THE 3M CBM FINAL REPORT

Volume I: Analysis and Results

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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December 14, 2000

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3M CBM Final Report Transmittal Letter

Dear Ladies and Gentlemen:

Enclosed is the final report on the 3M CBM modeling project. This report summarizes more than a year of work on this project. The report is intended to provide documentation and information of this effort for all interested parties. Because of the great volume of information reviewed and the number of computer simulations performed, detailed information and simulation data are included on a compact disk. That disk also includes an executable version of the simulator as well as many of the input files and results for the final runs.

It was a pleasure preparing this analysis for you, and if you have any questions about this report, please give me a call at (303) 277-1629.

Sincerely,

QUESTA ENGINEERING CORPORATION

Original signed, stamped and dated by the undersigned

Dave O. Cox, Vice President
Colorado Registered Professional Engineer #17831

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1.0. EXECUTIVE SUMMARY

Questa Engineering Corporation ("Questa") has prepared a basin-wide coalbed methane reservoir model of the Colorado portion of the San Juan Basin for the Southern Ute Indian Tribe ("SUIT"), the Colorado Oil and Gas Conservation Commission ("COGCC"), and the US Bureau of Land Management ("BLM"). This model, which is referred to as the 3M CBM MODEL, simulates the effects of production from all existing and proposed Fruitland coal wells in Colorado. The effects of dewatering, gas adsorption and desorption, and historical production are included in the model. The 3M CBM MODEL provides a tool to evaluate the effects of coalbed methane infill drilling and gas seepage at the outcrop, which have become increasingly important topics over the last several years.

The model builds on information from a separate groundwater or hydrologic model covering the entire basin that was prepared by Applied Hydrology Associates ("AHA"). The groundwater model simulates pre-production conditions for the reservoir model, and provides estimates of the amount of groundwater flowing through the Fruitland Coal hydrologic system.

1.1. The 3M CBM MODEL

The size, scale, and detail included in the 3M CBM MODEL extend beyond any previously published CBM model. The 3M CBM MODEL is based on up to 16 years of production data from 1,060 wells, 4,870 pressure measurements from 591 wells, thickness data from 742 wells, and water chemistry data from 572 wells. The project has benefited greatly from industry cooperation, data, financial assistance and peer review.

Because of the size and scope of the input data, existing commercial coalbed methane simulators were considered unsuitable for this project. A completely new model was written, and a public domain executable version of the model is contained with Volume II of this report. Key features of the model include handling 50,000+ gridblocks, thousands of wells, up to 1000 years of modeling, extremely efficient solver algorithms, outcrop boundary conditions, spatial temperature variation, and input and output using spreadsheets and/or databases. The model utilizes the standard Langmuir isotherm to account for gas adsorption in the coal, and also allows for free gas in the cleat system of the coal. The effect of matrix shrinkage as a result of production is included in the model.

A single layer was selected for the model to fit within the cost, time, and data constraints. It was not feasible to prepare a multi-layer model for this project, because the data on individual seams such as layer pressures and layer production that would be necessary to accurately calibrate multiple layers in a multi-layer model are lacking. However, coal thickness information was incorporated in a database by individual seams, to allow for future expansion to a multi-layer model if desired.

The 3M CBM MODEL has been tested against a commercial simulator and has been shown to accurately and efficiently reproduce the results of the commercial program.

Results to date from the 3M CBM MODEL confirm the presence of highly variable reservoir properties throughout the basin. Specific results and inferences from the 3M CBM MODEL include:

1.2. Flow Barriers and Baffles

A number of flow barriers or baffles were known or suspected to be present in the basin based on previous work by numerous investigators and operators. Features that had multiple lines of evidence (differences in initial pressure, water chemistry, water chemistry trends, structural faults, etc.) were included in the 3M CBM MODEL. Other barriers or baffles were introduced based on the absence of water seepage in particular areas. Industry representatives suggested that many additional barriers or baffles may be present in the Fruitland, but did not provide definitive data to support more barriers. The only such features that were directly included in the 3M CBM MODEL were those baffles or barriers that had multiple lines of evidence or incontrovertible reasons for their inclusion.

1.3. Reservoir Properties

Reservoir properties were generally estimated through analysis of historical production from wells. Permeability was estimated from peak gas or water rates, with completion efficiency assumed based on completion type. Porosity was estimated from extrapolation of produced water trends. The initial permeability and porosity estimates obtained for each well were then gridded and contoured to interpolate information between wells. Permeability and porosity were adjusted (within reasonable limits) as necessary to achieve an acceptable history match. Coal thickness and structure were determined from well logs. Adsorption isotherms and gas content data were compiled from public information where available, and through matching performance in some areas where sufficient data were available to allow gas content to be reliably determined.

1.4. High Water Production Wells

Analysis of the largest water producers completed in the Fruitland indicated they have produced much more water and are connected to much more water than could be contained in the Fruitland coal at those locations. Further investigation suggested that the Fruitland Coal and the Pictured Cliffs Formation are in hydraulic communication in some areas through natural fracturing, and that the Pictured Cliffs is the main source of additional water in those areas. The 3M CBM MODEL porosity and formation compressibility were increased in the high water production areas to account for communication with the Pictured Cliffs Formation in those areas..

1.5. Gas Seepage

The 3M CBM MODEL predicts that gas seepage has occurred and will continue to occur in areas where it has already been observed: on the north margin of the basin in the Pine River area and near the South Fork of Texas Creek, and along the west side at Valencia Canyon and Soda Springs. Additional seeps may start along the ridge east of the Pine

River Valley and in other areas to be determined, but most of the seepage in the model occurs near existing seep locations.

There are few direct measurements of seepage volumes, including:

- Gas seepage of 10-25 Mcfd since late 1995 has been measured from a seep collector in Valencia Canyon gap, but it covers an area of less than 2000 ft^2 out of several linear miles of outcrop that are now seeping.
- Seep pyramids installed in the Pine River Valley cover only a few square feet. Amoco (1994) extrapolated volumes measured in seep pyramids in the Pine River to estimate seepage there at 200 Mcfd in mid-1994.
- Soil gas measurements in various locations. The BLM has been measuring soil gas at numerous locations over time. In addition, Dr. Phil Bennett of the University of Texas at Austin measured methane flux at selected points in the Pine River Valley.

Based on the above information, and comparison to other known seeps outside the San Juan Basin, gas seepage from the basin as of early 1995 is estimated to have increased by 0.5 to 2 MMcfd over predevelopment levels.

Areas with significant gas seepage include the following: Pine River, Texas Creek, Carbon Junction, Ridges Basin (Basin Creek), Soda Springs and Valencia Canyon Gap. The increasing numbers of trees that are newly dead or dying indicates seepage is expanding laterally along the strike of the Fruitland Formation in these areas. Soil gas testing indicates elevated or increasing levels of seepage in other areas as well. Accordingly, gas seepage from the basin as of early 2000 is estimated to have increased by at least 3 MMcfd, and possibly as much as 10 MMcfd over predevelopment levels.

The 3M CBM MODEL data inputs were adjusted to reflect the observed degree of communication between the basin and the outcrop. In the initial runs, the outcrop was modeled with perfect connection to the basin, which led to simulated gas seepage 10 to 100 times higher than observed levels of seepage. These results indicated that a perfect connection does not exist in nature; otherwise, there would be much higher seepage levels even in areas where no gas seepage has been observed.

This restricted connection may be related to the structural hinge line between the coals in the basin and the outcrop, stratigraphic changes in the coal, coalbed geometry, capillary pressure or relative permeability effects, multi-layer effects, high absorptive capacity in the shallow coals, or other unidentified causes. By reducing the simulated connection from the outcrop to the basin, the model has been calibrated to match observed gas seepage locations and rates.

1.6. Infill Drilling

Results of model runs with infill wells indicate that in most cases no significant change in seepage should be expected as a result of infill drilling. The 3M CBM MODEL indicates long-term seepage will actually diminish as a result of infill drilling, because the infill wells will capture part of the gas that would otherwise migrate updip and escape out the Fruitland outcrop as seepage.

2.0. INTRODUCTION

2.1. Background on 3M

The 3M Project is a combined effort of industry and governmental representatives to study the Fruitland Formation in the Colorado portion of the San Juan Basin. The study area encompasses the portions of La Plata and Archuleta counties in southwest Colorado that are underlain by Fruitland coal (see **Figures 1 and 2**). The three M's in the 3M Project stand for **Mapping**, **Modeling**, and **Monitoring**. The 3M Project was designed as a long-term project to provide tools to develop a more comprehensive understanding of gas and water production from the Fruitland Formation and potential impacts at the Fruitland Formation outcrop. This report covers the coalbed methane simulation modeling that was performed as a portion of the **Modeling** part of the 3M Project.

The 3M Project was originally conceived in 1998. The Southern Ute Indian Tribe ("SUIT"), the Colorado Oil and Gas Conservation Commission ("COGCC") and the US Bureau of Land Management ("BLM") provided funding and support for the project. Following approval by the State of Colorado's Joint Budget Committee, the initial meeting for the 3M Project was held on Feb. 2, 1999. Representatives of the various parties attended that meeting, along with industry representatives and consultants.

The Mapping portion of the 3M Project was conducted by the Colorado Geological Survey and is reported on in their Open File Report (Wray, 2000). The SUIT and the COGCC are handling the Monitoring portion of the 3M Project, and their efforts to install additional monitor wells are ongoing.

In addition to the 3M CBM MODEL, Applied Hydrology Associates ("AHA") prepared a separate hydrologic or groundwater model (the AHA HYDROLOGIC MODEL, as documented in their report, Applied Hydrology Associates, 2000). Coal beds in the Fruitland Formation play a number of roles in the San Juan Basin. The coal is the source of the CBM, and is also the reservoir rock unit that is produced by the CBM wells. In addition, the Fruitland Formation is also one of the regional aquifers in the San Juan Basin. The hydrologic model, which was prepared using standard groundwater simulation programs, was designed to cover the entire San Juan Basin. The AHA HYDROLOGIC MODEL provided groundwater recharge and discharge information to establish boundary conditions for the 3M CBM MODEL. The hydrologic model also incorporated groundwater travel times and water geochemistry information to delineate the properties of the Fruitland aquifer.

2.2. The Purpose of the 3M CBM MODEL

The original purpose of the 3M CBM MODEL was to develop a tool for a more complete understanding of gas and water movement in the Fruitland Formation, and to aid in assessing potential impacts of gas and water production at the Fruitland outcrop in the Colorado portion of the San Juan Basin. It was also envisioned that the model would incorporate information obtained from new monitor wells, and provide a tool that could be periodically updated with additional production and pressure data.

Additional uses for the 3M CBM MODEL were quickly identified. During 1999 and early 2000, sufficient progress had been made on the 3M CBM MODEL to allow the effects of proposed infill drilling to be evaluated. A summary of the results was prepared for the SUIT, COGCC and BLM on May 26, 2000 (Questa Engineering Corporation, 2000 a), and it was followed by a presentation at the June 5, 2000 COGCC hearing regarding increased well density in the Ignacio-Blanco Field (Questa Engineering Corporation, 2000 b, c).

2.3. The 3M Technical Peer Review Team

A key part of the 3M Project has been technical peer review throughout the process. Experienced oil and gas industry personnel have provided information, critiques, and questions that have been invaluable. The data, laboratory work, and geological and engineering interpretations contributed by the 3M Technical Peer Review Team greatly enhanced the final product.

It is not possible to list all the contributions of all the Peer Review Team members. Some of the more noteworthy contributions included (in alphabetical order by company):

- <u>BP Amoco</u> provided geological cross sections near portions of the outcrop, and geological and engineering information on the Pictured Cliffs Formation near the Pine River and surrounding areas.

- <u>Enervest</u> provided monitor well information and test data along the west side of the basin.

- <u>Hallwood</u> provided monitor well information and test data along the west side of the basin.

- <u>J. M. Huber Corp.</u> provided Fruitland monitor well data and Pictured Cliffs information in the north central part of the study area.

- <u>Vastar Resources</u> performed geochemical testing and provided their results and interpretations of this work.

These and other operators also provided pressure data and various other analyses and interpretations that helped to constrain and improve the model.

Some of the requests and comments made by the 3M Technical Peer Review Team members were not included in the final model. In most of these cases, the team member's requests were not included because of differences of opinion or engineering judgment between the modelers and the team members. In other instances, the changes proposed by the team members could not be incorporated because of time, budget or model constraints. The questions and concerns expressed by the 3M Technical Peer Review Team are discussed further in Section 6 of this report.

2.4. Interaction with Applied Hydrology Associates

As previously noted, Applied Hydrology Associates prepared a separate hydrologic model of the basin. The AHA HYDROLOGIC MODEL covers the entire basin, and was used to provide a starting point for the 3M CBM MODEL. The initial pressure and saturation conditions, and the recharge and discharge volumes, were obtained from the AHA HYDROLOGIC MODEL and used as input values for the 3M CBM MODEL.

There are two major differences in the set up of the two models:

- Grid Size: the AHA HYDROLOGIC MODEL used 2640 ft (½ mile) square grid blocks, while the 3M CBM MODEL utilized 880 ft (1/6 mile) square blocks. This difference was primarily a result of the different areas covered – the whole basin for the AHA HYDROLOGIC MODEL, versus the Colorado portion of the basin in the 3M CBM MODEL.

- Fluids Considered: the AHA HYDROLOGIC MODEL considered only water flow, while the 3M CBM MODEL accounted directly for both gas and water flow and storage.

Even though they have different grid spacing, both models utilize the same UTM coordinate system, so that there are exactly 9 blocks in the 3M CBM MODEL for each block in the AHA HYDROLOGIC MODEL. During the course of this project, data files were exchanged several times to make the models basically the same in their characterization of the reservoir or aquifer system. As a result of these data exchanges, the final versions of the AHA HYDROLOGIC MODEL and the 3M CBM MODEL used the same values for common input parameters, including permeability, porosity, water saturation, coal thickness, and coal midpoint structural elevation.

3.0. MODEL DEVELOPMENT

3.1. Basic Theory

Gas presence and transport in coalbed methane ("CBM") reservoirs are governed by fundamental laws of nature. Certain of these laws are similar to or the same as those that govern flow in conventional oil and gas reservoirs, while others are specific to coalbed methane reservoirs. The term "unconventional gas reservoir" is used to describe CBM reservoirs because the reservoir rock is the source rock and because the gas is stored by the process of adsorption rather than just through the effects of pressure (compression). Numerous papers have been written on the subject (for example, Gray, 1987, and Paul, *et al*., 1990).

3.1.1. Gas in Place in the Cleat System

Gas in CBM reservoirs occurs in two ways: as free gas in the cleat or fracture system, and as sorbed gas. The amount of gas stored in the cleats is given by the usual volumetric equation:

$$G_{free} = 43.56\, A\, h\, \phi\, S_g \,\frac{P}{Z\,T}\,\frac{T_b}{P_b}$$

where

G_{free} = Free Gas in Place, Mscf

A = Area, acres

h = Thickness, feet

ϕ = Porosity, decimal

S_g = Gas Saturation, decimal

P = Reservoir Pressure, psia

Z = Gas compressibility factor, decimal

T = Reservoir Temperature, degrees R

P_b = Pressure Measurement Base, psia

T_b = Temperature Measurement Base, degrees R

Equation 1

3.1.2. Langmuir Isotherm

The gas sorbed on the internal coal surfaces has been found to generally follow a formula known as the Langmuir isotherm:

$$G_{sorbed} = \frac{A h \rho\ (1-a)}{1000} \frac{P V_L}{P + P_L}$$

$where$

$G_{sorbed} = Sorbed\ Gas\ in\ Place, Mscf$

$A = Area, acres$

$h = Thickness,\ feet$

$\rho = Coal\ density,\ tons/acre\text{-}\ ft$

$a = Ash\ Content, decimal$

$P = Reservoir\ Pressure,\ psia$

$V_L = Langmuir\ Volume, scf/ton$

$P_L = Langmuir\ Pressure, psia$

Equation 2

A typical CBM isotherm expressed in terms of gas content is shown in **Figure 3**. If the gas content of the coal is equal to the holding capacity of the coal at that pressure, as determined from the isotherm, the coal is considered *saturated*. If the coal contains less gas than would be expected from the isotherm, the coal is said to be *undersaturated*. In general, except for high pressure conventional gas reservoirs, more gas can be stored in coal by adsorption than through compression.

3.1.3. Gas Movement through Coal

In addition to being unconventional in that the gas is sorbed on the coal, the gas transport through the coal follows an unconventional process. First, the gas desorbs from the coal, which is a change in its physical state. Then, the desorbed gas diffuses through the coal matrix and/or through micropores, to reach the cleat, or natural fracture, system. Gas flow through the coal matrix follows Fick’s Law of diffusion, whereby the higher concentration of gas in the matrix diffuses to the lower concentration of gas in the cleats. Most coals have little or no porosity in the conventional sense, so the cleat system provides the chief mechanism for free gas storage as well as fluid movement. Once the gas gets into the cleat system, transport follows Darcy's Law for fluid flow through porous media.

The cleat system is normally described using the Warren and Root concept (1963), wherein the matrix blocks are considered to be rectangular parallelepipeds or cubes, and the fractures are considered to be parallel faces between the matrix blocks. In the most general case, a desorption time parameter is used to describe how rapidly the gas desorbs from the coal into the cleats. Fruitland Formation coals in the San Juan Basin generally have very short desorption times, of a few hours or less, so for this model, it was assumed that the pressure difference between the cleats and the matrix would equilibrate instantaneously. Sensitivity tests with a commercial model confirmed that this was an acceptable assumption.

3.1.4. Capillary Pressure

Another simplification was achieved by ignoring capillary pressure terms. Capillary pressure generally refers to the observation that when continuous free gas and water phases are present, the gas phase and the water phase in the reservoir experience different pressures. If one starts at a gas-water contact where the gas and water are in equilibrium, the two phases have the same pressure. Then, as one moves higher in the reservoir, the pressure in the gas phase changes by a gas gradient (typically 0.001 to 0.05 psi per ft), while the pressure in the water phase changes by the water gradient of 0.43 psi/ft. Thus, there is a difference in the pressures of the two phases that depends on the height above the gas-water contact, as well as the dimensions and properties of the pores or cleats and the water saturation in the reservoir.

The capillary pressure term in CBM reservoirs is usually a few psi to a few tens of psi. Sensitivity runs conducted with a commercial model support the conclusion that capillary pressure could be safely ignored in the 3M CBM MODEL (see VOLUME 2).

3.1.5. Remaining Model Variables: P and S_w

By ignoring capillary pressure and desorption time effects, it was possible to reduce the number of unknowns in each grid block and each time step from four unknowns (water saturation in cleats, gas pressure in cleats, water pressure in cleats, and effective gas pressure or concentration in matrix) to two unknowns (water saturation in cleats, and pressure). In other words, the three pressures that would be needed for the most general analysis were reduced to a single reservoir pressure in each grid block for each time step.

3.2. The Need for a New Model

The 3M CBM MODEL solves the flow equations and gas and water storage equations in each grid block for every time step. Two variables are solved for in each grid block: pressure, and water saturation in the cleat network. Hence, in a full-size model run with over 50,000 gridblocks, a total of 100,000 equations with 100,000 unknowns are solved in each time step. Actually, it is sometimes necessary to solve this series of equations several times during a time step, as the relative permeabilities, fluid properties, or matrix shrinkage effects are recomputed. In some cases, up to 50,000 time steps are needed for a run, so it is clear that extremely efficient numerical solvers and high-speed computers are needed.

At the time of the initial conceptualization of the 3M Project, there were at least four commercially available coalbed methane simulators available on the market. None of the commercial models was specifically set up to handle problems of the scale of the 3M Project. Several factors made the 3M CBM MODEL more difficult than nearly all published coalbed methane simulation problems, including:

- Number of gridblocks, being 50,553 total gridblocks for a 369 by 137 block grid,
- Number of wells, with more than 2000 wells total needed in the infill cases,
- Potential instabilities, with pressures ranging from atmospheric to 1683 psia and difficulties dealing with the outcrop conditions,

- None of the existing models included the Palmer-Mansoori matrix-shrinkage methodology,
- Different boundary conditions were needed to account more rigorously for the outcrop, recharge and seepage effects, and
- The COGCC requested a public domain version of the simulation model for distribution with the data sets.

After considering all of these factors, it was determined that the best way to incorporate these factors would be to write a new simulator, designated as the 3M CBM MODEL. The new simulator primarily uses spreadsheets and databases for input and output, and incorporates highly efficient, newly available, numerical solvers to solve the flow equations.

3.3. Benchmark and Test Results

Insofar as the 3M CBM MODEL is a newly written model, it was tested or benchmarked against an existing commercial model. The purpose of the benchmarking was to confirm that the models compute the same results when presented with the same problem. A total of 80 benchmark or test case runs were prepared to either test the validity of the assumptions of the 3M CBM MODEL, or to compare the two models head-to-head.

The test case runs confirmed that capillary pressure and desorption time could safely be neglected. The 3M CBM MODEL utilizes the Implicit Pressure – Explicit Saturation (or "IMPES") solution algorithm, which is better suited for large-scale simulations that a fully implicit solution algorithm. IMPES is also easier to program and takes less computations per time step than a fully implicit solution methodology. IMPES was found to be suitable for this scale of problem, with relatively large gridblocks (880 ft by 880 ft). For highly detailed cases with small gridblocks, a fully implicit solution algorithm is normally more appropriate.

In all the comparison cases, the 3M CBM MODEL and the commercial model computed virtually identical results. The various benchmark cases covered well spacing, bed dip, well control, initial water saturation, undersaturated coals, spatially varying permeability, as well as different solution methodologies (IMPES versus fully implicit). The results of one of the benchmark runs is shown in **Figure 4**, comparing the 3M CBM MODEL against the commercial model for a case with 100 wells in a dipping reservoir. As shown from this figure, there is basically no difference in the results of the two different models. In this case, cumulative gas production using the 3M CBM MODEL was 0.6% higher than the commercial model computation, and cumulative water production using the 3M CBM MODEL was 0.2% higher than the commercial model computation.

The main difference between the 3M CBM MODEL and the commercial model was found in the run times, especially for large problems. The 3M CBM MODEL typically took about 25-30% as long to run as the commercial model for small problems up to 100 wells. For extremely large problems containing 1,000 wells or more, as needed for the 3M sub-area runs or a whole basin run, the 3M CBM MODEL would require ¼ hr to several hours to run. It was impossible to run the largest benchmark cases with the commercial model on available computers. This is not meant to be a criticism of the commercial model, as it was not designed to handle problems of this magnitude, and the commercial program works well for the problems for which it was designed.

4.0. THE 3M PROJECT DATABASE

4.1. Model Grid

The 3M CBM MODEL was set up in a 369 by 137 block grid, totaling 50,553 gridblocks. Each grid block is a square one sixth of mile long (*i.e.*, 880 ft by 880 ft), covering 17.778 acres, or 1/36 of a section. The various reservoir properties were evaluated in each block using mapping programs with data from wells, outcrop studies, and previous reports. Many of the gridblocks are outside the area where the Fruitland is present, and those 18,660 blocks were therefore made inactive. Thus, a total of 31,893 gridblocks were active in the model.

The model coordinates were selected to use the Colorado-New Mexico state line as the southern boundary of the model. The remaining boundaries were set large enough that a rectangular (Cartesian) grid would encompass the entirety of the Colorado portion of the basin that contains Fruitland coal.

A special UTM transformation of the grid system was obtained from AHA, so that the gridblocks closely overlaid the township and section lines. The 3M CBM MODEL and the AHA HYDROLOGIC MODEL utilized the same global coordinate system, which allowed Questa and AHA to exchange datasets routinely during the course of this analysis.

4.1.1. Fruitland Outcrop

The location of the Fruitland outcrop was obtained from AHA, who digitized available USGS base maps. The outermost active gridblocks were selected based on the contact of the Fruitland with the Pictured Cliffs. In plan view, the width of the Fruitland at the outcrop varies with topography. For the 3M CBM MODEL, the outcrop was assumed to be two gridblocks wide, or a total of 1760 ft.

A variety of boundary conditions were used for outcrop gridblocks in the 3M CBM MODEL. Most of the outcrop gridblocks were considered closed at the surface, to avoid having every outcrop grid block acting as a source or sink term. About every third grid block along the outcrop was left open for possible seepage or inflow, depending on the pressures computed by the 3M CBM MODEL. Other gridblocks were set as recharge blocks where indicated by the AHA HYDROLOGIC MODEL. The recharge points were usually moved into the basin to where the standing water level occurred initially in the 3M CBM MODEL to avoid numerical instabilities associated with low flow rates at very low average water saturations. Finally, a few of the near outcrop gridblocks were set as specified head boundaries to account for the main rivers in the area. The locations of river nodes, and recharge and seepage blocks are shown in **Figure 5**.

4.1.2. Water Recharge and Discharge Locations

The location and amounts of recharge and discharge were initially determined using the AHA HYDROLOGIC MODEL. Recharge in the basin occurs as a result of precipitation (rain or snow) that enters the coal at the outcrops. Precipitation in the San Juan basin generally occurs at higher elevations around the basin margins, and typically totals about 12 inches per year (Applied Hydrology Associates, 2000). Total water recharge in the Colorado portion of the basin is estimated to be about 4,421 bpd (208 acre-feet/year) based on the results of the AHA HYDROLOGIC MODEL. The final 3M CBM MODEL runs utilized 4,007 bwpd (189 acre-feet/year) to obtain match the predevelopment potentiometric surface. The difference between the AHA HYDROLOGIC MODEL results and the 3M CBM MODEL results is caused by different grid block sizes leading to slightly different boundary conditions, and by the fact that the final 3M CBM MODEL stops at the Colorado-New Mexico state line.

Under steady-state conditions, the water that enters an aquifer through recharge exits the aquifer at certain specific discharge points. Discharge in the San Juan Basin occurs into the alluvium at the major river cuts, and at a few scattered springs (Applied Hydrology Associates, 2000).

The major rivers act as constant, specified head boundaries. Historically, there has been discharge from the Fruitland Formation subcrop into alluvium in the river valleys. As the reservoir pressure is reduced by production, these rivers may ultimately supply water to the coal. Constant head conditions were used at the Animas River, the Florida River, the Pine River, the Piedra River, and the San Juan River at its eastern egress from the basin. These five rivers each have sufficient water flowing at all times as to provide a constant water level regardless of whether water is entering or exiting from the Fruitland coal.

4.1.3. CBM Well Locations

The locations of existing and permitted wells were obtained from the COGCC. Locations of potential infill wells were based on the allowed drilling windows for such wells. The location of existing Fruitland CBM wells in the grid is shown in **Figure 6**, while proposed new wells are shown in **Figure 7**. Well locations in the 3M CBM MODEL were assumed to be in the center of the nearest grid block for modeling purposes. As a result of this, the simulated well locations differ slightly from the actual locations.

4.1.4. Subdivision of the Model Grid into Areas A-E

After setting up various cases, it was discovered that run times were excessive with the full model grid, even with the new simulation program that was developed. Accordingly, the model was subdivided into five smaller areas for quicker analysis, as shown on **Figure 8**. The five areas are summarized in **Table 1**:

Table 1: Description of Areas A-E

Area A	The west side of the study area, covering Townships 32, 33 and 34 North (both South and North of the Ute Line) and Ranges 10, 11 and 12 West. Includes blocks I = 1 - 81, J = 30 - 137.
Area B	The northwest portion of the study area, covering Townships 34 North (both South and North of the Ute Line) and 35 North and Ranges 8 and 9 West. Includes blocks I = 82 - 153, J = 1 - 78.
Area C	The northernmost and northeast part of the study area, covering Townships 34 North (both South and North of the Ute Line) and 35 North and Ranges 5, 6 and 7 West. Includes blocks I = 154 - 305, J = 1 - 78.
Area D	The west-central part of the area studied, covering Townships 32 and 33 North and Ranges 8 and 9 West. Includes blocks I = 82 - 153, J = 79 - 137.
Area E	The central part of the area studied, covering Townships 32 and 33 North and Ranges 5, 6 and 7 West. Includes blocks I = 154 - 250, J = 79 - 137.

The area east of Areas C and E was not included in the sub-areas, because there are no producing wells there. This included blocks with I values of 306 - 369 and J values of 1 - 137, and blocks with I values of 82 - 153 and J values of 79 – 137.

4.2. Geological Information

Geological information was obtained from existing literature as well as new information generated in the course of the 3M Project. The main geological factors considered were the structure and coal thickness.

4.2.1. Structure

The structural elevation of the coal was obtained from well logs. Vastar provided an extensive database of digital coal picks for 843 wells, which was supplemented by Questa personnel picking coal intervals from logs on another 62 wells. Additional data were obtained from the SUIT. These data were converted into a database format for easy access and analysis. The structural elevations were then computed based on the weighted-average midpoint of the coal. BP Amoco performed a quality control check, which helped to eliminate erroneous picks on a number of wells. Coal seams were weighted according to their thickness in the averaging. In addition to the well data, outcrop elevations were used to constrain the structure around the basin margins. The data were gridded and contoured using Golden Software's SURFER® program. The resulting map grids were then used in the simulation model. The simulation data set for midpoint structural elevation is shown graphically in **Figure 9**. In general, the highest gridblocks are located around the margins of the basin, with lower elevations in the center of the basin.

4.2.2. Coal Thickness

The coal thickness data were determined using the digital picks for the coal beds and a 2.00 g/cm^3 maximum density cutoff. Very thin or isolated coals were not included in the total net coal thickness if they aggregated less than 3 feet of coal within a 20-ft thick interval. The net coal thickness for the wells in the database averaged 54.7 ft. The thickest coal in the Fruitland section is generally found near the base of the Fruitland Formation, just above the top of the Pictured Cliffs Formation.

The coal thickness used in the 3M CBM MODEL is based on “as received” conditions, without correction for moisture or ash content. Because of this, the isotherm that was applied was also an “as received” isotherm.

In all, thickness values from 1,067 wells were used for mapping. The data were gridded and contoured using Golden Software’s SURFER® program. The resulting map grids were then used in the simulation model. The simulation data set for coal thickness is shown graphically in **Figure 10**. In general, the thickest coal (up to 125 ft thick) is found in the western part of the model area and the coal thickness declines toward the east. There is little well control in the Archuleta County area, so the extrapolated thickness in that area is subject to error.

4.3. Engineering Information

Engineering information was obtained from public records and through data contributed by operators in the basin.

4.3.1. Pressure

Initial (pre-1985) pressure data points were available from 65 wells or coreholes for this analysis. In addition to these data, ten other potentiometric elevations were selected based on the presence of rivers or historical springs that are considered representative of pre-development water levels. Pressure data were available from 32 wells between 1985 and 1989, 81 wells between 1990 and 1994, and 364 wells between 1994 and 1999. These totals include more than 400 pressure points obtained mostly from operators in 1999 as a result of the COGCC request for information.

Multiple data points were measured on many wells, so that overall, a total of 8,063 pressure points were used to calibrate the 3M CBM MODEL. Sheer numbers are somewhat misleading, in that 5 pressure observation wells collectively accounted for 7,332 of the total pressure measurements. These wells are summarized in **Table 2**:

Table 2: Pressure Information Summary

Measurement Location	No. of Pressure Measurements
Pole Barn Monitor	1,863
Burlington POW#1, Sec. 11, T32N, R11W	1,594
Burlington POW#2, Sec. 13, T32N, R11W	1,587
Gurr Well	1,528
Burlington POW#17, Sec. 9, T32N, R11W	760
SUBTOTAL, MONITOR WELLS	**7,332**
7 wells with 6 to 26 measurements each	89
96 wells with 2 to 5 measurements each	134
508 wells with 1 measurement each	508
TOTAL, ALL MEASUREMENTS	**8,063**

The initial pressure data were converted to an equivalent potentiometric elevation (**Figure 11**) for comparison to the AHA HYDROLOGIC MODEL and for comparison to simulated results. The potentiometric elevation is the elevation to which water would rise in a non-producing well. Water from rainfall or snowmelt enters the Fruitland Formation at higher potentiometric elevations around the higher topographic elevations on the outcrop, and exits the basin at lower potentiometric (and outcrop topographic) elevations at the river cuts or springs.

4.3.2. Initial Water Saturation

The Fruitland coal is an aquifer in the area, so the initial water saturation was assumed to be 100% except for those gridblocks that were sufficiently near the outcrop as to be either partially or totally drained.

4.3.3. Production Information

Monthly production data for the wells was obtained through Dec. 1998 from the COGCC. Cumulative production to this date from 1,073 wells totaled 1.66 trillion cubic feet of gas and 244 million barrels of water. The monthly production data were input into a database for quality control checks, and 45 obvious errors were corrected where order of magnitude data entry mistakes had been made. Certain wells had little or no water production reported at the beginning of their production. Because the apparent missing water production constituted only a few million barrels or less out of 244 million barrels reported production, it was decided to leave the reported water production values as stated. In instances where production was reported by lease, the reported production was divided by the number of wells and allocated to the individual wells in the lease for modeling purposes.

Bubble maps of cumulative gas and water production (**Figures 12 and 13**) were prepared to assist in defining production trends and reservoir characteristics across the basin. In general, the largest gas producers are located in the fairway area in the southwest portion of the grid. The high gas production fairway corresponds to a trend of higher permeability and lower porosity in the coal, and the trend extends beyond the model grid into New Mexico. The largest water producers tend to occur in scattered bands in the northern portion of the model area and are largely caused by localized communication with the Pictured Cliffs Formation. This subject is discussed at greater length in Section 4.4.

4.3.4. Permeability

Absolute permeability was estimated based on the maximum observed gas or water production rates from each well and an assumed well efficiency. Permeability of the shallow coal near the outcrop was increased to account for lower stress because of less overburden. Previous work in the Pine River area (Advanced Resources International, Inc., 1994) indicated greater porosity and permeability is present in the shallow coal near the outcrop, and the model was initially set up to reflect higher values for porosity and permeability in those regions.

Permeability values were adjusted during the history matching process to calibrate the model by matching the production and pressure data. The resultant permeability distribution following history matching is shown graphically in **Figure 14**. As seen from this figure, the highest permeability occurs on the extreme margins of the basin and in the

Pine River area. Permeability is generally high in the fairway area and the high water production area in the northwest part of the active grid. Permeability is generally lower in the basin center, the Mesa Mountain area, the Tiffany area, and the eastern part of the model area. The computed permeability in Archuleta County to the east is based on extrapolation of permeability trends, as there has been very little production in Archuleta County.

4.3.5. Porosity

Porosity was estimated based on an extrapolation of the ultimate water production from each well. Porosity of the shallow coal near the outcrop was increased to account for lower stress because of less overburden. Previous work in the Pine River area (Advanced Resources International, Inc., 1994) indicated greater porosity and permeability is present in the shallow coal near the outcrop, and the model was initially set up to reflect higher values for porosity and permeability in those regions.

Porosity values were adjusted during the history matching process to calibrate the model by matching the production and pressure data. The resultant porosity distribution following history matching is shown graphically in **Figure 15**. As seen from this figure, the highest porosity occurs in the north and northwest portion of the grid where higher water production values are observed. The porosity was increased where necessary to account for indicated communication to the underlying Pictured Cliffs. Porosity is generally low in the fairway area and the basin center, the Mesa Mountain area, and the Tiffany area. A porosity of 2% was assumed in most of Archuleta County to the east; this estimate is subject to revision in that there has been very little production in Archuleta County.

4.3.6. Gas Content/Isotherms

Very little gas content or isotherm data are publicly available. Accordingly, a typical adsorption isotherm based on a Langmuir pressure (P_L) of 315 psia and a Langmuir volume (V_L) of 550 scf/ton as received was applied through most of the basin. In the “fairway” portion of the model, the performance of the pressure monitor wells necessitated a change to a Langmuir pressure of 805.5 psia and a Langmuir volume of 500 scf/ton as received. These parameters are consistent with published information in the area (*e.g.*, Resource Enterprises, Inc., 1991).

It is important to note that the isotherms used in the 3M CBM MODEL are "as received" isotherms, because the coal thickness used in the model is based on "as received" conditions, without correction for moisture or ash content.

4.3.7. Relative Permeability

Relative permeability curves define the relative permeability to gas and water in the cleat system for various water saturations. In all, a total of 13 different sets of relative permeability curves were needed for the 3M CBM MODEL. Relative permeability was used as a minor matching variable, while most of the matching was done through adjusting absolute permeability and porosity.

It is important to recognize that the relative permeability relations used in a model depend on the gridding and other assumptions used in the model. In particular, the use of a single layer in the 3M CBM MODEL causes any multilayer effects to become part of the relative permeability curves. Different relative permeability relationships should be used in a multilayer model.

The various relative permeability curves used in the 3M CBM MODEL are shown in **Figures 16 to 18**. A basin average curve is shown in **Figure 16**, along with an average curve for the fairway area, and the average curve used in Area B. These average curves were suitable for the majority of the area being evaluated. Compared to conventional reservoir relative permeability curves, the water relative permeability drops very rapidly as the gas saturation in the cleats increases, while the gas relative permeability increases in a more normal fashion.

A few wells and a few areas required the use of "wet" relative permeability curves, such as those shown in **Figure 17**. The "wet" relative permeability curves have higher water relative permeability than the average curves. Areas requiring “wet” curves were selected based on well performance.

Different relative permeability curves were needed in the shallow areas near the outcrop, as shown in **Figure 18**. Originally, the basin-wide curves were extended to the outcrop, but it was found that gas seepage in very large volumes would have occurred throughout most of the outcrop area. Since this is not the case, the gas relative permeability near the outcrop had to be substantially reduced. Different water relative permeability curves were also used to differentiate “wet outcrop” and “dry outcrop” cases for water flow. The “wet outcrop” relative permeability curves were used for the shallow outcrop blocks that had water saturation of 50% or more, while the “dry outcrop” relative permeability curves were used for shallow outcrop blocks that had water saturation below 50%.

4.3.8. Temperature

A temperature gradient was determined from measured shut-in bottomhole temperatures from 88 wells. These data were considered more representative than log temperatures, which are influenced by cooling from drilling mud circulation. It was found that nearly 90% of the data fell within 10°F of the correlation line (**Figure 19**). Reservoir temperature was also compared to initial pressure, coal midpoint elevation, and other factors, but the best correlation was obtained by computing temperature as a function of depth. The analysis indicates a base temperature of 60°F, and a geothermal gradient of 2.0°F per 100 ft. of depth.

4.3.9. PVT Data

Properties of gas and water were determined using standard industry correlations. Pseudo-critical properties of the gas are determined using the Brown et al. correlation (1948), with the Wichert and Aziz modifications for impurities (1972). The gas was assumed to average 0.65 specific gravity, with 10% carbon dioxide, and no nitrogen or hydrogen sulfide. Obviously, different areas have somewhat different compositions, but the differences have a small impact on gas viscosity or formation volume factor within the ranges evaluated. Gas viscosity was determined using the Carr, *et al.* method (1954), and Z-factors were determined with Hall and Yarborough's method (1971). Water formation volume factors were determined using Dodson and Standing's correlation (1944), and water viscosity was computed from Meehan's correlation. The gas and water properties were considered to be functions of both pressure and temperature.

4.3.10. Matrix Shrinkage Parameters

Matrix shrinkage was input using the Palmer-Mansoori methodology (1996). The shrinkage parameters were determined from history matching. The effect of matrix shrinkage is greatest in the fairway area. Matrix shrinkage in the 3M CBM MODEL was included only in the fairway area.

4.3.11. Baffles and Barriers

The possible presence of barriers or baffles was a frequent discussion topic in the 3M Technical Peer Review Team meetings. For the 3M CBM MODEL, it was decided to only include barriers or baffles whose existence could be conclusively demonstrated either through incontrovertible evidence, or through multiple reasons for inferring their existence. A distinction is made in the model between barriers, which allow absolutely no flow, and baffles, which restrict flow but still allow a portion of the flow to pass through. Various lines of evidence considered in selecting the locations of baffles and barriers included:

- Pressure data and initial potentiometric surface contours
- Water salinity, both as to initial values and changes over time
- Gas-water ratio behavior
- Water geochemistry and age dating
- Structural features and surface lineaments
- Locations and relative volumes of springs

In addition to the barriers and baffles which are considered to exist in the reservoir based on these various lines of evidence, it was also necessary to introduce several baffles in the north and northwest part of the model to account for connections to the Pictured Cliffs

Formation, as discussed at greater length in the following section. The baffles or barriers introduced for this purpose should be considered model artifacts, and do not correspond to actual physical baffles or barriers present in the reservoir.

The location of baffles and barriers in the 3M CBM MODEL is shown in **Figure 20**. The baffles and barriers on the west side are considered to reflect actual baffles and barriers in the reservoir, while the other features are the model artifacts described in the previous paragraph.

4.4. Pictured Cliffs Formation

Analysis of the largest water producers completed in the Fruitland indicated they have produced much more water and are connected to much more water than could be contained in the Fruitland coal at those locations. Further investigation suggested that the Fruitland Coal and the Pictured Cliffs Formation are in hydraulic communication in some areas through natural fracturing, and that the Pictured Cliffs is the main source of additional water in those areas.

Data provided by J. M. Huber Corp. confirmed the presence of natural fractures in the Pictured Cliffs and communication to the Fruitland in parts of Area B. An old water well had been completed in the Pictured Cliffs at a high producing rate. Since the Pictured Cliffs normally has relatively low permeability, the high producing rate indicated the presence of high permeability presumably caused by the natural fractures. Natural fractures were also visually observed with a borehole televiewer. The well initially flowed naturally at the surface. After completion of Fruitland CBM producers in the area, the fluid level in the well dropped substantially, to a level comparable to recent pressures in the Fruitland. J. M. Huber Corp. also prepared thickness maps indicating the presence of up to 80 feet of Pictured Cliffs porosity development in the same areas where the high Fruitland water production has been recorded.

BP Amoco representatives provided similar information regarding the presence of porosity development in the Pictured Cliffs near several high Fruitland water producers in the north-central part of the model in Area C, in and around the Pine River area. Although they did not have data from any water wells completed in the Pictured Cliffs, they presented cross-sections that clearly show the existence of porous Pictured Cliffs sandstone immediately underlying the basal Fruitland coal. In some cases, there was no shale or siltstone at all apparent on the well logs between the Fruitland coal and porous Pictured Cliffs sandstone. Once again, the thickest porosity development in the Pictured Cliffs correlated directly to the Fruitland CBM wells with excessive water production.

The 3M CBM MODEL utilizes a single layer, so it was not possible to directly input the effects of the Pictured Cliffs in the 3M CBM MODEL. A conceptual model for connection between the Fruitland and the Pictured Cliffs is shown in **Figure 21**. Throughout most of the Colorado portion of the basin, the Pictured Cliffs sandstone has low porosity and low permeability. In a few areas, there is localized porosity development. If this occurs where the Pictured Cliffs Formation is in direct connection to the Fruitland, either through fracturing or because of lack of a sealing bed between them, then the connected portion of the Pictured Cliffs effectively acts like a portion of the Fruitland aquifer system in that area (see upper drawing on **Figure 21**). As CBM wells are pumped, the water level will eventually drop below the top of the Pictured Cliffs porosity development (see upper drawing on **Figure 21**), thereby allowing a portion of the water stored in the Pictured Cliffs Formation to drain into a Fruitland CBM well. The maps provided by J. M. Huber and BP Amoco did not indicate a direct connection between the outcrop and porosity development in the Pictured Cliffs Formation, except for possible connections near the South Fork of Texas Creek and along the ridge several miles east of Pine River. Because of this general lack of connection, it is inferred that the Pictured Cliffs Formation water that is in communication with the Fruitland is generally meteoric water that entered through the Fruitland outcrop, instead of being recharge water that entered the Pictured Cliffs Formation directly.

With the concept of the preceding paragraph in mind, the correction for connection to the Pictured Cliffs was performed as follows:

- Thickness not adjusted. The total gas volume present depends on the coal thickness, so it would have been incorrect to adjust the coal thickness.

- Permeability not adjusted. Inasmuch as the permeability computed for these wells was generally based on the total water production rate and the model thickness, the model permeability did not need to be adjusted because it already accounts for the total permeability-thickness associated with the units in hydraulic communication with the wells.

- Porosity Adjustment. The total porosity needed adjustment to allow additional water to be present beyond that included in the coal alone. An initial estimate of the porosity change was determined by computing the combined porosity-feet in the Fruitland coal and the Pictured Cliffs, assuming 2% porosity for the coal and 8% porosity for the Pictured Cliffs, and then dividing by the coal thickness. Porosity was not allowed to exceed 25%. The porosity was then adjusted during history matching, which effectively provides a measure of the degree of connection between the Pictured Cliffs and the Fruitland.

Compressibility Adjustment. The pore volume compressibility was also adjusted as needed for these specific blocks to allow sufficient water to come out of the Pictured Cliffs into the coal. There is little or no gas in the Pictured Cliffs in this area, but gravity drainage and gas movement from the Fruitland into the Pictured Cliffs provide sufficient drive energy that substantial volumes of water can move from the Pictured Cliffs back into the coal.

5.0. MODEL RUNS AND ANALYSIS

5.1. Model Setup and Methodology

5.1.1. Initialization

It was originally conceived that the 3M CBM MODEL would utilize initial pressures and recharge and discharge volumes from the AHA HYDROLOGIC MODEL. After several attempts to make both models run with the same grid spacing, it was determined that it was not feasible for the initial conditions for the 3M CBM MODEL to be determined with the AHA HYDROLOGIC MODEL which covers a much larger area. Accordingly, it was decided to use the 3M CBM MODEL to initialize the pressure conditions for the Colorado portion of the basin, and use the AHA HYDROLOGIC MODEL to determine the recharge volumes. The AHA HYDROLOGIC MODEL was then used to provide independent confirmation of the validity of the 3M CBM MODEL initialization.

5.1.2. Preliminary Subarea History Matches

Prior to making the full area initialization runs, preliminary history matches were prepared for several subareas of 9 to 12 sections each. The purpose of the subarea runs was to confirm the general suitability of the initial reservoir parameters used, especially the basin-wide relative permeability curves and the adsorption isotherm. The subareas considered included a tight area near Mesa Mountain, a fairway area with detailed test information and pressure observation wells, a wet area in the northwest part of the grid, and the Pine River area that had been previously studied. The preliminary subarea runs indicated the general suitability of the reservoir parameters and the 3M CBM MODEL itself, and also indicated the applicable isotherm in the fairway area differs substantially from the isotherm in other parts of the basin. The fairway isotherm was found to be close to the other published information in that area (Resource Enterprises, Inc., 1991). In addition, the preliminary runs in the Pine River Area confirmed that previous characterizations of that area (Advanced Resources International, Inc., 1994) still provided reasonable matches.

5.1.3. History Match Runs

After initialization was completed, history match runs were made. Because of excessive runtimes for the full model, history matching was conducted separately on smaller portions of the full model. The main match parameters were permeability and porosity, although in a few instances it was also necessary to adjust relative permeability curves or add baffles or barriers.

The 3M CBM MODEL uses the actual production data from each well for input. Each well in the model was normally started or driven using water production, with gas production and well pressure being calculated. Once significant gas production was achieved from a well, the simulation was changed to specified gas production for that well, with water production and well pressure being calculated. At late times, wells reached a minimum bottomhole pressure constraint; after that time, the model was driven with a specified producing bottomhole pressure, with gas and water production being calculated. Because the reservoir properties and production characteristics vary from well to well and from time to time for each well, the resultant match is a combination of different production rates or pressures being specified for different wells. In general, most of the wells produced with specified water rates for their first 1-3 years of production, and then utilized specified gas rates until the bottomhole pressure dropped so low that the well could no longer sustain the gas rate.

Matching with the 3M CBM MODEL therefore followed a somewhat different procedure than is commonly used with other types of models. For example, in groundwater modeling, it is commonplace to adjust match parameters to an observed head distribution. In this case, however, the match procedure was more complicated. The producing wells initially act like water wells, with very little gas production. At later times, the wells tend to dry up, leaving gas as the primary producing phase. Furthermore, there is a great deal of production data, but relatively little pressure data available.

Because of these considerations, the match procedure generally used permeability as the first match parameter. Permeability was the main parameter for matching observed production rates. If the assumed permeability was too low, the well or area would not be able to support the observed water or gas production rates. Similarly, if the assumed permeability was too high, there would be insufficient pressure drop in the reservoir and it would not be possible to match observed pressure data.

The produced water volume is the main factor influencing the porosity match. If the assumed porosity value was too low, the well would be unable to produce the observed cumulative water production. If the assumed porosity value was too high, dewatering would be less effective, so that the observed gas production would not be reached. The shape of the gas-water ratio curve thus depends strongly on the porosity.

The relative permeability curves were normally held constant throughout the matching procedure, and were only changed from the base curves around the outcrop, or around wells with high water production rate capacity that would otherwise produce too much gas if the basin average relative permeability curves were used.

The adsorption isotherm was also used as a match parameter in the fairway area. In order to match measured pressures for pressure monitor wells in the fairway, it was necessary to change the Langmuir pressure and Langmuir volume. The revised parameters are consistent with published information in the area (*e.g.*, Resource Enterprises, Inc., 1991), and lead to a generally lower gas content in the fairway area than for the rest of the model.

Match parameters were generally changed first over large areas containing a township or more, with subsequent matches covering a few sections. Finer-scale matching on the scale of a section or less was also needed in the areas where the Pictured Cliffs Formation is in communication with the Fruitland coal.

5.1.4. Forecast Runs

After acceptable history matches were achieved, long-term forecasts were prepared. A time scale of 200 years was used so that the long-term potential for seepage could be assessed. During the forecast runs, any well making less than 10 Mcfd after more than 10 years of production was shut in. Forecast runs were prepared for two cases:

- Base Case, with existing wells and infill locations approved prior to March 31, 2000.
- Infill Case, with all the wells from the Base Case, plus the additional infill wells proposed in Cause No. 112 before the COGCC.

5.2. Model Initialization

After preliminary history matches were obtained for the various areas, recharge amounts around the margins of the basin were adjusted until a good fit to the reported initial pressures was achieved. The following methodology was used to initialize the model:

1. Preliminary heads and initial recharge estimates were obtained from AHA. The first run was prepared with preliminary reservoir parameters estimated from historical gas and water rates for permeability, and extrapolated ultimate water production for porosity.

2. A history match run was made with various reservoir parameters and an initial potentiometric head distribution. The initialization runs were prepared using zero gas and uniform porosity, for more stable model performance. Because water was flowing at essentially steady conditions prior to CBM development, these simplifications were acceptable for the initialization runs.

3. The match parameters were adjusted and the history match was rerun until a visually acceptable match was obtained by calibrating on heads.

4. The initialization runs were then recalculated with the revised reservoir parameters. Typically 200,000 to 2,000,000 days (500 to 5,000 years) were needed to restabilize the system.

5. Steps 2 through 4 were repeated until an acceptable overall match was achieved. At that point, the data were exchanged again with AHA to ensure the two models were functioning in the same manner, and AHA also recalculated the recharge with their model.

Each time a significant new data set or information was provided or eliminated during the project, the initialization had to be completely redone. A typical initialization run would take 2 to 4 hours on a 600-megahertz personal computer, followed by several hours of analysis to determine what to do on the next run.

For initialization purposes, the pressures computed by the 3M CBM MODEL were converted into potentiometric elevations. The pressure data obtained from various public and industry sources were screened and are presented in **Figure 22**. For this map, only the highest pressure for any particular well was used. The computed initial potentiometric surface elevations (**Figure 11**) were then subtracted from the observed levels to identify errors, as shown in **Figure 23**. A generally good match was achieved, considering the different vintages and sources of the data. A regression between the simulated and actual pre-1985 data is shown in **Figure 24**. The correlation coefficient for the regression is $r^2 = 0.75$.

5.3. Subdivision of the Model into Areas A to E

As described earlier in this report, it was found that history match and forecasting run times were so large with the entire model that it became necessary to divide the model into smaller parts to facilitate the analysis. The following five areas were selected for this purpose (**Figure 8**):

- Area A: The west side of the study area
- Area B: The northwest portion of the study area
- Area C: The northernmost and northeast part of the study area
- Area D: The west-central part of the area studied

- Area E: The central part of the area studied

The area to the east of Area E was not included in these areas, because there are no wells there.

The various areas were expanded to have 1 to 1.5 miles of overlap between each area. The overlapping portions of the areas were not included in the summaries. Test runs were made to assure that splitting the model in this fashion was acceptable. It was found that the combined totals and individual well performance in the overlap areas was essentially the same whether a combined model was used, or the model was split in areas as described. This is of course only true for the history match and forecast runs, where the initiation of production from the wells causes pressure gradients and flow that are much larger than the predevelopment levels. The initialization runs still had to be performed for the entire model area.

The analysis and results for each area are described below.

5.4. Area A Results

5.4.1. Area A Description

Area A contains the westernmost part of the model, and includes portions of the outcrop from the state line to the Animas River valley. The West Side Seep area is contained in Area A, as well as many of the fairway wells in the Colorado portion of the basin. Area A also contains the Indian Creek / Bridge Timber Mountain area, which historically had little production because of high water rates.

5.4.2. Area A Matches

The overall match for Area A is contained in **Figure 26**. Actual production from the wells in Area A through Dec. 31, 1998 totaled 995 Bcf of gas and 60.9 million barrels of water. The simulated production through the same period was 996 Bcf of gas and 66.8 million barrels of water. Matches for individual townships in the area are presented in **Figures 31 through 35**. The matches were generally good.

5.4.3. Area A Pressure Monitors

Several pressure observation wells are present in Area A. Excellent matches were obtained at the Ute 32-1 POW #1 (**Figure 52**) and the Ute 32-11 POW #2 (**Figure 53**). The shape of the match to the Ute 17 (**Figure 54**) is very similar to the actual response, but the timing is off by several months. The match to the Southern Ute 10-3 (**Figure 55** is poor, and the trend is also poor. The poor match in this well is probably related to uncertainties in the location of barriers near this well and the properties of those barriers.

5.4.4. Area A Seepage

The estimated seepage with and without infill wells for Area A is shown in **Figure 63**. Seepage on the west side was noticed in early 1995, and grew to significant levels of more than 100 Mcfd by the end of 1995. A sensitivity study indicated the start of seepage and the peak seep volumes were extremely sensitive to the gas relative permeability at the outcrop. The best match for Area A was achieved with a maximum gas relative permeability at the outcrop of 0.02. Higher values for this parameter led to earlier seepage and a higher peak level of seepage, while lower values for this parameter led to later seepage and a lower peak level of seepage. Possible reasons for the low gas relative permeability near the outcrop are discussed in the section on GAS SEEP RESULTS. A single value for the gas relative permeability at the outcrop was used in Area A. This value can be adjusted in future versions of the model to match observed seep locations and volumes more accurately.

The simulation runs indicate seepage in Area A should be expected to increase for the next several years. The projected peak seep rate is about 5 MMcfd. The peak rate is reached in 2011 in the Base Case or 2007 in the Infill Case. Infill wells are expected to reduce seepage in Area A substantially after 2010.

5.5. Area B Results

5.5.1. Area B Description

Area B contains the northwestern part of the model, and includes portions of the outcrop from the Animas River valley to near the South Fork of Texas Creek. Area B contains many of the high volume water producers in the basin, and has generally produced more barrels of water per Mcf of gas than the other areas. The high water production is a consequence of connection to naturally fractured, porous Pictured Cliffs sandstone in this area.

5.5.2. Area B Matches

The overall match for Area B is contained in **Figure 27**. Actual production from the wells in Area B through Dec. 31, 1998 totaled 209 Bcf of gas and 95.6 million barrels of water. The simulated production through the same period was 192 Bcf of gas and 95.4 million barrels of water. Matches for individual townships in the area are presented in **Figures 36 through 39**. The matches were generally good.

5.5.3. Area B Pressure Monitors

Three pressure observation wells are present in Area B. An excellent match was obtained at the Huber-Garcia 1-22 (**Figure 56**). A poorer match was seen for the Marie Shields Gas Unit A 1 (**Figure 57**), where the model underestimated the initial pressure and shows a slightly faster decline response. The underestimation of initial pressure is a consequence of trying to match the initial potentiometric head trends and majority of the values, rather than matching this well exactly. The difference in the rate of pressure decline during 1999 and early 2000 may indicate slightly too much connection in the 3M CBM MODEL with the other wells in this area. The match for the Day V Ranch 1-35 (**Figure 58**) is also poorer. The model shows pressure increasing over time as gas is moving updip, which is not consistent with measured pressures. This is also probably the result of too much connection in the 3M CBM MODEL in this area.

5.5.4. Area B Seepage

The estimated seepage with and without infill wells for Area B is shown in **Figure 64**. Although gas seepage has been reported in the Animas River Valley for many years, it was arguable whether there was a significant increase in seepage in Area B through 1999. To set the model parameters, the seepage was computed for Area B assuming significant increases in seepage might occur as soon as mid-2000. This led to a maximum gas relative permeability at the outcrop of 0.03. If incremental seepage is not observed until some later date, the indicated degree of connection between the basin and the outcrop in Area B would be smaller yet, which would indicate that a smaller maximum gas relative permeability at the outcrop should be used.

The simulation runs indicate seepage in Area B should be expected to increase for several years once significant incremental seepage is observed. The projected peak seep rate is about 1 to 1.5 MMcfd, and would be reached around 2017 to 2020. Infill wells are expected to reduce seepage in Area B substantially after 2015.

An early component of seepage was computed by the model from 1985 through 1992. That computation was the result of the initialization being for the entire model, rather than just for Area B. This early “seepage” is an error introduced by non-equilibrium conditions at the start of the model for Area B, and is not a real phenomenon. (It may be notable that there have been historic seeps reported around the basin rim, which may indicate the near outcrop areas may not have been completely equilibrated prior to CBM development.)

5.6. Area C Results

5.6.1. Area C Description

Area C contains the north central part of the model, and includes portions of the outcrop from the South Fork of Texas Creek to the Piedra River. The Pine River seep area is contained in Area C. Area C contains many high productivity wells, including both high rate water producers and high rate gas producers.

5.6.2. Area C Matches

The overall match for Area C is contained in **Figure 28**. Actual production from the wells in Area C through Dec. 31, 1998 totaled 146 Bcf of gas and 51.7 million barrels of water. The simulated production through the same period was 146 Bcf of gas and 56.7 million barrels of water. Matches for individual townships in the area are presented in **Figures 40 through 43**. The matches were generally good.

5.6.3. Area C Pressure Monitors

Two important pressure observation wells are located in Area C: the Gurr Federal GU 1 (**Figure 59**) and the Pole Barn Monitor (**Figure 60)**. The model starting pressure for both wells was higher than the actual pressure, which may indicate slightly greater permeability is needed in the model between these wells and the spill point in the Pine River Valley. The pressure gauges in both of these wells have been subject to considerable error from time to time through the last several years, and a portion of the discrepancy between measured and simulated pressure trends may be the result of gauge problems. In particular, the period from Aug, through Oct. 1998 on the Gurr Federal GU 1, and the period from Aug. 1994 through Oct. 1995 on the Pole Barn Monitor are obviously incorrect.

5.6.4. Area C Seepage

The estimated seepage with and without infill wells for Area C is shown in **Figure 65**. Seepage in the Pine River area was reported in mid-1993, and it has been one of the more conspicuous gas seep areas since that time. Seepage was reported around the South Fork of Texas Creek not long after it was observed in the Pine River area. These two areas continue to be two of the higher volume seep areas in the basin. The best match for Area C was achieved with a maximum gas relative permeability at the outcrop of 0.03. A single value for the gas relative permeability at the outcrop was used in Area C. This value can be adjusted in future versions of the model to match observed seep locations and volumes more accurately.

The simulation runs indicate that without additional infill drilling, seepage in Area C should be expected to increase perhaps 10% over current levels through 2011, and then begin to decline. If infill wells are drilled in Area C, the projected seepage may increase to about 25% higher than current levels by 2010. Overall, infill wells are expected to have little impact on seepage in Area C.

5.7. Area D Results

5.7.1. Area D Description

Area D covers the west-central part of the model, and has no outcrop blocks. Area D includes some fairway wells on its west side, as well as some lower permeability areas toward Mesa Mountain.

5.7.2. Area D Matches

The overall match for Area D is contained in **Figure 29**. Actual production from the wells in Area D through Dec. 31, 1998 totaled 279 Bcf of gas and 31.0 million barrels of water. The simulated production through the same period was 279 Bcf of gas and 31.3 million barrels of water. Matches for individual townships in the area are presented in **Figures 44 through 47**. The matches were generally good.

5.7.3. Area D Pressure Monitors

There were no pressure observation wells in Area D.

5.7.4. Area D Seepage

Area D is more than five miles from any outcrop. For this reason, no seepage calculations were made for Area D.

5.8. Area E Results

5.8.1. Area E Description

Area E is located in the south-central part of the model, and has no outcrop blocks. includes portions of the outcrop from the state line to the Animas River valley. The Tiffany area is part of Area E.

5.8.2. Area E Matches

The overall match for Area E is contained in **Figure 30**. Actual production from the wells in Area E through Dec. 31, 1998 totaled 47 Bcf of gas and 13.3 million barrels of water. The simulated production through the same period was 47 Bcf of gas and 13.8 million barrels of water. Matches for individual townships in the area are presented in **Figures 48 through 51**. The matches were generally good.

5.8.3. Area E Pressure Monitors

There were no pressure observation wells in Area E.

5.8.4. Area E Seepage

All of the wells in Area E are more than six miles from any outcrop. For this reason, no seepage calculations were made for Area E.

5.9. Summary Results

5.9.1. Overall Results

The overall 3M history match was excellent (**Figure 25**). The aggregate match to cumulative gas production was accurate to within 0.1%, and the match to cumulative water production was accurate to within 5%.

Table 3 compares the simulated results to the volumetric gas and water in place. From this table, it is seen that Area A has the highest gas recovery efficiency through 1998 of 20.1% of the gas in place, while Area C has the highest recovery of water in place at 11.7%. Overall, only 8.6% of the total gas in place and 11.7% of the total water in place in Areas A-E were recovered through 1998.

A similar comparison is given in **Table 4** for the projected recovery with existing wells. From this table, it is seen that Area A has the highest gas and water recovery efficiencies through 2030 of 57.9% of the gas in place and 33.1% of the water in place. The overall recovery efficiencies through 2030 without infill wells are still only 31.1% of the total gas in place and 28.4% of the total water in place in Areas A-E were recovered through 2030.

Table 5 contains projections through year 2030 with existing and infill wells. From this table, it is seen that Area A has the highest gas recovery efficiency through 2030 of 65.8% of the gas in place, while Area D ends up with 35.9% of the water in place. The overall recovery efficiencies through 2030 with infill wells reach 39.2% of the total gas in place and 31.7% of the total water in place in Areas A-E.

Table 3: Simulated Results by Area through 1998

Area	Original Gas-in-Place, Bcf	Original Water-in-Place, MMbbl	Cum Gas Production through 1998, Bcf	Cum Water Production through 1998, MMbbl	Gas Recovery Efficiency through 1998, % OGIP	Water Recovery Efficiency through 1998, % OWIP
A	4,957	528	995	60.9	20.1%	11.5%
B	3,504	757	209	95.6	6.0%	12.6%
C	3,762	543	146	51.7	3.9%	9.5%
D	3,500	190	279	31.3	8.0%	16.5%
E	3,820	153	47	13.8	1.2%	9.0%
Total, Areas A-E	19,542	2,171	1,676	253	8.6%	11.7%

Table 4: Simulated Results by Area through 2030

Area	Original Gas-in-Place, Bcf	Original Water-in-Place, MMbbl	Cum Gas Production through 1998, Bcf	Cum Water Production through 1998, MMbbl	Gas Recovery Efficiency through 2030, % OGIP	Water Recovery Efficiency through 2030, % OWIP
A	4,957	528	2,871	174.4	57.9%	33.1%
B	3,504	757	959	205	27.4%	27.1%
C	3,762	543	565	140.6	15.0%	25.9%
D	3,500	190	1,272	60	36.3%	31.6%
E	3,820	153	419	35.8	11.0%	23.4%
Total, Areas A-E	19,542	2,171	6,086	616	31.1%	28.4%

Table 5: Simulated Results by Area through 2030 with Infill Wells

Area	Original Gas-in-Place, Bcf	Original Water-in-Place, MMbbl	Cum Gas Production through 1998, Bcf	Cum Water Production through 1998, MMbbl	Gas Recovery Efficiency through 2030, % OGIP	Water Recovery Efficiency through 2030, % OWIP
A	4,957	528	3,260	186.6	65.8%	35.4%
B	3,504	757	1,335	227.4	38.1%	30.0%
C	3,762	543	852	161.5	22.6%	29.7%
D	3,500	190	1,532	68.1	43.8%	35.9%
E	3,820	153	676	44.5	17.7%	29.0%
Total, Areas A-E	19,542	2,171	7,655	688	39.2%	31.7%

The change in reservoir pressure over time was obtained by combining the results for Areas A-E together. **Figure 66** shows the initial reservoir pressures used in the 3M CBM MODEL. As expected, the higher pressures correspond to greater depth in the basin. (**Figure 66** contains the same information as the initial potentiometric map presented in **Figure 11**, but on a pressure basis rather than a head basis.) By the year 2000, the model predicts considerable pressure drop has occurred (**Figure 67**), especially in the fairway area. By the year 2030, the pressure in and around the fairway will have dropped to below 200 psi, and the rest of the basin will also have reduced pressures (**Figure 68**).

Maps of water saturation show similar results. Initially, the coal is assumed to be water saturated throughout the basin (**Figure 70**), except at structural locations higher than the flow paths between the recharge areas and the discharge points. By the year 2000 (**Figure 71**), there is considerable gas saturation present in the model, especially in the fairway. The areas with high water saturation in **Figure 71** correspond to areas needing dewatering. Using only current wells in the model, there would still be large parts of the basin left to dewater by year 2030 (**Figure 72**).

Changes in gas content over time clearly show the areas without development. The initial gas content variations (**Figure 74**) correspond to differences in depth, and whether or not a well is in the fairway. By the year 2000, the model shows considerable reduction in gas content in the fairway and around the Pine River area, but less change elsewhere (**Figure 75**). By the year 2030 (**Figure 76**), the fairway area will be largely depleted, but much of the rest of the Colorado portion of the basin would still have relatively high gas contents in the base case without infill wells.

5.9.2. Gas Seepage

The combined total gas seepage computed with the 3M CBM MODEL is shown in **Figure 61**. Overall, the model projects current seepage as of year 2000 at about 5 MMcfd. The model projects seepage will peak at 10 MMcfd, or about twice the current level, around year 2009. Cumulative seepage is computed to have been 4 Bcf through 1999, and is projected to reach more than 100 Bcf by 2030. Long-term seepage to year 2200 is shown in **Figure 62**. Cumulative gas seepage according to the model could reach 380 Bcf by the year 2200.

Seep locations are shown graphically in **Figure 78**, which is a bubble map of projected seepage at Jan. 2000. Larger bubbles indicate the more active seeps, which the model predicts to be located in the Pine River Area and around Valencia Canyon Gap. **Figure 79** shows computed seepage in 2030. A comparison between the two figures indicates additional seeps may occur between Indian Creek and the Animas drainage on the west, and from Pine River to the South Fork of Texas Creek to the north. The actual extent and gas emission from seeps in these areas will depend on the degree of connection between the basin and the outcrop, and the volumes of gas and water produced.

5.9.3. Infill Wells

The 3M CBM MODEL was used to evaluate the impact of infill drilling on gas seepage and production. Infill locations approved prior to Dec. 31, 1999 were assumed to be drilled in Jan. 2000. New infill wells proposed in Cause No. 112 were scheduled at 100 wells per year over a 7 year period beginning in July 2000. This is obviously an oversimplification, but was used to provide an estimate of the maximum changes that might be associated with infill drilling.

Figure 80 shows projected production to 2030 with the infill wells and without the infill wells. The infill wells lead to 1.54 Tcf additional gas production to 2030, which is an increase of 25% over the level without infill wells. The infill wells also lead to almost 73 million barrels of additional water production to 2030, which is an increase of 12% over the level without infill wells.

Figure 69 shows the computed pressure in the Fruitland in year 2030 assuming the infill wells are drilled. As seen from this figure, pressures will be reduced to low levels throughout the majority of the northwest part of the basin, but there would still be higher pressure in the tighter regions around Mesa Mountain, and the undeveloped areas to the east. The increase in gas saturation in the basin in year 2030 as a result of infill drilling can be determined by comparing **Figure 72** (without infill wells) with **Figure 73** (with infill wells). Similarly, the production increase from infill drilling can be seen by comparing the gas content in year 2030 with infill wells (**Figure 77**) versus the case without infill wells (**Figure 76**).

The infill wells are projected to have a mitigating effect on gas seepage. Cumulative seepage through year 2030 is projected to be 11% lower with infill wells than without infill wells (**Figure 61**), and cumulative seepage through year 2200 is projected to be 21% lower with infill wells than without infill wells. The results of the 3M CBM MODEL runs indicate the infill wells will capture part of the gas that would otherwise migrate updip and escape at the outcrop.

6.0. QUESTIONS RAISED BY THE 3M TECHNICAL PEER REVIEW TEAM

Numerous questions or concerns have been expressed by the 3M Technical Peer Review Team during the course of this analysis. This section reviews and addresses the major concerns that were expressed.

6.1. Single Layer v. Multilayer Models

Numerous parties pointed out potential problems with using a single layer model for a system that is known to have multiple layers. It was not feasible to prepare a multilayer model within applicable cost and time constraints. Furthermore, the only data that are available throughout the study area that can be accurately assessed by layer is coal thickness. There are no breakdowns by layer for production, pressure, permeability, porosity, etc.

The main difference between a multilayer model and a single layer model (besides cost and run times) is in the matching procedure. In the single layer approach, the match parameters are a single value of permeability, a single value of porosity, and a single set of relative permeability curves at each location. The effects of connection between layers and different properties in the different layers are handled through the relative permeability relationships. In a multilayer model, a single relative permeability curve is used that may be a laboratory measured curve, and the match parameters are the permeability and porosity of the various layers, and the vertical permeability between the various layers. The multilayer model thus has a greater number of variables that can be adjusted than the single layer model.

A two-layer model would have been helpful for handling the connections to the Pictured Cliffs Formation. However, it was possible to adjust the properties of the single layer to handle this connection, as described in Section 4.4.

The other factor that would be handled differently in a multilayer model than a single layer model is matrix shrinkage. This is discussed in Section 6.5 below.

6.2. Baffles and Barriers

The methodology used in developing the 3M CBM MODEL was to only use baffles or barriers where multiple lines of evidence or incontrovertible evidence existed.

For example, the West Side Seep Area in Area A exemplifies a compelling case with multiple lines of evidence. Years of data gathering and analysis have clearly demonstrated the presence of several baffles and barriers in that area based on extensive pressure data, differences in production response, and water geochemistry changes.

An example of baffles that have essentially incontrovertible evidence is seen in the far southwest corner of the model area. McDermott Arroyo has the lowest Fruitland Formation outcrop elevation of any point on the west side of the model in Colorado. If no baffles were present, virtually all of the water on the west side should spill out in McDermott Arroyo. Instead, more significant historical springs occurred at Soda Springs and at Valencia Canyon Gap, which are at higher topographic elevations than McDermott Arroyo. Thus, it was necessary to place baffles east and north of McDermott Arroyo to keep the water from all spilling out at that location. Baffles in this area would still have been necessary even if the model had been extended into New Mexico, because otherwise the water would try to spill out at the low point where the San Juan River cuts the outcrop on the west side. Thus, the existence of baffles or barriers in this area is considered incontrovertible.

Many additional baffles and barriers were proposed by the 3M Technical Peer Review Team. The majority of the proposed additions fell into three main classes: an outcrop seal, large-scale linear barriers running through the basin, and various local features.

6.2.1. The Proposed Outcrop Seal

Some of the operators had proposed that a barrier or severe restriction to flow was present around the hinge line of the basin, where the dip of the beds changes from steep dips characteristic of the outcrop to shallower dips observed in the middle of the basin. In the 3M CBM MODEL, it was not feasible to apply a complete seal or nearly complete seal around the basin, because it would be inconsistent with the observed predevelopment head distribution, which appears to follow regional gradients that are consistent with steady hydrologic flow through the basin.

However, it was necessary to reduce the outcrop relative permeability to gas in the 3M CBM MODEL to 2 to 3% to reduce gas seepage to observed levels. Although this is not a complete seal, it is a very good baffle. The cases where gas relative permeability in the shallow coal was allowed to reach 10 to 100% showed gas breaking out at high levels all over the outcrop, which is contrary to actual observations.

The exact reasons for reduced gas movement in the shallow coal are not known. Possible explanations include:

1. Faults or structural discontinuities in the coal
2. Reduced permeability associated with greater stress caused by structural alteration in the coal above the hinge line
3. Stratigraphic variations in the coal, whereby certain coal beds may not extend from the basin all the way to the outcrop
4. Relative permeability hysteresis caused by degassing of the shallow coal over geological time
5. Multilayer effects, whereby gas movement on a regional scale may happen in different beds at different locales, and the specific beds that have most of the flow in the basin may be poorly connected to the outcrop

6.2.2. Large-scale Linear Barriers Running Through the Basin

The possibility of large-scale barriers running through the basin was raised. Such barriers would be associated with basement features that have been observed on gravity or aeromagnetic surveys. It was not feasible to incorporate such features in the 3M CBM MODEL, because it would be inconsistent with the observed predevelopment head distribution, which appears to follow regional gradients that are consistent with steady hydrologic flow through the basin.

6.2.3. Local Features

Smaller scale features extending for portions of a mile to several miles in length were proposed by several of the operators. Many such features exist and can be documented based on differences in pressure or performance between adjoining wells. One area with particularly strong evidence is the Mesa Mountain area in the south-central part of the study area. It was not practicable to place all possible baffles or barriers in the model. The evidence for such smaller scale features was usually not sufficient to allow the length, azimuth, and degree of flow restriction to be accurately determined. Accordingly, the smaller scale features were not included in the 3M CBM MODEL which was designed to be a large-scale model.

6.3. Water Age Dates

As part of the 3M Project, produced water samples were dated based on decay of radioactive iodine and/or chlorine isotopes. Many of the samples had indicated ages greater than 20 million years. Other samples had “young” water less than 1 million years in apparent age. If the properties of the Fruitland coal used in the 3M CBM MODEL are correct, there should be groundwater flow through the basin corresponding to meteoric water entry into the formation in the range of 10,000 years or more along the most active flow paths, and up to several million years in age for fairly static areas. The difference between the model results and the apparent ages determined from radionuclide age dating of the waters has not yet been completely explained.

6.4. Pictured Cliffs

The possibility that hydraulic connection to the Pictured Cliffs Formation could account for some of the large water producers was expressed as early as 1994 (Amoco, 1994). The 3M CBM MODEL was initially set up with no connection between the Fruitland coal and the Pictured Cliffs. It was not possible to adequately account for all of the water production without such a connection. In May 2000, representatives of J. M. Huber Corp. presented information (described in Section 4.4) that demonstrated the existence of higher permeability in the Pictured Cliffs in Area B. Later that month, BP Amoco representatives presented similar information regarding Area C. Additional runs with the 3M CBM MODEL indicated the high water production could be adequately accounted for through connection to the Pictured Cliffs in local area.

6.5. Matrix Shrinkage

The 3M CBM MODEL has a provision to compute the effects of matrix shrinkage using the Palmer and Mansoori method (1996). Addition of matrix shrinkage effects increases the model runtime substantially, because additional iterations have to be performed when the porosity and permeability change during a time step due to matrix shrinkage. For this reason, matrix shrinkage was only included in the fairway region in the 3M CBM MODEL. However, matrix shrinkage has much less effect outside the fairway.

Some of the members of the 3M Technical Peer Review Team reported that they had observed the pressure effects of matrix shrinkage outside the fairway. Such effects would be more noticeable in a multilayer model if some of the layers have significantly lower porosity than other layers. In such a case, matrix shrinkage could be important in some layers but not in others. Because the 3M CBM MODEL is a single layer model, such changes effectively lead to slight differences in the permeability, porosity, or relative permeability curves in such areas.

6.6. Scale Effects

The methodology used in calculating permeabilities implicitly assumes the permeability in the vicinity of the well is the same as that at greater distance from the well. He noted that well tests they have conducted in the Mesa Mountain area indicate an effective permeability of 1 to 5 md. Their recent infill wells had nearly virgin pressure, which suggests somewhat lower permeability applies between wells. Thus, Vastar has observed higher permeability near the well than further out in the reservoir, which implies that in that area the permeability depends on the scale considered. This is clearly not the case throughout the entire basin, because otherwise the pressure observation wells would have recorded much less change.

A plausible explanation for permeability scale dependence is that the coal beds may be less continuous or more stratified in the Mesa Mountain area than in other areas. If so, there could be lateral flow restrictions that would cause the permeability to be lower at some distance from the wells.

Another possible explanation is that matrix shrinkage might be causing an improvement in permeability near the wells, at least in some of the coal layers. It should be possible to choose between these explanations once sufficient production and pressure data are available from the infill wells. If matrix shrinkage is causing this difference, the permeability of the infill wells should measurably increase over time.

7.0. CONCLUSIONS & RECOMMENDATIONS

The 3M CBM MODEL has been developed to provide a tool that can be used to evaluate the impact of various factors on gas seepage. In addition, it can be used to evaluate potential infill drilling, alternative production or operation scenarios, or other concepts for CBM production that may arise in the future.

Although this report is entitled the "3M CBM Final Report", it really documents a work in progress. The datasets and parameters used in the 3M CBM MODEL are a framework for future work. As additional production, pressure and monitor data become available, the 3M CBM MODEL can be updated and refined. In addition, smaller scale models can be extracted from the 3M CBM MODEL to evaluate the localized impacts of proposed infill wells that may be very close to the outcrop.

It is important to recognize that the 3M CBM MODEL was developed as a basin-wide type of model, and should not be expected to provide exact reserves or production forecasts for individual wells. As specific wells or areas are modeled more accurately, the 3M CBM MODEL input parameters can be refined to utilize the more detailed reservoir characterization that would be obtained from such an analysis.

The 3M CBM MODEL has already provided many important results, including:

- The 3M CBM MODEL predicts gas seepage would generally have occurred in the areas where gas seeps have actually been observed.

- Long-term gas seepage has been projected. The 3M CBM MODEL indicates under current well spacing and operating conditions, significant levels of gas seepage will persist for a considerable period into the future.

- The effect of proposed infill wells on gas seepage has been quantified. The 3M CBM MODEL indicates infill wells will reduce long-term gas seepage, but will have little impact over the next 10 years.

- Most of the wells with extremely high water production can be explained with the 3M CBM MODEL as resulting from hydraulic connection to the Pictured Cliffs Formation in local areas.

- Several barriers and baffles in the basin have been identified or confirmed.

Recommendations for future analysis include:

- More data measurements near the outcrop are needed to better characterize the shallow environment in the coal. Information from the remaining monitor wells of the 3M Project, continued and/or expanded soil gas vapor tube measurements, and additional seep collectors at strategic seepage locations will provide important calibration data for future versions of the 3M CBM MODEL.

- Additional pressure and production data from producing wells and monitor well pressure data should be incorporated into future versions of the 3M CBM MODEL. Because of the time and cost associated with complete data entry and reanalysis, it will probably be most cost effective to update the historical datasets (pressures and rates) semiannually or annually. Rematching and preparation of new forecasts will only be necessary as dictated by a significant divergence between projected and actual results.

- It would be advantageous to enhance the 3M CBM MODEL at some time in the future. The three most useful improvements are:

    1. Multilayer Capability, for multiple coal or sandstone layers

2. Fully Implicit Solution Algorithm, to allow longer time steps to be feasible
3. Compositional Capability, for analysis of enhanced CBM recovery through nitrogen or carbon dioxide injection

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