THE 3M CBM FINAL REPORT

Volume II: The 3M CBM Model Users Guide

Prepared for

The Southern Ute Indian Tribe,

The Colorado Oil and Gas Conservation Commission,

and

The U.S. Bureau of Land Management

Prepared by

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1.0 INTRODUCTION

The 3M Coalbed Methane (CBM) Model is a program that was specifically developed to conduct a large-scale, two-dimensional simulation of the Colorado portion of the Fruitland Coal in the San Juan Basin for the 3M Project. 3M CBM Model simulates a single layer coalbed methane reservoir using a standard IMPES (implicit saturation, explicit pressure) formulation. It is written in standard FORTRAN 90/95 programming language and compiled with COMPAQ's Digital Visual Fortran Compiler (Version 6.1.A). The program utilizes MICROSOFT (MS) Excel and Access for data manipulation, input, and post-processing. It is designed to run on a standard Pentium PC within the MS Windows Command prompt environment.

The executable models (EXE files) are sized according to the dimensions of the reservoir problem. The basin-wide model was run using a 369 by 137 grid containing 50,553 grid blocks. Smaller executable files were generated for the 3M Project Areas (A, B, C, D, and E) for increased performance and shorter run times.

This User's Guide discusses the features and functionality of the 3M CBM model, and includes descriptions of input and output data. It is important to note that the 3M CBM Model has been designed for the sophisticated reservoir simulation user. As such, it contains limited error checking of input data and limited reporting of data input error messages. The user is cautioned to exercise extreme care when modifying and building data input sets in order to avoid run-time errors.

1.1 General Features

The 3M CBM Model is a 2-D (single layer) coalbed methane simulation program written using a standard IMPES solution algorithm for large-scale, basin-wide simulations. The simulator is designed to handle a large number of wells or source terms, including water recharge and discharge points, gas seeps, and infill wells. The current executable file for the program (Version 1.0) can handle a maximum grid size of 369 blocks in the x-direction and 137 blocks in the y-direction and a maximum of 3,000 wells.

Because of the large amounts of data associated with the 3M Project, data preparation and input (pre-processing) are handled with MS Excel spreadsheets and an MS Access database for production data. Post-processing of the output data is also handled with MS Excel spreadsheets and macros.

The simulator was designed with a matrix shrinkage option as presented by Palmer and Mansoori[1]. This feature allows for shrinkage of the coal matrix with methane desorption and the resulting permeability enhancement with production. Matrix shrinkage is an important phenomenon in the "fairway" portion of the basin.

Special source term and boundary conditions were developed to allow for the unique reservoir properties and constraints associated with the 3M Project. For example, grid blocks designated as water recharge/discharge points or as potential gas seeps can be operated at a constant atmospheric pressure condition. Under this scenario, an outcrop grid block could be either a water recharge and discharge point, or a gas seep or air injection point, depending on the computed properties and pressures of neighboring gridblocks.

A special well-control feature was developed for infill wells that allows them to begin producing with a flowing bottom-hole pressure at 20% of the current reservoir pressure, which is then stepped down to a specified minimum pressure over a five-year period.

The model allows for sub-set analysis of a large-scale simulation. In this case, the user can specify the grid block addresses of a sub-set region that is extracted from the large-scale input and run separately. This methodology is used to match regions within a large-scale simulation first and then to piece the regions together for a full-scale simulation.

Other features in the model include:

- Automatic time-step control
- Simulation run restarts
- Automatic gas and water PVT calculations based on pressure, temperature, gas gravity, gas impurities, and water salinity.
- Inactive grid blocks, which saves computation time.
- Variable well constant (net pay, skin, wellbore radius) by well for each recurrent data entry.
- Gathering Centers - Production from wells may be grouped by gathering centers that allow for commingled production at the surface and matching of production on a large-scale basis.
- Variable temperature by grid block.

Features *not* included in this model include:

- Gas desorption time: In the Fruitland Formation, methane desorbs relatively quickly (0.1-3 days) from the coal and diffuses into the coal fracture system. Adding this variable to solution of this large-scale problem was unnecessary because it does not influence the simulation results on a field-wide or large-scale

basis over long periods of time. The absence of gas desorption time in the 3M CBM Model was tested using benchmark case runs, and found to have a minimal effect on the results (See **Section 4.0**).

- Capillary pressure: Capillary pressure is the difference in pressure between two phases. In a coalbed methane reservoir, these two phases are gas and water. This pressure difference between gas and water is difficult to measure on representative coal samples in the laboratory, but it is not normally significant for a problem of the scope of the 3M Project. The absence of capillary pressure in the 3M CBM Model was tested using benchmark case runs, and found to have a minimal effect on the results (See **Section 4.0**).

1.2 System Requirements

The 3M CBM Model was designed to run on a standard Windows-based PC, under Windows 95/98/NT/2000. As currently compiled, the model can handle a simulation grid up to 50,553 grid blocks (369 by 137) with up to 3,000 producing wells, recharge wells, and outcrop seepage source terms. For basin-wide simulations, it is recommended that the user's PC have a minimum of 256 MB of RAM to run the model and manipulate input and post-processing files using MS Excel, as well as 3-5 GB of available hard disk space for storing data input and output files.

1.3 Installation

The 3M CBM Model consists of a series of DOS-based executable files (**3M*.EXE**) that are sized for a particular reservoir simulation problem. All available executable files are contained on the 3M Project CD in the **\Executable Files** directory. To install any one of these files, for example **3M 90x108.EXE**, first create a directory or folder on the PC's hard drive and copy the file from the CD to the hard drive. For ease of use, input files and output files are usually contained in separate directories or sub-directories, with the executable file in the input directory.

1.4 Execution

The simulator executable file is run under a DOS or Windows Command prompt as follows:

C:\<Executable filename> <input filename> <output filename>

The input filename is the path and name of the MS Excel input file (*.XLS). If using the ASCII input option for the well production file (*.INP) and recurrent interrupt file (*.REC), all files must have the same base file name. For example, a simulation run contained on the 3M Project CD for Area A is **26A-128**. This run consists of the following three input files:

26A-128.XLS
26A-128.INP
26A-128.REC

To execute this simulation run from a directory called **\AREA_A**, the user would type:

C:\AREA_A>3M90x108 26A-128 \AREA_A\OUTPUT\26A-128

In this case, the input files and the executable files would have been located in a directory called **\AREA_A**, and the output files would be written to the existing sub-directory called **\AREA_A\OUTPUT**.

Specifying the output filename and path upon execution is optional. If the output file name is not specified, the output files are written to the same directory as the input files under the same base name. For example, if running the simulation called **26A-128** from the above example with the input files in the same directory as the executable file, the user could type:

C:\AREA_A>3M90x108 26A-128

In this case, the output files would be written to the **\AREA_A** directory.

A complete example of loading the simulation files, executing a simulation, and post-processing the results is contained in **Appendix E**.

Note: The simulator can load an open MS Excel input file; however, the file will load much faster if it is closed when executing the program.

1.5 File Management

1.5.1 Input Files

The 3M CBM Model accepts reservoir data input and simulation control inputs from MS Excel spreadsheet files. Input file name conventions are summarized in **Table 1**. Since the 3M CBM Model was designed for use with large data sets, MS Excel files are more efficient for manipulating the data than ASCII files. The simulator can read MS Excel files created with a specific file format and with specific sheet names. To create a new input file, copy an existing input file from the simulation disk (e.g., **26A-128.xls**) and make any necessary modifications. This method will yield the best success at avoiding data input errors. The user must take care to not modify sheet names (e.g., **DX, DY, DZ**, etc.) or column headings on individual sheets in the MS Excel input file as these are required for proper input.

Production or recurrent data sets may be created in ASCII format or by using a specific format in an MS Access database file. Again, since the data sets for the 3M Project were quite large, with over 1,000 producing wells, it was much more efficient to manipulate and format the production data using MS Access as the database manager, rather than create ASCII files with a text editor. An example of an MS Access table that was used in the 3M Project is **3M.MDB**, which can be found in the **\3M Simulation Files** directory on the 3M Project CD. Note that this file is in MS Access 2000 format, which is not downwardly compatible with MS Access 98.

The production data in the MS Access file are contained in a specific format in a table named **MONTHLY** on a well-by-well basis. During a simulation run, the simulator translates the data from the MS Access table into a formatted ASCII file for reading by the simulator. This extra translation step saves processing time over having the simulator repeatedly read data from the MS Access table for each recurrent data interrupt. From the MS Access table, the simulator will create ASCII input files containing the well production data (*.INP) and the recurrent interrupt (*.REC) data.

The user can elect not to rebuild these ASCII files each run if the data have not changed (See **REBUILD** keyword). In other words, the production and recurrent input files need only be created from the MS Access table one time, as was the case with the 3M Project simulation runs. All production data originated from the **3M.MDB** table. However, once the individual *.REC and *.INP files were created, this file was not actively used in the simulations runs. If the user desires to update the production data and re-run the 3M Project simulations, all updates should be made in the **3M.MDB** file, and the *.INP and *.REC files will be re-created during the ensuing simulation runs.

Table 1: Input File Naming Conventions

File	Description
*.XLS	MS Excel simulation input file that contains reservoir data and simulation controls.
*.INP	ASCII data input file with production data, skin, net pay, rate/pressure controls by well. This file can be automatically created from the MS Access production data or by using a text editor.
*.REC	ASCII data input file with recurrent data controls for time steps, interrupts, and total simulation time. This file can be automatically created from the MS Access production data or by using a text editor.

1.5.2 Output Files

The 3M CBM Model outputs data for post-processing to both ASCII and binary files. Output file naming conventions are summarized in **Table 2**. Reservoir property data are output in array format and well data are output in columnar format by time step. The user can control the type of output data and the frequency of the output. At the end of the simulation, the binary data files can be read by the simulator and translated directly into

Comma Separated Values (CSV) format for direct input into MS Excel (See description for the **CSV** keyword).

Reservoir property (array) data that can be output include:

- Grid block Pressure
- Gas Saturation
- Water Saturation
- Permeability
- Porosity
- Gas Content

Well data that can be output include:

- Gas production/injection rate
- Water production/injection rate
- Cumulative gas production/injection
- Cumulative water production/injection
- Flowing bottom-hole pressure
- Average reservoir pressure

The 3M CBM Model makes use of the gathering center concept for history matching production on a large-scale basis. A gathering center allows the user to aggregate data from an unlimited number of wells. Gathering center data that can be output include:

- Gas production/injection rate
- Water production/injection rate
- Cumulative gas production/injection
- Cumulative water production/injection
- Average flowing bottom-hole pressure for all wells in the gathering center

Total results that can be output include:

- Gas production/injection rate
- Water production/injection rate
- Cumulative gas production/injection

Cumulative water production/injection

Output file format descriptions and examples are contained in **Appendix B**.

Table 2: Output File Naming Conventions

File	Description
*.OUT	ASCII simulation output input file containing detailed simulation run-time information that is not echoed to the screen during runs.
*.LOG	ASCII simulation run log that echoes screen output.
*.PVT	ASCII output file with calculated PVT tables.
*.BIN	Binary well data output files.
*.ARR	Binary array output files.
*.CSV	CSV format output files for array data, well data, run totals, and gathering center data.

2.0 METHODOLOGY AND MODEL DESCRIPTION

2.1 3M CBM Model Limitations

The 3M CBM Model was designed specifically for simulation of the Fruitland Formation coalbed methane production in the Colorado portion of the San Juan Basin. Because of the size of this undertaking, the model is a "basin-wide" model designed to match reservoir properties on a large-scale basis, rather than an individual well basis as with most simulations. Although the model can be used to run single-well problems, it does have limitations in this area. For example, as written, the model offers only an IMPES solution algorithm designed for speed of execution of large-scale, field-wide simulations. The model was designed as a single layer model because lack of individual coal seam data and to enhance run-time speed. Given the nature of this basin-wide model, capillary pressure and methane desorption time were not included in the model as a means to increase run-time speed.

Specific model limitations are as follows:

- Maximum X-Dimension Grid blocks: 369
- Maximum Y-Dimension Grid blocks: 137
- Maximum No. of Wells: 3000
- Maximum No. of Layers: 1
- Maximum Relative Permeability Tables: 25
- Maximum Gathering Centers: 25
- PVT Table Pressure Increments: 500
- PVT Table Temperature Increments: 10
- Maximum No. of Cutbacks: 10
- Maximum No. of Solution Iterations: 10

2.2 Coordinate System

The 3M CBM Model uses a 2-dimensional areal grid system in the horizontal plane to simulate a single coal layer (**Fig. 1**). The x-direction indexes (*i*) increase from left to right. The y-direction indexes (*j*) increase from top to bottom.

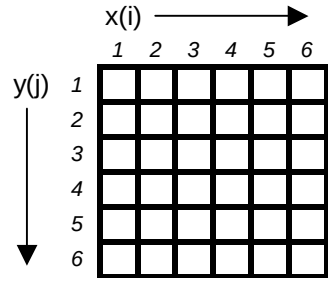

Figure 1: 2-D Areal Grid System

2.3 Inactive Grid Blocks

The 3M CBM Model allows any grid block to be active or inactive. Normally, any grid block outside of the active simulation area would be set as inactive (**Fig. 2**). Setting a grid block as inactive saves computer time during a simulation run and avoids the need to enter specific reservoir properties. To set a grid block to an inactive status, the user must enter a porosity value of zero for that block.

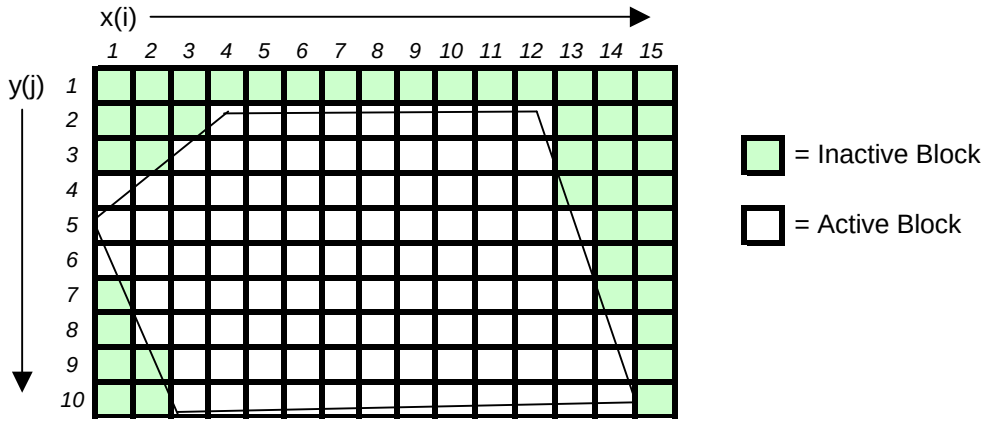

Figure 2: Active and Inactive Grid Blocks

2.4 Transmissibility Modifiers

The transmissibility of a grid block is defined as its fluid conductance capacity or degree of connection with the adjacent blocks in either the x- or y-direction. To simulate barriers (sealing faults) or baffles (leaky faults) the 3M CBM Model allows the user to

modify the calculated transmissibility of a grid block in a given direction. For example, **Fig. 3** depicts a sealing fault cutting across a simulation area. To simulate the sealing fault, which has no transmissibility, the user would approximate the fault trace along the edges of the existing grid blocks, and then set the transmissibility modifier to zero for each grid block that approximates the location of the fault.

To modify the transmissibility between cells *i* and *i +1*, the modifier is place on the *ith* block. Using the example in **Fig. 3**, in order to set the x-direction transmissibility to zero between block (3,8) and block (4,8), the user would enter a zero for the x-direction modifier for block (3,8) on the **TxMlt** sheet in the MS Excel input file. The same logic would apply when using a transmissibility modifier in the y-direction. That is, to modify the transmissibility between cells *j* and *j+1*, the modifier is place on the *jth* block.

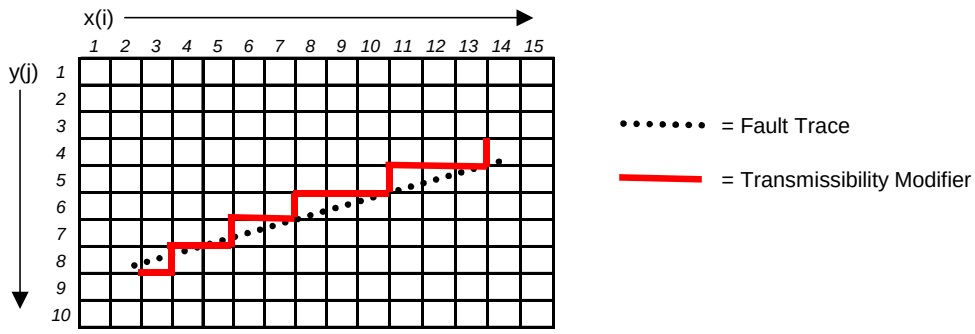

Figure 3: Transmissibility Modifiers

2.5 Fluid Properties

The 3M CBM Model uses standard fluid property correlations to automatically generate fluid properties (density, viscosity, formation volume factors) for the water and gas phases over the user specified range of pressures and temperatures. Fluid properties for water are based on the specified water salinity. Fluid properties for gas are based on the specified gas gravity and other impurities (e.g., CO_2, N_2, and H_2S). The user specifies the range of anticipated pressures and temperatures to be encountered during the simulation,

as well as the number of pressure and temperature increments used in the PVT tables for interpolation between these ranges of values.

2.6 Pressure Dependent Reservoir Properties

In a conventional reservoir, the porosity and permeability of the reservoir rock are a function of the reservoir pressure. Generally, as the reservoir pressure decreases, the pore volume compresses and the formation permeability decreases. The 3M CBM Model accounts for these conventional reservoir phenomena through the use of pore volume compressibility (c_ϕ) and a permeability exponent (k_{exp}). The pore volume compressibility is defined as:

$$c_\phi = \frac{1}{\phi}\frac{d\phi}{dP}$$

Equation 1

where:

c_ϕ = pore volume compressibility, psi^{-1}
ϕ = reservoir porosity, fraction
P = reservoir pressure, psi

The variation in permeability is related to the variation in porosity as follows:

$$\left(\frac{k}{k_0}\right) = \left(\frac{\phi}{\phi_0}\right)^{k\exp}$$

Equation 2

where:

k = reservoir permeability at some reservoir pressure (P), md
k_0 = initial reservoir permeability, md
ϕ = reservoir porosity at some reservoir pressure (P), fraction
ϕ_0 = initial reservoir porosity, fraction
k_{exp} = permeability exponent, dimensionless

2.7 Matrix Shrinkage

As discussed in **Section 2.6**, in conventional reservoirs porosity and permeability are generally functions of reservoir pressure that decline with declining reservoir pressure. However, in coalbed methane reservoirs, it is well documented that porosity and permeability can increase in some cases with declining reservoir pressure due to shrinkage of the coal matrix as methane desorbs from the coal. The 3M CBM Model incorporates this matrix shrinkage effect as defined by Palmer and Mansoori[1] as follows:

$$d\phi = c_m\, dp + \varepsilon_\ell \left[\frac{K}{M} - 1\right] \frac{d}{dp}\left(\frac{\beta\, p}{1+\beta\, p}\right) dp$$

Equation 3

where:

$$c_m = \frac{1}{M} - \left[\frac{K}{M} + f - 1\right]\gamma$$

Equation 4

and

ϕ = reservoir porosity, fraction
p = reservoir pressure, psi
M = constrained axial modulus, psi
K = bulk modulus, psi
f = fraction between 0 and 1
γ = grain compressibility, psi^{-1}
ε_l = parameter of the Langmuir Volume curve match, dimensionless
β = parameter of the Langmuir Pressure curve match, psi^{-1}

The model is highly dependent on the Langmuir Volume and Langmuir Pressure used in conjunction with the value of the matrix shrinkage constant, ε_l / β. **Fig. 4** shows the permeability increase as a function of pressure for various values of porosity. From this figure, it is evident that matrix shrinkage has more dramatic effect with low porosity coal and high pressure drawdown.

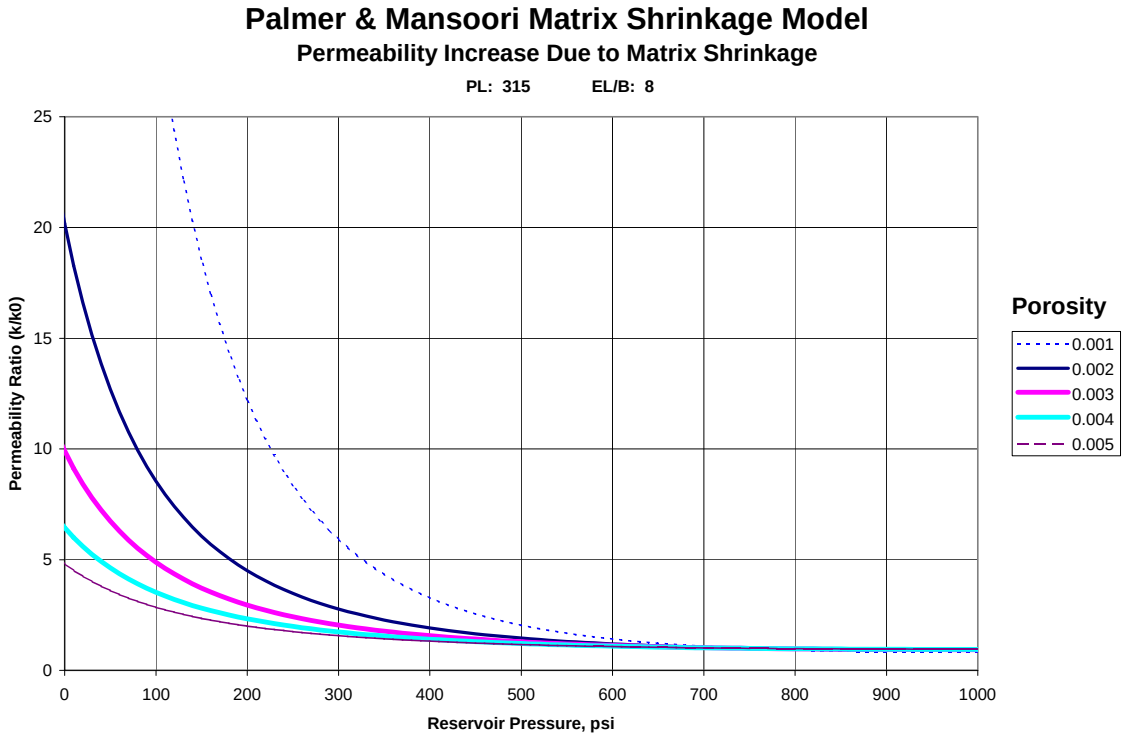

Figure 4: Matrix Shrinkage Model

In the 3M CBM Model, matrix shrinkage is a user-defined option that the user can turn on or off for some, or all, grid blocks in the simulation area. The user can also vary the matrix shrinkage constant by grid block to better match the selected desorption isotherm for that grid block. With the current 3M CBM Model formulation, the matrix shrinkage option is somewhat unstable when used in conjunction with low transmissibility modifiers. The user is cautioned to not use the matrix shrinkage option in grid blocks with or adjacent to grid blocks that have transmissibility modifiers.

2.8 Relative Permeability

The 3M CBM Model allows the user to specify a relative permeability table for each grid block, with up to 25 different tables. The relative permeability values are calculated at 1% saturation increments from 0 to 100% saturation for a total of 101 data points in each table. All relative permeability tables must have data for all 101 saturations increments to be complete. The user may specify the individual values for water and gas relative

permeability or calculate them utilizing the following empirical relationships in the **KRDATA** worksheet in the MS Excel input file:

$$k_{rw} = \left(\frac{S_w - S_{wi}}{1 - S_{wi}} \right)^{Nw}$$

Equation 5

$$k_{rg} = \left(\frac{S_g - S_{gc}}{1 - S_{wi} - S_{gc}} \right)^{Ng}$$

Equation 6

where:

k_{rw} = relative permeability to water, dimensionless
k_{rg} = relative permeability to gas, dimensionless
S_w = water saturation, fraction
S_{wi} = initial water saturation, fraction
S_g = gas saturation, fraction
S_{gc} = critical gas saturation, fraction
N_w = water relative permeability exponent, dimensionless
N_g = gas relative permeability exponent, dimensionless

2.9 Initial Pressure

The 3M CBM Model allows the user to enter initial reservoir pressures by grid block, or to calculate the static pressures based on the pressure and elevation at the gas/water contact. If specifying pressures by grid block, the user can initialize the reservoir pressure in a hydrodynamic state, rather than hydrostatic, as was the case with the 3M Project simulations.

When using the hydrostatic pressure initialization option, the user specifies the reservoir pressure at the gas/water contact elevation. The simulator then calculates all pressures below this elevation assuming a water gradient and all pressures above this elevation assuming a gas gradient.

The 3M CBM Model does not include capillary pressure effects. Therefore, by definition, the pressures in the gas and water phases are equal at all times. It is important to note that this does not imply that there are not potential differences between the water and gas phases. Potential differences between the two phases are account for based on differences in fluid densities.

2.10 Initial Water Saturation

Initial water saturations are entered into the model by individual grid block. Any block may be completely water saturated, completely gas saturated, or any level in between. However, the user must ensure that the specified water saturations do not extend beyond the saturation end-points specified in the relative permeability table for any grid block.

2.11 Langmuir Isotherm

Gas desorption in the 3M CBM Model is controlled by the Langmuir isotherm (**Fig. 5**), which is defined by the Langmuir Volume and Langmuir Pressure. Once pressure in the reservoir drops below the initial desorption pressure (i.e., pressure at which gas begins desorbing from the coal), the reservoir pressure controls the gas content of the coal:

$$G.C. = \left(\frac{V_L \bullet P}{P + P_L} \right)$$

Equation 7

where:

$G.C.$ = gas content, scf/ton of coal
P = reservoir pressure, psi
V_L = Langmuir Volume, scf/ton
P_L = Langmuir Pressure, psi

The initial gas content is specified by grid block and may allow for the coal to be either fully saturated, or under-saturated. A saturated coal is one in which the initial gas content

is on the specified isotherm, whereas an under-saturated coal occurs when the initial gas content is specified below the isotherm.

The 3M CBM Model allows the user to correct for ash content of the coal. However, if the Langmuir isotherm values are reported on an "as received" basis, then ash content should be entered as zero.

The 3M CBM Model has been explicitly designed with a gas re-adsorption option. If free gas is available, the model will allow gas to re-adsorb onto the coal in the case of increasing reservoir pressure, for example in the case of water injection or up-dip gas migration.

Example Langmuir Isotherm

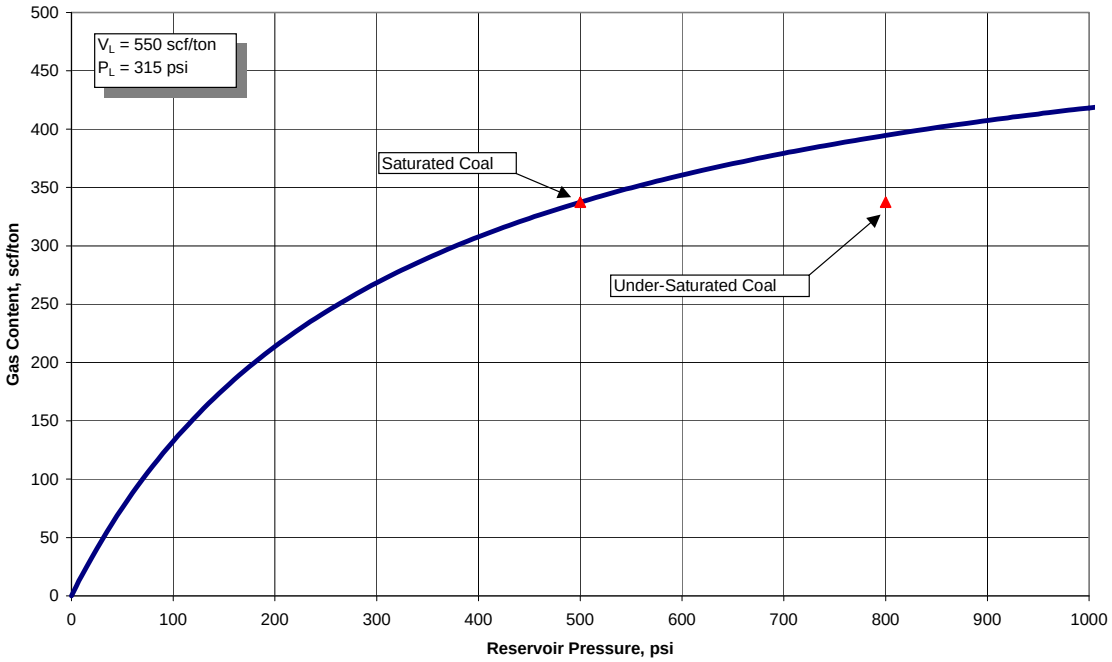

Figure 5: Example Langmuir Isotherm

2.12 Simulator Time Step Control

The 3M CBM Model provides for automated time-step control during simulation runs based on user-specified constraints. The user must specify the initial time step size and the maximum time step size allowed for each recurrent data interrupt in the *.REC file.

The user also specifies the time step multiplier that is used to increase the size of the time steps from the initial time step up to the maximum time step. With the IMPES formulation, the allowable size of any given time step is generally controlled by the throughput of each grid block. Therefore, smaller grid blocks will be constrained by smaller allowable time steps.

Limits are also placed on the size of the allowable time step by the user-specified maximum allowable pressure and saturation changes, and the pressure and saturation convergence tolerances. If the specified time step is too large, such that the model cannot solve for all variables within a limited number of solution iterations, it will perform a time step cutback, which automatically decreases the size of the current time step.

2.13 Termination of a Simulation Run

The length of a simulation run can be controlled by either the maximum number of allowable time steps, the maximum simulation days, or by the specified interrupts in the recurrent data set. Each of these parameters becomes the limiting factor with regard to the simulation run length.

2.14 Recurrent Data Interrupts

The 3M CBM Model handles recurrent data through interrupts (*.REC file). That is, the simulation is interrupted after the specified number of days, and a new set of well data is read. For each data interrupt line in the *.REC file, the simulator is expecting to read one or more lines of well data from the *.INP file. With the data interrupt, the user can change the simulator well conditions, such as the average daily production rate for a well over the next month, or specified number of days. A data interrupt can also be used to change the well output frequency at any point in time.

2.15 Restarts

The 3M CBM Model allows the user to write restart files, so that a simulation run may be re-started at any point in time to simulate a different set of well constraints or run

scenarios. For example, a simulation could be set up to run only the historical production period of a field for history matching purposes. Once the history match is made, a restart file could be written at the end of the production history. Any future simulations could then be re-started from that point in time without having to re-run the same production history. See the **RESTART** keyword.

2.16 Solvers

Most of the CPU time used during a simulation run is spent solving fluid flow equations. In the 3M CBM Model, a series of matrixes with up to 50,000 equations and 50,000 unknowns must be solved for each time step. The efficiency of the solver is critical to achieving good simulator run-time performance. Several different matrix solvers were tested and incorporated into the 3M CBM Model (**Table 3**). The solvers that are most efficient for large-scale simulations such as the 3M Project are the sparse matrix solvers. These solvers essentially reduce the size of the problem to be solved by eliminating any zero values (caused by inactive cells, etc.) from the solution matrix. Since it takes extra computing time to eliminate zero values, sparse matrix solvers become less efficient for small-scale problems. The user may select from any solvers in **Table 3** by using the **SOLVER** keyword with the appropriate solver code.

Table 3: Matrix Solver Descriptions

Solver Code	Description
0	Gauss Elimination
1	Conjugate gradient with pre-conditioner
2	Conjugate gradient with Jacobi pre-conditioner
3	LAIPE Sparse Matrix Solver
4	IMSL Sparse Solver without Iterative Refinement
5	IMSL Sparse Solver with Iterative Refinement
6	IMSL Banded Solver without Iterative Refinement
7	IMSL Banded Solver with Iterative Refinement
8	TOUGH2 Bi-Conjugate Gradient Squared Solver
9	TOUGH2 Bi-Conjugate Gradient Solver
10	TOUGH2 Generalized Minimum Residual Solver

3.0 THEORY

The 3M CBM Model is a two-dimensional coalbed methane reservoir simulation model that describes a single coal layer in the horizontal plane. The planes or directions in the model are defined as the x-, y-, and z-directions. These dimension are then associated with directional indices defined as *i*, *j*, and *k*, which correspond to the x-, y-, and z-directions (**Fig. 6**). The single reservoir layer is divided into an array of grid blocks in the x- and y-directions that are used to describe reservoir properties (e.g. permeability, porosity, thickness, elevation, etc.), and allow these reservoir properties to vary by grid block. A series of fluid flow equations are written for each grid block and solved simultaneously over discrete time intervals or time steps for the duration of the simulation run.

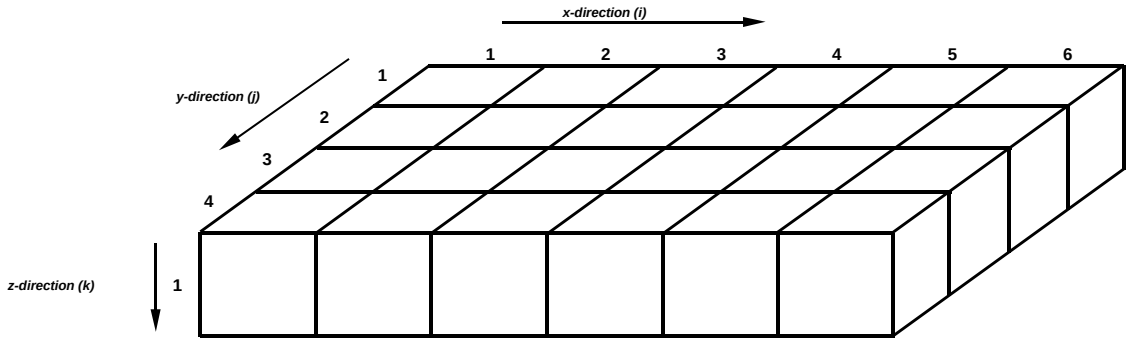

Figure 6: 2D, Single Layer Simulation Grid

The flow equations used in the reservoir simulator are derived from the solution of the radial diffusivity equation (**Eqn. 8**), which is a combination of the law of conservation, an equation of state, and Darcy's Law.

$$\frac{\partial^2 P}{\partial r^2} + \frac{1}{r}\frac{\partial P}{\partial r} = \frac{\phi\ \mu\ c_t}{k}\frac{\partial P}{\partial t}$$

Equation 8

where:

P = pressure, psi

r = distance in the radial direction, ft

k = permeability, md

t = time, hours

ϕ = porosity

μ = fluid viscosity, cp

c_t = total system compressibility, psi^{-1}

The diffusivity equation in **Eqn. 8** can be used to describe fluid flow in a conventional gas reservoir. However, coalbed methane reservoirs are unique when compared to conventional gas reservoirs in that the coal is both a source rock and a reservoir rock. Therefore, a source term that describes the storage of adsorbed methane in the coal reservoir (in addition to any free gas in the coal porosity) must be included in the solution. As such, the Langmuir Equation (**Eqn. 9**) is used as the source term to describe the adsorption and desorption of coalbed methane.

$$Gas\ Content\ (Scf/ton) = \left(\frac{V_L P}{P + P_L} \right)$$

Equation 9

where:

P = pressure, psi

V_L = Langmuir Volume, scf/ton

P_L = Langmuir Pressure, psi

Flow of methane within the coal matrix to the coal cleats or fracture system is through diffusion (Fick's Law), which is governed by methane concentration gradients. Once the methane reaches the fracture system, flow is then governed by pressure differences within the reservoir (Darcy's Law). For purposes of improving run-time performance of the 3M CBM Model for the large-scale simulation problem, the diffusion or desorption

time was ignored, thereby eliminating one variable from the solution. This assumption is considered valid for the 3M CBM Model given the relative quick desorption times of the Fruitland Coal (0.1 to 3 days) and the long time frames used in the simulations (100's of years).

A similar model simplification was used with regard to capillary pressure. In coalbed methane reservoirs, capillary pressure is used to describe the differences in pressure between the gas and water phases. Given the scope and size of the 3M Project, ignoring capillary pressure provided another simplification to the model with negligible loss of accuracy.

Simplification of the diffusivity equation for water and gas phases in two dimensions (ignoring methane desorption time and capillary pressure as discussed above) with the addition of the gas desorption term yields a set of partial differential flow equations that are applicable to coalbed methane reservoirs (**Eqns. 10 and 11**).

For water:

$$\frac{\partial}{\partial x}\left[\lambda_w\left(\frac{\partial P}{\partial x}-\gamma_w\frac{\partial z}{\partial x}\right)\right]+\frac{\partial}{\partial y}\left[\lambda_w\left(\frac{\partial P}{\partial y}-\gamma_w\frac{\partial z}{\partial y}\right)\right]=\frac{\partial}{\partial t}\left(\frac{\varphi S_w}{B_w}\right)+Q_w$$

Equation 10

For gas:

$$\frac{\partial}{\partial x}\left[\lambda_g\left(\frac{\partial P}{\partial x}-\gamma_g\frac{\partial z}{\partial x}\right)\right]+\frac{\partial}{\partial y}\left[\lambda_g\left(\frac{\partial P}{\partial y}-\gamma_g\frac{\partial z}{\partial y}\right)\right]=\frac{\partial}{\partial t}\left(\frac{\varphi S_g}{B_g}\right)+\frac{\partial}{\partial t}\left(\frac{V_L P}{P+P_L}\right)+Q_g$$

Equation 10

where:

P = pressure in the gas and water phases, psi
x = distance in the x-direction, ft
y = distance in the y-direction, ft
k = permeability, md

t = time, hours

ϕ = porosity

S_g = gas saturation

S_w = water saturation

B_g = gas formation volume factor, rcf/scf

B_w = water formation volume factor, rbbl/stb

Q_g = gas production/injection rate, Mcfd

Q_w = water production rate, stbd

γ_g = gas density, psi/ft

γ_w = water density, psi/ft

$\lambda_g = kk_{rg}/\mu_g B_g$ md/cp·rcf/scf

$\lambda_w = kk_{rw}/\mu_w B_w$ md/cp·rbbl/stb

Finite difference techniques are used to express these partial derivatives in terms of algebraic approximations for a single grid block (i,j) with respect to time (**Eqns. 12 and 13**).

For water:

$$\left[\Delta_x T_{xw} \Delta_x \left(P-\gamma_w h\right)\right]_{i,j} + \left[\Delta_y T_{yw} \Delta_y \left(P-\gamma_w h\right)\right]_{i,j} = V_{bulk} \Delta_t \left(\frac{\varphi S_w}{B_w}\right)_{i,j} + Q_{w_{i,j}}$$

Equation 12

For gas:

$$\left[\Delta_x T_{xg} \Delta_x \left(P-\gamma_g h\right)\right]_{i,j} + \left[\Delta_y T_{yg} \Delta_y \left(P-\gamma_g h\right)\right]_{i,j} = V_{bulk} \Delta_t \left(\frac{\varphi S_g}{B_g}\right)_{i,j} +$$

$$V_{bulk} \gamma_{coal} \Delta_t \left(\frac{V_L P}{P+P_L}\right)_{i,j} + Q_{g_{i,j}}$$

Equation 13

where:

T_{xg} = gas transmissibility in the x-direction, Mcfd/psi

T_{xw} = water transmissibility in the x-direction, stbpd/psi

T_{yg} = gas transmissibility in the y-direction, Mcfd/psi

T_{yw} = water transmissibility in the y-direction, stbpd/psi

V_{bulk} = bulk volume of coal, ft^3

γ_{coal} = coal density, ton/ft^3

h = coal thickness, ft

Δ_x = finite difference with respect to the x-direction

Δ_y = finite difference with respect to the y-direction

Δ_t = finite difference with respect to time

The solution to these equations utilizes a 5-point grid block formulation in which fluid flow in a given grid block *(i,j)* is influenced by the four opposing grid blocks in the x- and y-directions (**Fig. 7**). Using this formulation, as series of matrixes are derived with coefficients for pressure and saturation, as determined by the size of the reservoir simulation grid, and solved for each time step in the simulation.

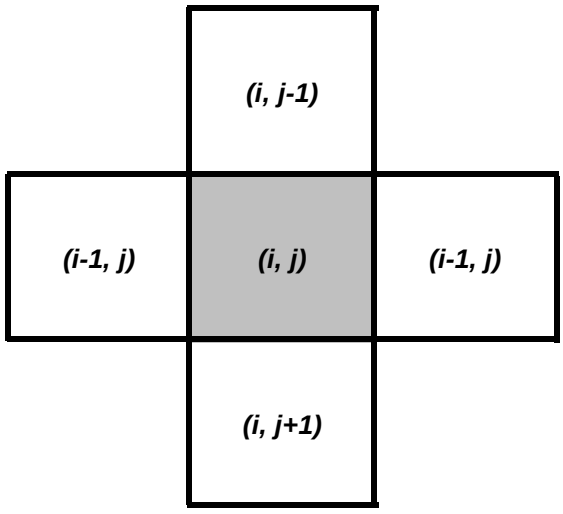

Figure 7: 5-Point Grid Block Formulation

The 3M CBM Model utilizes a standard IMPES (implicit pressure/explicit saturation) formulation of these equations to solve for pressure and saturations for each grid block at

each time step. In this formulation, all grid block pressures are solved for implicitly (i.e., the current time step) while using explicit saturations (i.e., from the previous time step). This formulation is well suited for large-scale reservoir problems that simulated over long periods of time, such as the case with the 3M Project.

4.0 BENCHMARK CASES

4.1 Objectives

More than 80 benchmark cases were designed and tested against the 3M CBM Model and a commercially available coalbed methane reservoir simulator. Cases were designed to test the 3M CBM Model against the commercial model with regard to four primary performance criteria:

1. Consistency in results (e.g., produced water and gas volumes, rates) between the two models.
2. Run-time performance (e.g. speed).
3. Differences in results due to simplification in the 3M CBM Model (e.g., no desorption time, no capillary pressure).
4. Differences in results when comparing the IMPES solution algorithm to a fully implicit solution algorithm in the commercial model.

4.2 Case Descriptions

Various scenarios and cases were run to test and compare the overall performance of the 3M CBM Model with a commercial CBM model. **Table 4** describes the reservoir and well properties used for the benchmark cases. Small-scale (5 by 5 grid blocks) cases with a single well on 320 acres were run primarily to compare the consistency or accuracy of the results between the two models. Large-scale (100 by 100 grid blocks) cases with up to 1,000 wells were used to check the overall agreement between the models and to test the run-time performance. Within these groups of benchmark cases, well controls, reservoir dip, and initial water saturation were also varied from the base case for comparative purposes.

Table 4: Reservoir and Well Properties for Benchmark Cases

Property	Value
Permeability (x-direction), md	50
Permeability (y-direction), md	50
Porosity, %	1
Pore Volume Compressibility, psi^{-1}	0.0001
Langmuir Volume, scf/ton	653
Langmuir Pressure, psia	315
S.G. of Coal	1.36
S.G. of Gas	0.58
Water Salinity, ppm	10,000
Depth, ft	2,000
Coal Thickness, ft	70
Initial Pressure, psia	900
Reservoir Temperature, ˚F	100
Wellbore Radius, ft	0.333
Skin	-2.0
Initial Water Production Rate, bwpd	500
Minimum Flowing BHP, psi	50

Several cases without methane desorption time and without capillary pressure were run with the commercial simulator in order to compare the results against the 3M CBM Model, which does not include these properties. Since the 3M CBM Model utilizes only the IMPES solution algorithm, several identical cases were also run with the commercial CBM model using either the IMPES or fully implicit algorithm to test for any significant differences in overall results. A description of the primary benchmark cases used is contained in **Table 5**.

Table 5: Benchmark Cases Descriptions

Case No.	Commerical Model Solution Algorithm	No. of Grid Blocks in X-direction	No. of Grid Blocks in Y-direction	Grid Block Dim. (ft)	Area (acres)	No. Wells	Desorp Time (days)	Well Prod Control Method	Res Dip (Deg)	Init Water Sat (%)	Cap Press Used	Abs Perm Allowed to Vary	Pore Volume Comp. Set to Zero
Single Well Bases Cases													
1	Implicit	5	5	747	320	1	0	Water	0	100	No	No	No
1a	IMPES	5	5	747	320	1	0	Water	0	100	No	No	No
2	Implicit	5	5	747	320	1	0	Water	10	100	No	No	No
2a	IMPES	5	5	747	320	1	0	Water	10	100	No	No	No
3	Implicit	5	5	747	320	1	0	Water	30	100	No	No	No
3a	IMPES	5	5	747	320	1	0	Water	30	100	No	No	No
4	Implicit	5	5	747	320	1	0	Water	30/25	100	No	No	No
4a	IMPES	5	5	747	320	1	0	Water	30/25	100	No	No	No
5	Implicit	5	5	747	320	1	0	Gas	0	90	No	No	No
6	Implicit	5	5	747	320	1	0	Pressure	0	100	No	No	No
7	Implicit	50	50	880	44,444	1	0	Water	0	100	No	No	No
7a	IMPES	50	50	880	44,444	1	0	Water	0	100	No	No	No
8	Implicit	50	50	880	44,444	1	0	Water	3	100	No	No	No
100 Well Bases Cases													
9	Implicit	50	50	880	44,444	100	0	Water	0	100	No	No	No
9a	IMPES	50	50	880	44,444	100	0	Water	0	100	No	No	No
10	Implicit	50	50	880	44,444	100	0	Water	3	100	No	No	No
1,000 Well Bases Cases													
11	Implicit	100	100	880	177,778	1,000	0	Water	0	100	No	No	No
11a	IMPES	100	100	880	177,778	1,000	0	Water	0	100	No	No	No
12	Implicit	100	100	880	177,778	1,000	0	Water	3	100	No	No	No
12a	IMPES	100	100	880	177,778	1,000	0	Water	3	100	No	No	No
Single Well With Fine Grid													
13	Implicit	21	21	178	320	1	0	Water	0	100	No	No	No
13a	IMPES	21	21	178	320	1	0	Water	0	100	No	No	No
Desorption Time Sensitivities													
14	Implicit	5	5	747	320	1	1	Water	0	100	No	No	No
15	Implicit	5	5	747	320	1	10	Water	0	100	No	No	No
16	Implicit	5	5	747	320	1	100	Water	0	100	No	No	No
17	Implicit	5	5	747	320	1	1,000	Water	0	100	No	No	No
Capillary Pressure Sensitivities													
18	Implicit	5	5	747	320	1	0	Water	0	100	Yes	No	No
19	Implicit	5	5	747	320	1	0	Water	10	100	Yes	No	No
Absolute Permeability Variation Sensitivities													
20	Implicit	5	5	747	320	1	0	Water	0	100	No	Yes	No
21	Implicit	5	5	747	320	1	0	Water	10	100	No	Yes	No
Pore Volume Compressibility Sensitivities													
22	Implicit	5	5	747	320	1	0	Water	0	100	No	No	Yes
23	Implicit	5	5	747	320	1	0	Water	10	100	No	No	Yes

All benchmark cases were run on same PC with a 450-MHz Pentium II processor, 256 MB of RAM, with Windows NT operating system. For consistency, simulations were run with the same simulator run-time controls over a period of 10 years (**Table 6**).

Table 6: Simulator Run Controls for Benchmark Cases

Property	Value
Maximum Water Saturation Change, %	5
Maximum Gas Saturation Change, %	5
Maximum Pressure Change, psi	100
Pressure Convergence Tolerance, psi	0.1
Saturation Convergence Tolerance, %	0.1
Initial Time Step Size, days	0.01
Time Step Multiplier Factor	1.5
Maximum Time Step Size	30
Total Simulation Time, days	3,650

4.3 Results

Overall, the results of the benchmark runs indicated good agreement between the 3M CBM Model and the commercial CBM model. Results for the primary benchmark case are summarized in **Table 7**. For the small-scale cases (Cases 1-7), the average differences in cumulative gas and water production were 0.35% and 0.12%, respectively. For the large-scale cases, with 100 wells, the cumulative gas and water production were within 0.37% and 0.12%, respectively. The 3M CBM Model ran these large-scale problems about 33% faster than the commercial CBM model. Large scale cases with 1,000 wells would not run with the commercial CBM model.

Cases run with and without desorption time (Cases 14-17) indicate that the differences in the results with and without desorption time do not become significant until a desorption time of at least 100 days was used. Since the desorption time of the Fruitland Coal is on the order of 0.1 to 3 days, these cases confirmed the assumption that the absence of desorption time in the 3M CBM Model would have very little, if any, effect on the accuracy of long-term simulations.

Similar results were achieved with regard to the absence of capillary pressure in the 3M CBM Model. Runs made using the commercial CBM model with and without capillary pressure (Cases 18-19) show no substantial differences in the simulated reservoir performance.

A comparison of cases run with the commercial CBM model using both IMPES and fully implicit solution algorithms indicated comparable results. In Cases 9 and 9a, cumulative gas and water production were different by only 0.02% and 0.36%, respectively. As expected, run-times were shorter (by 44%) using the IMPES solution algorithm than with the fully implicit solution. These runs confirmed that using the IMPES formulation in the 3M CBM Model would not result in substantial differences in results, but would provide faster run-times.

Table 7: Benchmark Case Results

	Commercial CBM Model					3M CBM Model					3M vs. Commercial		
Case No.	Cum Gas (MMcf)	Cum Water (Mbbl)	Run Time (sec)	Total Time Steps	Total Itera-tions	Cum Gas (MMcf)	Cum Water (Mbbl)	Run Time (sec)	Total Time Steps	Total Itera-tions	Cum Gas Differ (%)	Cum Water Differ (%)	Run Time Differ (%)
Single Well Bases Cases													
1	9,192	798	7.0	140	338	9,226	800	2.0	135	368	0.36	0.29	-72
1a	9,195	801	8.0	140	317	9,226	800	2.0	135	368	0.33	-0.09	-76
2	9,084	756	8.0	140	353	9,145	754	3.8	266	1,180	0.66	-0.28	-53
2a	9,098	758	15.0	323	723	9,145	754	3.7	266	1,180	0.51	-0.57	-75
3	7,514	698	9.0	140	355	7,562	696	5.5	342	1,575	0.64	-0.30	-39
3a	7,528	700	16.0	391	841	7,562	696	5.5	342	1,575	0.46	-0.51	-66
4	6,881	745	11.0	168	536	6,954	742	7.9	550	2,457	1.07	-0.46	-28
4a	6,894	747	12.0	200	681	6,954	742	7.9	550	2,457	0.87	-0.70	-34
5	1,825	308	8.0	140	276	1,825	310	1.8	134	268	0.00	0.68	-77
6	9,170	796	8.0	140	346	9,260	800	2.0	149	435	0.98	0.50	-76
7	756	1,825	102.0	140	253	748	1,825	44.3	134	245	-1.02	0.00	-57
7a	754	1,825	70.0	140	253	748	1,825	44.3	134	245	-0.72	0.00	-37
8	319	1,825	166.0	140	374	299	1,825	57.9	142	142	-6.21	0.00	-65
8a	319	1,825	113.0	140	367	299	1,825	57.9	142	142	-6.45	0.00	-49
100 Well Bases Cases													
9	1,085,500	104,950	225.0	140	413	1,087,848	105,214	111.2	140	674	0.22	0.25	-51
9a	1,085,300	105,330	125.0	140	391	1,087,848	105,214	111.2	140	674	0.23	-0.11	-11
10	1,012,900	103,930	229.0	140	428	1,019,472	104,176	145.7	149	869	0.65	0.24	-36
1,000 Well Bases Cases													
11	**CASE DID NOT RUN**					6,376,423	475,826	497.8	139	688	N/A	N/A	N/A
11a	**CASE DID NOT RUN**					6,376,423	475,826	497.8	139	688	N/A	N/A	N/A
12	**CASE DID NOT RUN**					6,121,533	487,522	964.0	161	1,420	N/A	N/A	N/A
12a	**CASE DID NOT RUN**					6,121,533	487,522	964.0	161	1,420	N/A	N/A	N/A
Single Well With Fine Grid													
13	8,853	785	68.0	140	358	8,942	790	132.0	1,030	4,458	1.00	0.57	94
13a	8,864	788	177.0	354	811	8,942	790	132.0	1,030	4,458	0.88	0.23	-25
Desorption Time Sensitivities													
14	9,190	798	7.0	140	340	9,226	800	2.0	135	368	0.39	0.29	-72
15	9,168	798	7.0	140	346	9,226	800	2.0	135	368	0.63	0.29	-72
16	8,953	798	7.0	140	357	9,226	800	2.0	135	368	3.05	0.28	-72
17	7,159	790	7.0	140	368	9,226	800	2.0	135	368	28.86	1.21	-72
Capillary Pressure Sensitivities													
18	9,170	809	8.0	140	343	9,226	800	2.0	135	368	0.61	-1.08	-76
19	9,137	762	9.0	140	357	9,145	754	3.8	266	1,180	0.08	-1.09	-58
Absolute Permeability Variation Sensitivities													
20	8,579	780	9.0	140	340	8,602	781	3.0	194	850	0.27	0.17	-67
21	8,478	746	9.0	140	352	8,513	744	3.7	263	1,147	0.41	-0.20	-59
Pore Volume Compressibility Sensitivities													
22	9,341	745	9.0	140	337	9,380	747	2.8	199	913	0.41	0.31	-69
23	9,277	699	8.0	140	352	9,345	698	3.9	267	1,185	0.73	-0.13	-51

5.0 INPUT METHODS: SPREADSHEETS AND DATABASES

Input data for use with the 3M CBM Model are created in spreadsheets using MS Excel and databases using MS Access. MS Excel was chosen to manipulate the reservoir property data in 2D arrays (i.e., columns and rows) that are well suited for spreadsheets. On the other hand, the well production data for the more than 1,000 producing wells with up to 15 years of history in the 3M Project was well suited for manipulation in an MS Access database.

The simulator can read both MS Excel and MS Access files directly, however, reading the historical production data from an MS Access file during a simulation was found to be time-consuming. To enhance the speed of the simulations, the production data are read from the MS Access file by the simulator and then formatted and written to two ASCII files for use during run-time. This step significantly reduces simulation run times.

5.1 Input Data Description

5.1.1 5.1.1 MS Excel Input File Description

The MS Excel input file contains all simulation input data except for the production and recurrent data. The file consists of several Excel worksheets. The file uses specific names for the worksheet tabs. **IMPORTANT:** The names of these tabs must not be changed by the user, or the simulator will not be able to read the input data. The user can add additional worksheets to the file as needed. The order of the worksheets is not critical, just the reserved names.

Within any worksheet, the user can use equations in cells to calculate input values for the simulator to read. It is not necessary to convert the results of the equations to values for the simulator to read them. For example, the user could write an equation to calculate the initial reservoir pressure based on the structural elevation.

The spreadsheets are designed with a specific format for reading by the simulator. This file format must be maintained. Within an array input sheet, it is important that the user not alter the format of the column headings (**Fig. 8**).

X/Y	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10
X1	0	0	63.0	63.0	63.0	62.9	62.7	62.4	62.6	63.7
X2	0	0	62.8	62.8	62.8	62.8	62.9	63.0	63.5	65.2
X3	0	0	0	62.6	62.6	62.6	62.8	63.3	64.1	65.7
X4	0	0	62.3	62.1	62.1	62.3	62.6	63.2	64.0	65.3
X5	0	0	0	62.7	62.5	62.4	62.4	62.6	63.3	64.2
X6	0	0	0	63.2	62.5	62.2	62.0	62.0	62.3	63.0
X7	0	0	0	0	62.3	62.1	62.0	61.6	61.4	61.7
X8	0	0	0	0	62.4	62.1	61.4	60.6	60.3	60.5
X9	0	0	0	0	0	61.4	60.3	59.3	59.2	59.2
X10	0	0	0	0	0	59.9	58.9	58.4	58.0	57.9

Figure 8: Example Array Input Sheet

In **Fig. 8**, the *Y1, Y2, Y3*, etc. column headings are used by the simulator to locate a specific column of data. Therefore, the user must not change the name, location, or order of these column headings.

Standard (*i, j*) cell numbering consists of x-direction grid blocks increasing in value from left to right in columns and y-direction grid blocks increasing in value from top to bottom in rows. Because of the limitation of 256 columns in MS Excel, a data entry option was added to the simulator to allow for the array data to be "flipped" in the case of a full-field 369 by 137 simulation (as in **Fig. 8**). In other words, the y-direction grid blocks increase in value from left to right in columns and x-direction grid blocks increasing in value from top to bottom in rows. See the **FLIPIT** keyword description for using this option.

Note: All of the 3M Project simulations are configured in the "flipped" on inverted format with the Y-direction cell running across the top of the sheet.

5.2 Macro Descriptions

The MS Excel input file contains two macros that can be used to manipulate the input data while saving the user the burden of performing the actual key strokes. The two macros are the **Subset Region Macros** (**Section 5.2.1**) and the **Copy XLS File Macro** (**Section 5.2.2**). These macros are attached to the **MACROS** worksheet within the MS Excel input file (**Fig. A.1**).

5.2.1 Subset Region Macro

This macro creates a subset of the data file based on the *i, j* cell addresses. It is used for creating an input file for a smaller subset area within the large data set. For example, if the user wanted to run a simulation on a 10 x 10 area in the middle of a larger simulation area, they would enter the *i, j* coordinates for the uppermost corner and the lowermost corner and then run the macro. The macro returns the modified simulation input file, renumbering all *i, j* cell addresses to correspond to the new coordinates.

5.2.2 Copy XLS File Macro

This macro creates a copy of the current MS Excel input file without any formulas. It is used to reduce the size of the MS Excel input file once all of the input values are calculated and will remain static. It is not necessary to convert the equations to values in order to run a simulation. However, doing so saves hard disk space and allows the simulator to read the input file faster.

5.3 Input Worksheet Description

This section describes each worksheet within the MS Excel input file and the data that are entered on each of these worksheets. Data on the worksheets are entered either in column format, under specific column headings, or in two-dimensional array format (2D-array) corresponding to *i, j* grid block indexes. For any 2D-array, values (i.e., porosity, permeability, etc.) may vary by grid block. The specific worksheets are described in **Table 8.** They are listed in the same order that they are contained in the MS Excel input files.

Table 8: MS Excel Input File Worksheet Descriptions

Sheet Name	Description	Units
MACROS	Contains data entry cells for running two different macros within the spreadsheet as discussed in Section 5.2. See example of the **MACROS** worksheet in **Fig. A.1**.	
MAIN	Contains simulator keywords for input and run control. The keywords are entered in the **KEYWORD** column. The values for any keywords which require data entry are entered to the right in the **VALUE** column. See example of the **MAIN** worksheet if **Fig. A.2**.	
DX	Contains two columns consisting of the x-direction grid block number and length of the grid block in the x-direction. This length is the length of the grid block projected onto the horizontal plane. The simulator accounts for the true length of the grid block in the x-direction based on the elevation differences (i.e., dip) between adjacent grid blocks in the x-direction.	ft
DY	Contains two columns consisting of the y-direction grid block number and length of the grid block in the y-direction. This length is the length of the grid block projected onto the horizontal plane. The simulator accounts for the true length of the grid block in the y-direction based on the elevation differences (i.e., dip) between adjacent grid blocks in the y-direction.	ft
DZ	2D-array with net pay thickness values	ft
KX	2D-array with x-direction permeability values.	md
KY	2D-array with y-direction permeability values.	md
PHI	2D-array with porosity values. Notes: Inactive grid blocks are turned off in the simulator by setting the porosity to zero. When calculating adsorbed gas-in-place, the bulk matrix volume is decreased by the pore volume.	fraction
SW	2D-array with initial water saturation values.	fraction
Pi	2D-array with initial reservoir pressure values at the grid block mid-point. Note: This option is only used if the **PDATUM** keyword is set to –999 on the **MAIN** worksheet, which allows for a non-hydrostatic starting condition in the reservoir.	psi
ELEV	2D-array with mean sea level elevation values to the top of a grid block	ft
RTEMP	2D-array with reservoir temperature values at the grid block mid-point.	°F
GCONTENT	2D-array with gas content values. The gas content values may represent a saturated reservoir condition in which the gas content values are on the Langmuir isotherm, or an under-saturated condition in which the gas content is below the isotherm.	scf/ton
CPORE	2D array with pore volume compressibility values of the coal. Note: **CPORE** can either be used as a global value specified on the **MAIN** worksheet, or as an individual grid block value specified on the **CPORE** worksheet. The 2D-array option is used by setting **CPORE** to –999 on the **MAIN** sheet to override the global value. The matrix shrinkage option can be turned on for individual grid blocks by entering –999 for **CPORE** on the **MAIN** worksheet and –888 in the individual cell values on the **CPORE** worksheet.	psi^{-1}
VL	2D-array with Langmuir volume values for the adsorption isotherm. The Langmuir volume defines the maximum volume of gas that can be adsorbed on the coal.	scf/ton
PL	2D-array with Langmuir pressure values for the adsorption isotherm. The Langmuir pressure defines the pressure at which one-half of the maximum volume of gas is adsorbed on the coal.	psi
ELB	2D-array with El/B values. The El/B value is a matrix shrinkage control parameter (See **Matrix Shrinkage** in **Section 2.7**).	psi^{-1}
TXMLT	2D-array with x-direction transmissibility modifier values. The transmissibility modifier acts as a multiplier for grid block transmissibility. The modifier can by set to 0 to indicate a complete barrier to flow or 1.0 to indicate no modification. The value for each active grid block must be explicitly set to 1.0 to indicate that no modified is to be applied by the simulator. The modification occurs at the boundary between the "i" and "*i+1*" grid blocks.	fraction

<table>
<tr><th>Sheet Name</th><th>Description</th><th>Units</th></tr>
<tr><td>TYMLT</td><td>2D-array with y-direction transmissibility modifier values. The transmissibility modifier acts as a multiplier for grid block transmissibility. The modifier can by set to 0 to indicate a complete barrier to flow or 1.0 to indicate no modification. The value for each active grid block must be explicitly set to 1.0 to indicate that no modified is to be applied by the simulator. The modification occurs at the boundary between the “j” and “j+1” grid blocks.</td><td>fraction</td></tr>
<tr><td>RELPERM</td><td>2D-array with relative permeability table numbers. The values entered correspond to the relative permeability table for the grid block. All active grid blocks must be assigned a relative permeability table number.</td><td>integer</td></tr>
<tr><td>WELL</td><td>Contains the complete list of wells with (i, j) locations used in the simulation. This list includes all existing wells and all wells planned for any forecasts. The required data input format consists of four columns: WELLID, WNAME, I_LOCATION, and J_LOCATION.
<table>
<tr><th>Example:

WELLID</th><th>WNAME</th><th>I_LOCATION</th><th>J_LOCATION</th></tr>
<tr><td>0506707296</td><td>ROBERT DULIN GAS UNIT D 1</td><td>26</td><td>24</td></tr>
<tr><td>0506706778</td><td>EVELYN PAYNE GAS UNIT A 1</td><td>41</td><td>28</td></tr>
<tr><td>0506707176</td><td>CUNDIFF GAS UNIT C 1</td><td>7</td><td>19</td></tr>
</table>
WELLID is the unique identified used in the simulator for each well up to 15 characters in length. A common identified would be the well API no.

WNAME field consists of the user-specified well name, up to 30 characters in length.

I_LOCATION field is the x-direction address for the grid block in which the well is located.

J_LOCATION field is the y-direction address for the grid block in which the well is located.</td><td></td></tr>
<tr><td>GATHERING</td><td>Contains the list of gathering centers used in the simulation. Gathering centers are used to aggregate production/injection volumes for gross, large-scale history matching and/or to handle wells with commingled production. The required data input format consists of two columns: CNTRNO and CNTRNAME.

Example:
<table>
<tr><th>CNTRNO</th><th>CNTRNAME</th></tr>
<tr><td>1</td><td>34N-5 & 6W SUL (19 Wells)</td></tr>
<tr><td>2</td><td>34N-7W SUL (47 Wells)</td></tr>
<tr><td>3</td><td>34 & 35N- 5 & 6W NUL (30 Wells)</td></tr>
<tr><td>4</td><td>34 & 35N-7W NUL (75 Wells)</td></tr>
</table>
CNTRNO is a user-assigned sequential gathering center number in integer format.

CNTRNAME is the user-assigned name or identifier for the gathering center, up to 80 characters in length.</td><td></td></tr>
</table>

<table>
<tr><th>Sheet Name</th><th>Description</th><th>Units</th></tr>
<tr><td>WELL_GATHERING</td><td>Contains a list of wells assigned to each gathering center. A well may be assigned to more than one gathering center. The required data input format consists of two columns: CNTRNO and WELLID.
Example:

<table>
<tr><th>CNTRNO</th><th>WELLID</th></tr>
<tr><td>1</td><td>0500706099</td></tr>
<tr><td>1</td><td>0500706088</td></tr>
<tr><td>2</td><td>0506707989</td></tr>
<tr><td>2</td><td>0500706098</td></tr>
<tr><td>3</td><td>0506706532</td></tr>
<tr><td>4</td><td>0506706356</td></tr>
</table>

CNTRNO is a user-assigned sequential gathering center number in integer format.

WELLID is the unique identified used in the simulator for each well up to 15 characters in length.</td><td></td></tr>
<tr><td>KRDATA</td><td>Contains all relative permeability tables used in the simulation. The simulator allows up to 25 relative permeability tables. The simulator uses uniform spacing of the relative permeability saturation increments to provide for faster table lookups during run-time. Each table contains saturation 101 entries that range from 0 up to 100 percent gas saturation, incremented by one saturation unit. The required data entry format consists of four columns: KRTABLENO, SG, KRW, and KRG.

Example:

<table>
<tr><th>KRTABLENO</th><th>SG</th><th>KRW</th><th>KRG</th></tr>
<tr><td>1</td><td>1.00</td><td>0.00000000</td><td>1.00000000</td></tr>
<tr><td>1</td><td>0.02</td><td>0.76316065</td><td>0.01077608</td></tr>
<tr><td>1</td><td>0.01</td><td>0.87438875</td><td>0.00453078</td></tr>
<tr><td>1</td><td>0.00</td><td>1.00000000</td><td>0.00000000</td></tr>
</table>

KRTABLENO is the user-assigned sequential relative permeability table no. in integer format.

SG is the gas saturation value specified as a fraction.

KRW is the water relative permeability value corresponding to SG.

KRG is the gas relative permeability value corresponding to SG.</td><td></td></tr>
</table>

Table A.1 in **Appendix A** is an example of the **MAIN** worksheet of the MS Excel input file. It contains the primary simulator controls and allows the user to select various options using a keyword input format. As with any worksheet in the MS Excel input file, the user must not modify the columns headings (e.g., **KEYWORD, VALUE**). The

keywords are entered in the **KEYWORD** column, and any necessary values are specified in the **VALUE** column.

5.4 Input Keyword Description

The 3M CBM Model uses a conventional keyword format for inputting data. Within the MS Excel input file, the keywords are specified on the **MAIN** worksheet in the keyword column as discussed in **Section 5.3**. For each keyword, the description specifies the type (real, integer, flag), the units, whether the keyword is required, and the default value, where applicable. Keywords that are indicated as "flags" do not have a value associated with them. By definition, when a flag-type keyword is used, that flag or option is changed from "off" to "on."

The complete list of input keywords and descriptions can be found in **Table C.1** of **Appendix C**.

5.5 MS Access Production Data File Description

The MS Access Production Data file is used to created and manipulate the recurrent simulation data set. Within the MS Access database, production data are stored in a table called **MONTHLY**. For each well in a given simulation, the MS Access file contains the historical well production by month, along with well constant data (wellbore radius, net pay thickness, and skin), well control codes, and operating pressure constraints. Data must first be sorted by month, and then by the well identifier (usually API No.) for use in the simulator. A description of the **MONTHLY** table file format is contained in **Table 9**.

Table 9: MS Access Database – Monthly Table Format Description

Field	Description	Type	Units
MONTH	Production month. Date format MM/1/YYY	Date	N/A
WELLID	Well identifier, which is usually the API no.	Text (15)	N/A
RW	Wellbore radius, ft	Real (Double)	ft
SKIN	Value for wellbore skin.	Real (Double)	N/A

Field	Description	Type	Units
NETPAY	Coal net pay thickness coal.	Real (Double)	Ft
WCNTRL	Well control code.	Integer	N/A
QWMAX	Actual average daily water production rate for the production month.	Real (Double)	bwpd
QGMAX	Actual average daily gas production rate for the production month.	Real (Double)	Mcfd
PWMIN	Minimum flowing bottom-hole pressure for wells on rate control.	Real (Double)	psi
BHP	Currently not used by the simulator. Enter a zero value.	Real (Double)	N/A

For the 3M Project, monthly production data were converted to average daily production on a monthly basis. Based on the relative volumes of water and gas production, an MS Access query was used to determine the well control codes for each well each month. Estimated net pay values and skin values were then added based on completion information.

Use of the MS Access Production Data file with the simulator is optional. The simulator opens and reads this *.MDB file based on a Database Source Name (DSN) established under the Windows Open Database Connectivity (ODBC) format. The DSN should match the name of the simulation input file. For example, in the 3M Project, the production database DSN was **3M**, which corresponds to the **3M.MDB** database file and was used in conjunction with an MS Excel input file (e.g., **3M.XLS**). Using the **3M.MDB** database file and the **REBUILD** keyword option with the MS Excel input file (**3M.XLS**), the simulator created the Recurrent Production Data file (**3M.INP**) and the Recurrent Interrupt file (**3M.REC**) in ASCII format. As long as the recurrent data do not change, the **REBUILD** option was only needed one time to create the recurrent data files in ASCII format. For example, if this same simulation is run again after modifying reservoir properties, the **REBULD** option could be turned off by the user, and the simulator would use copies of the **3M.INP** and **3M.REC** input files.

The two recurrent data files *.INP and *.REC are described in **Sections 5.6** and **5.8**, respectively.

5.6 Recurrent Production Data Input File Description

The recurrent production data input file (*.INP) contains the historical well production, well constant parameters, and well controls. As discussed in **Section 5.5**, the data can be stored in an MS Access database, or created using a text editor. The data format is the same whether created in MS Access or with a text editor. Although the data are entered as free format, caution should be used to maintain the exact character spacing described. While this character spacing is not critical for input into the simulation, it does become critical when reading data for post-processing. There are no default values for the recurrent production data.

A "#" sign is used to indicate a comment line for the title, blank lines, and the column headings. The data headings are not required in the file, but are used to label the data columns. **Table 10** contains a description of all data elements found in the recurrent production data file.

Table 10: Recurrent Production Data File Description

Heading	Description	Units
MONTH	Production month in "MM/D/YYYY" format (e.g., " 1/1/1985"). The format allows for 9 characters within double quotes. The production day is always used as the first of the month.	None
WELLID	Usually the API number for the well. The format allows for 15 characters within double quotes.	None
RW	Wellbore radius.	ft
SKIN	Skin factor.	psi
NETPAY	Net perforated interval for the well. The net pay can be different from the coal thickness specified in the **DZ** 2D-array input worksheet.	Ft
WCNTRL	Simulator well control code. Determines if the well is on rate or pressure control. See **Section 5.7** for the well control code descriptions.	None
QWMAX	Daily water production or injection rate for the well. Production is positive; injection is negative. For historical production, this value is the actual average daily production for the month or interrupt time period. For a well on rate control, this is the water rate that the simulator will attempt to produce from the well. For a well on pressure control, this is the maximum water rate at which the well can either produce or inject.	bpd
QGMAX	Daily gas production or injection rate for the well. Production is positive; injection is negative. For historical production, this value is the actual average daily production for the month or interrupt time period. For a well on rate control, this is the gas rate that the simulator will attempt to produce from the well. For a well on pressure control, this is the maximum gas rate at which the well can either produce or inject.	Mcfd

Heading	Description	Units
PWMIN	Flowing bottom-hole pressure for the well. For a well on pressure control, this is the flowing bottom-hole pressure at which the simulator will attempt to produce from or inject into the well. For a well on rate control, this the minimum bottom-hole flowing pressure for a producing well, or the maximum flowing bottom-hole pressure for an injection well.	Psi
BHP	Currently not be used by the simulator. Enter a zero value.	None

The data format is designed to handle all historical well production by month and well. All data should be sorted first by month, then by well ID. When the simulator reads the data, it will read all the data having the same interrupt period or date, which is generally monthly for historical data, and then process that data before moving to the next month. Any well that is listed in the MS Excel input file on the well list, but does not have any recurrent production data, is assumed by the simulator to be shut-in. If a well's status does not change for a given interrupt period, it is assumed to maintain the same status from the prior interrupt. Therefore, a well does not have to be listed for each interrupt period if its status does not change. In the example data set below (**Table 11**), **Well 0506706527** is not listed for the month of May 1986, but is listed for June 1986. Therefore, the simulator would assume that the well was shut-in (or not drilled yet) for May 1986.

The data format allows the user to modify the well constant, which is effectively controlled by the net pay, wellbore radius and skin at any point in time during the simulation. This feature is useful for modifying the well constant for a well which was originally cased and hydraulically, and subsequently sidetracked and cavitated. In this case, the net pay, wellbore radius and skin effect could be modified for the new wellbore conditions. The user can also specify a net pay thickness in the recurrent data set which is less than the gross interval thickness specified in the **DZ** worksheet to represent only the perforated interval, as opposed to the entire coal thickness.

Table 11: Example Recurrent Production Data Input Format

#	MM/D/YYYY	Well ID		Rw	Skin	NetPay	WCntrl	QwMax	QgMax	PwMin	BHP
	" 5/1/1986"	"0506706688	"	0.25	-3	46.259	6	1.839	4.839	50	0
	" 6/1/1986"	"0506706527	"	0.25	0	55.859	6	136.067	12.967	50	0

" 6/1/1986"	"0506706528	"	0.25	0	51.535	6	34.033	19.733	50	0
" 6/1/1986"	"0506706704	"	0.25	-3	38.954	5	28.7	0	50	0
" 6/1/1986"	"0506706713	"	0.25	-3	42.646	6	40.7	0	50	0
" 6/1/1986"	"0506706529	"	0.25	0	38.198	6	0	2.867	50	0
" 6/1/1986"	"0506706637	"	0.25	0	48.394	6	0	20.6	50	0
" 6/1/1986"	"0506706729	"	0.25	0	46.025	0	0	0	50	0
" 6/1/1986"	"0506706570	"	0.25	-3	53.163	0	0	0	50	0
" 6/1/1986"	"0506706703	"	0.25	-3	29.308	6	0	0.733	50	0
" 6/1/1986"	"0506706723	"	0.25	-3	33.903	6	0	4.067	50	0
" 6/1/1986"	"0506706702	"	0.25	-3	37.951	6	0	0.633	50	0
" 6/1/1986"	"0506706633	"	0.25	-3	54.19	6	0	19.1	50	0
" 6/1/1986"	"0506706688	"	0.25	-3	46.259	6	0	2.467	50	0
" 7/1/1986"	"0506706527	"	0.25	0	55.859	6	56.677	10.065	50	0

If the MS Access database option is used to build the production data set with **REBUILD** keyword, the *.INP file is automatically created based on the data and months contained in the MS Access Production Data file.

5.7 Well Control Codes

In the recurrent production input file (*.INP), each well that is entered must have a specified well control code. The well control code dictates how the simulator will handle the well as either a producer, an injector, or as a shut-in. Producers and injectors are usually on both rate and pressure control. The user can specify which control (rate or pressure) will be the primary well control and which will be the secondary well control. For rate control, the user also specifies which phase (gas or water) is the limiting or controlling phase.

For example, for history matching production, a producing well initially put on production with a high water rate might be “driven on water”, which means it is specified as being on primary water rate control and secondary pressure control (well control code 5). If the well is specified at 400 bwpd and a minimum bottom-hole flowing pressure of 50 psi, the simulator would attempt to produce the well at 400 bwpd until reaching a minimum flowing bottom-hole pressure of 50 psi . The simulator would also calculate the corresponding gas flow rate resulting from the specified water rate. Once the bottom-

hole pressure limit is reached, the well is automatically switched over to pressure control at the specified minimum bottom-hole pressure for both water and gas production.

A well could also be specified with the flowing bottom-hole pressure being the primary control and water or gas rate being the secondary control. In this case, the simulator attempts to produce the well at the specified bottom-hole pressure, or unless the maximum specified rate is reached.

Special rate control codes have been designed for water recharge/discharge source terms (wells), as well as seeps and springs. **Table 12** contains a description of all valid well control codes.

Table 12: Well Control Codes

Code	Type	Description
0	Observation Well/Shut-in	No production. The reported flowing bottom-hole pressure for a shut-in well is the same as the reservoir pressure.
1	Pressure Control/Water Production Control	Primary control is the specified minimum bottom-hole pressure; secondary control is specified maximum water production rate.
2	Pressure Control/Gas Production Control	Primary control is the specified minimum bottom-hole pressure; secondary control is specified maximum gas production rate.
3	Pressure Control/Water Injection Control	Primary control is the specified maximum bottom-hole pressure; secondary control is specified maximum water injection rate.
4	Pressure Control/Gas Injection Control	Primary control is the specified maximum bottom-hole pressure; secondary control is specified maximum gas injection rate.
5	Water Production Control/Pressure Control	Primary control is the specified water production rate; secondary control is the specified minimum bottom-hole pressure. This well control type is used for matching well production history.
6	Gas Production Control/Pressure Control	Primary control is the specified gas production rate; secondary control is the specified minimum bottom-hole pressure. This well control type is used for matching well production history.
7	Water Injection Control/Pressure Control	Primary control is the specified water injection rate; secondary control is the specified maximum bottom-hole pressure.
8	Gas Injection Control/Pressure Control	Primary control is the specified gas injection rate; secondary control is the specified maximum bottom-hole pressure.
9	Water Recharge/Discharge operating at a constant specified pressure	Allows a well to operate at a constant pressure and either inject (recharge) or produce (discharge) water. This well control type is used for designated river recharge/discharge points.
10	Spring/Seep	Operates at a constant specified atmospheric pressure allowing both water and gas to seep out, and only air to be sucked into the grid block.
11	Gas Seep	Operates at a constant specified atmospheric pressure allowing gas to seep out and air to be sucked into the grid block.

Code	Type	Description
12	Vent Well	Primary control is the specified minimum bottom-hole pressure with no secondary well control. This well control code is used in conjunction with the **VENT_SG** keyword which specifies the minimum gas saturation in the grid block that is necessary before the well is allowed to vent gas both gas and water.
13	N/A	Currently not used
14	Infill Well	Provides for the drilling of an infill type producing well that initially comes online at a flowing bottom-hole pressure that is 20% lower than the reservoir pressure. From this point the flowing bottom-hole pressure is "stepped down" uniformly over a 5-year period until the specified minimum bottom-hole pressure is reached.

5.8 Recurrent Interrupt File Description

The recurrent data are control by two different data files. The first, discussed in **Section 5.6**, is the production and well control data of the Recurrent Production Data file (*.INP). The second is the Recurrent Interrupt file (*.REC). The recurrent interrupt file controls the timing of each data interrupt. A data interrupt occurs whenever the user wants the simulator to change how it is handling or controlling the wells during the simulation.

For each interrupt specified in the Recurrent Production Data file (as indicated by a unique MM/D/YYYY entry), the Recurrent Interrupt file must contain a line of text. Each line indicates the length of time until the next interrupt. For historical well production data based on monthly values, data interrupts are necessary for each month with the length of the interrupt period (**DTIME**) being equal to the days in a given month. Conversely, a well could also be put on pressure control for the duration of simulation run by only specifying one data interrupt line.

Table 13 contains a description of all data elements contained in the recurrent production data file in the same order in which they must appear in the file:

Table 13: Recurrent Production Data File Description

Heading	Description	Units
DTIME	The total time increment for this interrupt. For historical well production data, this time would usually be equal to the days in a given month.	Days

Heading	Description	Units
DTSTART	The initial time step size for this interrupt. For historical production data, the initial time step size may be in the range of 0.1 to 1.0 days, since each change in well rates usually causes the simulator to take smaller time steps in order to maintain stability.	Days
DTMAX	The maximum time step size allowed for this interrupt. Generally speaking, the larger the maximum specified time step, the more unstable the solution becomes. By limiting the maximum time step size, the user can avoid excessive numbers of time step cutbacks which tend to decrease simulation run-time.	Days
DTMLT	The time step multiplier factor used by the simulator for automatic time step control. After taking the initial step for this interrupt, the simulator will attempt to increase the size of the next time step by the DTMLT factor until the maximum (DTMAX) time step size is reached. However, due to the potential for instability in the simulator, the maximum time step may never actually be reached.	None
OUTFREQ	The frequency at which well output data or well report is written to the output file (*.OUT) for this interrupt.	Days
WRITERST	Currently not used by the simulator. Enter a zero here.	None

In **Table 14**, the interrupt time periods (**DTIME**) correspond to the number of days in a month for the historical data as shown for the three months listed in **Table 13**. After each interrupt, the initial time step increment is 0.5 days, increasing by a factor of 1.5 each time step, up to a maximum of 30 days. Well data output is set to match the number of days in each month, so that the resulting output is written monthly.

Table 14: Example Recurrent Interrupt Data Format

# DTIME	DTSTART	DTMAX	DTMLT	OUTFREQ	WRITERST
31	0.5	30	1.5	31	0
30	0.5	30	1.5	29	0
31	0.5	30	1.5	31	0

If the MS Access database option is used to build the production data set with **REBUILD** keyword, the Recurrent Interrupt Data file (*.REC) is automatically created based on the data and months contained in the MS Access Production Data file.

6.0 OUTPUT DATA DESCRIPTION

3M CBM Model output data consists of a run-time log file (*.LOG), a simulator output file (*.OUT), a PVT output file (*.PVT), array output files (*.ARR, *.ASC), and well data output files (*.BIN). Array and well output data can be written in either ASCII or binary format. In general, run-time is improved by writing the data to binary files, and then having the simulator convert the binary data to ASCII files in CSV format at the end of the simulation run using the **CSV** keyword option. Detailed output file formats for the binary, CSV, and PVT output files are contained in **APPENDIX B**.

6.1 Simulator Log File (*.LOG)

The simulator log file contains the screen output from a run in ASCII format. This file is useful for reviewing run performance, particularly when used under Windows 95 & 98 where the Command Prompt/DOS windows do not have a scroll bar.

6.2 Simulator Output File (*.OUT)

The simulator output file contains the detailed performance information from a simulation run, including all input parameters, recurrent data interrupts, production and injection rates, average pressures and saturations, a well report, iterations, cutbacks, warning messages, and a simulation summary. The simulator output file can be very large (10's of MB), especially when there is a re-occurring error message during a run. To save some disk space, the user can specify the **NO_ECHO** keyword option to avoid inclusion of the simulation input data set at the beginning of this file. The user can also control whether the well report is included in this file (**WELLRPT** keyword), which corresponds to the specified well reporting frequency (**OUTFREQ**). To save even more space in the simulator output file, the user can also specify the **SPRSS_MSG** keyword option which suppresses all simulator output messages to the output file.

6.3 PVT Output File (*.PVT)

The PVT output file contains PVT data set calculated by the simulator for both water and gas. The 3M CBM Model allows for variable reservoir temperature by grid block, so the PVT table is two-dimensional in pressure and temperature. To have the simulator print the PVT output file, the user must specify the **PVT** keyword option on the **MAIN** worksheet in the MS Excel input file.

6.4 Array Output Files (*.ARR, *.ASC)

The arrays available for output consist of pressure, gas saturation, water saturation, permeability, porosity, and gas content. The choice of which arrays will be printed is controlled by the appropriate "map" keyword. The frequency of output is controlled by the **ARRAYFREQ** keyword. Using the **BINARY** keyword, the arrays are written in binary format to a *.ARR output file name. With the **ASCII** keyword, the arrays are written to ASCII files with a corresponding *.ASC extension. Run-time performance is enhanced by allowing the simulator to write the arrays in binary format, and then create the MS Excel CSV files from the binary files at the end of the simulation run via the use of the **CSV** keyword option.

6.5 Well Output Files (*.BIN)

The well output files consist of production and injection rates, cumulative production and injection, flowing bottom-hole pressure, and average reservoir pressure by well. One binary file is written for each data type (e.g., water production, gas production, etc.) under the corresponding data name. Using the **CSV** keyword option, the user can have the simulator read and combine these data into a single CSV file (<input name>.CSV) for all wells in the simulation run that contains all of the rate, cumulative production, and pressure data by well. This CSV file can then be read directly by the MS Excel post-processing application.

6.6 CSV Output Files (*.CSV)

By default, the simulator well output data are written in binary format (*.BIN) for speed of run-time execution. Using the CSV keyword option, the user can have the simulator read these binary files and combine them into CSV files. For the individual well production, the data are combined data into a single CSV file (<input name>.CSV) for all wells in the simulation run that contains all of the rate, cumulative production, and pressure data by well based on the well output frequency (**OUTFREQ**). For the gathering centers, the rate, cumulative production data, and average pressures are aggregated based on the wells in each gathering center (<input name>_CEN.CSV). The data output frequency for the gathering center files is controlled by the **GC_FREQ** keyword.

Total production from all wells is aggregated in the totals CSV file (<input name>_TOT.CSV) for all time steps. The user is cautioned with regard to the use of the totals file. The totals files will include production from all wells and source terms in the simulation, including seeps and recharge/discharge points. Therefore, these total production figures can be misleading if used improperly. To obtain total production for just the producing wells in a simulation, for example, the user would be better served by establishing a gathering center for just those wells.

All three of these CSV files (wells, totals, and gathering centers) can be read directly by the post-processing application.

The **CSV** option also initiates the writing of CSV files for the output array data from the binary *.ARR files based on the MAPS specified by the user. With this option turned on, the simulator will read the *.ARR files and write the corresponding *.CSV file. If the keyword **FLIPIT** is turned on because of the size of the simulation grid, the array output data are written in the same inverted format as the input data. This means that the y-direction grid values increase across the top of the sheet in rows, and the x-direction grid values increase down the sheet in columns.

6.7 Output Keyword Description

Table D.1 in **Appendix D** contains a description of all keywords used for data output control. As with the input data controls, the keywords are specified on the **MAIN** worksheet of the MS Excel input file (**Section 5.0**). For each keyword, the description specifies the type (real, integer, flag), the units, whether the keyword is required, and the default value, where applicable. Keywords that are indicated as "flags" do not have a value associated with them. By definition, when a flag-type keyword is used, that flag or option is changed from "off" to "on."

7.0 POST-PROCESSOR

Post-processing of output data from the 3M CBM Model is handled using MS Excel spreadsheets and macros. The post-processor allows the user to view simulated production and pressures as a function of time on conventional X-Y plots. In additional, the user can load actual production and pressure data from wells in the 3M Project and graphically compare them against the simulated data.

The master post-processor file is named **MASTER POST-PROCESSOR.XLS** and is contained in the **\3M CBM Model Users Guide\Post-Processing Files** directory on the 3M Project CD. Once data from a given run are loaded into the master post-processor, the file should be saved under a new name corresponding to the simulation run. The naming convention adopted for the 3M Project simulation runs utilizes the simulation input file name with the addition of the letters "PP" (for post-processor) to the end of the file name. For example, if the input file were named **3M-15A.XLS**, the post processor file would be named **3M-15A PP.XLS**.

The post-processing application utilizes a series of MS Excel macros to load and process the simulator output data. These macros are common to all post-processing files and are stored in each individual spreadsheet file. Therefore, when loading a post-processing file, the user will want to activate the macros when prompted by MS Excel.

The post-processing spreadsheet contains several tabs for loading, storing, and viewing the output data. As with the MS Excel input files, the user should take care not to re-name any of the existing tabs. A description of each tab is contained in **Table 15**.

Table 15: Post-Processing Spreadsheet Tabs Description

Sheet	Description
Load Data	Contains macros used to load the actual and simulated data sets, and organize the data either by gathering centers or individual wells.
Plot Data	Contains the actual and simulated well data for plotting.

Sheet	Description
Production Plot	Contains the X-Y plot of actual and simulated production and pressure data versus time by well. **Macros Buttons** **Print All:** Prints the production plot for all wells. **Print Next 25:** Prints the production/pressure plot for the next 25 wells in the well list. **<|:** Move back to the first well in the well list. **<<:** Move back 25 wells in the well list. **Prev Well:** Move back one well in the well list. **Next Well:** Move ahead one well in the well list. **>>:** Move ahead 25 wells in the well list. **>|:** Move ahead to the last well in the well list.
GC Data	Contains the actual and simulated gathering center data for plotting.
GC Plot	Contains the X-Y plot of actual and simulated production and pressure data versus time by gathering center. **Macros Buttons** **Print All:** Prints the production plot for all gathering centers. **<|:** Move back to the first gathering center in the well list. **Prev GC:** Move back one gathering center in the well list. **Next GC:** Move ahead one gathering center in the well list. **>|:** Move ahead to the last gathering center in the well list.
Total Data	Contains the total actual and simulated data used for plotting.
Total Plot	Contains the X-Y plot of actual and simulated production and pressure data versus time by gathering center.
Well	Contains the list of wells from the simulation input file.
Gathering	Contains the list of gathering centers from the simulation input file.
Well_Gathering	Contains the list of well and gathering center combinations from the simulation input file.
Actual	Contains the actual production data by well.
Simulated	Contains the simulated production data by well.
GC Simulated	Contains the simulated production data by gathering center.
Total Simulated	Contains the total simulated production data for all wells.
BHP Data	Contains the observed shut-in bottom-hole pressure data by well ID and date.
PWF Data	Contains the observed flowing bottom-hole pressure data by well ID and date.

The user can make a comparison of actual versus simulated production and pressure data using the three different plots in the post-processing file for history-matching purposes. The data can be viewed by well, by gathering center, or by totals. For wells or gathering centers, the plot sheets contain buttons that allow the user to page forward or backward in the well and/or gathering center list. The user also has the option of printing copies of the plots.

For individual wells, the post-processing file displays the simulated flowing bottom-hole pressure and a simulated average reservoir pressure (if the **CALC_PAVG** keyword was specified in the simulation). Where actual pressure data are available, the post-processor will also display the observed shut-in pressures and calculated flowing bottom-hole pressures on the individual well plots.

7.1 Data Input

The **Load Data** worksheet is used to load the simulator output data into the post-processor. This worksheet contains macros attached to nine buttons that are used to load and organize data as follows:

- Simulated Data
- Load Totals
- Load Wells
- Load Gathering

- Actual Data
- Load Production
- Load Well List
- Load Gathering
- Load Pressure
- Sort By Gathering Center
- Sort by Well ID

To load the data, first enter the file paths and file names in appropriate cells. Then load the actual and simulated data. For subsequent runs of the same simulation area, only the simulated data will need to be loaded if the actual data have not changed. The well data are initially sorted by well ID upon loading. However, the ***Sort by Well ID*** button, will sort the wells by gathering center, then by well ID. This option groups the wells together by gathering center for viewing and printing. To sort the data by gathering center for

viewing or printing, use the ***Sort by Gathering Center*** button. Currently, each well may be in only one gathering center for post-processing purposes.

Pressure data used by the post-processor are stored in a file named **3M PRESSURE DATA.XLS**. This file contains measured (or calculated) shut-in and flowing bottom-hole pressures. Pressures are tied to an individual well ID with a measurement date. The pressures specified in this spreadsheet are corrected to the gridded mid-point depth of the corresponding grid block for the well. Pressure data may be added to this file, but the user should not change the name of the file, the file format, or the sheet name.

Fig. 9 shows the instructions for loading data in the "Load Data" worksheet of the post-processor:

Instructions:

1. Enter input and output file path names.

2. Enter input file and output file names.

3. Load actual data if this is a new run or actual well data have changed
   a. Load Production
   b. Load Well List
   c. Load Gathering

4. Load pressures if they haven't already been loaded or have changed.
   a. Load Pressure

5. Well data are initially sorted by API number upon loading. Sort by gathering if you want data by gathering center
   a. Sort By Gathering Center

6. Re-load simulated data after each run.
   a. Load Totals
   b. Load Wells
   c. Load Gathering

7. Group wells within gathering centers to view or print well curves together
   a. Sort By Well ID

Figure 9: Instructions for the LOAD DATA worksheet in the Post-Processor

8.0 REFERENCES

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9.0 LIST OF INCLUDED FILES

3M CBM Model Report\

3M CBM Simulator\

- Executable Files\
  - 3M369x137.exe
  - 3M90x108.exe
  - 3M85x85.exe
  - 3M158x85.exe
  - 3M85x66.exe
  - 3M103x66.exe
- Simulation Support Files\
  - AVIEW100.dll
  - AVIEW110.dll
  - DFORRT.dll
  - TECIO.dll
  - f90SQLDVF.dll
- Post-Processing Files\
  - Master Post-Processor.xls
  - 3M Pressure Data.xls

3M Simulation Files\

- 3M.mdb
- Initialization\
  - 3M369x137.exe
  - 26-33Sw&Pi.xls
  - 26-33.log
  - 26-33.out
  - 26-33.rec
  - 26-33.xls
- Area A\
  - 3M90x108.exe
  - 26A-127.xls
  - 26A-127.inp
  - 26A-127.rec
  - 26A-128.xls
  - 26A-128.inp
  - 26A-128.rec
  - 26A-127 PP.xls
  - 26A-182 PP.xls
- Area B\
  - 3M85x85.exe
  - 26B-69.xls
  - 26B-69.inp
  - 26B-69.rec
  - 26B-70.xls
  - 26B-70.inp

26B-70.rec
26B-69 PP.xls
26B-70 PP.xls

Area C\
3M158x85.exe
26C-32.xls
26C-32.inp
26C-32.rec
26C-33.xls
26C-33.inp
26C-33.rec
26C-32 PP.xls
26C-33 PP.xls

Area D\
3M85x66.exe
26D-31.xls
26D-31.inp
26D-31.rec
26D-32.xls
26D-32.inp
26D-32.rec
26D-31 PP.xls
26D-32 PP.xls

Area E\
3M103x66.exe
26E-13.xls
26E-13.inp
26E-13.rec
26E-14.xls
26E-14.inp
26E-14.rec
26E-13 PP.xls
26E-14 PP.xls

Appendix A -- INPUT FILE EXAMPLES

Table A.1: Example of MACROS worksheet in the MS Excel input file

Subset Region Macro:						
Instructions:						
1. Enter the coordinates for the upper left and lower right corners of the sub-set area.						
Remember that I coordinates increase from left (west) to right (east) and J coordinates increase from the						
Top (north) to the bottom (south) of the grid.						
2. Click the button marked "Subset".						
Subset	**Subset Region Corners**					
		I	**J**			
	Upper Left	148	1			
	Lower Right	305	85			
	NX	158				
	NY	85				
Copy XLS File Macro: (Copies input data to new .XLS file as values)						
Copy File	**Path:**	X:\3m\input				
	New File Name:	3m-field-19 copy				

Table A.2: Example of the MAIN input worksheet

	KEYWORD	VALUE	
Example:	**WORD**	1	
# Coalbed Methane Simulation Input File			
# Title Lines (up to 5 total)			
	TITLE1		
	3M Model Subset Region		
	TITLE2		
	158 by 85 Grid		
	TITLE3		
	(148,1) to (305,85)		
	TITLE4		
	SOLVER: 8 (TOUGH2 Bi-Conjugate Gradient Squared Solver)		
# INITIALIZATION SECTION			
# Grid Size			
	NX	158	
	NY	85	
# Maximum No. of Wells			
	WELLSMAX	320	
# Solution Algorithm			
	IMPES		
# Run Control, Tolerances, and Convergence			
	TSTEPMAX	9999	
	DAYSMAX	6000	
	ITRMAX	10	
	DSMAX	0.02	
	DPMAX	50	
	SCONVERGE	0.1	
	PCONVERGE	10	
	SOLVER	8	
	RESTART	250	
	RSTFREQ	100	
	NEW_WELLS		

	KEYWORD	VALUE	
# Reservoir properties are read as 2-D arrays from specified workbook sheets			
# with X-direction values in columns and Y-direction values in rows (normal X-Y ordering).			
# For large simulations where the X-direction grid block count exceeds the width of an			
# Excel spreadsheet (256 cells), the input ordering direction may be switched by turning the			
# FLIPIT switch from "0" to "1" (0 = no, 1 = yes).			
	FLIPIT	1	
# Initial Pressure and Datum - Note: Set PDATUM to -999 if using Pi array input			
	PDATUM	-999	
	HDATUM	8690.716	
# Gross Well Control			
	QGMIN	10	
	ECO_LIMIT_TIME	10	
# Coal Properties: Ash Content (fraction), Specific Gravity (water=1.0), Pore Compressibility, Perm Exponent			
	ASHCON	0	
	SPGCOAL	1.3605	
	CPORE	-999	
	KEXP	3	
	YOUNGS_MOD	4.45E+05	
	FRACTION	0	
	GRAIN	0	
	M/E	2	
	K/M	0.76	
	EL/B	-999	
# Water and Gas Properties			
	SALINITY	10000	
	SPGAS	0.65	
	CO2	0.1	
	N2	0	
	H2S	0	
# Reservoir Temperature Ranges and Maximum Pressure for PVT Tables			
	TEMPMIN	55	
	TEMPMAX	145	
	PMIN	1	
	PMAX	3000	
# Temperature (Deg F) and Pressure (psi) Increments for Calculated PVT Tables			
	TINCRMNT	10	
	PINCRMNT	10	

	KEYWORD	VALUE	
# Total No. of Relative Permeability Tables			
	KRTABLES	6	
# Gathering centers can be used to specify production regions (e.g., outcrop wells) or			
# to gross up individual well production for large-scale history matching			
# Total No. of Gathering Centers			
	CNTRCOUNT	8	
# Subset region of entire simulation to be run			
	NOSUBSET		
	I_MIN	3	
	I_MAX	7	
	J_MIN	3	
	J_MAX	7	
# TIME DEPENDENT SECTION			
# Start Date (dd/mm/yyyy) and Time (hh:mm:ss)			
	STARTDATE		
	01/01/1984		
	TIME		
	00:00:00		
# Array and Well Output Frequency (in days) for Parameter Specified with OUTPUTON			
	ARRAYFREQ	180	
	GCFREQ	30	
# Output control Flags			
	OUTPUTON		
	WELLRPT		
	ASCII		
	CSV		
	CALC_PAVG		
	ECHO_OFF		
	PMAP		
	SWMAP		
	KXMAP		
	KYMAP		
	SGMAP		
	GCMAP		
	SPRSS_MSG		
	PVT		
# Recurrent Data Controls			
	REBUILD		
	SUBPROD		

	KEYWORD	VALUE	
# Recurrent Data			
	RECURRENT		
	DATABASE		

Appendix B – OUTPUT FILE FORMATS

B.1 Binary Well Output Format (*.BIN)

The binary well output format consists of a series of eight files (*_QG.BIN, *_QW.BIN, *_GP.BIN, *_WP.BIN, *_GI.BIN, *_WI.BIN, *_PR.BIN, *_PAVG.BIN). Each file contains a specific well parameter for each well for every time step, as follows:

File Name	Well Parameter	Type	Units
*_QG.BIN	Gas Production/Injection Rate	Real	Mcfd
*_QW.BIN	Water Production Injection Rate	Real	Bpd
*_GP.BIN	Cum Gas Production	Real	MMcf
*_WP.BIN	Cum Water Production	Real	Mbw
*_GI.BIN	Cum Gas Injection	Real	MMcf
*_WI.BIN	Cum Water Injection	Real	Mbw
*_PR.BIN	Flowing Bottom-hole Pressure	Real	psi
*_PAVG.BIN	Avg. Bottom-hole Pressure	Real	psi

For each time step, the simulation time is written, followed by the well parameters for all wells in the well list up to the total well count (*Well Count*). Data for each well is written in the same order that they were read from the input files. Since the data are written for every well at each time step, the Well ID is not written in these files. The simulation time is written in days.

Data Format:

Time (*1*), days
Value(WellID(*1*))
Value(WellID(2))
Value(WellID(3))
.
.
.
Value(WellID(*Well Count*))
Time (*2*), days
Value(WellID(*1*))
Value(WellID(2))

Value(WellID(3))

.
.
.

Value(WellID(*Well Count*))

B.2 CSV Well Output Format (*.CSV)

The CSV well output file (*.CSV) contains the production, injection, and pressure data by well. It is a standard comma delimited MS Excel CSV file. The first row of the first column contains the simulation start date, followed by 10 columns of data.

Row 1

Column No.	Field Name	Length	Decimals	Type	Units
1	Start Date (MM/DD/YYYY)	10	0	Date	None

Row 2 to End of File

Column No.	Field Name	Length	Decimals	Type	Units
2	Well ID	15	0	Text	None
3	Simulation Time	12	3	Real	days
4	Gas Production/Injection Rate	12	3	Real	Mcfd
5	Water Production/Injection Rate	12	3	Real	bpd
6	Cum Gas Production	12	3	Real	MMcf
7	Cum Water Production	12	3	Real	Mbw
8	Cum Gas Injection	12	3	Real	MMcf
9	Cum Water Injection	12	3	Real	Mbw
10	Avg. Flowing Bottomhole Pressure	12	3	Real	psi
11	Avg Reservoir Pressure	12	3	Real	psi

B.3 Gathering Center Output Format (*_CEN.CSV)

The gathering center output file (*_CEN.CSV) contains the production, injection, and pressure data by gathering center. It is a standard comma delimited MS Excel CSV file. The first row of the first column contains the simulation start date, followed by 12 columns of data.

Row 1

Column No.	Field Name	Length	Decimals	Type	Units
1	Start Date (MM/DD/YYYY)	10	0	Date	None

Row 2 to End of File

Column No.	Field Name	Length	Decimals	Type	Units
2	Gathering Center Number	2	0	Integer	None
3	Simulation Time	12	3	Real	days
4	Gas Production Rate	12	3	Real	Mcfd
5	Water Production Rate	12	3	Real	bpd
6	Gas Injection Rate	12	3	Real	Mcfd
7	Water Injection Rate	12	3	Real	bpd
8	Cum Gas Production	12	3	Real	MMcf
9	Cum Water Production	12	3	Real	Mbw
10	Cum Gas Injection	12	3	Real	MMcf
11	Cum Water Injection	12	3	Real	Mbw
12	Avg. Flowing Bottomhole Pressure	12	3	Real	psi
13	Avg Reservoir Pressure	12	3	Real	psi

B.4 Totals Output Format (*_TOT.CSV)

The totals output file (*_TOT.CSV) contains the production, injection, and pressure data for all wells, seeps, recharge, and discharge points. It is a standard comma delimited MS Excel CSV file. The first row of the first column contains the simulation start date, followed by 9 columns of data.

Row 1

Column No.	Field Name	Length	Decimals	Type	Units
1	Start Date (MM/DD/YYYY)	10	0	Date	None

Row 2 to End of File

Column No.	Field Name	Length	Decimals	Type	Units
2	Simulation Time	12	3	Real	days
3	Gas Production Rate	12	3	Real	Mcfd
4	Water Production Rate	12	3	Real	bpd
5	Gas Injection Rate	12	3	Real	Mcfd
6	Water Injection Rate	12	3	Real	bpd
7	Cum Gas Production	12	3	Real	MMcf
8	Cum Water Production	12	3	Real	Mbw
9	Cum Gas Injection	12	3	Real	MMcf

Column No.	Field Name	Length	Decimals	Type	Units
10	Cum Water Injection	12	3	Real	Mbw

B.5 ASCII Array Output Format (*.ASC)

Array data can be written in ASCII array output format for pressure (*_PR.ASC), water saturation (*_SW.ASC), gas saturation (*_SG.ASC), porosity (*_PHI.ASC), x-direction permeability (*_KX.ASC), y-direction permeability (*_KY.ASC), and gas content (*_GC.ASC) by the use of the **ASCII** keyword and the appropriate "map" keyword.

Based on the array output frequency specified by the user (**ARRAYFREQ**), the simulation time is written, followed by the entire array of values for the specified parameter. The array size is based on the x and y dimensions specified for the simulation (**NX** and **NY**).

Data Format:

ARRAY REPORT:

STEP NO. = ##### CUM TIME, DAYS = #######.##

Y/X	1	2	3	4……..Nx
1	Value(*1,1*)	Value(*2,1*)	Value(3,1)	Value(*4,1*)….. Value(*Nx,1*)
2	Value(*1,2*)	Value(*2,2*)	Value(*3,2*)	Value(*4,2*)….. Value(*Nx,2*)
.	.	.	.	. .
.	.	.	.	. .
.	.	.	.	. .
Ny	Value(*1,Ny*)	Value(*2,Ny*)	Value(*3,Ny*)	Value(*4,Ny*)…Value(*Nx,Ny*)

B.6 Binary Array Output Format (*.ARR)

Array data can be are written in binary array output format for pressure (*_PR.ARR), water saturation (*_SW.ARR), gas saturation (*_SG.ARR), porosity (*_PHI.ARR), x-direction permeability (*_KX.ARR), y-direction permeability (*_KY.ARR),and gas content (*_GC.ARR) by the use of the BINARY keyword and the appropriate "map" keyword.

Based on the array output frequency specified by the user (**ARRAYFREQ**), the simulation time is written, followed by the entire array of values for the specified parameter. The array size is based on the x and y dimensions specified for the simulation (**NX** and **NY**).

Data Format:

Time (*1*)
Value(*1,1*)
Value(2,*1*)
Value(3,*1*)
.
.
.
Value(*1,2*)
Value(*2,2*)
Value(*3,2*)
.
.
.
Value(*Nx,Ny*)
Time (*2*)
Value(*1,1*)
Value(2,*1*)
Value(3,*1*)
.
.
.
Value(*1,2*)
Value(*2,2*)
Value(*3,2*)
.
.
.
Value(*Nx,Ny*)

B.7 PVT Output File Format (*.ARR)

The PVT output file consists of a series of six tables. The file contains one table for each for the formation volume factor, density, and viscosity for both gas and water. For each property, the values are written in columns and rows for the user specified ranges of pressure and temperature and pressure.

The PVT table names, parameters, and units are as follows:

Table	PVT Parameter	Units
Bg	Gas Formation Volume Factor	rcf/scf
Rhog	Gas Density	psi/ft
Ug	Gas Viscosity	cp
Bw	Water Formation Volume Factor	rcf/scf
Rhow	Water Density	psi/ft
Uw	Water Viscosity	cp

Data Format:

<PVT Table Name>

P & T	Temperature (*1*)	Temperature (*2*)……. Temperature(*y*)
Pressure(*1*)	Value(*1,1*)	Value(*1,2*)……..Value(*1,y*)
Pressure(*2*)	Value(*2,1*)	Value(*2,2*) ……..Value(*2,y*)
Pressure(*3*)	Value(*3,1*)	Value(*3,2*) ……..Value(*3,y*)
.	.	. .
.	.	. .
.	.	. .
Pressure(*x*)	Value(*x,1*)	Value(*x,2*) ……..Value(*x,y*)

Example Data:

Bg Table

P & T	90.0	100.0
5.0	3.10771	3.16434
25.0	0.62002	0.63142
500.0	0.02927	0.02992

Rho g Table

P & T	90.0	100.0
5.0	0.00009	0.00009
25.0	0.00044	0.00044
500.0	0.00942	0.00921

Ug Table

P & T	90.0	100.0
5.0	0.01117	0.01133
25.0	0.01113	0.01129
500.0	0.01168	0.01182

Bw Table

P & T	90.0	100.0
5.0	1.00391	1.00612
25.0	1.00388	1.00609
500.0	1.00318	1.00539

Rho w Table

P & T	90.0	100.0
5.0	0.43057	0.42978
25.0	0.43060	0.42982
500.0	0.43138	0.43060

Uw Table

P & T	90.0	100.0
5.0	0.75889	0.67858
25.0	0.75889	0.67858
500.0	0.75892	0.67862

Appendix C – INPUT KEYWORDS

Table C.1: Input Keyword Descriptions

Keyword	Description	Type	Units	Rqd	Default
PDATUM	Formation pressure at a specified datum used to initialize the grid block pressures if static equilibrium is assumed. A gas gradient is assumed above the contact and a water gradient is assumed below the contact. If set to –999 by the user, the pressures are read from the **Pi** 2D-array input worksheet.	Real	PSI	No	None
HDATUM	Elevation of the gas/water contact used by **PDATUM** to establish grid block pressure. If no contact exists, set **HDATUM** to the upper-most point of elevation within the simulation grid.	Real	Ft	No	None
TDATUM	Temperature at the specified datum. For pressure initialization purposes, fluid densities are calculated at the average of the grid block pressure and the datum pressure.	Real	°F	No	None
TITLE1	Free form text field for title description of a simulation run.	Text	None	No	None
TITLE2	Free form text field for title description of a simulation run.	Text	None	No	None
TITLE3	Free form text field for title description of a simulation run.	Text	None	No	None
NX	Number of total grid blocks in the x-direction. **NX** cannot exceed the x-direction limit on the executable file.	Integer	None	Yes	None
NY	Number of total grid blocks in the y-direction. **NY** cannot exceed the y-direction limit on the executable file.	Integer	None	Yes	None
WELLSMAX	Maximum number of wells in the simulation run. **WELLSMAX** cannot exceed the maximum well limit for the executable file.	Integer	None	Yes	None
IMPES	Flag to indicate IMPES solution formulation.	Flag	None	No	IMPES
TSTEPMAX	Maximum number of time steps allowed in the simulation run.	Integer	None	Yes	None
DAYSMAX	Maximum number of days allowed in the simulation run.	Integer	None	Yes	None
ITRMAX	Maximum number of solution iterations attempted for a given time step before the time step is cutback and re-run.	Integer	None	No	10
DSMAX	Maximum allowable saturation change for a given time step. If the saturation change exceeds this value in any grid block, the time step is cutback and re-run. This parameter directly affects the simulation stability and run-time.	Real	Fraction	No	0.05
DPMAX	Maximum allowable pressure change for a given time step. If the pressure change exceeds this value in any grid block, the time step is cut back and re-run. This parameter directly affects the simulation stability and run-time.	Real	PSI	No	100.0
SCONVERGE	Saturation convergence tolerance for the implicit saturation solution. This parameter establishes the accuracy to which the grid block saturations are solved for each time step. A low tolerance value (e.g., 0.0001) takes more iterations to achieve and therefore requires more run-time.	Real	Fraction	No	0.001
PCONVERE	Pressure convergence tolerance for the implicit pressure solution. This parameter establishes the accuracy to which the grid block pressures are solved for each time step. A low tolerance value (e.g., 0.01) takes more iterations to achieve and therefore requires more run-time.	Real	PSI	No	0.1

Keyword	Description	Type	Units	Rqd	Default
SOLVER	Selects the solver routine to be used in the solution of the pressure and/or saturation matrixes. The following options are available: **Solver** **No.** **Description** 0 Gauss Elimination 1 Conjugate gradient with pre-conditioner 2 Conjugate gradient with Jacobi pre-conditioner 3 LAIPE Sparse Matrix Solver 4 IMSL Sparse Solver without Iterative Refinement 5 IMSL Sparse Solver with Iterative Refinement 6 IMSL Banded Solver without Iterative Refinement 7 IMSL Banded Solver with Iterative Refinement 8 TOUGH2 Bi-Conjugate Gradient Squared Solver 9 TOUGH2 Bi-Conjugate Gradient Solver 10 TOUGH2 Generalized Minimum Residual Solver	Integer	None	No	8
RESTART	Indicates the simulation time step no. from which to begin a restart run. If a run is not being restarted, this value should be set to 0. If entered as –1, the simulator will read the available restart records from the restart file (*.RST) and display the time step no. and simulation time to the output file (*.OUT). **Notes**: For restart runs, the user should specify the same **STARTDATE** as the original run. When a simulation restart is specified, the simulator will attempt to read a new data interrupt beginning at the time of the restart. Therefore, the data interrupt files (*.REC and *.INP) must be modified to a contain data beginning with the time of the restart. When **RESTART** is used in conjunction with **RSTFREQ**, the simulator will read the restart record at begin the simulation from that point. Once it begins to write the new restart records to the restart file (*.RST), the prior existing restart records are over-written with the new records.	Integer	None	No	0
RSTFREQ	Specifies the frequency (in time steps) at which the restart records are written to the restart file (*.RST). If a value greater than 0 is specified, the simulator will also write a restart record at the end of the simulation run. If no restart records are to be written, the value should be specified as 0. If a value of –1 is entered, the simulator will only write on restart record at the end of the simulation run. **Notes**: If the **RSTFREQ** is specified as a positive no., or –1, the simulator will create the restart file in the output directory (*.RST) using the simulation file name. To use this restart file, the user must copy it under the new simulation name corresponding to the new restart run in the output directory.	Integer	None	No	0

Keyword	Description	Type	Units	Rqd	Default
NEW_WELLS	Flag that allows the user to specify a new well list when restarting a run. By default, when re-starting a run, the simulator will use the well list from the original run and retain all cumulative production from the original wells. With the **NEW_WELLS** flag, the user can specify a new well list, thereby adding new wells to the original simulation. In this case, cumulative production from the prior run is lost.	Flag	None	No	False
FLIPIT	A value of 1 is used to indicate that data contained in the MS Excel input file is flipped in the X and Y directions. In MS Excel, the limiting no. of columns (normally the X-direction) is 256. In order to get the input data in the spreadsheet for the 3M Project (369 by 137), the X and Y locations must be flipped. In either event, the (1,1) grid block always starts in the upper left corner of the sheet.	Integer	None	No	0
QGMIN	Minimum gas rate or economic limit by well on a global basis. Once any producing well reaches this limit, it is shut-in by the simulator. The minimum gas rate is not checked by the simulator until the cumulative time for the simulation run is greater than the **RATE_LIMIT_TIME**.	Real	MCF/D	No	0
RATE_LIMIT_TIME	Minimum cumulative simulation time before the simulator will check producing well rates against the minimum gas rate **QGMIN**. Specifying the rate time limit allows for wells which initially do not produce gas upon de-watering, and should not be shut-in as uneconomic.	Real	Days	No	None
VENT_SQ	Minimum gas saturation which must be present in a grid block to allowing the use of the gas vent well type code (12). This option is used to prevent modeled vent wells from producing excessive water volumes at high water saturations.	Real	None	No	0.5
ASHCON	Average ash content of the coal.	Real	Fraction	No	0
SPGCOAL	Average specific gravity of the coal relative to water (62.428 lb/ft^3).	Real	None	No	None
CPORE	Pore volume compressibility of the coal on a global basis. Set **CPORE** to -999 to use the 2D-array input worksheet method to change the values by grid block. $C_{pore} = d \ln \phi / d P$	Real	psi^{-1}	Yes	None
KEXP	Permeability exponent used in the relationship between permeability and porosity: $k/k_{initial} = [\phi/\phi_{initial}]^{KEXP}$	Real	None	No	0
SALINITY	Salinity of the water. Used in PVT calculations.	Real	PPM	Yes	None
SPGAS	Specific gravity of the gas relative to 28.96 g/mole. Used in PVT calculations.	Real	None	Yes	None
CO2	Fraction of carbon dioxide in the gas stream. Used in PVT calculations.	Real	Fraction	No	0
N2	Fraction of nitrogen in the gas stream. Used in PVT calculations.	Real	Fraction	No	0
H2S	Fraction of hydrogen sulfide in the gas stream. Used in PVT calculations.	Real	Fraction	No	0
TEMPMIN	Minimum temperature at which gas and water properties are calculated in the PVT tables. This value should represent the minimum reservoir temperature observed in the simulation.	Real	°F	Yes	None
TEMPMAX	Maximum temperature at which gas and water properties are calculated in the PVT tables. This value should represent the minimum reservoir temperature observed in the simulation.	Real	°F	Yes	None

Keyword	Description	Type	Units	Rqd	Default
PMAX	Minimum pressure at which gas and water properties are calculated in the PVT tables. This value should represent the maximum reservoir temperature observed in the simulation.	Real	PSI	Yes	None
PMIN		Real			
TINCRMNT	Temperature increment between **TEMPMIN** and **TEMPMAX** at which PVT properties are calculated in the PVT tables. Normally 5 or 10 degrees.	Real	°F	Yes	None
PINCRMNT	Pressure increment between zero and **PMAX** at which PVT properties are calculated in the PVT tables. Normally 25 or 50 psi.	Real		Yes	None
KRTABLES	Number of relative permeability tables used in the simulation.	Integer	None	Yes	None
CNTRCOUNT	Number of gathering centers used in the simulation.	Integer	None	Yes	None
SUBSET	Flag to indicate that a subset of the entire simulation grid is to run. Either **SUBSET** or **NOSUBSET** is required.	Flag	None	No	No
NOSUBSET	Flag to turn off the **SUBSET** feature (i.e., full grid simulation).	Flag	None	No	None
I_MIN	Minimum I-direction address of a **SUBSET** simulation.	Integer	None	No	None
I_MAX	Maximum I-direction address of a **SUBSET** simulation.	Integer	None	No	None
J_MIN	Minimum J-direction address of a **SUBSET** simulation.	Integer	None	No	None
J_MAX	Maximum J-direction address of a **SUBSET** simulation.	Integer	None	No	None
STARTDATE	Start of the simulation in "MM/DD/YYYY" format.	Date	None	No	None
TIME	Start time of the simulation in "HH:MM:SS" format.	Time	None	No	None
REBUILD	Flag to indicate if the ASCII input files for the recurrent data (*.INP and *.REC) are to be rebuilt from the MS Access database. On the first run, or after the recurrent data are changed, this flag should be set to update the input files. ASCII files are created from the MS Access file because the simulator can read these files much quicker than Access files. If the recurrent data do not change, there is no need to rebuild the ASCII files for each run.	Flag	None	No	No
SUBPROD	Flag to turn on the sub-production option which extracts only the needed recurrent data records (production data) from a larger data set. This option is used in the 3M CBM Model to create a subset of the recurrent data files (*.REC and *.INP) from the entire 3M recurrent data files when running sub-area simulations. Generally speaking, it is used only one time to create the recurrent files for a sub-area, and then turned off for subsequent runs for that sub-area.	Flag	None	No	No
RECURRENT	Flag to indicate that the recurrent data are to follow in the input file. Currently not used in Version 1.0 of the simulator.	Flag	None	No	None
DATABASE	Flag to indicate that the recurrent data are to be read from the MS Access database or the Recurrent Interrupt Data files (*.REC and *.INP) if they exist.	Flag	None	No	None

Appendix D – OUTPUT KEYWORDS

Table D.1: Output Data Control Keywords

Keyword	Description	Type	Units	Rqrd	Default
OUTPUTON	Flag to indicate that data output (well data and array data) will be written to the output files. This flag acts as the main output switch.	Flag	None	No	No
ARRAYFREQ	The time frequency, in days, at which the array data are written to binary array output files (*.ARR). A frequency of 0 means that the arrays are not written.	Integer	Days	No	0
GC_FREQ	The time frequency, in days, at which the well production, injection, and pressure data are written to gathering center output files (*_CEN.CSV). a frequency of the 0 means that the arrays are not written.	Integer	Days	No	No
WELLRPT	Flag to indicate that the well output report within the simulation output file is turned on.	Flag	None	No	No
ASCII	Flag to indicate that the array output files are to be written in ASCII format during run-time. These files may be read with a text editor.	Flag	None	No	No
BINARY	Flag to indicate that the array output files are in binary format. These files are used to generate MS Excel CSV formatted output files with the **CSV** keyword option.	Flag	None	No	No
CSV	Flag to indicate that well output data will be read from the binary files and written to CSV files at the end of the run. This option, used in conjunction with the BINARY option to create ASCII output files at the end of the run improves run-times over use of the ASCII option. The CSV files are named as follows: **Production/Pressure Output Files From Well Data:** <input file>.CSV: Well output <input file>_CEN.CSV: Gathering center output <input file>_TOT.CSV: Totals output **Array Output Files:** <input file>_PR.CSV: Pressure array <input file>_SW.CSV: Water saturation array <input file>_SG.CSV: Water saturation array <input file>_KX.CSV: X-direction permeability array <input file>_KY.CSV: Y-direction permeability array <input file>_PHI.CSV: Porosity array <input file>_GC.CSV: Gas Content array	Flag	None	No	No
CALC_PAVG	Flag to turn on the option to calculate an average reservoir pressure for each well. The average reservoir pressure for each well is calculated as the 9-block, bulk volume weighted average grid block pressure for blocks surrounding the well.	Flag	None	No	No
ECHO_OFF	Flag to turn off the simulation input data which is echoed back at the top of the simulation output file (*.OUT). Using this option minimizes the size of the output file, but saves only a small amount of run-time.	Flag	None	No	No

Keyword	Description	Type	Units	Rqrd	Default
SPRSS_MSG	Flag to suppress all simulator output messages to the output file (*.OUT). This option is used to save disk space and to increase run-time performance.	Flag	None	No	No
KXMAP	Flag to indicate that the x-direction permeability array will be written. The file name is <input file>_KX.ARR	Flag	None	No	No
KYMAP	Flag to indicate that the y-direction permeability array will be written. The file name is <input file>_KY.ARR	Flag	None	No	No
PMAP	Flag to indicate that the pressure array will be written. The file name is <input file>_PR.ARR	Flag	None	No	No
SWMAP	Flag to indicate that the water saturation map will be written. The file name is <input file>_SW.ARR	Flag	None	No	No
SGMAP	Flag to indicate that the gas saturation map will be written. The file name is <input file>_SG.ARR	Flag	None	No	No
GCMAP	Flag to indicate that the gas content map will be written. The file name is <input file>_GC.ARR	Flag	None	No	No
PHIMAP	Flag to indicate that the porosity map will be written. The file name is <input file>_PHI.ARR	Flag	None	No	No
PRINT_PVT	Flag to indicate that the PVT output file (*.PVT) will be written. This file contains the PVT data (formation volume factor, density, and viscosity) for both gas and water over the user-specified pressure and temperature ranges.	Flag	None	No	No

Appendix E – EXAMPLE SIMULATION RUN

Example Simulation Run

This appendix contains specific instruction on how to make a simulation run from Area A (**Case 26A-128**) of the 3M Project, from setting up a project area, to running the simulation, and finally to post-processing. All files used in this example are contained on the 3M Project CD as described on the **List of Included Files**.

Project Area Set Up

1. On the computer's hard drive, use the Windows Explorer or the DOS Command Prompt to establish a new directory called **C:\ AREA A**. Under this directory, also created a subdirectory called **C:\AREA A\Output**.

   Note: The **C:** prompt can refer to any designated hard drive on the PC.

2. Copy the **Area A** input files (**26A-128.XLS**, **26A-128.INP**, and **26A-128.REC**) from the **\3M Simulation Files\Area A** directory on the 3M Project CD to **C:\AREA A** directory on the hard drive.

3. Copy **MASTER POST-PROCESSOR.XLS** from the **\Post-Processing Files** directory on the 3M Project CD to **C:\AREA A\Output** directory on the hard drive.

4. Copy the **3M PRESSURE DATA.XLS** from the **\Post-Processing Files** directory on the 3M Project CD to the **C:\AREA A** directory on the hard drive.

5. Copy the all of the support files (*.DLL) from the **\Support** directory of the 3M Project CD to the **C:\AREA A** directory on the hard disk. These files are needed to run the simulator and must be in the same directory as the executable file.

E.1.1 Running the Simulation

This example assumes that the user will run 3M Project Case 26A-128 as contained on the 3M Project CD. However, at this point, the user could modify the existing files as desired before execution.

1. Open a Windows DOS or Command Prompt.
2. Change into the **C:\AREA A** directory.
3. At the DOS prompt, type: **3M90x108 26A-128 C:\3M\Output\26A-128**

The simulator will start to load the input files (**Fig. E.1**).

```
C:\3m\26A>3m90x108 26a-128 c:\3m\26a\output\26a-128

3M CBM Model Ver 1.0...by Questa Engineering, November 2000

 Input File:  26a-128
 Output File: c:\3m\26a\output\26a-128

 Loading data........
```

Figure E.1 – Loading Data for Simulation Run for Case 26a-128

After loading the input files, the simulation will begin. The output on the screen will show the time steps, cumulative time, production rates, incremental material balance errors, and the CPU run-time as show in **Fig. E.2**.

```
Writing initial output file...
 Done

 Writing restart data...
 Done

 Input File:  26a-128
 Output File: c:\3m\26a\output\26a-128

 Begin simulation:

Time    Cum      Gas      Water    Cum    Cum       Avg     Avg                          CPU
Step    Time     Rate     Rate     Gas    Water     Press   Water   Water    Gas       Time
 No.   (days)   (Mcfd)   (bwd)  (MMcf)   (Mbw)     (psi)    Sat.    IMBE    IMBE      (sec)
----   ------   ------   ------ ------ ------    ------   -----   -----   -----     -----
   0      0.0       0.       0.      0.      0.   588.26   0.742   0.000   0.000      0.00
   1      0.1       0.     948.      0.      0.   588.26   0.742  -0.461  -1.000      1.93
   2      0.2       0.     948.      0.      0.   588.26   0.742  -0.016  -1.000      2.93
   3      0.5       0.     948.      0.      0.   588.26   0.742  -0.018  -1.000      3.89
```

Figure E.2 – Start of Simulation Run for Case 26a-128

At the end of the simulation, the screen will indicate that the run is completed and that the simulator is creating ASCII files for output.

E.1.2 Loading Data into the Post-Processing File

Once the simulation run is completed, the MS Excel post-processing spreadsheet can be used to load the input and output data for viewing rates and pressures as a function of time. To load data into the post-processing file for **Case 26A-128**, perform the following steps:

1. Open **MASTER POST-PROCESSOR.XLS**, which should be located in the **C:\AREA A\Output** directory.
2. Go to the **LOAD DATA** worksheet.
3. Following the instructions on the sheet, enter the input file path name as **C:\AREA A** in cell **B3**
4. Enter the input file name as **C:\AREA A\Output** in cell **B4**.
5. Enter the file name **26A-128** for both the input file name and the output file name in cell **B5** and **B6** since the input and output files have the same name from the simulation run.
6. Load the actual production for this case by pressing the **Load Production** button.

7. Load the actual well list by pressing the **Load Well List** button.
8. Load the actual gathering center list by pressing the **Load Gathering Centers** button.
9. Load the actual well pressures by pressing the **Load Pressure** button.
10. The actual well data are sorted by API number upon loading. Press the **Sort by Gathering Center** button to sort the wells by their gathering center.
11. Load the simulated well totals by pressing the **Load Totals** button.
12. Load the simulated well data by pressing the **Load Wells** button.
13. Load the simulated gathering center data by pressing the **Load Gathering** button.
14. Save the file as **26A-128 PP.XLS** so that the original master post-processing file remains unchanged.

E.1.3 Viewing Well, Gathering Center, and Totals Data

The post-processing file allows the user to view gas and water production rate curves by individual wells, gathering centers, and totals for the simulation. In this case, the production plots will show both the actual production history, as well as the forecasted production rates. For individual wells, the post-processing file also displays the simulated flowing bottom-hole pressure and a simulated average reservoir pressure (if the **CALC_PAVG** keyword was specified in the simulation). Where actual pressure data are available, the post-processor will also display the observed shut-in pressures and calculated flowing bottom-hole pressures on the individual well plots.

1. To view the production plot for the gathering centers, go to the **GC Plot** worksheet.
2. The gathering center plot shows both the actual production rates and the simulated production rates in aggregate for the wells in the gathering center. The box in the upper left corner of the plot indicates the actual and simulated cumulative production for the gathering center.
3. All or any individual gathering center plot may be printed with the buttons at the upper left corner.

4. Step forward or backward through the available gathering centers using the buttons in the upper right corner.
5. The well data are currently sorted by gathering centers. To view the production rates, cumulative production, and pressures by individual well, press the **Sort by Well** button on the **Load Data** worksheet to re-sort the data. Then, go to the **Plot Data** worksheet.
6. The **Totals Plot** is not useable in this case because of the addition of the seeps, recharge, and discharge sources terms skews the totals plot for history matching purposes.