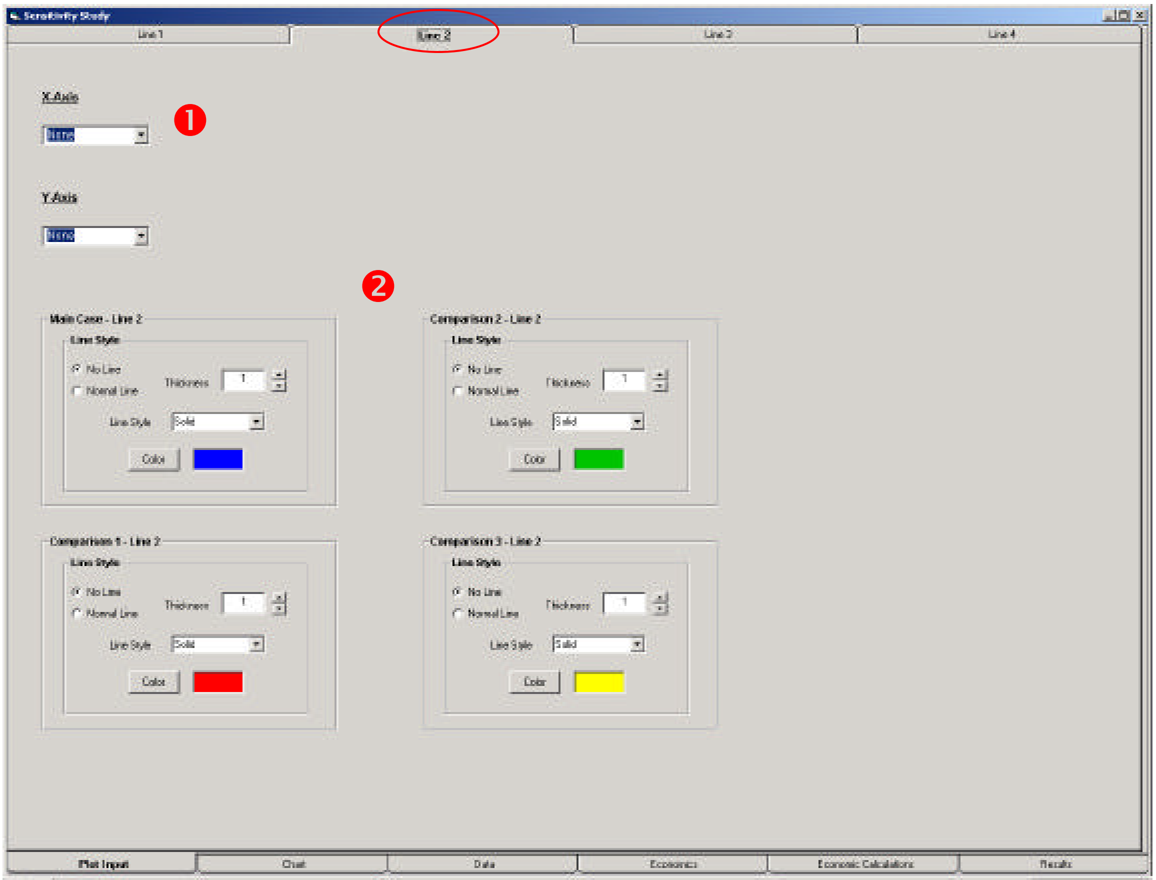


Figure 4: Model Screen Shot *Plot Input (b)*

3.2.2 Chart

After having selected all desired parameters, the user will be able to view and print out plots (Figure 5). Click the 'Plot' button to view the graph, as well as each time any parameter is changed, as the graph will not be automatically updated. The printout will show the plot and the legend.

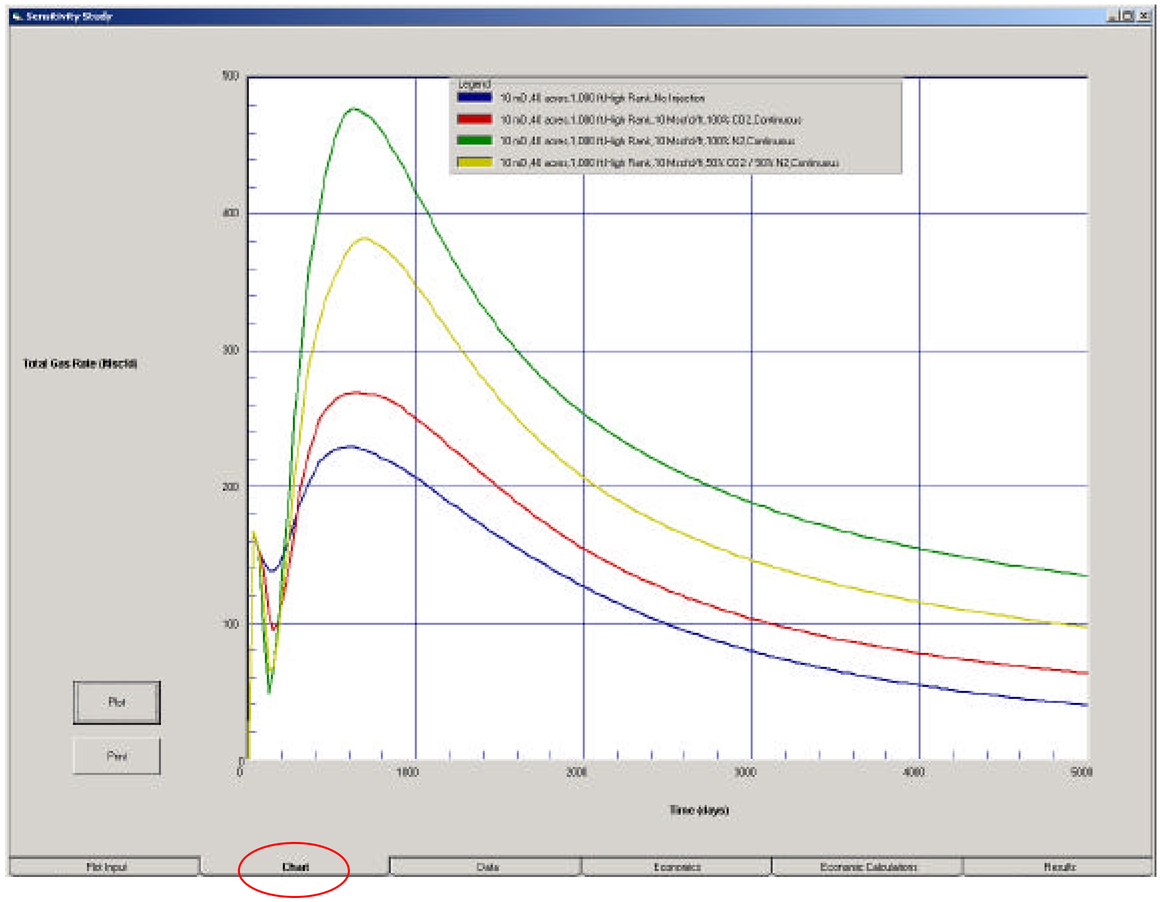


Figure 5: Model Screen Shot *Chart*

Note: the format for the printout can only be "Landscape"; the user cannot change this option.

Important Note: All the simulations have been run on a ¼ five spot basis for a thickness of 10 feet, but the necessary corrections have been made so that the plots represent an entire well. However, the data under the Data tab are directly coming out of the simulations so are for ¼ of a well in a 10 feet coal (i.e., they will not directly correspond to the values on the plot).

3.2.3 Data

Four tables allow looking at the data for each case. Each table is composed of the following fields:

- Time elapsed
- Cumulative CH_4 produced
- Cumulative N_2 produced
- Cumulative CO_2 produced
- Cumulative N_2 injected
- Cumulative CO_2 injected
- CH_4 gas rate
- N_2 gas rate
- CO_2 gas rate
- N_2 injection rate
- CO_2 injection rate

Note again that all these data are for ¼ of a well in a 10 feet coal.

3.2.3.1 Exporting Data

For each case, the data can be exported as a .csv (Microsoft Excel Comma Separated Values File) using the 'Export Data to CSV' button. The data will be automatically saved in the folder CoalSeq containing the executable as *filename.coalseq.csv* where the file name is assigned as explained below.

Each case can depend on up to seven parameters.

The first letter represents the permeability.
The letter 'a' will be assigned to a permeability of 1 mD.
The letter 'b' will be assigned to a permeability of 10 mD.
The letter 'c' will be assigned to a permeability of 100 mD.

The second letter represents the spacing.
The letter 'a' will be assigned to a spacing of 40 acres.
The letter 'b' will be assigned to a spacing of 160 acres.
The letter 'c' will be assigned to a spacing of 640 acres.

The third letter represents the depth.
The letter 'a' will be assigned to a depth of 1,000 feet.
The letter 'b' will be assigned to a depth of 5,000 feet.
The letter 'c' will be assigned to a depth of 10,000 feet.

The fourth letter represents the coal rank.
The letter 'a' will be assigned to a high coal rank.
The letter 'b' will be assigned to a medium coal rank.
The letter 'c' will be assigned to a low coal rank.

The fifth letter represents the injection rate (if injection).
The letter 'a' will be assigned to a 10 Mscfd/ft injection rate.
The letter 'b' will be assigned to a 50 Mscfd/ft injection rate.

The letter 'c' will be assigned to a 100 Mscfd/ft injection rate.
The letter 'd' will be assigned to a non-injection case.

The sixth letter represents the injection gas (if injection).
The letter 'a' will be assigned to a 100% CO_2 injection.
The letter 'b' will be assigned to a 100% N_2 injection.
The letter 'c' will be assigned to a 50% CO_2 / 50% N_2 injection.

The last letter represents the injection timing (if injection).
The letter 'a' will be assigned to an injection occurring the first 7.5 years.
The letter 'b' will be assigned to an injection occurring the second 7.5 years.
The letter 'c' will be assigned to a continuous injection for 15 years.

To illustrate, if the case is the following: 10 mD, 40 acres, 10,000 ft, high rank coal, 100% CO_2 continuous injection @ 100 Mscfd/ft; the file will be saved as bacacac.coalseq.csv. However, if this were a non-injection case, the last 2 parameters would be discarded. Let's consider the case, as above but without injection; the file would then be saved as bacad.coalseq.csv.

Note: the exact same method has been used to name all the files in the database.

3.2.4 Economic Evaluation

In this section, how the performance data from the simulations can be converted into a cash flow analysis, depending upon assumptions on costs, expenses, revenues and taxes, is presented. The final results of the economic evaluation are the net present value, breakeven gas price and breakeven CO_2 cost (see ❼ on Figure 6). Note that all computations are on a performed per-well basis. The results can then be upscaled to the desired project size (number of producers/injectors) "offline" by the user. The model assumes an injector-to-producer ratio of 1:1 (5-spot pattern).

All the economic calculations are made on an incremental basis between the main case and a comparison case that the user will define (see ❶ on Figure 6). Note that it also assumes the producer wells are already in-place, (hence the lack of operating expenses for production wells); only the capital and operating expenses for injection facilities/wells are required, as well as the incremental produced gas. The incremental CH_4 recovery can be viewed on the graph (*Plot* tab) by clicking the 'Plot the CH_4 Incremental Recovery' button followed by the 'Plot' button to update the data. The maximum and minimum values for the Y-axis are not automatically calculated; the user has to select them under the *Plot Input* tab.

The analysis extends over the duration of interest as defined by the user (see ❷ on Figure 6), but limited to a maximum 15 years.

The user must input four types of data (on a per-well basis):

❸ Capital Expenses

- CO_2/N_2 Separation/Capture costs (\$/well)
- CO_2/N_2 Pipeline/Distribution costs (\$/well)
- Injection Well cost (\$/well)

These values are allocated to a single well.

❹ Operating Expenses

- Injector well operating (\$/month/well) considered being null if the incremental injection rate is null.
- Cost of the injected gas (\$/Mcf). For a mixture, this cost should be the average price of CO_2 and N_2.
- CO_2/N_2 transportation and compression costs (\$/Mcf)
- Cost of the (incremental) produced gas processing (\$/Mcf)

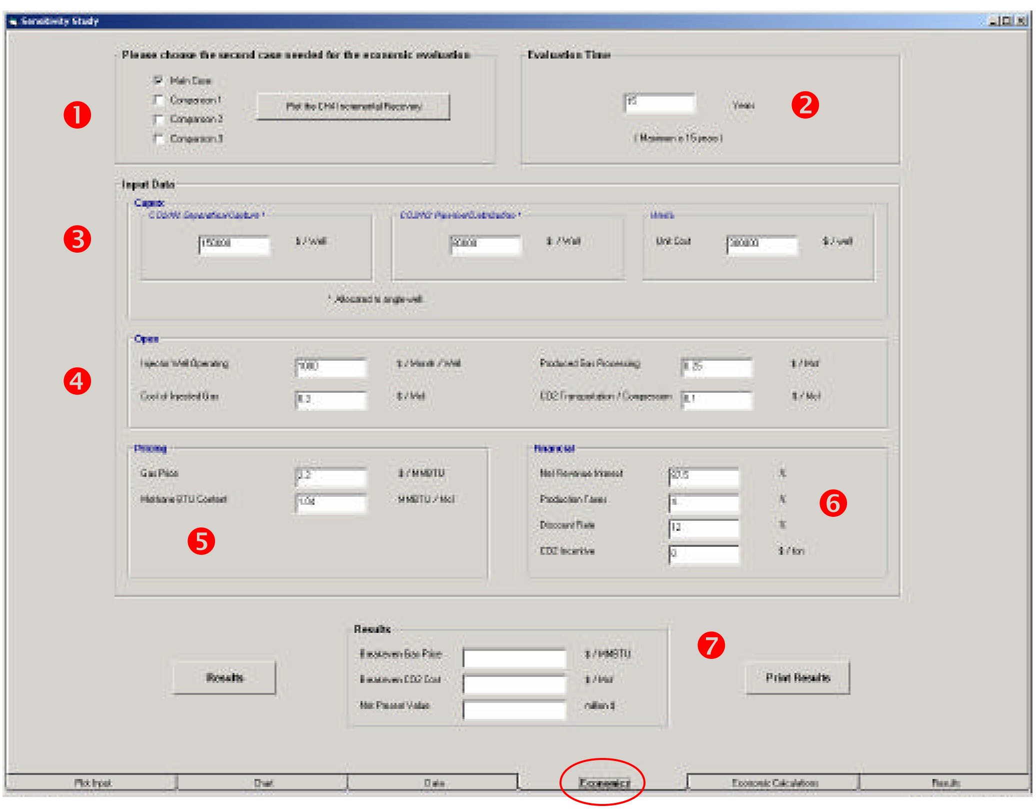
❺ Pricing

- Gas price (\$/MMBTU)
- Methane BTU Content (MMBTU/Mcf)

❻ Financial

- Net Revenue Interest (%)
- Production Taxes (%)
- Discount Rate (%)
- CO_2 Incentive (\$/ton)

Figure 6: Model Screen Shot *Economics*



After entering the required information, clicking the “Results” button will execute the calculations and return the results.

Remark: the breakeven gas price and breakeven CO_2 price are computed using a loop so the results will not be immediate, they will appear after a few seconds. The results can then be printed if desired. The printout will show the parameters of the two cases used for the analysis, all the input data and the results. In addition, a detailed cash flow table is provided under the *Economic Calculations* tab. An example is shown on Figure 7.

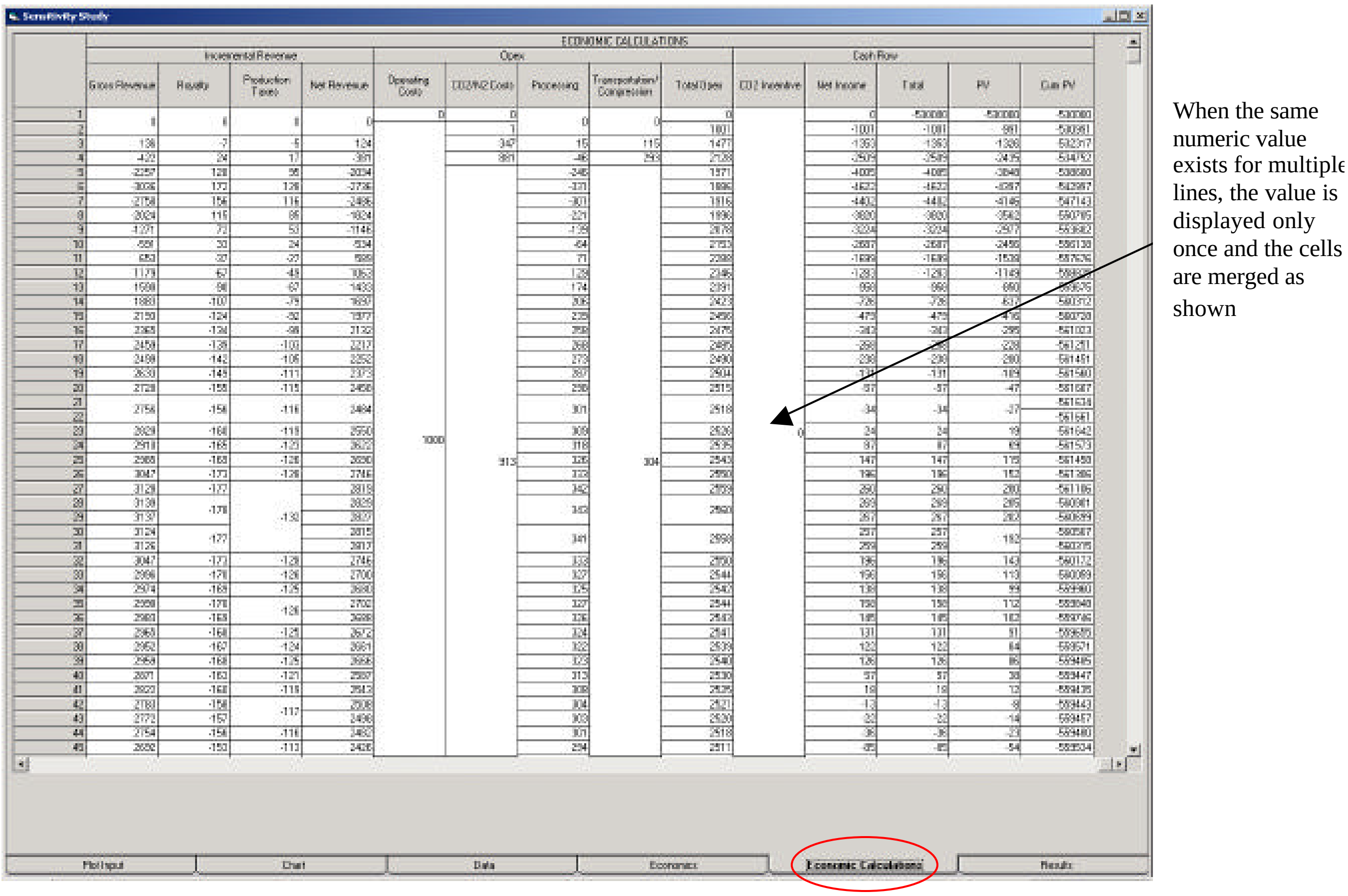


Figure 7: Model Screen Shot *Economic Calculations*

3.2.5 Results

Finally, a table is provided that summarizes the results of the comparison (Figure 8). The results table includes (when applicable):

- The total CH_4 recovery
- The incremental CH_4 recovery (increment from the non-injection case)
- The percentage improvement over primary production
- The total sequestration volume (only if CO_2 is injected)

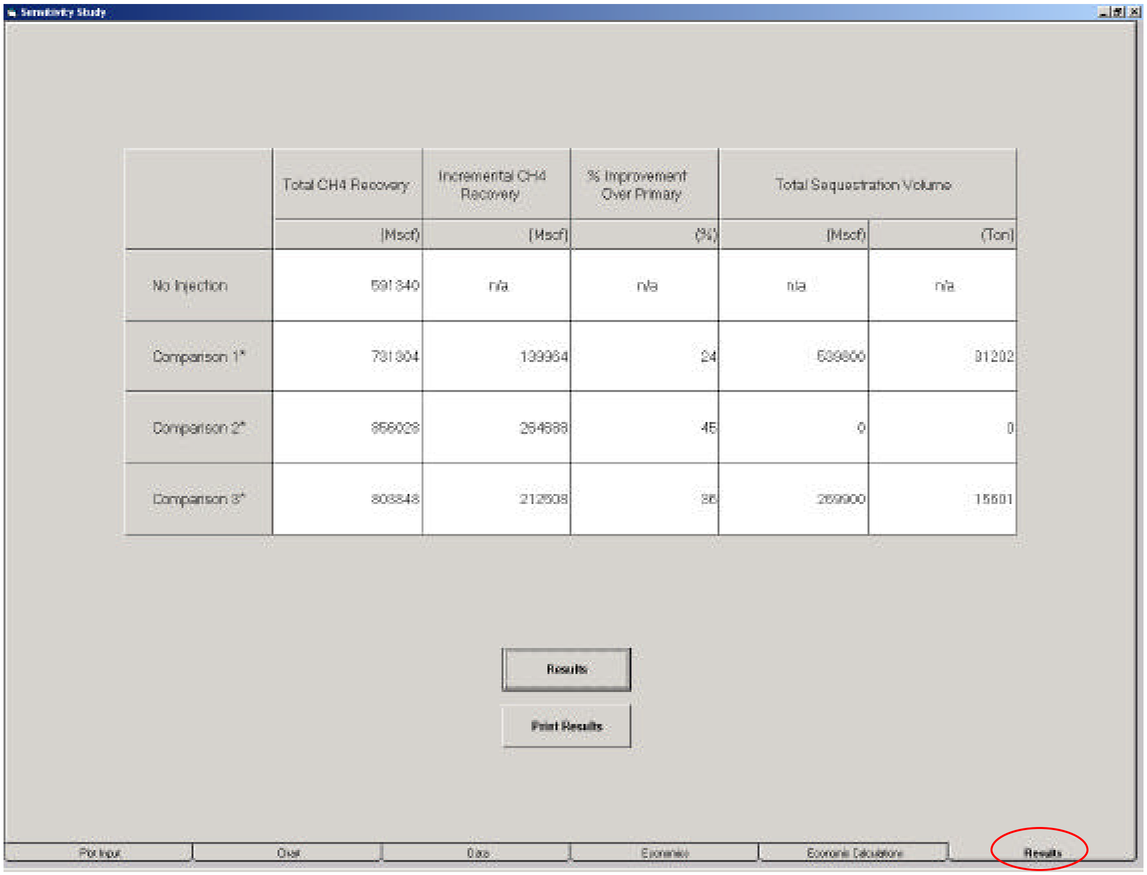


Figure 8: Model Screen *Results*

The results table can be printed if desired.

3.3 Help

For any comments or questions, please contact Anne Taillefert or Scott Reeves by phone or e-mail.

☎ (713) 780-0815
Anne Taillefert: ataillefert@adv-res-hou.com
Scott Reeves: sreeves@adv-res-hou.com

3.4 Frequently Asked Questions

- <u>I cannot run the model from the CD</u>.

The model cannot be run from the CD, it has to be installed on your computer as explained in chapter 3.1 (Installation) on page 6 of this manual as well as on the inside cover of the CD case.

- I get an error message when I hit the 'Start' button.

Some people got the following error message: " Runtime Error 339: The component MSHFLXGD.OCX and its dependencies are missing or cannot be found." The following components, MSHFLXGD.OCX, COMCAT.DLL AND MSSTDFMT.DLL are missing and need to be installed on your computer.

Please follow the instructions from the Microsoft web site provided in the following link.
http://msdn.microsoft.com/library/default.asp?url=/library/en-us/dnaskdr/html/askgui05152001.asp

4.0 References

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