COALBED METHANE AND ITS RESERVE ESTIMATION

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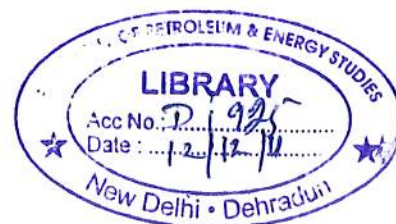
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CERTIFICATE

This is to certify that work contained in this thesis titled "COALBED METHANE AND ITS RESERVE ESTIMATION" has been carried out by Ashish Shukla and Aashutosh A. Asthana under our supervision.

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ABSTRACT

This project is on coal bed methane and its reserve estimation by using F.A.S.T. CBM™ software which focuses on nearly all important aspects of exploration and production of coal bed methane. The objective of the project is to study various methods applied in the estimating the methane in coal bed methane reserve.

The need for exploration of non-conventional source of energy to bridge the ever increasing energy gap is felt all over the globe as the world production of oil and gas is likely to peak within the next twenty years and finding and exploiting new reserves at economic cost is becoming more challenging. Against the backdrop of scenario of dwindling oil reserves base, it becomes important to develop and strengthen the reserve base of gas for sustainable production in the coming decades. To augment the effort of searching out alternative energy sources, exploration and production of coal bed methane (CBM), natural gas hydrates, shale oil and gas and tar sands is being targeted in many countries.

The major project on "Coal bed Methane and Its Reserve Estimation" presents an understanding of reservoir engineering aspects of coal bed methane reserves and deals with the methods for quantifying the amount of gas in them. The main focus of this project is on the generation of coal bed gases, the reservoir engineering aspects of coal bed seams and the estimation of coal bed gas content.

The project deals with the reservoir engineering aspects of reserves of coal bed methane gas. This is useful to understand how the reservoir properties of coal differ from those of conventional gas reservoirs, understand how these properties affect production from coal bed methane reservoirs and evaluate the reserve and production potential of coal bed methane. The project also covers procedures used for determining the gas-in-place volume of coalbed reservoirs. Gas-in-place is the volume of gas stored within a specific bulk reservoir rock volume. Accurate gas-in-place analysis is crucial to reliably evaluating coalbed gas exploration prospects, forecasting the gas production rates of coalbed reservoirs, and evaluating the potential severity of natural gas emissions during coal mining operations. Coalbed reservoir gas-in-place analysis is very complex process. Four physical reservoir parameters are needed to calculate the gas-in-place volume: reservoir or well drainage area, gross reservoir rock thickness (consisting of both coal and other

organic bearing rock type), average reservoir rock density and average in-situ gas conent. The concept and procedures which apply to bituminous coal and other reservoirs dominated by adsorptive capacity rather than compressible storage in porosity. The purpose of this is to develop a clear understanding of the concept of measuring coalbed gas content, estimating the coal bed gas content, sorption, adsorption and estimating the loss of gas, present the most reliable technology for collecting and interpreting gas desorption data, provide practical method for estimating coal bed gas content and explain the advantages and the limitation of the methods. This part of the project provides background information needed to understand the basic theories and practices for determining coal bed gas content.

The project also deals with determination of reserves of coal bed methane by using F.A.S.T. CBM™ software. In case of coal bed methane the proper estimation of gas content is very important. Its analysis and its reserves estimation of coal bed methane reserves is important for determining the feasibility of the project.

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LIST OF FIGURES & TABLES

NOMENCLATURE

V	: volume, scf
A	: drainage area, acres
H	: thickness, ft
D	: depth in meters
R_p	: recovery factor
C_{gi}	: initial adsorbed gas concentration
C_{ga}	: abandonment pressure adsorbed gas concentration.
G_s	: gas content
G_p	: Cumulative gas production
W_p	: Cumulative water production
q_t	: production rate at time t
q_o	: cumulative producing time (t)
r_e	: drainage radius
r_w	: wellbore radius
k	: permeability
S_{wi}	: initial water saturation
B_{gi}	: initial formation volume factor
p_B	: bulk density of coal
W_e	: water influx
P, T	: pressure, Temperature
Pi	: initial pressure
Z_i	: compressibility factor at Pi
T_{sc}	: temperature at standard conditions
P_{sc}	: pressure at standard conditions
G_P	: cumulative gas produced, scf
G	: gas originally adsorbed, scf
G_F	: original free gas, scf
G_A	: gas currently adsorbed, scf
G_R	: remaining free, scf

Φ : porosity, fraction

E_{gi} : gas expansion factor at p, in scf/ bbl

V_m : Langmuir isotherm constant, scf/ ton

M   : slope of curve

A   : exponential decline constant

B   : Langmuir pressure constant, psia^{-1}

C_w : isothermal compressibility of water, psia^{-1}

C_f : isothermal compressibility of the formation, psia

SUBSCRIPTS

i   : initial conditions

p   : production

w   : water

f   :formation

1   : at time $t = t$

0   : at time $t = 0$

A   : adsorbed

R   : remaining

F   : free

E   : drainage

g_a : adsorbed gas at abandonment

g_i : adsorbed gas at initial condition

ABBREVIATIONS

OGIP : Original Gas in Place

CGIP : Current Gas in Place

STB : Stock Tank Barrels

CBM : Coal Bed Methane

CH_4 : Methane Gas

CO_2 : Carbon Dioxide Gas

N_2 : Nitrogen Gas

N_2O : Nitrogen Oxide

H_2S : Hydrogen Sulphide

COOH : Carboxyl Group

-OCH_3 : Methoxyl Group

FC : Fixed Carbon

VM : Volatile Matter

H_2O : Water

Daf : Dry ash free

Bscf : Billion standard cubic feet

Mscf : Million standard cubic feet

1. INTRODUCTION

Oil has been a major source of energy but because of the increasing gap between the demand and supply there is a steady shift towards gas as the major source of energy. Many sources of gas have now been considered that include both the conventional as well as the un- conventional sources.

1.1 Coals: Type, Rank & Coalification

1.1.1 Types of coal

As geological processes apply pressure to dead matter over time, under suitable conditions, it is transformed successively into:

- Peat, considered to be a precursor of coal. It has industrial importance as a fuel in some countries, for example, Ireland and Finland.

- Lignite, also referred to as brown coal, is the lowest rank of coal and used almost exclusively as fuel for steam-electric power generation. Jet is a compact form of lignite that is sometimes polished and has been used as an ornamental stone since the Iron Age.

- Sub-bituminous coal, whose properties range from those of lignite to those of bituminous coal and are used primarily as fuel for steam-electric power generation.

- Bituminous coal, a dense coal, usually black, sometimes dark brown, often with well-defined bands of bright and dull material, used primarily as fuel in steam-electric power generation, with substantial quantities also used for heat and power applications in manufacturing and to make coke.

- Anthracite, the highest rank; a harder, glossy, black coal used primarily for residential and commercial space heating.

- Graphite, technically the highest rank, but difficult to ignite and is not so commonly used as fuel: it is mostly used as pencil lead and, when powdered, as a lubricant.

The classification of coal is generally based on the content of volatiles. However, the exact classification varies between countries. According to the German classification, coal is classified as follows:

Table 1-Classification of Coal

Name	Volatiles%	C Carbon %	H Hydrogen %	O Oxygen %	S Sulphur %	Heat Content kJ/kg
Braunkohle (Lignite)	45-65	60-75	6.0-5.8	34-17	0.5-3.0	< 28470
Flammkohle (Flame Coal)	40-45	75-82	6.0-5.8	>9.8	~1	< 32870
Gasflammkohle (Gas Flame Coal)	35-40	82-85	5.8-5.6	9.8-7.3	~1	< 33910
Gaskohle (Gas Coal)	28-35	85-87.5	5.6-5.0	7.3-4.5	~1	< 34960
Fettkohle (Fat Coal)	19-28	87.5-89.5	5.0-4.5	4.5-3.2	~1	< 35380
Esskohle (Forge Coal)	14-19	89.5-90.5	4.5-4.0	3.2-2.8	~1	35380
Magerkohle (Non Baking Coal)	10-14	90.5-91.5	4.0-3.75	2.8-3.5	~1	< 35380
Anthrazit (Anthracite)	7-12	>91.5	<3.75	<2.5	~1	<35300

1.1.2 Classification and Rank of Coal

The kinds of coal, in increasing order of alteration, are lignite (brown coal— immature), sub-bituminous, bituminous, and anthracite (mature). Coal starts off as peat. After a considerable amount of time, heat, and burial pressure, it is metamorphosed from peat to lignite. Lignite is considered to be "immature" coal at this stage of development because it is still somewhat light in color and it remains soft.

Figure 1-Classifications and Rank of Coal
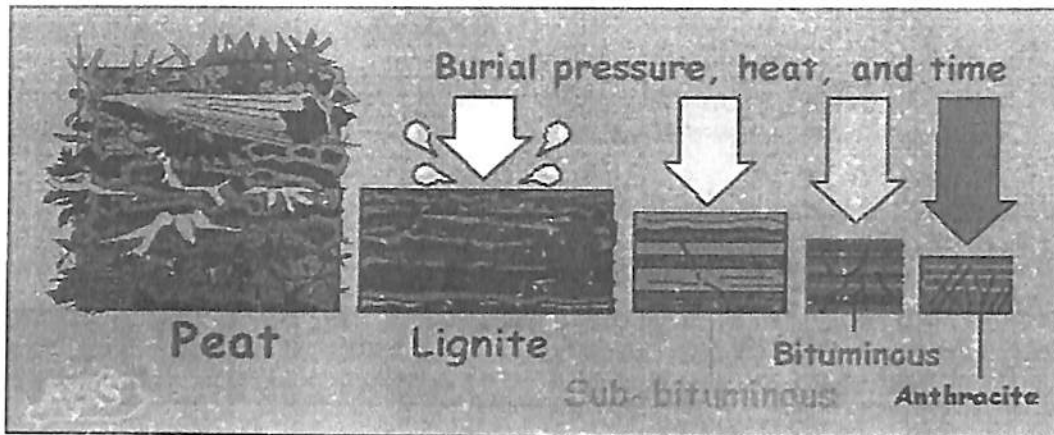
Source: C.F.R.L, 1979: '"Indian Coal Quality Evaluation Data". Vol 2, Jharia Coalfield, Dhanbad

As time passes, lignite increases in maturity by becoming darker and harder and is then classified as **sub-bituminous** coal. As this process of burial and alteration continues, more chemical and physical changes occur and a the coal is classified as **bituminous.** At this point the coal is dark and hard. **Anthracite** is the last of the classifications, and this terminology is used when the coal has reached ultimate maturation. Anthracite coal is very hard and shiny. The degree of alteration (or metamorphism) that occurs as a coal matures from peat to anthracite is referred to as the "rank" of the coal. Low-rank coals include lignite and sub-bituminous coals. These coals have a lower energy content because they have a low carbon content. They are lighter (earthier) and have higher moisture levels. As time. heat, and burial pressure ail increase, the rank does as well. High-rank coals, including bituminous and anthracite coals, contain more carbon than lower-rank coals which results in a much higher energy content. They have a more vitreous (shiny) appearance and lower moisture content then lower-rank coals.

1.1.3 Coalification

Characteristics of Coal Forming Environments

- Coal forms during the accumulated decay of plants (vegetable matter) in the absence of oxygen.

- Coal deposits are commonly formed in environments such as river flood plains, lakes, swamps, deltas and coastal environments, where the water is relatively still and stagnant, with bacteria using up all the oxygen.

The Process of Coalification — Transforming Vegetable Matter into Peat and Coal

- The process of Coalification is measured by the term rank.
- Rank advance is the degree of Coalification.
- The higher the rank the greater the carbon content of the coal.
- Coalification is the process by which plant material has been progressively altered through peat, lignite, sub-bituminous, and bituminous coals to anthracite.

Table 2-Processes of Coalification

Form of coal/process	Description of Process	
Peat, Plant debris, spongy mass, large amounts of water in it's pores)		
↓ diagenesis	Biochemical transformation with mild temperature and pressure	
Lignite (moisture driven out, brown coal)		Rank advance
↓ catagenesis		
Bituminous coal (transformed into harder, darker coal)	Geochemical transformation with deep burial and high temperature and pressure	
↓ metagenesis		
Anthracite (hard,black coal with high carbon content)		

Characteristics of petroleum forming environments

- Ideal conditions for petroleum forming environments are periods of high global sea level, where the continental margins are covered by oceans.
- Large quantities of sediment settle to the bottom along with dead marine organisms.
- Layers of sediment cover the organisms over a period of thousands to millions of years.
- The marine organisms eventually decay into simpler organic compounds.
- Heat and pressure transform the compounds into petroleum.

The maturation of petroleum - diagenesis, catagenesis and metagenesis

An excellent summary of the coalification process is given by Levine. Many physical and chemical changes, governed by biological and geological factors, occur during these processes. Whereas darkening in colour and increase in hardness and compactness are the main physical changes, loss in moisture and volatile contents, and increase in carbon content are the main chemical changes. Many acids (humic, fatty, tannin, gallic, etc.) and dry and wet gases (CH_4, CO_2, N_2, N_2O, H_2S, ethane, propane, butane, etc.) are formed during decomposition of the organic matter. All the changes brought about are attributable to the release of –COOH (carboxyl), >C=O (carbonyl), -OH (hydroxyl) and -OCH$_3$ (methoxyl) functional groups from the organic compounds which cause the decomposition of vegetal source matter.

Biochemical stage of Coalification begins with the accumulation of vegetal matter and terminating at the sub-bituminous stage of coal formation, leads to the formation of a wide range of degradational products- the organo-petrographic entities of coal (termed "macerals") by the partial oxidation and hydrolytic decomposition of dead vegetal matter accumulated in water-saturated wet lands (basins/grabens) by micro-organisms (fungi, aerobic bacteria, insects, etc.). Further decomposition by anaerobic bacteria extracts oxygen from organic molecules of vegetal matter and results in high concentration of hydrogen. Part of this hydrogen is released as methane or 'marsh' gas and the rest is absorbed by humic colloids.

During subsequent geochemical stage of coalification, rising temperatures and pressures, due to subsidence of the basin/graben, either by growing thickness of overburden or by tectonic activities, generate hydrocarbons (hydrogen-rich constituents). Thermal cracking of the free lipid hydrocarbon fraction and/or cracking of the kerogen fraction of coal generates methane gas.

1.2 Coal Bed Methane

1.2.1 Generation: Coal Bed Methane

Methane gas is generated during the formation of coal through 'coalification' process of vegetal matter. This can broadly be divided into biochemical and physico-chemical stages of coalification incorporating five successive steps:

- Peatification (anaerobic degradation of organic materials in the peat swamp)
- Humification (formation of dark coloured humic substances by aerobic degradation)
- Bituminization (generation of hydrocarbons with increase in temperature and pressure)
- De-bituminization (thermal degradation of matter and generated hydrocarbons)
- Graphitization (formation of graphite).

Thus, the generation of coal bed methane during coal formation occurs in two ways:

- By metabolic activities of biological agencies (biological process), and
- By thermal crackin \ of hydrogen-rich substances (thermogenic process).

Methane generated at shallow depths (<10 m) and lower-rank stage (sub-bituminous) by the first process (active up to 50° -80° C) is termed 'biogenic' or 'diagenetic methane". Methane generated during this process is about 10% of the total methane generated by subsequent steps of coalification (catagenetic: > 80° -150° C, RQ max > 0.50-2.0% and metagenetic: > 150° -200° C, RQ max > 2.0-4.0%). Though most of the gas generated during early stages of coalification generally escapes into the atmosphere through the exposed peat or due to low hydrostatic pressure, some amount can accumulate under certain specific geologic conditions like rapid subsidence and burial, and thus may get trapped in shallow reservoirs.

Gas produced at greater depths and higher rank stages of the second process, the thermogenic methane, constitutes bulk of the coal bed methane. The gas generation, by this process, begins at vitrinite reflectance (*Mo* max) values of 0.70-0.80%. peaks near the boundary between medium-volatile bituminous and low-volatile bituminous coal stages [Ro max 1.1-1.4% (maximum at 1.2%), temperature 100° -150° C], and declines further with the rise in temperature and reflectance values. Thus, it could reasonably be presumed that the prospect of generation of coal bed methane is more in the regions of high palaeogeothermal gradient as well as in the vicinity-of intrusive bodies.

Although, methane is the major gas component of coal gases; water, carbon dioxide, wet gases and liquid hydrocarbons are also released during coalification. Total amount of methane generated during the coal formation (between Ro max 0.5-2.0%) approximately ranges between 2000 and >5000 Scf/ton. However, part of methane generated is retained in coal beds/seams and is termed 'coal bed methane' (CBM); and the excess above the retention capacity of the coal bed, tends to migrate to the surrounding reservoir rocks (e.g. sandstones). Retention of methane in the coal beds is:

- as 'adsorbed' molecules on internal surfaces or 'absorbed' within the molecular structure of the coal
- as gas molecules held within the matrix porosity (macro- and micro- porosity)
- as free gas within the fracture network
- as gas dissolved in groundwater within the coal bed.

Since methane is generated during coal formation processes, all coals invariably contain methane. However, the gas content of the coal normally increases with (i) rank of the coal, (ii) depth of burial of the coal seams, provided the roof and overburden are impervious to methane and (iii) the thickness of the coal seams. Content of coal bed methane is assessed by several factors, amongst which the rank of the coal is the most important. According to Tang et al. economically important quantities of methane (> 300 Scf/ton) are generated by thermogenic process, since large quantities of gas production are impossible until a certain threshold of thermal maturation is attained. This requirement is met in the high-volatile A bituminous rank at *RQ* max between 0.8 and 1.0%. Investigations, world over, have shown that high rank coals buried at great depths (> 300-1200 m or more) are suitable for coal

bed methane exploration, provided certain other geological and inherited coal seam characteristics are favorable as well.

Generally, gas is more concentrated in geologically active areas, such as folded and faulted regions as well as the surrounding and adjoining areas of the faults. The well-developed cracks and fractures in the coal seams owing to tectonic disturbances provide permeability to coal seams. The permeability of the seam is also related to the cleat system present in coals. The sealing capability and thickness of the seam roof and floor rocks play a significant role in methane-accumulation. The fluvial basins, having higher rate of subsidence accompanied by thermal events and moderate tectonism, are the prospective sites for the exploration of coal bed methane.

The methane-generating capacity of coal is, however, related to the coal macerals. Whereas macerals of the vitrinite and liptinite (or exinite) groups are the greatest contributors of methane gas, the macerals of the inertinite group have relatively little hydrocarbon generating potential, though they have the greatest capacity for storage of methane. Of the exinite groups, the liptinite macerals have the highest gas generating potential.

Besides the cleats and other fracture systems, the mesopore structure of certain macerals (including structured inertinite) significantly enhance the permeability of methane within the coal seams. Therefore, vitrinite-rich coals of higher rank are reasonably the most important sources of coal bed methane for they have more micro-porosity (that is much higher absorbing capacity) than the other two maceral groups. Ash content of the coal also has an influence on the coal bed methane content: lower the ash content; higher is the gas content of the coal seam.

Methane gas sorbed on coal particles can be liberated by desorption of coal seams. The gas pressure in coal seams is released either by dewatering the coal seams or by drilling borewells which facilitate the flow of gas through cracks, joints and fractures. As stated earlier, the amount of methane produced depends on desorption capacity of coals, which varies from coal to coal depending on its physical and chemical properties, especially the type of coal maceral composition. The amount liberated however, may be enhanced by using stimulation techniques as have been in practiced in some other countries. Existing techniques of methane production being expensive, many companies are engaged in developing appropriate technologies for cost-effective production of this gas.

1.2.2 Vitrinite

Vitrinite is one of the primary components of coals and most sedimentary kerogens. Vitrinite is a type of maceral, where "macerals" are organic components of coal analogous to the "minerals" of rocks. Vitrinite has a shiny appearance resembling glass (vitreous). It is derived from the cell-wall material or woody tissue of the plants from which coal was formed. Chemically, it is composed of polymers, cellulose and lignin.

The vitrinite group, which consists of various individual vitrinite *macerals*, is the most common component of coals. It is also abundant in kerogens that are derived from the same biogenic precursors as coals, namely land plants and humic peats. Vitrinite forms diagenetically by the thermal alteration of lignin and cellulose in plant cell walls. It is therefore common in sedimentary rocks that are rich in organic matter, such as shales and marls with a terrigenous origin, or some terrigenous content. Conversely, carbonates, evaporites and well-sorted sandstones have very low vitrinite contents. Vitrinite is absent in pre-Silurian rocks because land plants had not yet evolved.

Vitrinite Reflectance

The study of vitrinite reflectance is a key method for identifying the temperature history of sediments in sedimentary basins. The reflectance of vitrinite was first studied by coal explorationists attempting to diagnose the thermal maturity, or *rank*, of coal beds. More recently, its utility as a tool for the study of sedimentary organic matter metamorphism from kerogens to hydrocarbons has been increasingly exploited. The key attraction of vitrinite reflectance in this context is its sensitivity to temperature ranges that largely correspond to those of hydrocarbon generation (i.e. 60 to 120°C). This means that, with a suitable calibration, vitrinite reflectance can be used as an indicator of maturity in hydrocarbon source rocks. Generally, the onset of oil generation is correlated with a reflectance of 0.5-0.6% and the termination of oil generation with reflectance of 0.85-1.1%.

1.2.3 Permeability of Coal Bed Methane Reservoirs

Almost all the permeability of a coal bed is usually considered to be due to fractures, which in coal are in the form of cleats. The permeability of the coal matrix is negligable by comparison. Coal cleats are of two types: butt cleats and face cleats, which occur at nearly

right angles. The face cleats are continuous and provide paths of higher permeability while butt cleats are non-continuous and end at face cleats. Hence, on a small scale, fluid flow through coal bed methane reservoirs usually follows rectangular paths. The ratio of permeabilities in the face cleat direction over the butt cleat direction may range from 1:1 to 17:1. Because of this anisotropic permeability, drainage areas around coal bed methane wells are often elliptical in shape.

1.2.4 Intrinsic Properties affecting gas production

Gas contained in coal bed methane is mainly methane and trace quantities of ethane, nitrogen, carbon dioxide and few other gases. Intrinsic properties of coal as found in nature determine the amount of gas that can be recovered.

Porosity

Porosity of coal bed reservoirs is usually very small ranging from 0.1 to 10%.

Adsorption Capacity

Adsorption capacity of coal is defined as the volume of gas adsorbed per unit mass of coal usually expressed in SCF {standard cubic feet, the volume at standard pressure and temperature conditions} gas/ton of coal. The capacity to adsorb depends on the rank and quality of coal. The range is usually between 100 to 800 SCF/ton for most coal seams found in the US. Most of the gas in coal beds is in the adsorbed form. When the reservoir is put into production, water in the fracture spaces are drained first. This leads to a reduction of pressure enhancing desorption of gas from the matrix.

Fracture Permeability

As discussed before, the fracture permeability acts as the major channel for the gas to flow. The higher the permeability, higher is the gas production. For most coal seams found in the US the permeability lies in the range of 0.1 to 50 milliDarcies.

The thickness of the formation is directly proportional to the volume of gas produced. Also, the pressure difference between the well block and the sand face should be as high as possible as is the case with any producing reservoir in general.

Other Properties

Other affecting parameters include coal density, initial gas phase concentration, critical gas saturation, irreducible water saturation, relative permeability to water and gas at conditions of $S_w = 1.0$ and $S_g = 1-S_w$ irreducible respectively.

1.3 Reservoirs

1.3.1 Coalbed Gas Reservoirs

In coalbed reservoirs the natural gas is predominantly stored (~98%) as a molecularly adsorbed phase within micropores. A small amount of natural gas (~2%) is stored by a combination of compression within natural fractures and absorption in formation water. Very little natural gas can be stored by compression in coalbed reservoirs because the fracture porosity generally ranges from less than 1% to 5% and is typically more than 90% water saturated at initial reservoir conditions. Coalbed gas reservoirs result from a unique set of geologic processes wherein the coal performs the dual roles of organic source and reservoir for hydrocarbon gases formed as cogenetic products of the natural coalification process. The gas storage capacity of a coalbed reservoir varies as a function of the reservoir temperature and pressure, the coal compositional properties, the micropore structure and its surface properties, and the molecular properties of the adsorbed gas constituents. However, the actual in-situ adsorbed phase gas content is also a complex function of geologic factors which affected the retention of adsorbed phase gas within the reservoir. Thus, an accurate in-situ gas content value cannot be calculated solely from knowledge of physical coal properties but instead must be directly determined through measurements performed on freshly-cut reservoir coal samples. The primary characteristic of coalbed reservoirs which makes them commercially attractive as sources of natural gas is their ability to store extraordinarily high gas-in-place volumes at relatively shallow depths. The

high gas storage capacity is due to the adsorbed phase natural gas having a liquid-like density. For example, the following figure illustrates a comparison of the gas-in-place *per* unit reservoir volume for a typical coalbed gas reservoir in the San Juan Basin, Fruitland Formation compared to that of a conventional sandstone reservoir of 25% porosity and 70% gas saturation.

1.3.2   Coal Is a Source Rock and a Reservoir Rock

The depositional environment and burial history of the coal affect the composition of the gas as well as the gas content, diffusivity, permeability, and gas storage capacity of the coal.

1.3.3   The Gas Storage Mechanism of Coal

Most of the gas in coal reservoirs is adsorbed onto the internal structure of the coal, whereas most of the gas in conventional reservoirs is in a free state within the pore structure of the rock. Because large amounts of gas can be stored at low pressures in coal reservoirs, the reservoir pressure must be drawn down to a very low level to achieve high gas recovery.

1.3.4   The Fracture System of Coal Reservoirs

Coals contain small (typically, several per inch), regularly-spaced, naturally occurring fractures called face cleats and butt cleats. Coal reservoirs also contain larger-scale natural fractures.

1.3.5   Coal Reservoirs Often Require Pumping Water Before Gas Is Produced

Typically, water must be produced continuously from coal seams to reduce reservoir pressure and release the gas. The cost to treat and dispose of produced water can be a critical factor in the economics of a coalbed methane project.

1.3.6   The unique mechanical properties of coal

Coal is relatively compressible compared to the rock in many conventional reservoirs. Thus, the permeability of coal is more stress dependent than most reservoir rocks. The friable, cleated nature of coal affects the success of hydraulic fracturing treatments, and in

certain locations allows for cavitation techniques to dramatically increase production. Because of these and other coal reservoir characteristics, successfully developing a coalbed methane property requires careful evaluation of the geologic and reservoir properties.

1.3.7 Proved Recoverable Coal Reserves

Table 3-Proved Recoverable Coal Reserves at the end of 2006 (teragrams)

Country	Bituminous (including Anthracite)	Sub-Bituminous and Lignite	Total	Share
USA	111,338	135,305	246,643	27.1
Russia	49,088	107,922	157,010	17.3
China	62,200	52,300	114,500	12.6
India	90,085	2,360	92,445	10.2
Australia	38,600	39,900	78,500	8.6
South Africa	48,750	-	48,750	5.4
Ukraine	16,274	17,879	34,153	3.8
Kazakhstan	28,151	3,128	31,279	3.4
Poland	14,000	-	14,000	1.5
Brazil	-	10,113	10,113	1.1
Germany	183	6,556	6,739	0.7
Colombia	6,230	381	6,611	0.7
Canada	3,471	3,107	6,578	0.7
Czech Republic	2,094	3,458	5,552	0.6
Indonesia	740	4,228	4,968	0.5
Turkey	278	3,908	4,186	0.5
Greece	-	3,900	3,900	0.4
Hungary	198	3,159	3,357	0.4
Pakistan	-	3,050	3,050	0.3
Bulgaria	4	2,183	2,187	0.2
Thailand	-	1,354	1,354	0.1
North Korea	300	300	600	0.1
New Zealand	33	538	571	0.1
Spain	200	330	530	0.1
Zimbabwe	502	-	502	0.1
Romania	22	472	494	0.1
Venezuela	479	-	479	0.1
Total	478,771	430,293	909,064	100

1.3.8 Status in India

India, in 1992 embarked on evaluating its coal bearing basins for their coalbed methane potential. In 1997 India tested and flowed coalbed methane for the first time from a well drilled in the Parbatpur block of Jharia basin. Since then, concerted efforts are being made to cost effectively exploit this energy source. The Government of India has announced lucrative terms and conditions to attract investments in CBM exploration and production activities (Kelafant and Stern). India, which has the 6th largest coal reserves in the world, is expected to have potential for coalbed methane. About 99% of the coal reserves of India are found in the Gondwana basins while 1% lies within the Tertiary basins. Some of the Gondwana basins have been prioritized for evaluating their coalbed methane plays. The priority that has emerged is as follows

- Jharia basin East Bokaro basin
- Ranisani basin
- North Karanpura basin
- South Karanpura basin
- Rajmahal basin
- Pench-Kanhan Valley
- Pranhita-Godavari basin

The prospect for coal bed methane is mainly related to the coal resources of the country. India has huge Gondwana (mainly Permian, 99.5%) and Tertiary (Eocene and Oligocene) coal deposits distributed in several basins located in peninsular and extrapeninsular regions. About 204 billion tons of coal reserves have been established and approximately 200 million tons or so are likely to be added in the near future by further explorations. The main Gondwana coal basins are rifted intra-cratonic grabens having thick sequence of coal seams, and hold considerable prospects for coal bed methane. The major part of Indian Gondwana coals (mostly up to 300 m depth) is of low rank, far below the threshold value of thermogenic methane generation. However, high rank coals, amenable for generation of coal bed methane, mostly occur in untapped deeper parts of basins covered by younger sediments.

In 1990, efforts to exploit coal bed methane were initiated by Essar Oil (a private oil company) under the advice of American experts. The methane emission and desorption studies on Gondwana coal samples from Jharia Coalfield (Bihar) were carried out by Central Mine Planning and Design Institute Limited (Ranchi) and Central Mining Research Institute (Dhanbad). The content of gas and gas emission rate from these samples were found to be 1.8-2.3 m3/1000 m2 of surface and 12.7-17.3 having the 3rd largest proven coal reserves and being the 4th largest coal producer in the world. India holds significant prospects for commercial recovery of CBM. Prognosticated CBM resource has been estimated to be. around 4.6 TCM.

1.4 Methane Retention in Coal Beds

1.4.1 Gas Generation and Composition

The term "coalbed methane" is not completely accurate because coalbed gas, though composed primarily of methane, includes other gases. When peat is formed, methane and other gases are produced, first by anaerobic fermentation, bacterial, and fungal alteration, and later in the process of coalification by geomechanical alteration through heat and pressure. The gaseous hydrocarbon generated in greatest quantity is methane. Very small amounts of ethane, propane, and butane are also created during peat formation. Because of the low pressure in the swamp environment, nearly all of these gases escape during peat formation. The processes of peat formation and coalification increase carbon in the coal because of the loss of hydrogen and oxygen in the expelled moisture and volatiles. Because much of the volatiles that are produced escape, their volumes are uncertain. Volatiles produced include water (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrogen (N_2), and heavier hydrocarbons. More of these volatiles are retained during coalification than during peat formation because of the higher pressures from overlying sediments. Moisture content decreases as coal rank increases. Thus, most of the water produced during coalification (in addition to original moisture) is expelled from the coal. Humic material, which makes up peat, is composed largely of oxygen-rich lignin and cellulose. Because of the chemistry of a humic coal material, its hydrogen loss will be less than that for sapropelic material. Coal more readily adsorbs CO_2 than CH_4, but CO_2 is more soluble in

water. Thus, the retained volume of CO_2 tends to decrease and CH_4 increases as water is expelled during coalification.

1.4.2 Gas Retention by Adsorption

One characteristic that makes coal reservoirs different from conventional gas reservoirs is the manner in which the gas is stored. In conventional reservoirs, the gas exists in a free state in the pores of the reservoir rock, and thus its behavior can be described by the real gas law. In contrast, nearly all of the gas in coal exists in a condensed, near liquid-like state because of physical sorption. Gases also are present in coalbeds as free gas within the pores or fractures, and/or dissolved in solution (ground water) within the coalbed. Porosity exists in coal as fracture porosity and matrix porosity. Matrix porosity largely determines the ability of coal to retain methane. Most hydrocarbon gases in coal seams are retained by physical adsorption to the coal molecular structure. Proportionately more of the heavier hydrocarbons are retained because they are less mobile than methane. Physical adsorption is caused by weak attractive forces (Van der Waals forces) that exist between pairs of molecules or atoms. Adsorption of methane to coal is caused by such weak physical forces. Adsorption increases non-linearly with pressure and is reversible by increasing the temperature or decreasing the pressure. The sorption capacity of coal can be determined by adsorption testing. Isotherm tests are conducted at a specified moisture content or at equilibrium moisture and at the formation temperature or an assumed temperature. If the reservoir temperature and pressure are known, an isotherm can be used to estimate the maximum amount of methane that might be adsorbed in the coal, the pressure at which desorption will start (if gas content is known), and the amount of methane remaining in the coal at an assumed abandonment pressure.

1.4.3 Methane Content of Coal

The methane content of coal can be estimated or measured using a variety of procedures. Some methods are sometimes used to estimate gas content if there is no active drilling on a prospect. These methods include estimation from depth and rank relationships and estimation based on methane emission from coal mines in the area. Because of the tenuous nature of such estimates, you should use them with extreme caution and only until results

from desorption tests are available. Anomalously low gas contents can occur near faults if gas has desorbed from the coal and migrated from the strata through a fault or fracture system. Coalbed depth also can be misleading for estimating gas content. For example, some areas contain unconformities created by erosion of the coal and subsequent deposition of additional strata. In such areas, depth of the coals should be measured as the depth below the unconformity. Standard cores usually provide the most reliable gas content estimates. Other types of samples, such as side-wall cores, drill cuttings, and chips from slotting procedures, are sometimes used or desorption tests. However, these types of samples are not as reliable as standard cores.

1.5 Evaluating Gas Content

Gas is retained in coal mostly by adsorption. Sufficient hydrostatic pressure must be present through geologic history for gas to be retained. If pressure is reduced sufficiently by erosion, uplift, or other means, gas can desorb from the coal leaving little or no gas. Adequate desorption testing should be performed to verify not only the amount, but also the quality of the gas in the coal. The presence of other gases, primarily CO_2, should be determined by analyzing gas samples during desorption tests Flow of coalbed methane involves a three-step process, as methane molecules move along a pressure gradient. The processes involved in the transport of coal bed methane gas from the coal surface to the well-bore are desorption from internal coal surfaces, diffusion through the matrix and micro-pores and finally fluid (Darcy) flow in the natural fracture network (cleats) of coal.

1.5.1 Formulae Developed

Meissner (1984) plotted the log of volatile matter in coal versus the volume of methane generated.

Volume of methane generated (cc/gm) = -325.6 log(%VM(daf)/37.8)

It is assumed the methane is at 20° C and 1 atm pressure and the percentage of volatile matter was measured on dry ash free basis. The adsorptive capacity of a coal is a function of pressure (burial depth), coal rank, ash, moisture content and marceral composition.

Methane is retained in coal beds in the following four ways:

- As sorbed molecule in the interfacial surfaces and within the molecule structure of coal.
- As gas held in matrix porosity
- As free gas within the fracture network
- As dissolved gas in groundwater within coal bed

The total storage capacity is relative to temperature and pressure conditions of 100 °C and 1000 atm as related to appropriate rank. The figure indicates the following:

- Sorption capacity increases slightly with increasing rank.
- Pore volume storage is high for low rank coals.
- Pore volume storage is approximately equal to the sorbed storage at
- high ranks and low volatile matter content.
- Methane is expelled from coal when generation volume exceeds
- total storage capacity at 29% of VM(daf).
- Methane starts generating at 38% VM(daf)

Kim in (1977) developed a formula based on adsorption isotherms and the chemical composition of coal

$G(saf)=0.75(1-A-W_c)[k_o(0.095d)n_o0.14(1.18d/100+11)]$

Where: $k_o=0.8(X_{fc}/X_{vm})+5.6$

$n_o=0.315-0.01\ (X_{fc}/X_{vm})$

$G(saf)$- dry ash free storage capacity

A-Ash content, weight fraction

W_c-moistue content, weight fraction

d-depth of sample, m

X_{fc}-fixed carbon, weight fraction

X_{vm}-Volatile matter, weight fraction

1.5.2 Gas in Place

Gas-in-place is the volume of gas stored within a specific bulk reservoir rock volume. A gas-in-place analysis is generally performed for a specific purpose such as gas resource assessment, reservoir production modeling, or geologic hazard evaluation. Gas resource assessments play an important role in the evaluation of new reservoir exploration prospects. Accurate production modeling is critical to achieving optimal development decisions and reliable production potential forecasts for natural gas reservoirs. Gas-in-place analysis is also used in the mining industry to determine if natural gas emissions will be a hazard during tunnel construction or during the mining of coal, oil shale, and potash. Gas-in-place analysis is a very complex process that involves numerous data collection and analysis challenges. The complexity is due, to the fact that most reservoir parameters used for calculating the gas-in-place cannot be measured directly but must instead be indirectly estimated using data obtained by analysis of various rock properties. Four reservoir parameters are needed to calculate the gas-in-place for conventional gas reservoirs: reservoir or well drainage area; reservoir thickness; reservoir rock porosity; and the vapor phase saturation within the porosity. The equivalent four properties for coal gas reservoirs are the area, thickness, reservoir rock density, and in-situ gas content.

Important Geologic Properties that Influence Gas-In-Place and Deliverability of Coalbed Methane Reservoirs

• Coal Resource: Number, Thickness, and Extent of Coal Seams

• Coal Rank Type, and Quality

• Coal Cleats and Natural Fractures

• Gas Content and Composition

• Sorption and Diffusion Properties of Coal

• Coal Cleats and Natural Fractures

• Geoloeic Structure

• Siress Setting

• Kvdroioeical Characteristics

The reservoir or well drainage area and the reservoir thickness are usually determined through analysis of geophysical well logs, seismic data, and structure maps. The reservoir rock porosity, vapor phase saturation, density, and gas content are usually determined using data obtained from well logs or laboratory analysis of drill cuttings and core samples. The methodology used for determining the in situ gas content varies considerably depending upon such factors as the analysis type, purpose, and, most important, the reservoir type. The analysis type refers to the basic geologic unit being assessed such as a basin, region, or reservoir. The analysis purpose refers to whether the objective is gas resource appraisal, reservoir production modeling, or geologic hazard evaluation. The reservoir type refers to the physical reservoir environment and gas storage mechanism. There are four principal gas storage mechanisms within reservoir rocks:

Compression of gas molecules within rock pores.

Absorption of gas molecules by crude oil or brine.

Inclusion of gas molecules within solid, crystalline water molecule lattices.

Adsorption of gas molecules within micro-pores.

Another cause of gas-in-place analysis complexity is the fact that reservoir rock compositional properties and gas content *are* not uniform throughout a given formation but vary both vertically and laterally as a function of numerous geologic variables. Thus, geologic descriptions and physical property data derived from drill cuttings, cores, and well logs are only single sampling point measurements and may not be representative of the average in-situ rock properties throughout a reservoir. The greater the reservoir heterogeneity, the greater the number of samples and sampling sites needed for adequate characterization of the average in situ rock properties.

1.5.3 Coalbed Gas Recovery

The earliest record of gas recovery from coalbed reservoirs was in China in 900 A.D. where natural gas issuing from coalbeds was transported in bamboo pipes and used as fuel to generate heat for manufacturing salt by brine evaporation. In the United States, the earliest record of gas recovery from coalbed reservoirs was in the early 1900s when a water well drilled into a coal seam in the Powder River Basin was capped and the produced natural gas used as a heating fuel. However, prior to the 1950s the petroleum industry regarded

coalbeds only as sources of gas-kicks and blowout hazards during well drill operations. The first deliberate attempts to target coalbed reservoirs in the United States as gas well completion objectives was in the early 1950s in the San Juan Basin. Significant commercial coalbed gas production did not begin in the United States until the early 1980s. Today, technology for economically producing natural gas from coalbed reservoirs has reached a state of demonstrated maturity and these reservoirs are important natural gas exploration targets.

1.5.4 Coalbed Gas Content Analysis

The growing importance of commercial coalbed gas production has dictated the critical need for accurate gas-in-place data since this parameter is the basis for forecasts of the gas production rates and cumulative gas production volumes from these reservoirs. The in-situ gas content is a crucial parameter in the formula used to calculate the gas-in-place volume, but the accurate determination of in-situ gas content is neither simple nor straightforward. It is not currently possible to use geophysical logging technology to accurately determine the volume of gas stored insitu by molecular adsorption. This limitation occurs since the presence of adsorbed phase natural gas has little effect upon the physical properties of the bulk reservoir rock. For example, an in-situ adsorbed phase methane content of 400 scf/ton would increase the density of a 100% organic content sample having a density of 1.295 g/cm^3 by only 0.010 g/cm^3, or 0.8%. Three methods are commonly used for determining in-situ gas content values: pressure coring; direct methods; and indirect methods. Each of these methods has inherent shortcomings which can significantly affect the accuracy and comparability of gas content analysis results.

1.5.5 Pressure Coring

The pressure coring method involves trapping a cored rock sample down hole within a sealed barrel thereby preventing any loss of gas by desorption while the sample is being retrieved to the surface. The in-situ gas content is then determined by measuring the total volume of gas that desorbs from the sample. The primary advantage of pressure coring is that it is the only method capable of directly measuring the total in-situ gas content of the cored rock sample. However, this method requires specialized equipment that is difficult to

successfully operate on a routine basis in the field. Pressure coring is also about five times as expensive as conventional coring methods and its use has generally been restricted to research studies.

1.5.6 Direct Method Analysis

The direct method analysis procedure was originally developed by the coal mining industry to evaluate the potential severity of natural gas emissions during underground mining operations. This mining industry method involves sealing freshly cut drill cuttings or conventional core samples in an airtight desorption canister and then measuring the volume of gas that desorbs as a function of time at ambient temperature and pressure conditions. The measured desorbed gas volume is not equal to the total in-situ gas content since some gas desorbs and is lost during the sample collection process and some gas is usually retained by the coal at ambient temperature and pressure desorption conditions. The lost gas volume is commonly estimated by graphical analysis of the measured gas desorption data. The residual gas volume is determined by measuring the volume of gas released when the coal sample is crushed and heated at the conclusion of the desorption measurements. The total gas volume of the coal is equal to the sum of the estimated lost gas volume, the measured desorbed gas volume, and the measured residual gas volume. The chief limitation of the direct method analysis procedure is that it yields widely different in-situ gas content estimates depending upon the coal sample type and collection methodology, analysis conditions, and data analysis methods. This method-dependent gas content analysis result variation warrants careful consideration when planning or conducting a coalbed reservoir gas-in-place analysis since it indicates that some sample types, analysis conditions, and data analysis methods have inherent shortcomings which bias the gas content analysis result accuracy. For example, the in-situ gas content estimates obtained by analysis of drill cuttings and conventional core gas desorption data commonly differ by 25% or more. Gas content errors of this magnitude cause very large errors in the gas production rates and cumulative recovery estimated using reservoir simulation techniques.

Figure 2-Difference in predicted gas production rate and cumulative recovery
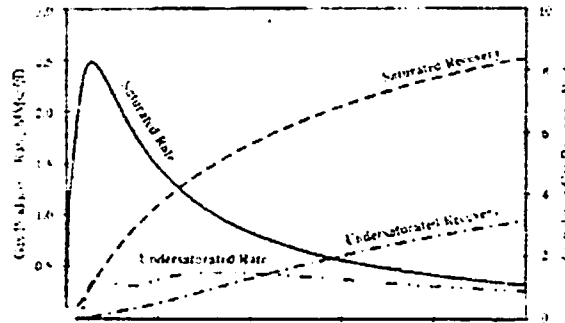
The above figure illustrates the differences in predicted gas production rate and cumulative recovery that results from a 30% gas content under-prediction for a typical high productivity San Juan Basin coalbed gas well. The maximum gas production rate was under-predicted by 82%, and the ultimate recovery (gas reserves) was underestimated by 63%. It is not uncommon for the cumulative gas volumes obtained from coalbed reservoir and gas-bearing shale wells with long production histories to be substantially less than or even greatly exceed the initial, producible reserve estimates. As an example, the 10 year cumulative gas production for 23 coalbed gas wells at the Oak Grove field in the Black Warrior Basin of Alabama was 3.2 Bscf, but only 1.55 Bscf of initial gas-in-place was originally calculated to be contained within the coal comprising the reservoirs. The discrepancy was believed to be due to low reservoir volume estimates and low initial gas content estimates. Variances between initial gas-in-place and cumulative gas production volumes of this magnitude warrant careful scrutiny since they indicate a significant potential for reserve growth in existing fields and for expanding the recoverable gas resource base by exploiting coalbed gas and gas-bearing shale resources that are currently viewed as uneconomic.

1.5.7 Indirect Method Analysis

The indirect method is used when reservoir coal samples are not available and basically involves evaluating the in-situ gas content using empirical correlations which relate known variations in gas content or storage capacity against variations in easily measured independent geologic variables such as coal rank or reservoir depth. Plots of measured in-situ gas content values against vitrinite reflectance or reservoir depth often exhibit apparent linear trends. However, the empirical correlations derived from such data trends

generally have very little predictive utility since there is no fundamental relationship between the dependent and independent variables.

Thus, the coefficients in the empirical correlations are highly sample set specific which biases their predictive accuracy. Indirect method in-situ gas content values can be very unreliable since coalbed reservoir gas content variation trends can be very erratic throughout a basin.

1.5.8 Additional Gas-in-Place Analysis

Other common sources of error in gas-in-place analysis are underestimation of the gross reservoir thickness and average reservoir rock density. Coal compositional properties and gas content are not uniform throughout the bulk rock comprising a coalbed reservoir but vary both vertically and laterally as a function of such geologic variables as coal rank, depth, ash content, and maceral composition. Analysis data from samples having a broad range of compositional values are needed for reliable determination of the gross reservoir thickness, average reservoir rock density and average in-situ gas content. Coal samples must also be carefully handled at the well site and during transport, storage and testing in order to preserve their original in-situ compositional properties. Air exposure, for example, results in time-dependent alteration of coal's gas emission and compositional properties due to a progressive degradation phenomenon known as weathering. If freshly cut reservoir coal samples are sealed in desorption canisters with a large headspace air volume the subsequent chemical reaction between the oxygen in the air and the coal can cause a significant underestimation error in the desorbed gas volume. Clearly, obtaining accurate gas-inplace values for coalbed reservoirs involves numerous data collection and analysis challenges. The key requirement for obtaining accurate values for average in-situ gas content, gross reservoir thickness, and average reservoir rock density is the use of proper sampling, testing, and data analysis methods.

1.6 Exploration and Exploitation Strategy for CBM

CBM exploration is a capital intensive and front end loaded technology. Except USA where only 3 out of 20 potential CBM basins could be brought to economical production, CBM projects are yet to be commercially productive in other countries where CBM exploration is being pursued. Reasons for this could be technical, fiscal or legal. The key to success for the CBM venture in these countries would be to collect maximum information to make decisions with minimum financial exposures. This could be achieved through phase development concept. A pre phase study of the basin to be explored for CBM is required, to know whether it holds speculative, commercial and potential value.

1.6.1 Phase-I: Exploration

During this phase information on coal resources: thermal maturity, cleat and fracture system and hydrology are collected from geoscientific survey at basin level for detailed analysis. With the help of subsurface data generated and gathered full set of maps, geological cross sections, structural contours, isopach, coal rank, gas in place maps are compiled. The above studies lead to qualitative estimation of prioritizing the basins, blocks etc.

1.6.2 Phase- II: Appraisal-Sizing

The phase includes detailed analysis, integration of geological, geochemical, geophysical and reservoir data. It includes drilling, casing, stimulation and testing of a production well. The test wells are flowed for several months until a stabilized pump off rate is achieved. Geological, geophysical and geochemical information coupled with engineering data during testing help in reservoir simulation. The most critical parameters that is gained from the test well is followed by a closely spaced multi well pilot for faster dewatering, more accurate production potential. The data from the pilot wells not only help in understanding reservoir anisotropy but also in accurate calculation of reserves

1.6.3 Phase-III: Development

The data generated in phase I and phase II is utilized in coal seam reservoir modeling by simulators depending upon the economic viability; a development scheme is drawn up.

Drilling, completion, stimulation of development wells, installation of artificial lifts and bringing the wells into production, erection of surface facilities etc. are carried out in this phase.

1.6.4 Phase-IV: Production

The production phase commences with the completion of installation of surface facilities and marketing tie ups. During this phase continuous reservoir and production management is required to keep up the production rate.

Figure 3-Production profile of a CBM well
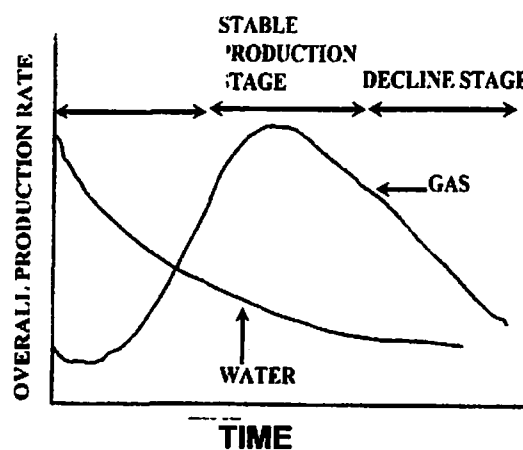
1.7 Understanding the Fundamentals of CBM Production

To successfully produce CBM wells, it is essential to:

1. Identify factors that control production in coal reservoirs

2. Understand the relationship between gas content and sorption isotherm for specific developments, and

3. Maintain low backpressure on wells to increase recovery. Each of these points is discussed below.

1.7.1 Factors Controling Production in Coal Reservoirs

Early work showed that gas is stored in an adsorbed state on coal, and thus for a given reservoir pressure much more gas can be stored in a coal seam than in a comparable

sandstone reservoir. Production of gas is controlled by a three step process—desorption of gas from the coal matrix, diffusion to the cleat system, and flow through fractures. Many coal reservoirs are water saturated, and water provides the reservoir pressure that holds gas in the adsorbed state.

1.7.2 Relationship Between Gas Content and Sorption Isotherm

Another mechanism that controls production is the relationship of gas content to sorption isotherm, as shown in the following figure. The sorption isotherm defines the relationship of pressure to the capacity of a given coal to hold gas at a constant temperature. Gas content is a measurement of the actual gas contained in a given coal reservoir. A coal reservoir is undersaturated if the actual gas content is less than the isotherm value at reservoir temperature and pressure.

1.7.3 Maintaining Low Backpressure on Wells

The ultimate recovery of gas depends on gas content and reservoir pressure. Gas production will not initiate until reservoir pressure falls below the point where the gas content of the coal is in equilibrium with the isotherm. Because most coal reservoirs are aquifers, production of water from the wellbore is the primary mechanism of pressure reduction. If the gas content of the reservoir is below the isotherm, as shown in the figure above, then the reservoir will produce only water initially. After this single phase flow period, bubble flow initiates when reservoir pressure reaches the saturation point on the isotherm. Eventually, two phase flow of gas and water occurs as pressure is further reduced in the reservoir. Because of the relationship between gas desorption and reservoir pressure, it is important to produce coalbed methane wells at the lowest practical pressure.

1.8 Generalized Material Balance Equation

The material balance equation is the fundamental tool for estimating the original gas in place "G" and predicting the recovery performance of conventional gas reservoirs. For conventional gas reservoirs, the MBE is expresses by the following linear equation:

$$\frac{P}{Z} = \frac{Pi}{Z_i} - \frac{(PscT)}{TscV} G_P$$

The great utility of the P/Z plots and the ease of their constructions for conventional gas reservoirs have led to many efforts, in particular the work of King (1993) and Seidle (1999), to extent this approach to unconventional gas resources such as coalbed methane

The material balance equation for CBM can be expressed in the following generalized form:

$$G_P = G + G_F - G_A - G_R$$

Where:

G_P = cumulative gas produced, scf

G = gas originally adsorbed, scf

G_F = original free gas, scf

G_A = gas currently adsorbed, scf

G_R = remaining free, scf

For a saturated reservoir (i.e. initiak reservoir pressure p_i = desorption pressure p_d) with no water influx, the four main components of the right hand side of the above equation can be determined individually as follows:

1.8.1   Gas Originally Adsorbed "G"

In terms of the coal density pB and the initial gas content Gc, the gas in place "G" is given by:

$$G = 1359.7 \, Ah \, p_B \, G_c$$

Where:

p_B = bulk density of coal, gm/cc^2

G_c = gas content, scf/ton

A = Drainage area, acres

h = Average thickness, ft

1.8.2   Original Free Gas "GF"

The initial free gas that occupies the coal cleats and natural fracture system is expressed by:

$$G_F = Ah \, \phi(1-S_{wi}) \, E_{gi}$$

Where:

G$_F$ = original free gas in place, scf

S$_{wi}$ = initial water saturation

∅ = porosity, fraction

E$_{gi}$ = gas expansion factor at ps in scf/ bbl given by

E$_g$ = 198.6p$_i$, scf/bbl TZ$_i$

1.8.3 Gas Currently Adsorbed "G$_A$"

The gas stored by adsorption at any pressure "p" is typically expressed with the adsorption isotherm or mathematically by Langmuir's equation as:

$$V = V_m (b_p/1 + b_p)$$

Where:

V = volume of gas currently adsorbed at "p" scf/ton

V$_m$ = Langmuir isotherm constant, scf/ton

p = current pressure, psia

b = Langmuir pressure constant, psia"[1]

The volume of the adsorbed gas "V" as expressed in scf/ ton at reservoir pressure "p" can be converted into scf by the following relationship:

G$_A$= 1359.7 A h pB V

Where:

G$_A$ = adsorbed gas at p, scf

V = adsorbed gas at p, scf/ ton

1.8.4 Remaining Free Gas "G$_R$"

Where:

p$_i$ = initial pressure, psi

W$_p$= cumulative water produced, STB

B$_w$= water formation volume factor, bbl/STB

A = drainage area, acres

C$_w$ = isothermal compressibility of water, psia

Q = isothermal compressibility of the formation, psia

S_{wi} = initial water saturation, fraction

Using the above estimated average water saturation, the following relationship for the remaining gas in cleats is developed:

$$G_R = \frac{7758\,A\,h\,\emptyset\,[\,(B_w W_p /\,7758\,A\,h\,\emptyset) + (1\text{-}S^*) - (p_i\text{-}p)\,(1+ C_w S_{wi})]E_g}{1\text{-}(\,P_i - p\,)\,C_f}$$

Here G_R is the remaining gas at pressure p, scf.

Substituting and rearranging the equations we get:

$$G_p + B_w W_p E_g = Ah[1359.7\ p_B\{G_c\text{-}V_m\ (b_p/1+b_p)\ E_g\}\text{-}7758(1\text{-}S_w)E_{gi}]+7758Ah\phi\ (1\text{-}S_{wi})E_{gi}$$

The equation is in the form of a straight line $y = mx + a$.

1.8.5 Production Decline and Reserve Estimation

Production decline equation for exponential decline is:
$$a = \frac{\ln(q_o) - \ln(q_t)}{t}$$
$$G_p = \frac{q_o - q_1}{a}$$
G_p= cumulative production production from the well

1.8.6 Cumulative Production from Reserve Estimation

A=Area of well

H=Thickness of seam

G_c=Gas Content

ρ=Density

Reserve = $A \times H \times G_c \times \rho$

Recoverable Reserves = Estimated Reserves * Recovery Factor

$$\text{Percentage error} = \frac{\text{Recoverable reserves -Recovered Reserves}}{\text{Recoverable Reserves}}$$

1.9 Screening Criteria For A CBM Project

Table 4- Screening Criteria for A CBM Project

Sr	Critical Parameters	Threshold Values/ Range
01.	Depth (m)	300-1200
02.	Cumulative coal thickness (m) and coal seam thickness (m)	As high as possible and >4
03.	Vitrinite Reflectance (VRo max)	>0.73
04.	Ash content (%)	5-15
05.	Coal Composition	Vitrinite rich
06.	Methane Content	>8.5cc/gm or300scf
07.	Methane Saturation (Desirable)	Vitrian bands should be cleated
08.	Cleat Frequency	Vitrian bands should be cleated
09.	Permeability (md) (Desirable	0.3-10

1.10 Challenges & Concerns

There are several concerns about CBM development and how to manage the water produced with methane.

1.10.1 The Quantity of the CBM Product Water:

Extraction of CBM involves pumping large volumes of water from the saturated coal seam in order to release the water pressure holding the gas in the coal seam. What to do with this volume of often marginal-quality CBM product water is a source of much debate. Each well produces 5 to 20 gallons of water per minute. At 12 gallons per minute, one well produces a total of 17,280 gallons of water per day. It is common to have to have one well every 80 acres, and in the Powder River Basin, there are up to three methane-bearing coal seams. Therefore, there may be up to three wells per 80 acres.

1.10.2 The Quality of CBM Product Water and Its Effects on Soil

CBM product water has a moderately high salinity hazard and often a very high sodium hazard based on standards used for irrigation suitability. Irrigation with water of CBM product water quality on range or crop lands should be done with great care and managed closely. With time salts from the product water can accumulate in the root zone to concentrations which will affect plant growth. Saline conditions stunt plant growth because plants must work harder to extract water from the soil.

The sodium hazard of CBM product water poses additional threats to certain soil resources. Sodic irrigation water causes soil crusting and impairs soil hydraulic conductivity, adversely affecting water availability and aeration and subsequent crop growth and yield. Upon wetting of soils containing swelling clay, sodium causes the degree of swelling in the clay to increase, leading to dispersion and migration of clay particles. Current research at Montana State University shows that water with sodium levels equal to typical Montana CBM product water can degrade the physical and chemical properties of heavier, clay soils, making such soils completely unsuitable for plant growth The risk of sodium degradation has been observed in other soil textures. Jim Oster (personal com.) observed crusting, poor soil tilth, hardsetting and aggregate failure on a sandy loam soil irrigated with water with EC ~ 1 and SAR ~ 7. Minhaus (1994) saw irreversible and severe reduction in infiltration .... sandy loam soil with long term irrigation under high SAR water followed by monsoon rain.

There are many factors in addition to soil textures that affect infiltration rates. Mineralogy, lime, sesquiozides, organic matter content, cultivation, irrigation method, wetting rate, antecedent water content and time since cultivation all play a roll in infiltration. The only way to be certain of the impacts of saline/sodic irrigation water on the soil is to periodically sample and test the irrigation water and the soil.

1.10.3 The quality of CBM product water and its effect on plants

Disposal of the quantities of CBM product water into stream channels and on the landscape poses a risk to the health and condition of existing riparian and wetland areas. High salinity

and sodium levels in product water may alter riparian and wetland plant communities by causing replacement of salt intolerant species with more salt tolerant species.

Current management practices for disposal of CBM product water Currently, CBM product water in the Powder River Basin is managed by the following methods:

- Discharged into a stream channel - Although direct stream discharge is no longer permitted on new wells, existing operations were "grandfathered" and are still discharging directly into streams. Also, proposals are being advanced to allow regulated discharges during certain flow conditions.

- Impounded - This method involves constructing a pond in which CBM product water is stored or allowed to infiltrate to the subsurface. There are several terms for these impoundments: "holding ponds", "zero discharge ponds" or "infiltration ponds". Although they do not directly discharge water on the land surface, most impoundments are not lined and do discharge to the subsurface. Some percentage of seepage flow from impoundments is likely to reach stream channels via subsurface flow.

- Land applied to crop or rangeland - through some form of irrigation equipment.

- Other uses - CBM product water is also used for dust control and, in some cases, is being used by coal mines.

Another option proposed for disposal of CBM product water in eastern Wyoming and Montana is to reinject the CBM product water back into an aquifer(s). This practice occurs in the southwest U.S., where CBM product water is injected into formations below CBM-bearing coal. This approach avoids surface discharge. Many opinions exist, and the iasibility - economic, physical, and environmental - of either reinjecting CBM product water to the coal seam from which it was pumped or injecting it into an aquifer above or below the CBM-bearing coal seam is being investigated.

1.10.4 Extensive Mineral Leases

CBM wells are generally less productive compared to conventional gas wells. Therefore companies seek to ensure that they obtain extensive, contiguous mineral leases for CBM development upon which they can drill enough wells to make a project economic. Since it

may take as many as 10 to 20 wells to extract the amount of gas that could be produced by two or three natural gas wells, these extensive mineral leases may translate into widespread surface development in an area. In the US a land base of at least one or two townships is considered desirable for a CBM project.

1.10.5 Venting and Flaring Of Coalbed Methane Gas

During the early part of the dewatering phase in CBM wells, only a small volume of gas will be produced. Companies may vent or flare it and defer the cost of the equipment required to capture and compress the gas until the volumes reach an economic threshold. Venting and flaring are of concern since the release of gas or its incomplete combustion causes air pollution. Methane, released to the atmosphere during venting and flaring, is also a powerful greenhouse gas contributing to climate change. The light and noise from flares may also be disruptive if they are close to a residence, livestock or wildlife.

1.10.6 Gas Migration into Groundwater Aquifers

Methane sometimes naturally migrates from gas reservoirs into aquifers, but this process can also occur as a result of incomplete casing on wells. Methane migration into groundwater aquifers has been a side effect of CBM development in some places in the US. Methane in groundwater can then flow to the surface and be released to the air via residential or agricultural groundwater wells or it may travel with the groundwater to the place where the water naturally outcrops at the surface or the bottom of a lake or river. The methane in groundwater can be a nuisance to groundwater users as it can interrupt the flow and pressure of water, and can be an explosion hazard if it is allowed to concentrate inside an enclosed structure or home. As indicated above, it is also a potent greenhouse gas.

2. Theory and Equations Used In F.A.S.T. CBM™

2.1 CONCEPT

2.1.1 About F.A.S.T. CBM™ (Version 3.0.0.30)

(License Valid: March 09 – Aug 2009)

Hardware Requirement

Hard Disc space requirement: 250 Mb

RAM: 1GB (Recommended)

Processor: Speed greater than 2.3 GHZ

F.A.S.T. CBM™ is a versatile, intuitive, easy to use software with full documentation support. The multiple tools supplied in the program allow the user to estimate reserves and generate production forecasts for new plays, or analyze production and pressure data for producing reservoirs.

The many useful features of F.A.S.T. CBM™ include:

- Isotherms: The Langmuir isotherm is plotted which allows visual comparison of measured gas content of coal with respect to pressure. Quick estimates of recovery factor and recoverable reserves based on abandonment pressure. Allows for dry ash free and as received basis.

- Volumetric: Gas in place calculations with a breakdown of adsorbed gas and free gas.

- Forecasting: Forecasts gas and water rates. Capable of forecasting inclining gas rates. The optional N wells feature allows the user to quickly determine the optimal drilling spacing for play areas.

- History Matching: Match historical data to determine reservoir parameters (permeability, skin, drainage area, and porosity).

- Matrix Shrinkage: Matrix shrinkage options available for forecasting/history matching. Correlations include Palmer & Mansoori, Seidle & Huitt, and Shi & Durucan. Permeability versus pressure plots are generated for visual confirmation of correlations.

- Decline Analysis: Decline analysis added for alternative estimation of recoverable gas in place.

- Material Balance: Determine original gas-in-place using static reservoir pressures and methods derived by King, Seidle and Jensen & Smith. Or, in the case of a dry or dewatered coal a flowing material balance can also be performed.

- Numerical Models: History match and forecast production using numerical models for vertical, hydraulically fractured or horizontal wells.

- Typecurve Analysis: Use an Agarwal-Gardner Rate-Time typecurve to estimate reservoir properties and gas in place (applicable to dry or dewatered coals only).

- Risk Analysis: Allows the user to perform a statistical prospect evaluation using the Monte Carlo simulation method.

- Importing/Exporting Data: Ability to import PI Dwights files, Merak files and .csv files. Ability to export all forecasts, and data to a .csv file for use in other software.

- Mapping: Imported wells can be visually grouped by various parameters such as permeability or initial pressure on the map page which is complete with one of four geographic coordinate systems.

- Plotting: All data is shown in customizable, user friendly plots

2.1.2 Isotherm and Volumetric Properties

Langmuir Adsorption Isotherm

Coal is able to store a significant amount of gas. The mechanism by which this occurs is called adsorption. In adsorption molecules of one substance become attached to the surface of another. Adsorption can be visualized by imagining a magnet attached to a metal surface, or lint attached to a sweater. This is different from absorption where one substance becomes trapped inside another, such as a sponge soaking up water. Adsorption is a reversible process, because that involves weak attraction forces.

The Langmuir adsorption isotherm assumes that the gas attaches to the surface of the coal and covers the surface as a single layer of gas (a monolayer). Nearly all of the gas stored by adsorption coal exists in a condensed, near liquid state. At low pressures, this dense state allows greater volumes to be stored by sorption than is possible by compression.

The typical formulation of Langmuir isotherm is:

$$\Gamma(P) = \frac{\Gamma_L P}{P_L + P}$$

where:

P = pressure (psia)

V(P) = amount of gas at P, also known as gas content (scf/ton)

V_L = Langmuir volume parameter (scf/ton)

P_L = Langmuir pressure parameter (psia)

The Langmuir isotherm equation has 2 parameters:

Langmuir Volume (V_L)

This is the maximum amount of gas that can be adsorbed on a piece of coal at infinite pressure. This value is asymptotically approached by the isotherm as the pressure increases.

The following image is of a typical isotherm and shows its relationship with V_L

Figure 4-Langmuir Volume
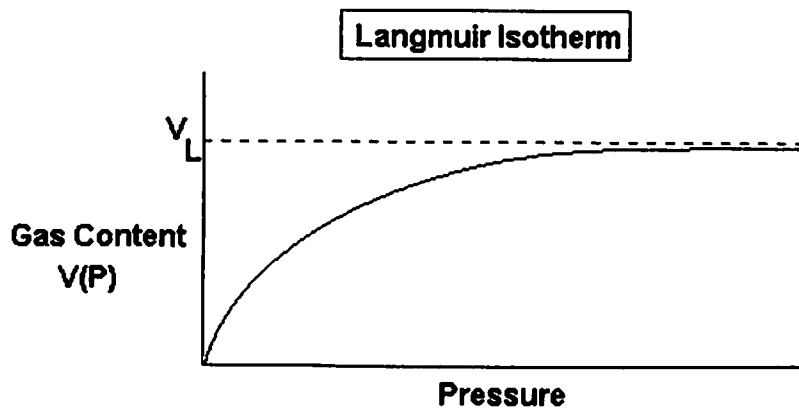
Typically, the units for the Langmuir volume parameter (VL) are scf/ton (volume gas per mass of unit coal). The volume parameter can be converted to a scf/ft³ (volume gas per volume unit coal) by multiplying it by the coal bulk density

Langmuir Pressure (P_L)

This parameter affects the shape of the isotherm. The Langmuir pressure is the pressure at which the Langmuir volume can be adsorbed.

Figure 5- Langmuir Pressure
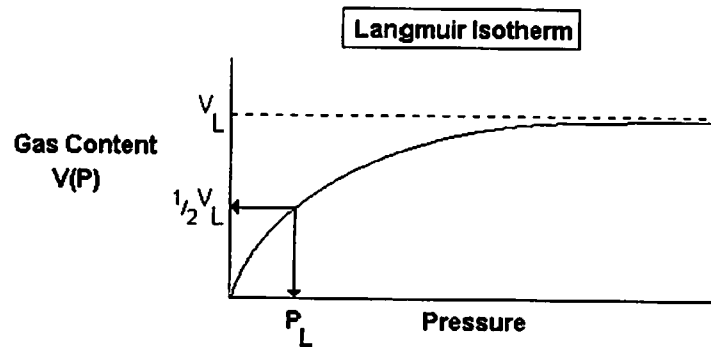
The other notation system that is used in F.A.S.T. CBM™ for representing the Langmuir isotherm is:

$$V(P) = \frac{V_m bP}{1+bP}$$

The variables used in this form of the equation are related in the software as follows:

$$P_L = \frac{1}{b}$$

And

$$V_L = V_m$$

Langmuir Adsorption Capacity

Coal can adsorb a significant amount of gas, even at low pressures. In this example the Langmuir adsorption mechanism is compared to a conventional reservoir. The coal is assumed to be dewatered.

Gas in coal = (adsorbed gas) + (gas in fracture system)

$$V = \left(\frac{V_L P}{P_L + P} \right) (\rho_B Ah) + \frac{\phi Ah(1 - S_w)}{B_g}$$

Where:

V = adsorbed gas (scf)

A = area (ft²) (F.A.S.T. CBM™ uses acres: 1 acre = 43560ft²)

h = net pay (ft)

(ρ_B) = coal density (lb/ft³)

P = reservoir average pressure (psia)

V_L = Langmuir volume parameter (scf/ton)

P_L = Langmuir pressure parameter (psia)

(Φ) = porosity (dimensionless)

S_w = water saturation (dimensionless)

B_g = gas formation volume factor (ft³/scf)

Gas Recovery

It is possible to determine the amount of gas that may be recovered from the coal by looking at the isotherm. Consider the isotherm shown in the following figure. Note that pressure on the X axis represents the average pressure of the reservoir.

Figure 6- Gas Recovery
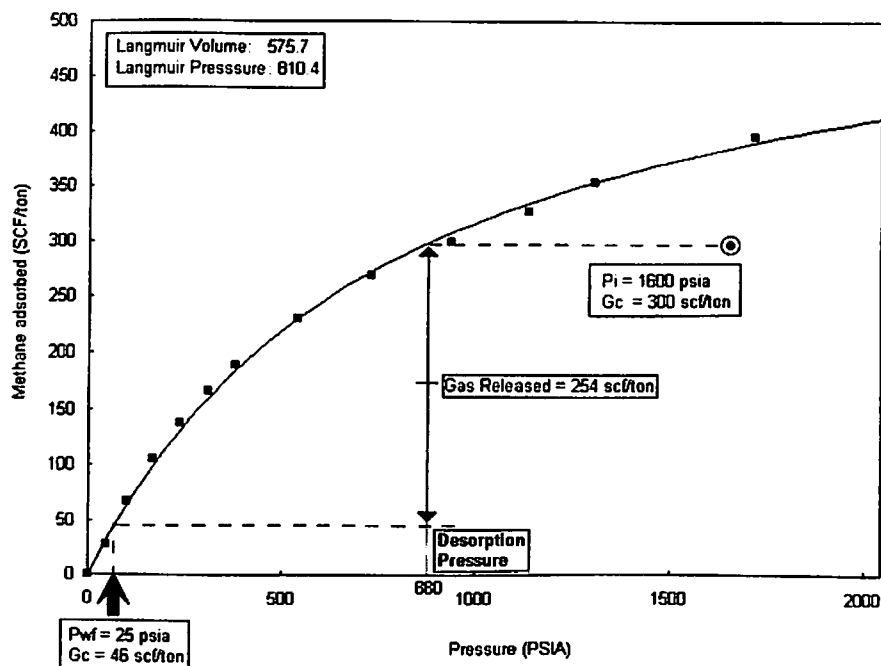
Sometimes, at the beginning of production, the operating point will be under the isotherm curve because the coal is undersaturated. As pressure is decreased, the gas remains in the coal until the desorption pressure is reached (880 psia in the above example). A further decrease in pressure will result in gas being released from the matrix. This amount of gas released can be calculated by taking the difference in the gas contents at the initial pressure and the final pressure.

Effect of Different Conditions on Isotherms

There are various elements that can affect an isotherm's shape. They include:

- **Temperature:** An isotherm is based on the assumption that the temperature is constant. The adsorption capacity of coal decreases as temperature increases. When doing any analysis on coal, it is important to use the isotherm based on the reservoir temperature.

- **Changes in composition of the adsorbed gas:** Different gases have different affinities to coal. For example, most coal samples can adsorb more than twice as much carbon dioxide as methane.

- **Moisture:** Moisture competes with methane for adsorption sites on the surface of coal. There is also a possibility that moisture blocks gas access to micropores. Gas adsorption measurements done on dry coal usually give higher values for gas content than for wet coal.

- **Ash:** Ash is part of coal that does not adsorb gas.

- **Basis of Calculation:** There are several bases for reporting isotherms. It is important to realize that the same coal sample can have significantly different parameter values depending on the basis used. There are two bases that are commonly used: "As Received" and "Dry and Ash Free".

- **"Dry and Ash Free" basis (DAF):** The DAF basis properties are calculated by excluding moisture and ash. The main usefulness of the DAF basis is to compare coal samples from different formations. Having coal on a DAF basis allows for direct comparison of the base amount of gas a certain sample of coal can hold. In gas content measurements, the DAF basis usually has a higher gas content values than the as received values for the same sample.

2.1.3 Matrix Shrinkage

The absolute permeability in coal can change due to changes in the pressure of the formation as it is depleted. There are two main components to consider when creating a permeability-pressure relationship:

Coal Compressibility

In naturally-fractured reservoirs, the rock compressibility can play a significant role in the deliverability potential of the well. As the pressure decreases, the overburden compresses the cleats thereby reducing the permeability. A schematic of this behaviour is shown in the following picture.

Figure 7- Coal Compressibility
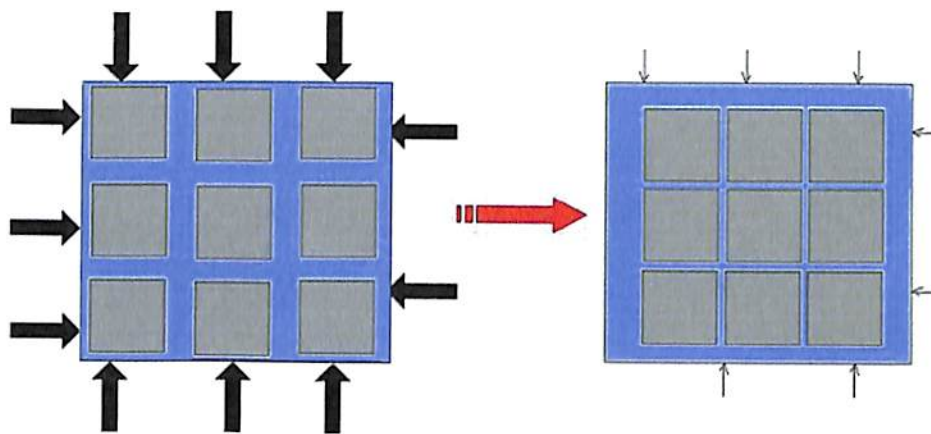
Matrix Shrinkage/Swelling

Gas is stored within the porous structure of the coal matrix. As gas is desorbed from the coal, the pressure exerted by the gas in these pores decreases. This causes the volume of the coal matrix to reduce in size. A reduction in the matrix size simultaneously acts to widen the cleats thereby increasing permeability.

Figure 8-Coal Shrinkage

width of cleat before shrinkage

width of cleat after shrinkage
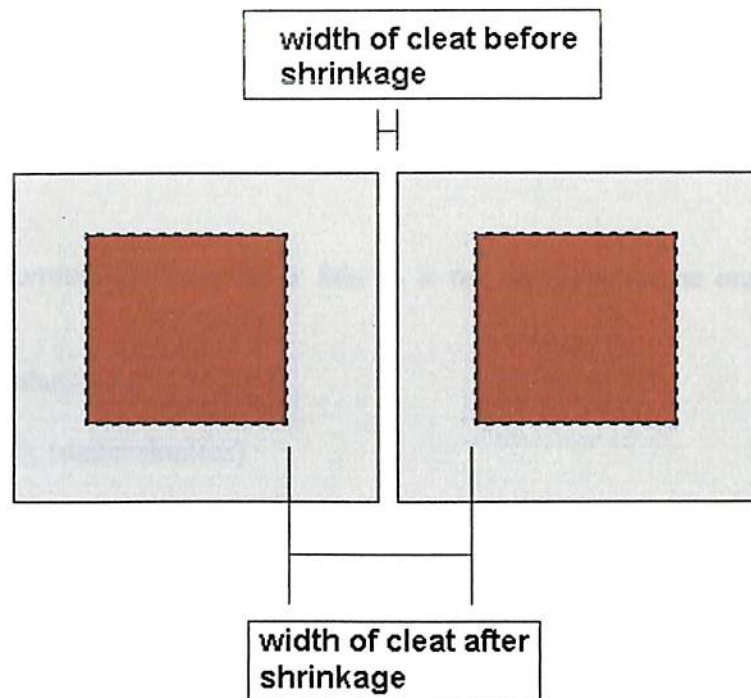
Fracture Permeability Relations

A more thorough development of matrix shrinkage/swelling has been suggested by a variety of literature sources. Four relations that relate matrix shrinkage to porosity were proposed by the following authors:

- Seidle and Huitt
- Palmer and Mansoori
- Shi and Durucan
- Constant Exponential Permeability Incline

Palmer and Mansoori also created a matrix shrinkage model. This model uses elastic moduli to describe the effect of changing pressure on the coal volume. The Palmer and Mansoori formulation is as follows:

$$\frac{\phi}{\phi_0} = 1 + \frac{c_m}{\phi_0}(P - P_i) + \frac{\varepsilon_l}{\phi_0}(\frac{K}{M} - 1)\left[\frac{P}{P_L + P} - \frac{P_i}{P_L + P_i}\right]$$

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

$$\frac{M}{E} = \frac{1-\upsilon}{(1+\upsilon)(1-2\upsilon)} \qquad \frac{K}{M} = \frac{1}{3}\left[\frac{1+\upsilon}{1-\upsilon}\right]$$

Where:

c_m = matrix compressiblity (/psi) (note: this c_m is not the same as the one used in the Seidle formulation)

E = Young's modulus (psia)

f = fraction (0 to 1), (dimensionless)

K = bulk modulus (psia)

M = constrained axial modulus (psia)

P = reservoir pressure (psia)

P_i = initial reservoir pressure (psia)

P_L = Langmuir pressure constant (psia)

υ = Poisson's ratio

ε_l = strain matched to Langmuir isotherm. This is the maximum strain that can occur as P approaches zero.

Y= grain compressibility (/psi)

ϕ= final porosity (dimensionless)

ϕ_O= initial porosity (%)

Moduli Definitions

Young's Modulus of Elasticity

Young's Modulus of Elasticity is defined as the ratio between axial stress and strain. It describes the elastic nature of a given substance and can conveniently describe the amount of deformation of a given object when a given stress is applied. Often this is referred to as

the "stiffness" of a material. The greater the value of the modulus, the less deformation occurs at a given pressure. Several examples of different moduli values are : high strength concrete is (4.5E6 psi) and a more ductile material such as polystyrene (0.45E6 psi).

$$E = \frac{\sigma}{\varepsilon}$$

Where:

E = Young's Modulus (psia)

ε = strain (dimensionless)

σ = stress (psia)

Constrained Axial Modulus

Constrained Axial Modulus Constrained Axial Modulus is defined as the ratio between axial stress and strain, but strain in only one axis is allowed. The compressed material is bounded on the sides, but not in the direction force is applied, as in the following diagram.

Bulk Modulus

Bulk Modulus is the ratio of the change in pressure to the fractional volume compression of the material. For example the bulk modulus for steel is 160E9 Pa while water is at 2.2E9 Pa. Therefore in an environment where the pressure is 2.2E7 Pa, we would expect the fractional change in water to be 1.0%.

Poisson's ratio

Poisson's ratio (Y) relates changes in size of an object along different axes. When compressive force is applied to a particular axis of a material, there will be tensile deformation along a different axis than from which the force was applied. Poisson's ratio is the ratio of contraction strain to extension strain. To give the value a direction, positive is said to be when strain occurs in the direction of a stretching force.

Permeability

Coal consists of cleats (fractures) and the matrix. The matrix stores the gas by adsorption and flow of gas in the matrix is by diffusion. For CBM production, permeability refers to the permeability of the cleats and not the matrix. The same applies for porosity and saturations (S_w or S_g).

The permeability of a system controls the deliverability of a well. There are major differences when comparing permeability in coal to a typical fractured reservoir. Some of these are:

- Porosity and its relationship to permeability
- Matrix shrinkage
- Relative permeability

Porosity

Coal consists of cleats (fractures) and the matrix. The matrix stores the gas by adsorption and flow of gas in the matrix is by diffusion. For CBM production, whenever the porosity is discussed, it is in reference to the cleat porosity and not to the matrix. The same applies for permeability and saturations (S_w and S_g).

To relate permeability to porosity, the following relation is used:

$$\left(\frac{k}{k_0} \right) = \left(\frac{\Phi}{\Phi_0} \right)^n$$

Where:

k_0 = initial permability

k = final permeability

Φ_0 = initial porosity

Φ = final porosity

n = exponent

The exponent n is typically set to 3, although it could be higher (12 or more), according to experimental evidence

2.1.4 CBM Production

Saturations

Coal consists of cleats (fractures) and the matrix. The matrix stores the gas by adsorption and flow of gas in the matrix is by diffusion. For CBM production, saturation (S_w or S_g) refers to the saturation of the cleats and not the matrix. The same applies for porosity and permeability.

Relative Permeability

The water saturation in the cleats changes as the coal is being de-watered. Darcy flow (function of permeability) occurs in the cleat structure, and so relative permeability relationships for water and gas flow in reservoirs are used. The two relations used by the software are:

- Corey (1956)

- Honarpour (1982)

Both equations are designed for use with oil and gas systems in sandstone and conglomerate reservoirs. However it is common practice to apply them to coal bed methane systems as well.

The relation for relative permeability proposed by Corey (1956) is as follows:

$$\frac{k_{rg}}{k_{rg0}} = \left(\frac{\overline{S}_g - S_{gc}'}{1 - S_{wc} - S_{gc}'} \right)^{n_g} \qquad \overline{S}_g \geq S_{gr}$$

$$\frac{k_{rw}}{k_{rw0}} = \left(\frac{\overline{S}_w' - S_{wc}'}{1 - S_{wc}} \right)^{n_w} \qquad \overline{S}_g \geq |1 - S_{wr}|$$

Where:

k_{rg} = relative permeability to gas

k_{rg0} = endpoint relative permeability to gas

k_{rw} = relative permeability to water

k_{rw0} = endpoint relative permeability to water

n_w = exponent of the water relative permeability curve

n_g = exponent of the gas relative permeability curve

S_g = average gas saturation

S_{gc} = irreducible gas saturation

S_w = average water saturation

S_{wc} = irreducible water saturation

Stages of Production

Production of gas from coal is often associated with a significant amount of water production. Most CBM reservoirs contain water in the cleats (fracture system) but some also contain free gas in the cleats. This gas is usually a small amount. The bulk of the gas is stored in the matrix.

A typical production scenario consists of dewatering the coal for a period of time. After the gas saturation in the cleats has reached a critical saturation (refer to relative permeability) production of gas starts. The gas rate increases as the relative permeability to gas improves. Eventually the gas rate declines as the reservoir pressure depletes. These various stages of production are detailed below.

Initial Conditions

Before any water or gas is produced, the reservoir will be at an initial pressure (P_i) and the coal will have an initial gas content (G_{ci}). After tests of coal samples obtained from the reservoir are completed, an isotherm can be determined. Plotting both of these sets of data on a chart, results in the following:

Figure 9- Initial Conditions of Reservoir
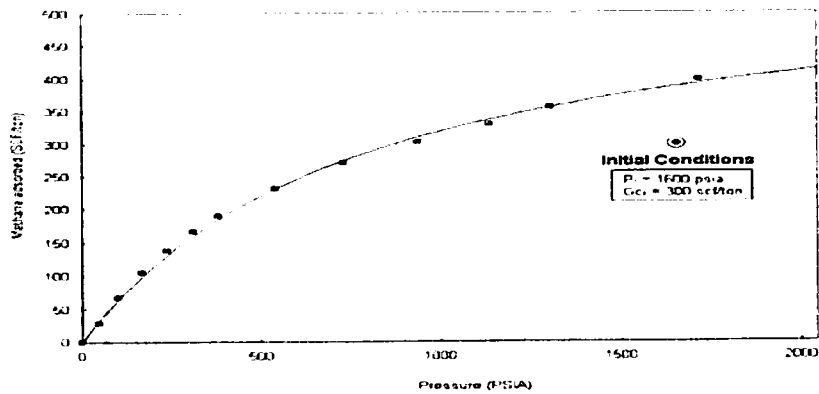
Stage 1: Water Production: Dewatering Stage

Coal reservoirs often contain a significant amount of water that is stored in the cleats (fracture system). The cleats provide main pathways for flow to the wellbore. In order to produce gas the cleats must be dewatered to provide a pathway for the gas to flow out of the well. So in a new CBM well, there is often pumping of single phase water from the reservoir. No gas is produced during this phase for two reasons:

The pressure in the reservoir is above the minimum pressure needed for the gas to be released from the coal (desorption pressure). The pressure must be low enough to intersect the isotherm before gas will be released. No gas is being produced so the gas content of the coal remains constant.

Even when there is gas in the cleats (either originally present or caused by desorption from the coal matrix) no gas will flow until the gas saturation exceeds the S_{gc} (critical gas saturation).

The dewatering stage appears as a horizontal line on the plot of an isotherm. This is shown in the following image:

Figure 10- Dewatering Stage
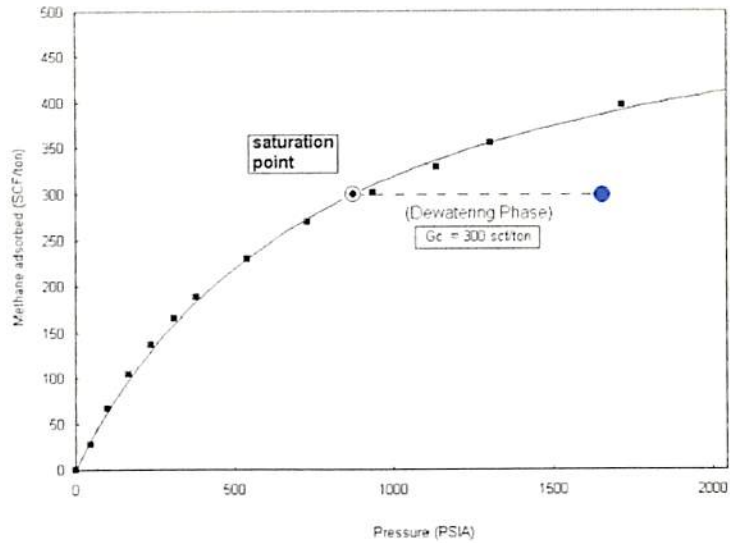
Water flow rate is initially limited by the pumping capacity of the dewatering system. Eventually as the reservoir pressure declines and the relative permeability to water decreases because of increasing gas saturation, the water flow rate decreases, as shown below.

Figure 11- Water Production vs Time
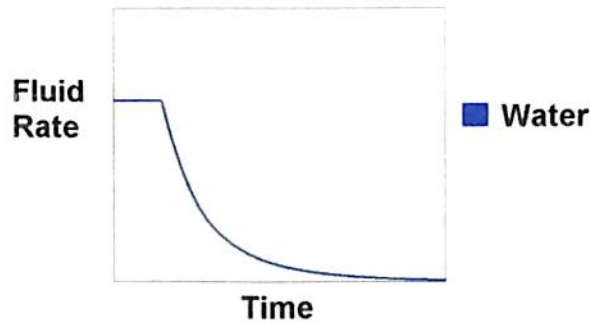
Stage 2: Gas Production: Dewatered Stage

After the saturation pressure has been reached, the coal will start to release gas. This gas will diffuse from the matrix and into the cleats. The amount of gas released will follow the behavior of the isotherm.

Figure 12- Dewatered Stage
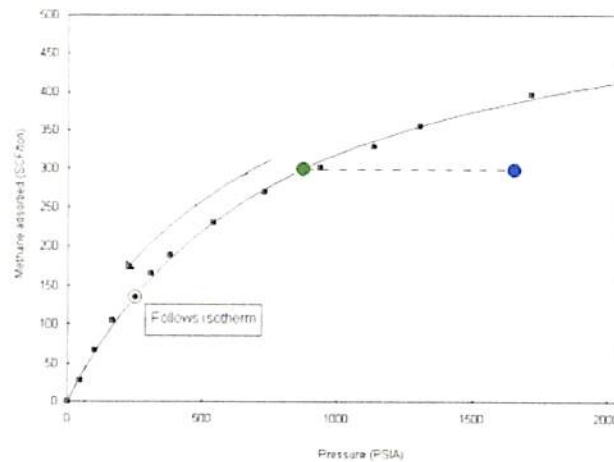
When critical gas saturation has been reached in the cleats, the gas will flow through the cleats and on to the wellbore to be produced. The rate at which the gas is produced depends, partly, on the relative permeability of the gas. As more water is removed and the gas saturation increases the rate will continue to increase to a maximum value. When depletion of the reservoir pressure is significant, the gas rate declines. The behavior of the gas in the system is shown in the following figure

Figure 13- Gas Production
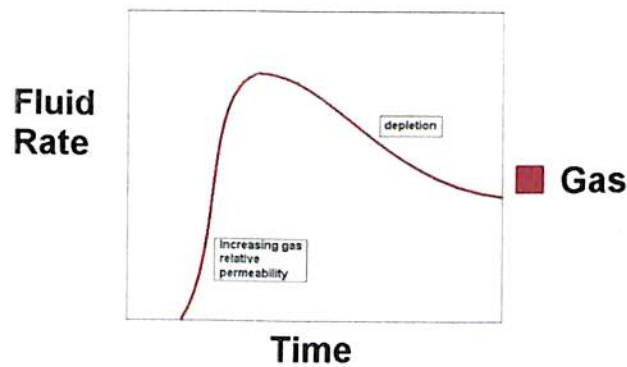
2.1.5 Deliverability

Deliverability is a function of the Langmuir isotherm. When the effects of adsorption are combined with Determining deliverability in coal is useful for comparing production and

creating forecasts. The difference between coal and a conventional reservoir is that the production two-phase flow, the characteristic curves have a very distinct shape.

The deliverability page in F.A.S.T. CBM is divided into three parts:

- Relative permeability
- Forecast
- History Match

Aquifer

If there is an aquifer providing pressure support to the CBM reservoir, this is important for determining the material balance and therefore the production performance and pressure decline. In F.A.S.T. CBM the aquifer is defined by original water in place (OWIP) and the aquifer productivity index (PI_A). The aquifer productivity index is a measure of the water inflow rate per unit pressure. The productivity index is typically found by history matching production. It is possible to model an aquifer of a given volume or an infinite reservoir. The aquifer option is not available for conventional gas layers.

2.2 Analysis Techniques

2.2.1 Gas in Place Calculation

Often it is useful to be able to estimate gas reserves for economic purposes. When calculating the amount of reserves for CBM wells, the adsorbed gas and the gas in the fracture system must be considered:

Gas in coal = (adsorbed gas) + (gas in fracture system)

For adsorbed gas, the basis used for calculation must be considered. The following are the equations using the two bases found in the software.

Calculation

This basis assumes that the gas content is based on the bulk volume of the sample/region considered. An as received sample will often contain water and ash.

$$GIP = Ah\rho_b G_c$$

$$G_c = \Gamma(P) = \frac{\Gamma_L P}{P_L + P}$$

Where:

A = area (ft²)

G_c = gas content (scf/ton)

GIP = gas in place (scf)

h = height (ft)

P = average reservoir pressure

P_L = Langmuir pressure parameter (psia)

V_L = Langmuir volume parameter (scf/ton)

ρ_b = bulk density of the coal (lb/ft³)

Dry and Ash Free Calculation

This basis assumes that the gas content is the value for pure coal.

$$GIP = Ah(1 - a - w_c)\rho_b G_{c,pure}$$

$$G_{c,pure} = \Gamma(P) = \frac{\Gamma_L P}{P_L + P}$$, V_L and P_L measured for pure coal.

Where:

a = ash content (dimensionless, mass %)

A = area (ft²)

$G_{c,pure}$ = gas content of pure coal (scf/ton)

GIP = gas in place (scf)

h = height (ft)

P = average reservoir pressure (psia)

P_L = Langmuir pressure parameter (psia)

V_L = Langmuir volume parameter (scf/ton)

w_c = water content (dimensionless, mass %)

ρ_b = bulk density of the coal (lb/ft³)

2.2.2 Deliverability

Determining deliverability in coal is useful for comparing production and creating forecasts. The difference between coal and a conventional reservoir is that the production is a function of the Langmuir isotherm. When the effects of adsorption are combined with two-phase flow, the characteristic curves have a very distinct shape.

Deliverability of CBM

The deliverability of CBM is modeled with the same equations as for conventional reservoirs.

$$q_g = \frac{k_g h \left[m(P) - m(P_{wf}) \right]}{(1422)T \left[\ln \frac{r_e}{r_w} - \frac{3}{4} + s \right]}$$

Where:

h = net pay (ft)

k_g = gas effective permeability (md)

m(P) = gas pseudo pressure (psi²/cp)

P = average reservoir pressure (psia)

P_{wf} = bottomhole flowing pressure (psia)

q_g = gas rate (MCFd)

r_e = external radius of reservoir (ft)

r_w = wellbore radius (ft)

s = skin

T = Temperature (R)

Prediction of the water rate

To predict the water rate during the dewatering phase, the equation for boundary dominated flow is used:

$$q_w = \frac{k_w h [\overline{P} - P_{wf}]}{141.2 \mu_w B_w \left[\ln \dfrac{r_e}{r_w} - \dfrac{3}{4} + s \right]}$$

Note: conventional layers in F.A.S.T. CBM are assumed to be dry gas reservoirs with no water production.

Where:

B_w = water formation volume factor (bbl/STB)

h = net pay (ft)

k_w = water effective permeability (md)

P = average reservoir pressure (psia)

P_{wf} = bottomhole flowing pressure (psia)

q_w = water rate (STB/day)

r_e = external radius of reservoir (ft)

r_w = wellbore radius (ft)

s = skin

μ_w = water viscosity (cp)

2.2.3   Static Material Balance

Material balance techniques can be used to determine the original gas in place (OGIP), estimate remaining reserves and determine production performance. F.A.S.T. CBM allows for two types of layers: coal bed methane and conventional.

CBM

In a coalbed methane reservoir, gas is stored in two places:

- Matrix gas is held by the coal matrix by adsorption.

- Cleats gas is stored in the fracture system of the coal. This is often referred to as "free gas", and is usually occupies a small volume.

There are 3 forms of the material balance that are discussed in the following sections:

- King (1993)
- Seidle (1999)
- Jensen and Smith (1997)

The following assumptions are used in all of the material balances:

➢ There is equilibrium between the free gas and adsorbed gas in the coal. In other words, this assumes that the coal is saturated, and follows the isotherm;

➢ The data used have been accurately estimated;

➢ The adsorption is a pseudo-steady state process.

King (1993)

The gas material balance proposed by King is the most comprehensive material balance. The following are considered when using the King material balance:

- Gas adsorbed in the coal matrix
- Gas contained in the cleats (fracture system)
- Water compressibility
- Water production
- Formation compressibility

Gas adsorbed

The gas adsorbed in the coal matrix can be described by the Langmuir isotherm. The isotherm can be written as:

$$V_{adsorbed} = Ah\rho_b \frac{V_L P}{P_r + P}$$

Where:

A = area (ft^2) (the software uses acres: 1 acre = 43560ft^2)

h = net pay (ft)

ρ_b = coal density (g/cm^3)

P = reservoir average pressure (psia)

V_L = Langmuir volume parameter (scf/ton)

P_L = Langmuir pressure parameter (psia)

Free Gas

The gas contained in the cleats is described by the equation for a volumetric storage system:

$$V_{cleats} = \frac{Ah\phi(1 - S_w)}{B_g}$$

at initial conditions, $\phi = \phi_i$ and $S_w = S_{wi}$

Where:

B_g = gas formation volume factor (dimensionless)

S_w = water saturation (dimensionless)

Φ= porosity (dimensionless)

The water saturation in the cleats and the cleat volume itself change with pressure and water influx/efflux. The water saturation in the cleats is affected by 3 mechanisms:

Expansion of the water due to the compressibility of the water

Water influx (aquifer) and efflux (production)

The change in pore volume caused by formation compressibility

The resulting equation is:

$$\overline{S_w} = \frac{S_{wi}\left[1 + c_w(P_i - P)\right] + \dfrac{5.615(W_e - B_w W_p)}{\phi_i Ah}}{\left[1 - c_f(P_i - P)\right]}$$

Where:

A = area (ft²)

B_w = water formation volume factor (ft³/scf)

c_w = water compressibility (/psia)

c_f = formation compressibility (/psia)

h = net pay (ft)

P = pressure (psia)

P_i = initial reservoir pressure (psia)

S_w = average water saturation

S_{wi} = initial water saturation

W_e = water encroached (bbls)

W_p = water produced (STB)

ϕ = porosity (dimensionless)

Gas produced

When all the water saturation and gas content terms are combined, the following equation for gas produced (G_p) will result:

$$G_p = \left[\Delta(Gas \quad in \quad Cleats) + \Delta(Gas \quad Adsorbed) \right]$$

or in its expanded form:

$$G_p = \left[\frac{Ah\phi_i(1-S_{wi})}{B_{gi}} - \frac{Ah\phi_i[1-c_f(P_i-P)](1-\overline{S}_w)}{B_g} \right]$$

$$+ \left[Ah\rho_B \frac{V_L P_i}{P_L + P_i} - Ah\rho_B \frac{V_L P}{P_L + P} \right]$$

or alternatively,

$$G_p = Ah\phi_i \frac{T_{sc}Z_{sc}}{P_{sc}T} \left(\left[\frac{P_i}{Z_i^*} \right] - \left[\frac{P}{Z^*} \right] \right)$$

Z^* is defined as:

$$Z^* = \frac{Z}{[1-c_f(P_i-P)](1-\overline{S}_w) + \dfrac{\rho_B B_g}{\phi_i} \dfrac{V_L P}{P_L + P}}$$

Where:

Z = gas compressibility factor (dimensionless)

Z* = gas factor for unconventional gas reservoir (dimensionless)

P_{sc} = Standard pressure (14.7 psia)

T_{sc} = Standard temperature (60 ^{0}F)

T = Reservoir temperature (^{0}F)

Z_{sc} = standard gas compressibility factor (1)

From the above equation, when we solve for OGIP we obtain:

$$OGIP = Ah\phi_i \frac{T_{sc}Z_{sc}}{P_{sc}T}\left[\frac{P_i}{Z_i^*}\right]$$

Dividing the G_p equation by the OGIP equation gives a useful form of the material balance:

$$\frac{P}{Z^*} = -\frac{P_i}{Z_i^*(OGIP)}G_p + \frac{P_i}{Z_i^*}$$

Where:

OGIP = original gas in place

Z^*_i = Z* evaluated at initial conditions

A plot of P/Z* versus cumulative production yields a graphical interpretation of the material balance with axis intersects at the initial pressure (P_i/Z_i^*) of the system and the original gas in place (OGIP):

Figure 14- P/Z vs Q
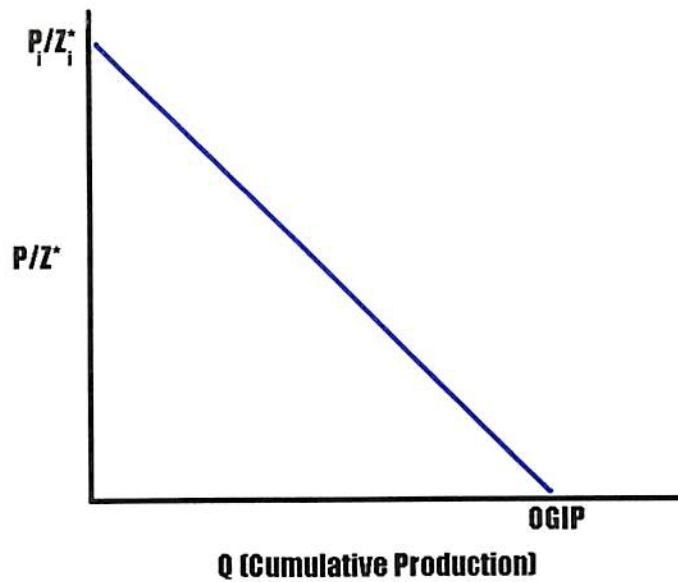
2.2.4 Forecasting

In order to create a forecast, the deliverability equation and material balance equation are used simultaneously. The procedure is fairly simple:

1. At any given point in time, the average reservoir pressure is known (using cumulative production and material balance equation). Using the above equations, q_g and q_w are calculated. The rate is assumed to be maintained for the specified time interval.

$$\textit{Gas Produced} = q_g \Delta t$$

$$\textit{Water Produced} = q_w \Delta t$$

2. The material balance equation is then applied to determine the reservoir pressure at the end of the time interval (which is the start of the new time step)

$$\textit{Gas Produced} = (\textit{Gas Content at } p_i) - (\textit{Gas Content at } p)$$

3. Based upon a new average reservoir pressure, continue with step 1. The forecast is terminated when q_g reaches the specified abandonment rate, or the length of the forecast is sufficient.

This procedure can be used for history matching production data, or for forecasting future performance. When applied to CBM production the above equation differs from its application in conventional reservoirs.

In a conventional reservoir, the average reservoir pressure is determined by tank type equations (p/Z).

In CBM, the average reservoir pressure is controlled by the Langmuir isotherm. Therefore in order to use a tank type model, a (p/Z*) term is used. The Z* term is used to linearize the material balance. Note that F.A.S.T. CBM uses the King material balance for forecasting

2.2.5 Decline Curve Analysis

Decline curve analysis is not derived from theoretical first principles of fluid flow through porous media, but from empirical observations of the production performance of oil and gas wells. Three types of decline have been observed historically, namely: exponential, hyperbolic and harmonic.

Decline curves represent production from the reservoir under "boundary dominated flow" conditions. This means that during the early life of a well, while it is still in "transient flow" and the reservoir boundaries have not been reached, decline curves should NOT be expected to be applicable. Typically, during transient flow, the decline rate is high, but it stabilizes once boundary dominated flow is reached. For most wells this happens within a few months of production. However for low permeability wells (tight gas wells, in particular) transient flow conditions can last several years, and strictly speaking, should not be analyzed by decline curve methods until after they have reached stabilization.

All decline curve theory starts from the definition of the instantaneous or current decline rate, D, as follows:

$$D = -\frac{(\Delta q / q)}{\Delta t} = -\frac{(\Delta q)}{\Delta t} / q$$

D, the decline rate, is "the fractional change in rate per unit time", frequently expressed in "% per year". In the diagram, D = Slope/Rate.

Figure 15- Decline curve
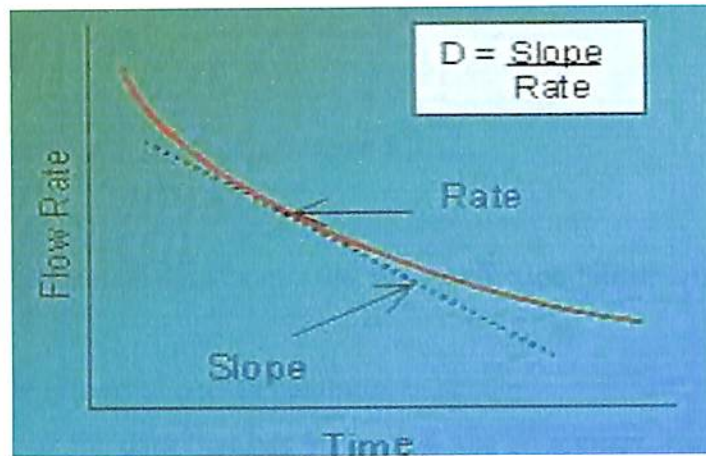
Exponential decline occurs when the decline rate, D, is constant. If D varies, the decline is considered to be either hyperbolic or harmonic, in which case, an exponent "b" is incorporated into the equation of the decline curve, to account for the changing decline rate.

Exponential decline

Exponential decline is given by:

$$\frac{q}{q_i} = \frac{1}{e^{Dt}}$$

where D is the nominal decline rate.

3. F.A.S.T. CBM™ With Example

3.1 Example

3.1.1 Historical Data (Refer Annexure A)

Production Editor

After importing the historical data from a file, the Production Editor window is divided into three frames:

- Top: contains the imported data in columns

- Bottom left: shows the data that has been imported on a chart. The chart has a pointer that shows the current selected data point. There is a grey band on the chart that shows the data that is currently visible in the table.

- Bottom right: contains a chart that shows the data that is highlighted by the grey band on the plot to the left. In other words, it shows a zoomed in view of the data that is currently visible in the table

Figure 16- Production Editor window
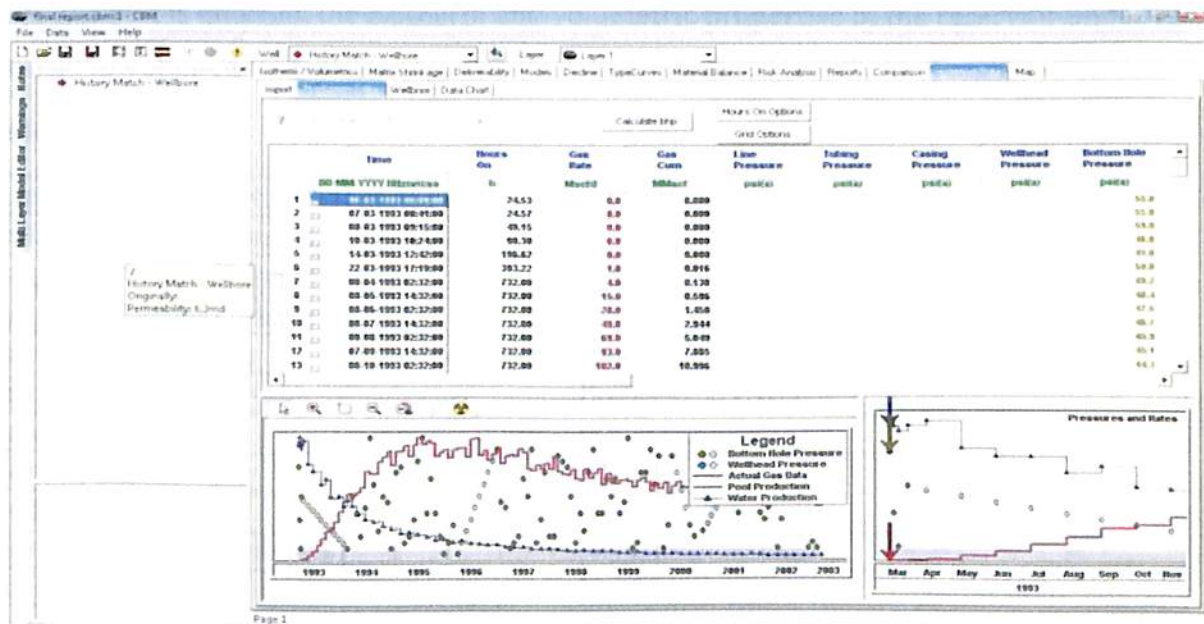
Prior to analyzing your data, it is a good idea to check your data. Click on the Data Chart tab under the Historical Data tab to see a plot of the imported data.

Figure 17-Data Chart
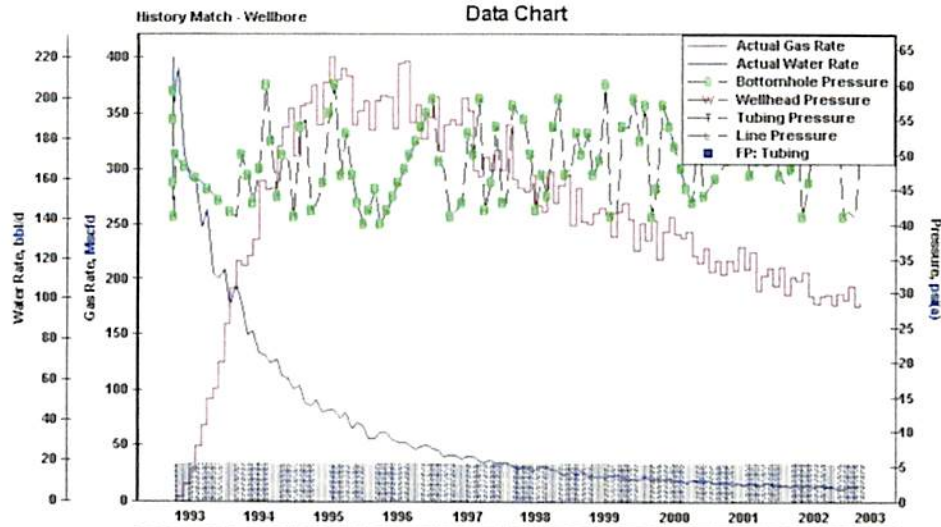
3.1.2 Isothermal/volumetric

CBM analysis is entering the isotherm and volumetric properties of the reservoir under the Isotherm/Volumetrics tab

Desorption Isotherm

Initial Adsorbed Methane (CH_4%)	100 %
Initial Adsorbed Carbon Dioxide (CO_2%)	0 %
Langmuir Methane Volume (V_L CH_4)	550.00 scf/ton
Langmuir Methane Pressure (P_L CH_4)	710.00 psi(a)
Initial Pressure (Pi)	1600 psi (a)
Initial Gas Content (Gci)	380.952 scf/ton
Area (A)	120.00 acres
Net Pay (h)	25.0 ft
Bulk Density (ρ_B)	1.50 g/ cm^3
Reservoir Temperature (T)	135.0 $^\theta$ F
Porosity (ϕ)	0.90 %
Initial Water Saturation (S_{wi})	100.0 %
Bottom hole abondonment pressure (Pabd)	100.0 psi(a)

Once this data has been entered the following isotherm plot will appear on the screen.

Figure 18-Desorption Isotherm
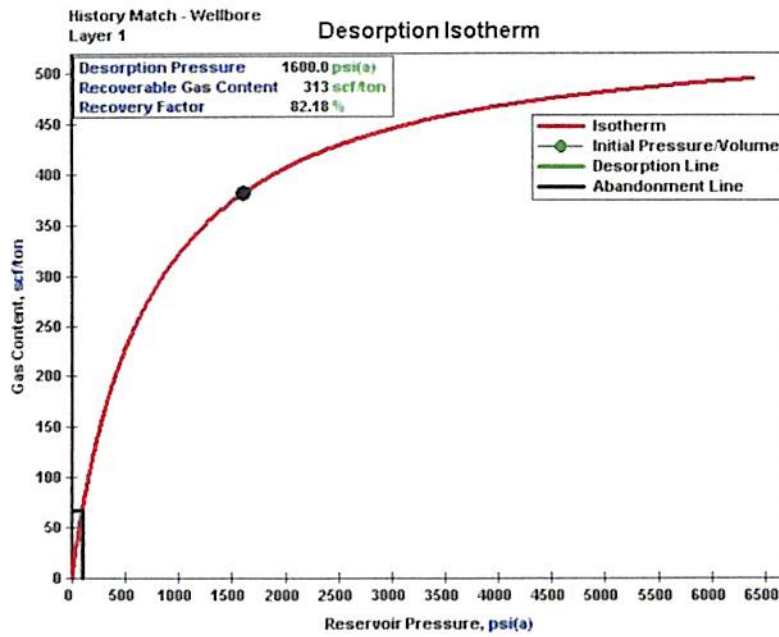
Gas recovery

Figure 19- Gas Recovery
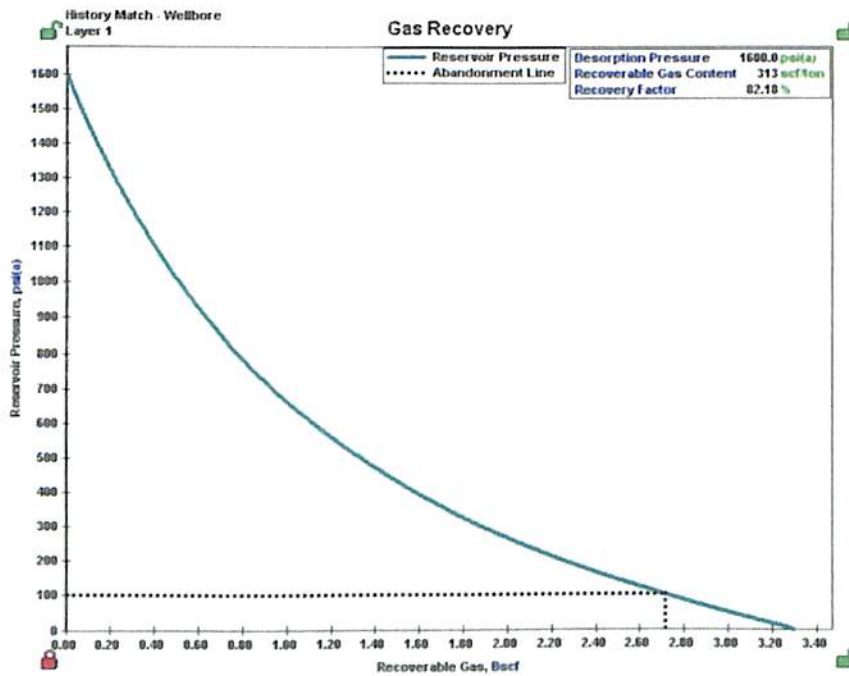
Output

Adsorbed Gas in Place ($OGIP_A$)	2.331 Bscf
Free Gas in Place ($OGIP_F$)	0.000 Bscf
Total Gas in Place (OGIP)	2.331 Bscf
Rcoverable Gas Content (G_{cr})	313.051 scf/ton
Recovery Factor (% Rec)	82.18 %
Recoverable Gas in Place (RGIP)	1.916 Bscf

3.1.3 Matrix Shrinkage

An optional step in performing a CBM analysis is choosing and quantifying a matrix shrinkage relation under the Matrix Shrinkage tab.

Now, in order for this relation to be used in subsequent calculations (forecast, history match, material balance, etc.) the Palmer & Mansoori model should be chosen from the "Active matrix shrinkage relation" drop down menu.

Data Entry

Poisson's Ratio (v)	0.39
Young's modulus (E)	4.5e+05 psi
Fraction (f)	0.50
Grain compressibility (Y')	0.0e+00 (1/psi)
Langmuir strain parameter	8.0
Porosity Ratio (n)	3.000

Permeability ratios

The following permeability ratio plot should be seen in the matrix shrinkage window.

Figure 20-Permeability ratio
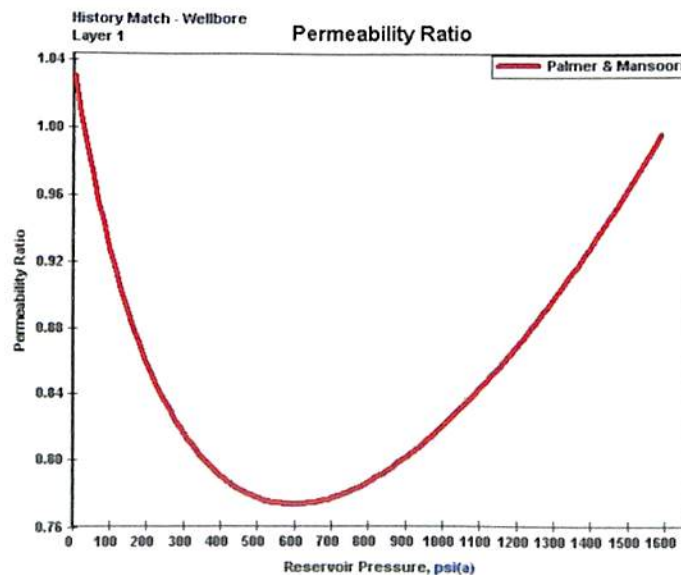
Porosity Ratio

Figure 21-Porosity ratio
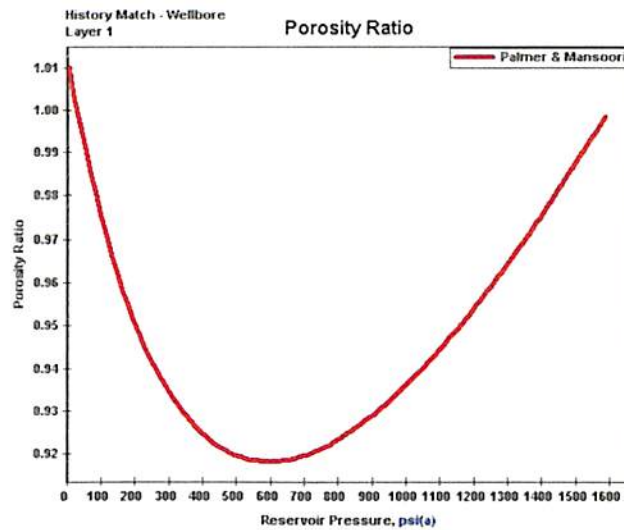
Output

Ratio of constrained axial modulus to Young's modulus (M/E)	1.995
Ratio of bulk modulus to constrained axial modulus (K/M)	0.760
Langmuir curve strain parameter (s_i)	0.011
1/constrained axial modulus (1/M)	1.127e-06 (1/psi)
Grain matrix shrinkage compressibility (c_m)	1.127e-06 (1/psi)

3.1.4 Deliverability

Prior to generating a forecast or history match the relative permeability relations must be specified the Deliverability: Relative Permeability tab

Relative Permeability

The Corey correlation will be used.

Data entry

Irreducible Water Saturation (S_{wc})	20 %
Irreducible Gas Saturation (S_{gc})	10 %
Water Curve Exponent (N_w)	3.5
Gas Curve Exponent (N_g)	1.5
Maximum Water Relative Permeability (K_{rwo})	1.0
Maximum Gas Relative Permeability (K_{rgo})	0.90

Entering this data a relative permeability plot similar to the following should be produced.

Figure 22-Relative Permeability
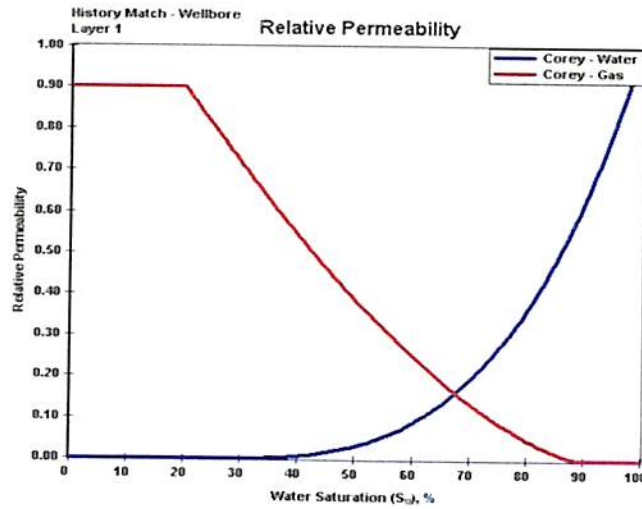
Forecast

A forecast of gas and water rates can be performed under the Deliverability: Forecast tab

Data entry

Permeability (k)	10 md
Skin	0.00
Wellbore Radius (r_w)	0.300 ft
Flowing Bottomhole Pressure (P_{wf})	100.0 psi(a)
Number of wells (Nwells)	1
Fracture half length (x_f)	0.00 ft

Figure 23-Forecast window
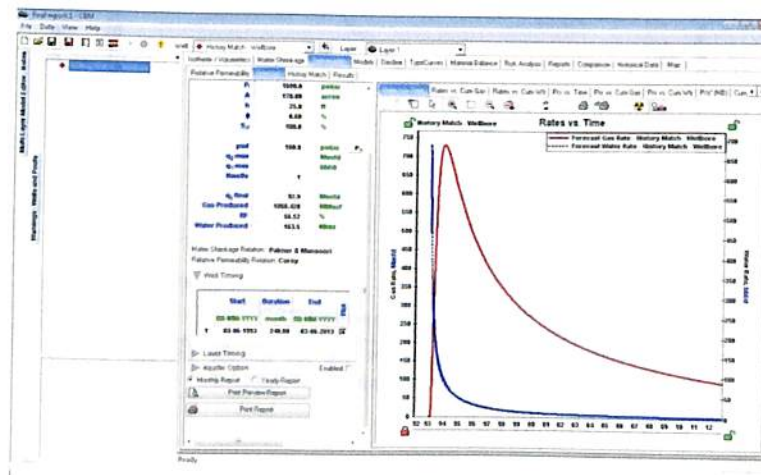
I. Rates v/s Time

Figure 24-Rate vs time
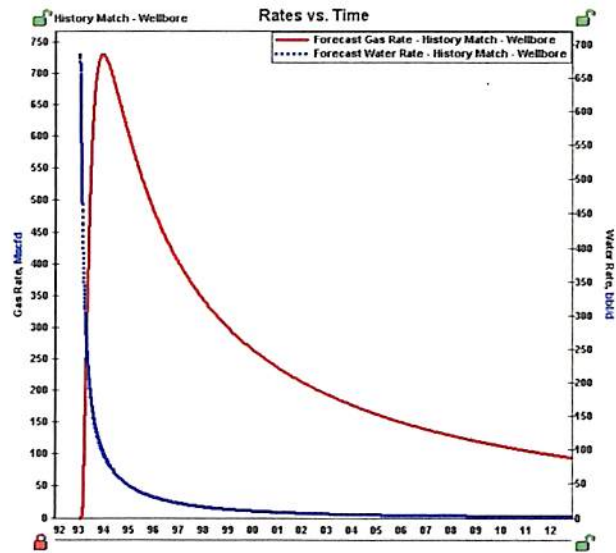
II. Rates v/s cumulative gas

Figure 25-rate vs cumulative gas produced
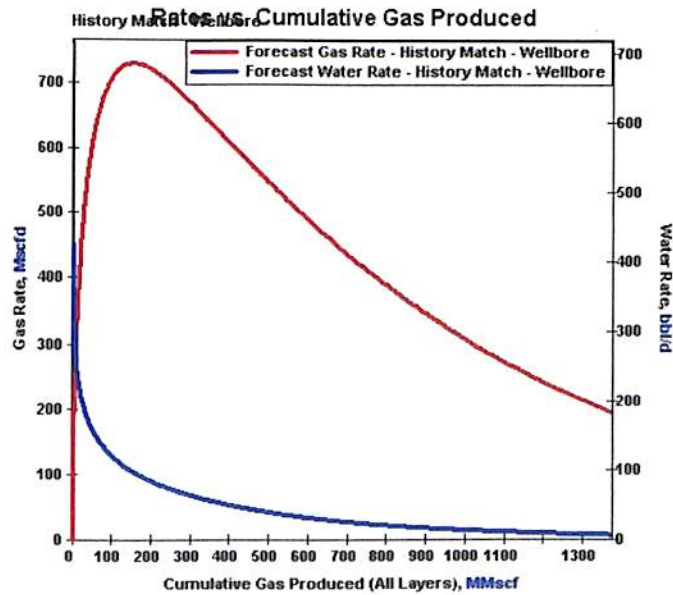
III. Rates v/s cumulative water

Figure 26-Rate vs Cumulative water produced

Rates vs. Cumulative Water Produced
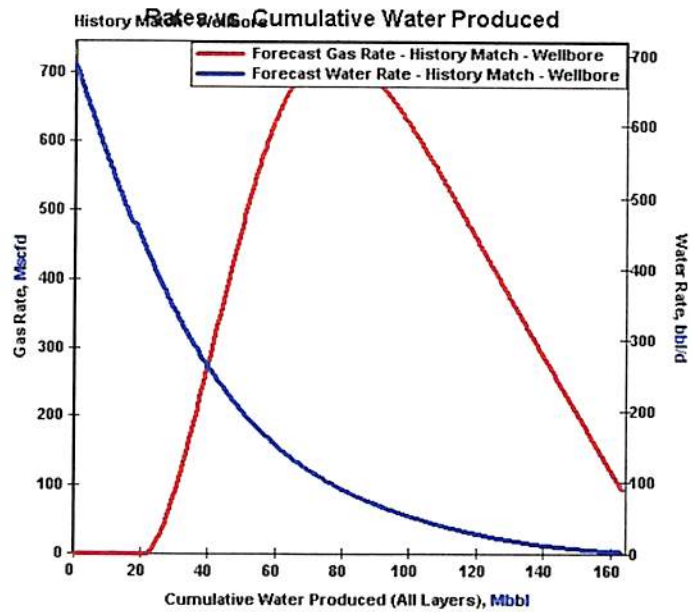
IV. Pressure v/s time

Figure 27- Reservoir Pressure vs Time

Reservoir Pressure vs. Time
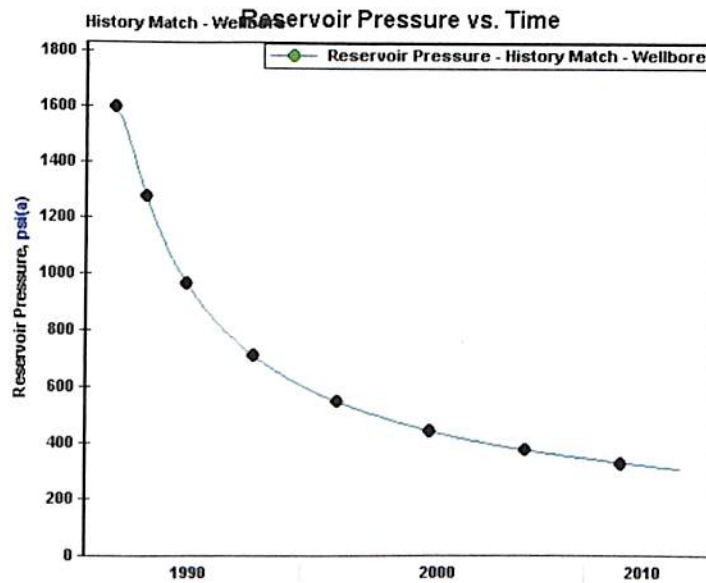
V. Pressure v/s cumulative gas

Figure 28- Reservoir Pressure vs Cumulative Gas produced

Reservoir Pressure vs. Cumulative Gas Produced
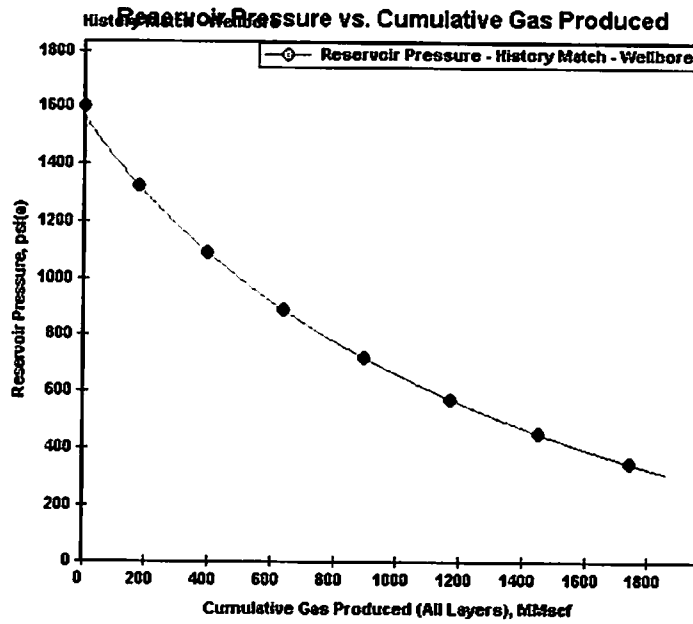
VI. Pressure v/s cumulative water production

Figure 29-Resevoir Pressure vs Cumulative Water Produced

Reservoir Pressure vs. Cumulative Water Produced
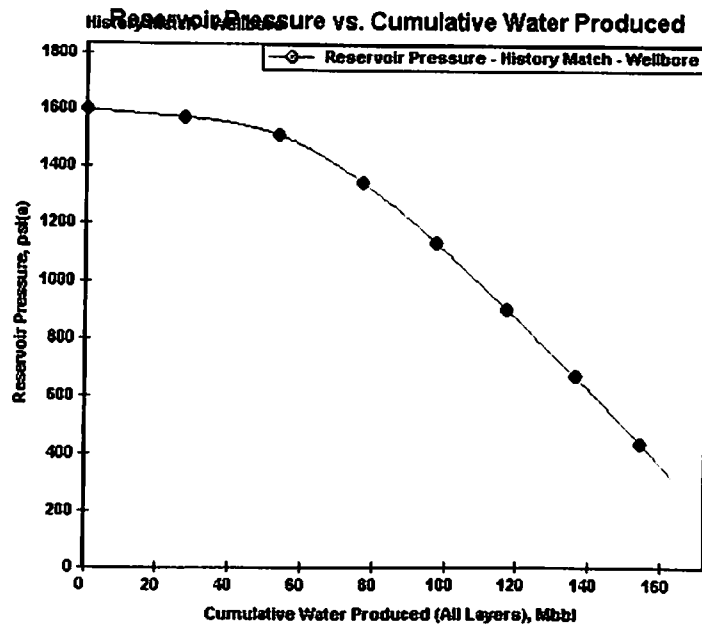
VII.   P/Z* v/s cumulative gas production

Figure 30-Resevoir Cumulative vs gas Produced
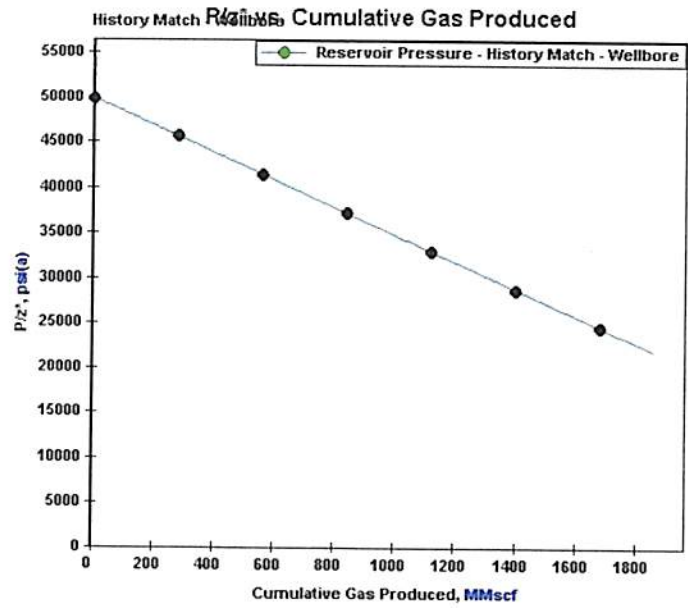
VIII.   Cumulative v/s time

Figure 31-Cumulative vs Time
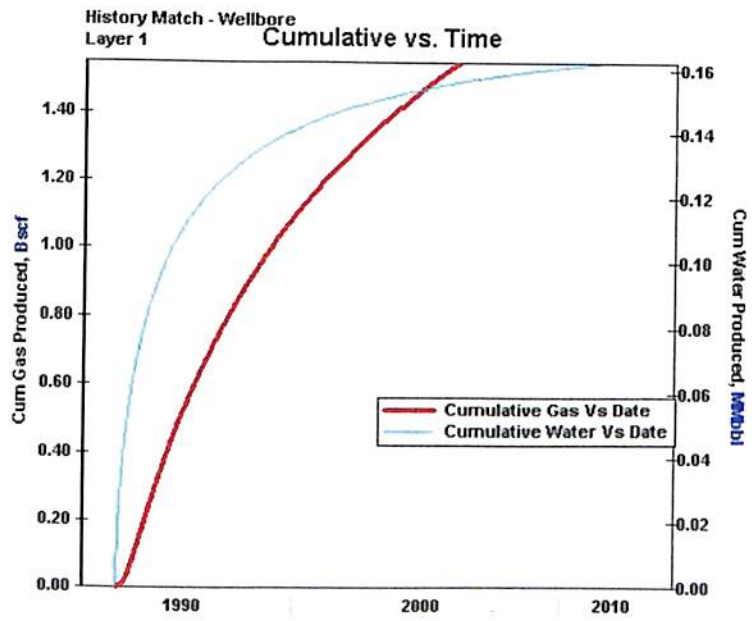
Output

Initial pressure (P_i)	1600.0 psi(a)
Area (A)	170.0 acres
Net pay (h)	25.0 ft
Porosity (ϕ)	0.60 %
Initial water saturation(S_{wi})	100.0 %
Final forecasted gas rate ($q_{g\,final}$)	193.7 Mscfd
Gas Produced (G_p)	1378.666 MMscf
Recovery Factor for Well (RF)	41.75 %
Water Produced (W_p)	151.1 Mbbl

History Match

A history match can be performed under the Deliverability: History Match tab.

Note: Some of the volumetric parameters (area, porosity, water saturation) specified on the Isotherm/Volumetrics page will change once the history match is complete because these parameters are used to match the imported data.

Data entry

Permeability (k)	6.25 md
Skin	1.000
Fracture half length (x_f)	0.000 ft
Wellbore radius (r_w)	0.300 ft
Area (A)	170.00 acres
Porosity (Φ)	0.60 %

I. **After entering the skin value**, the following history match plot should appear.

Figure 32-History Match-1
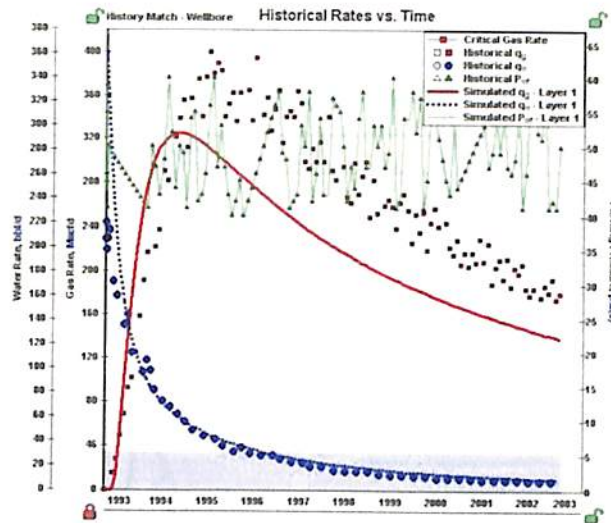
II. **History match at skin 1**

Figure 33-History Match-2
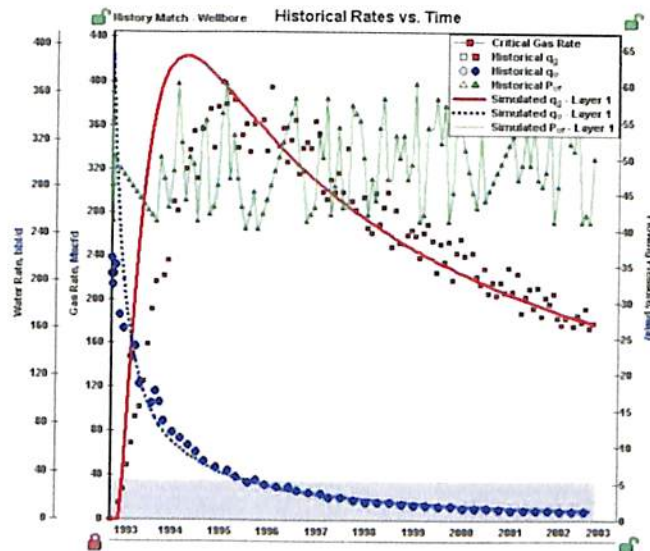
III. **This should generate a history match and forecast similar to the following.**

Forecast

Input

Skin	1.000
Fracture half length (x_f)	0.000 ft
Flowing Bottom hole Pressure (P_{wf})	79.1 psi(a)
Forecast Duration	120.00 months
Forecast end date	13-03-2013 DD-MM-YYYY

Figure 34-Forecast for next 10 year
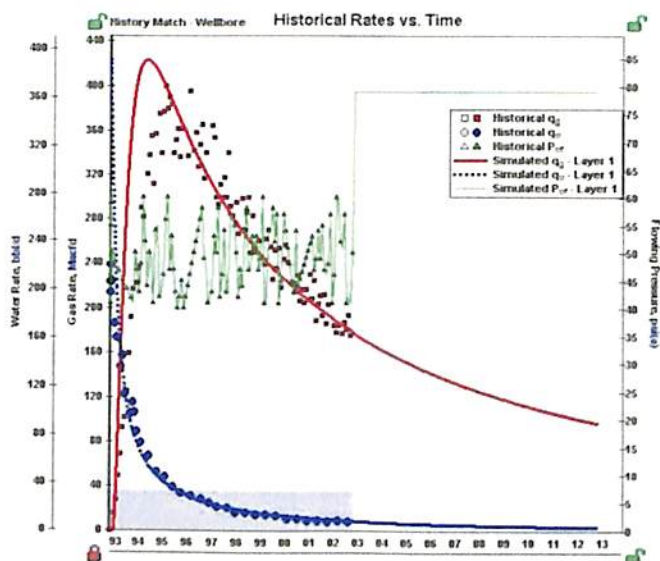
Output

Refer to: Annexure B

3.1.5 Comparison

The Comparison tab can be used to create custom plots. In this case, let's design a few plots that compare the history match and forecast results generated

The historical gas rate data

Figure 35-Historical gas rate
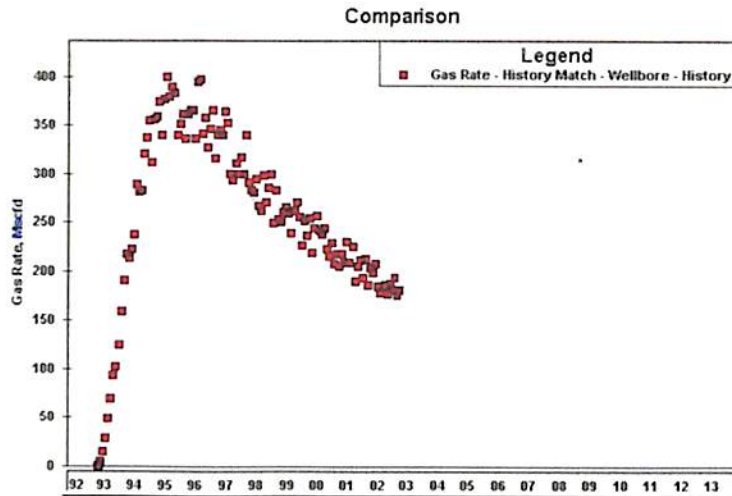
The history match data from the deliverability tab

Figure 36-Comparison of gas rate
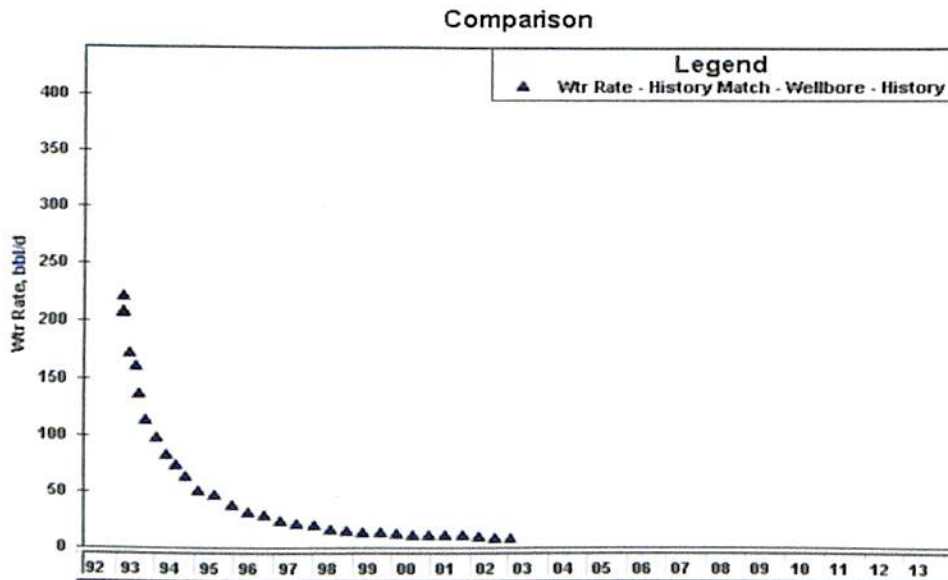
The historical water rate data

Figure 37-Historical water rate
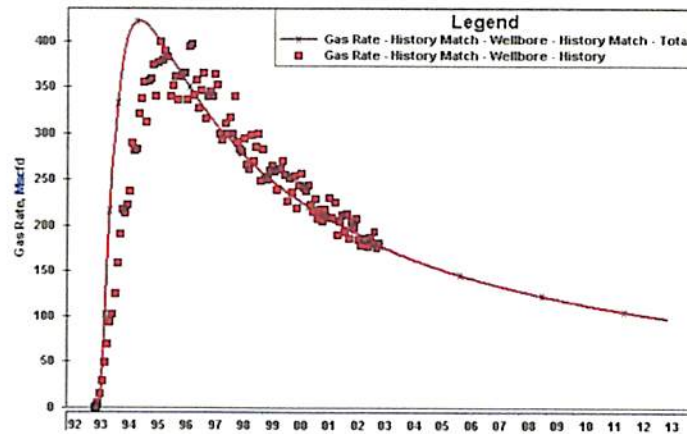
The water rate history match data from the Deliverability tab

Figure 38-Comparison of water rate
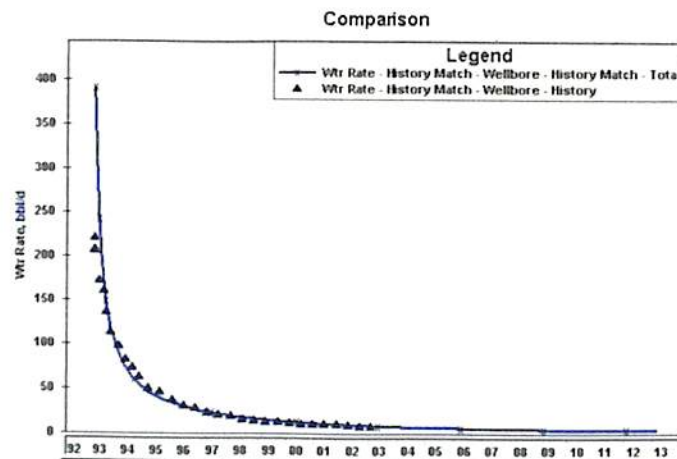
3.1.6 Decline Analysis

Traditional decline analysis can be performed on the production data by using the Decline Tab.

Select Gas Analysis 1 from the current analysis drop down menu.

An exponential model from the analysis parameters menu

Data entry

Decline Exponent (b)	0.000
Nominal Decline Rate (D)	0.099
Effective Decline Rate (D_e)	9.43 %
Start Date	14-02-2003 DD-MM-YYYY
Initial Rate (q_i)	0.178 MMscfd
End Date	16-03-2032 DD-MM-YYYY
Final Cumulative Production	1.563 Bscf
Final Rate (q_f)	0.010 MMscfd

Rate v/s Cumulative production

Figure 39- Rate vs Cumulative Production
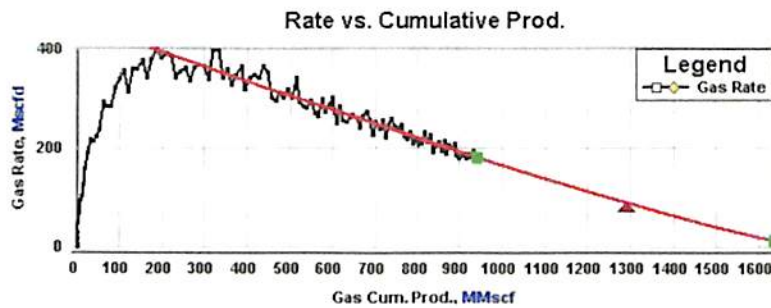
Rate v/s Time

Figure 40-Rate vs Time
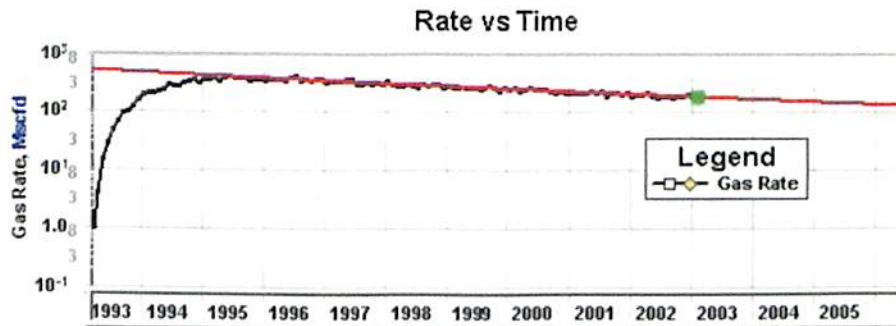
Output

Initial cumulative production (Q_i)	0.943 Bscf
Expected Ultimate Recoverable (E.U.R.)	1.563 Bscf
Recoverable Remaining (R.R)	0.620 Bscf
Last Production Date (T_o)	14-02-2003 DD-MM-YYYY
Gas Cumulative Production (G_p)	0.943 Bscf
Oil Cumulative Production (N_p)	0.0 Mbbl
Water Cumulative Production (W_p)	130.7 Mbbl

3.1.7 Material balance

A material balance analysis is performed under the Material Balance tab.
The King material balance method:
In order to perform a material balance, production data along with shut in pressure data must be supplied. As data points are entered, the plot will display the data and an analysis line

Input Data for Static Material Balance

Data Source	Date DD/MM/YYYY	Pressure Psi(a)	Gp Gas Production MMscf	Wp Water Production Mbbl
Production Data	08/10/1993	1600.0	7.876	36.8
Production Data	10/11/1997	1250.0	484.084	109.1
Production Data	13/10/2000	1000.0	766.824	123.6
Production Data	14/02/2003	900.0	937.934	130.4

Figure 41-P/Z* vs Cumulative Gas produced
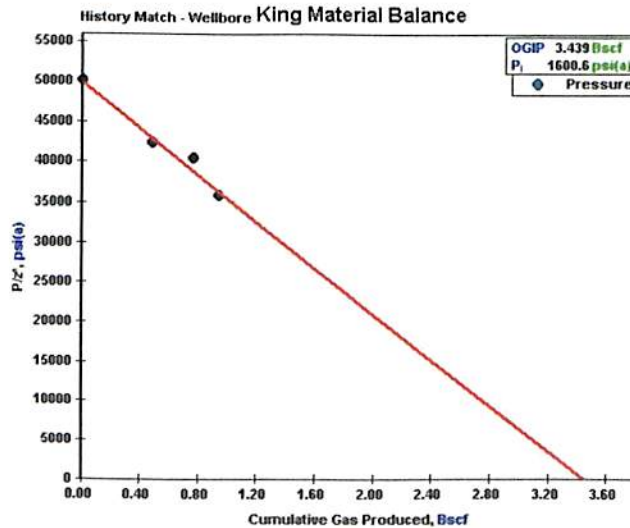
OUTPUT

Original Gas in Place OGIP	3.439 Bscf
Initial Desorption Pressure	1600.0 psia
Area	178.03 acres

4. Conclusion & Recommendations

4.1 Conclusion

Oil has been the major source of energy for the past many decades. But the formation of oil is much slower a process as compared to its consumption. Due to theis there is an ever increasing gap between energy and supply. It is important that new energy sources be tapped and extracted efficiently. Now the demand for gas is rising. Coalbed methane gas is an unconventional source of gas. In India there is high potential for CBM. A CBM project is very risky. The production of gas starts much after the production of water, and it might so happen that the production of gas is very less. It is thus very important to first estimate the reserves as accurately as possible and then exploit the CBM with efficient and economic methods. Gas content of the coal seams must be estimated as it is the most important parameter deciding the reserves. The methods mentioned in the report are used for the reserve estimation of CBM. CBM has the potential to decrease the energy gap to some extend. It is high time that CBM is given importance.

4.2 Recommendations

- Minimize the land area impacted by development

The impact of large numbers of wells and associated roads and pipelines can be reduced by locating several wells on one well pad and directionally drilling, where this is technically feasible. Wells can then be concentrated along a development corridor, limiting land fragmentation. It is technically possible to use directional drilling technologies to access a large underground area from a single well pad. Horizontal drilling from the base of the well bore, ' which is one type of directional drilling, has been used to access CBM in several areas in the US, although it may be difficult where there are many thin coal seams. If four wells are drilled directionally from one central pad, the area of land impacted is about 40% of the area affected by four separate wells. Any request for more than one well per section should be carefully scrutinized and a company should be required to evaluate the technical and economic feasibility for multiple wells from one well pad, to keep the number of well pads per section to a minimum.

Review the cumulative impacts of dewatering non-saline aquifers

It is essential to protect non-saline aquifers as these may be required for human use. Since there will be a relatively high density of wells to access CBM there could be widespread impacts as a result of dewatering coal seams in or adjacent to the groundwater protection zone (that is. where the water is non-saline, or close to the non-saline zone). This will likdy occur irrespective of whether single wells are drilled or multiple wells are drilled directionally from a single pad. A review of the regional impacts of this dewatering is essential. A company should be required to provide baseline data on the hydrology of the area, including a risk assessment of potential impacts. If test wells show the potential for widespread effects on non-saline water' aquifers as a result of dewatering.

• Evaluate the optimum method to use/dispose of different grades of non-saline water

A company that wishes to dispose of saline or marginal non-saline water from CBM wells should be required to seek synergies with the conventional oil and gas industry, where large quantities of non-saline water are being used for well d r i l l i n g and especially for enhanced recovery of oil. Where possible the CBM water should be used instead of non-saline water. The government would need to provide some guidelines to industry (for example, the radius within which the potential utilization of CBM-produced water should be investigated) and should verify that a company has fully investigated this potential use of the water.

• Avoid or minimize venting and flaring

Every effort must be made to eliminate or minimize venting and flaring, to reduce air pollution and greenhouse gas emissions. Every effort should be made to avoid or minimize the venting of methane, both to protect air quality and to minimize greenhouse gas emissions, since methane is far more potent than CO2 as a greenhouse gas. With a rapidly increasing number of CBM wells, venting even a small volume of methane at each well will increase methane emissions and make it more difficult to reach greenhouse gas reduction targets.

• Prevent and respond to problems associated with gas migration

While some gas migration occurs naturally, the potential for gas migration from CBM projects should be assessed. Dewatering the coal seams may sometimes result in the migration of methane previously trapped under pressure. While in genera' the methane will migrate to the CBM well bore, where pumping creates the lowest pressure, it may find other routes to the surface. This may occur via natural pathways through fractures

in the rock. Methane may also migrate to the surface through conventional wells in the vicinity that have not been properly cased or abandoned. This is a particular problem with old wells.

As part of the recommended precautionary approach, a company should be required to assess the risk of gas migration prior to starting a CBM project. A geological assessment of the strata should indicate if gas migration is likely. A company should be required to indicate what measures will be taken to monitor for and mitigate gas migration and the probability that these measures will be successful. This information should be provided as part of the project application and be clear, transparent and publicly available.

5. REFERENCES

1. A Guide to Coalbed Methane Operations, Copyright © 1992 by Gas Research Institute, By Vicki A. Hollub, Taurus Exploration, Inc. (Birmingham, Alabama), Paul S. Schafer, Schafer Associates (Oxford, Ohio)

2. A Guide To Coalbed Methane Reservoir Engineering, Published by Gas Research Institute Chicago, Illinois, U.S.A. Printed in the U.S.A. GRI Reference No. GRI-94/0397.

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ANNEXURE A

Date & Time	Gas Rate (Mcfd)	Water Rate (bbl/d)	Wellhead Pressure (psi(a))	Fluid Level (ft)
03-06-1993 08:09	0	207	55	20
03-07-1993 08:41	0	220	55	220
03-08-1993 09:15	0	219	59	170
03-10-1993 10:24	0	206	46	180
03/14/1993 12:42	0	198	41	170
03/22/1993 17:19	1	207	50	170
04-08-1993 02:32	4	214		160
05-08-1993 14:32	15	172		220
06-08-1993 02:32	28	160		160
07-08-1993 14:32	49	160		240
08-08-1993 02:32	69	136		180
09-07-1993 14:32	93	145		180
10-08-1993 02:32	102	113		220
11-07-1993 14:32	125	110		230
12-08-1993 02:32	159	115		200
01-07-1994 14:32	191	97		180
02-07-1994 02:32	217	107	41	160
03-09-1994 14:32	213	98	50	210
04-09-1994 02:32	222	82	47	160
05-09-1994 14:32	237	84	43	170
06-09-1994 02:32	290	73	48	230

07-09-1994 14:32	282	72	60	160
08-09-1994 02:32	283	68	52	160
09-08-1994 14:32	321	70	44	170
10-09-1994 02:32	338	62	50	170
11-08-1994 14:32	355	61	49	130
12-09-1994 02:32	312	56	41	140
01-08-1995 14:32	357	57	54	160
02-08-1995 02:32	359	49	55	150
03-10-1995 14:32	375	47	42	130
04-10-1995 02:32	340	50	43	180
05-10-1995 14:32	377	44	46	160
06-10-1995 02:32	400	45	56	130
07-10-1995 14:32	380	45	60	180
08-10-1995 02:32	390	41	47	170
09-09-1995 14:32	383	44	53	160
10-10-1995 02:32	340	36	47	140
11-09-1995 14:32	352	39	43	160
12-10-1995 02:32	362	37	40	140
01-09-1996 14:32	336	31	42	120
02-09-1996 02:32	362	31	45	130
03-10-1996 14:32	366	34	40	160
04-10-1996 02:32	365	34		170
05-10-1996 14:32	337	30		170
06-10-1996	395	29		120

02:32				
07-10-1996 14:32	397	29		140
08-10-1996 02:32	342	28		170
09-09-1996 14:32	358	25		160
10-10-1996 02:32	327	27		160
11-09-1996 14:32	347	28		150
12-10-1996 02:32	365	26	58	20
01-09-1997 14:32	316	25	49	20
02-09-1997 02:32	340	22	48	20
03-11-1997 14:32	345	23	41	20
04-11-1997 02:32	340	23	42	20
05-11-1997 14:32	364	21	43	20
06-11-1997 02:32	353	22	53	20
07-11-1997 14:32	299	22	50	20
08-11-1997 02:32	293	20	58	20
09-10-1997 14:32	311	19	42	20
10-11-1997 02:32	299	20	46	20
11-10-1997 14:32	317	19	54	20
12-11-1997 02:32	299	19	43	20
01-10-1998 14:32	340	19	43	20
02-10-1998 02:32	291	18	57	20
03-12-1998 14:32	283	16	56	20
04-12-1998 02:32	280	17	55	20
05-12-1998 14:32	295	15	50	20

06-12-1998 02:32	267	15	42	20
07-12-1998 14:32	262	17	47	20
08-12-1998 02:32	298	17	44	20
09-11-1998 14:32	270	15	54	20
10-12-1998 02:32	286	15	58	20
11-11-1998 14:32	299	13	47	20
12-12-1998 02:32	249	15	47	20
01-11-1999 14:32	283	13	53	20
02-11-1999 02:32	253	15	50	20
03/13/1999 14:32	250	13	53	20
04/13/1999 02:32	260	12	47	20
05/13/1999 14:32	265	12	49	70
06/13/1999 02:32	259	12	60	60
07/13/1999 14:32	239	13	41	70
08/13/1999 02:32	262	13	42	70
09-12-1999 14:32	270	12	54	60
10/13/1999 02:32	255	11	54	60
11-12-1999 14:32	226	11	58	70
12/13/1999 02:32	252	11	52	70
01-12-2000 14:32	236	12	57	70
02-12-2000 02:32	254	11	41	80
03/13/2000 14:32	219	11	45	60
04/13/2000 02:32	244	11	57	60
05/13/2000	257	11		80

14:32				
06/13/2000 02:32	241	10		50
07/13/2000 14:32	238	10		70
08/13/2000 02:32	244	9	45	50
09-12-2000 14:32	222	10	43	60
10/13/2000 02:32	215	10	54	80
11-12-2000 14:32	229	10	44	70
12/13/2000 02:32	207	10		80
01-12-2001 14:32	217	9		60
02-12-2001 02:32	205	9		80
3/14/2001 14:32	217	9		70
4/14/2001 02:32	208	8		70
5/14/2001 14:32	230	9		60
6/14/2001 02:32	209	8	53	70
7/14/2001 14:32	225	9	47	70
8/14/2001 02:32	189	8	49	80
9/13/2001 14:32	204	8	54	70
10/14/2001 02:32	211	9	49	70
11/13/2001 14:32	193	8	55	60
12/14/2001 02:32	212	8	47	80
1/13/2002 14:32	186	8	46	60
2/13/2002 02:32	203	7	48	70
3/15/2002 14:32	198	8	57	60
4/15/2002 02:32	207	7	41	80

5/15/2002 14:32	184	8	46	60
6/15/2002 02:32	178	7	60	60
7/15/2002 14:32	184	8	59	70
8/15/2002 02:32	186	7	52	80
9/14/2002 14:32	177	7	51	60
10/15/2002 02:32	187	6	57	60
11/14/2002 14:32	181	6	41	60
12/15/2002 02:32	193	7	42	60
1/14/2003 14:32	175	7	41	70
2/14/2003 02:32	180	7	50	60

ANNEXURE B

Date DD-MM-YYYY	Input qg Mscfd	Input qw bbl/d	Input Pwf psia	Input Gp MMscf	Input Wp Mbbl	Matched qg (Mscfd)	Matched qw (bbl/d)	Matched Pwf (psi(a))	Recovery factor
6/3/1993	0	207	55	0	0.2	0	391	55	0.00%
7/3/1993	0	220	55	0	0.4	0	387.7	55	0.00%
8/3/1993	0	219	59	0	0.9	0	383.5	59	0.00%
10/3/1993	0	206	46	0	1.7	0	380.2	46	0.00%
14-03-1993	0	198	41	0	3.4	0	368.8	41	0.00%
22-03-1993	1	207	50	0	6.7	0	343.1	50	0.00%
8/4/1993	4	214	49.2	0.1	13.3	0	302.3	49.2	0.00%
8/5/1993	15	172	48.4	0.6	18.5	0	242.8	48.4	0.02%
8/6/1993	28	160	47.5	1.4	23.4	41.5	201.3	47.5	0.04%
8/7/1993	49	160	46.7	2.9	28.3	102.3	171.3	46.7	0.08%
8/8/1993	69	136	45.9	5	32.4	162.3	148.9	45.9	0.15%
7/9/1993	93	145	45.1	7.9	36.8	216.1	131.7	45.1	0.23%
8/10/1993	102	113	44.3	11	40.3	262.3	118.2	44.3	0.32%
7/11/1993	125	110	43.5	14.8	43.6	300.7	107.2	43.5	0.43%
8/12/1993	159	115	42.6	19.7	47.2	332	98.2	42.6	0.57%
7/1/1994	191	97	41.8	25.5	50.1	357.1	90.7	41.8	0.74%
7/2/1994	217	107	41	32.1	53.4	376.9	84.4	41	0.93%
9/3/1994	213	98	50	38.6	56.4	391.9	78.3	50	1.12%
9/4/1994	222	82	47	45.4	58.9	403.2	73.8	47	1.32%
9/5/1994	237	84	43	52.6	61.4	411.5	69.8	43	1.53%
9/6/1994	290	73	48	61.4	63.7	417.2	65.8	48	1.79%
9/7/1994	282	72	60	70	65.9	420.6	62	60	2.04%
9/8/1994	283	68	52	78.7	67.9	422.5	59.4	52	2.29%
8/9/1994	321	70	44	88.5	70.1	423.2	57.1	44	2.57%
9/10/1994	338	62	50	98.8	72	422.8	54.3	50	2.87%
8/11/1994	355	61	49	109.6	73.8	421.5	52.1	49	3.19%

9/12/1994	312	56	41	119.1	75.5	419.7	50.3	41	3.46%
8/1/1995	357	57	54	130	77.3	417	47.9	54	3.78%
8/2/1995	359	49	55	141	78.8	413.9	46.1	55	4.10%
10/3/1995	375	47	42	152.4	80.2	410.8	44.9	42	4.43%
10/4/1995	340	50	43	162.8	81.7	407.3	43.3	43	4.73%
10/5/1995	377	44	46	174.3	83.1	403.5	41.7	46	5.07%
10/6/1995	400	45	56	186.5	84.4	399.3	40	56	5.42%
10/7/1995	380	45	60	198.1	85.8	395	38.6	60	5.76%
10/8/1995	390	41	47	209.9	87	391.1	37.8	47	6.10%
9/9/1995	383	44	53	221.6	88.4	386.8	36.5	53	6.44%
10/10/1995	340	36	47	232	89.5	382.8	35.6	47	6.75%
9/11/1995	352	39	43	242.7	90.7	378.7	34.7	43	7.06%
10/12/1995	362	37	40	253.8	91.8	374.7	33.8	40	7.38%
9/1/1996	336	31	42	264	92.8	370.6	32.8	42	7.68%
9/2/1996	362	31	45	275.1	93.7	366.5	31.8	45	8.00%
10/3/1996	366	34	40	286.2	94.7	362.5	31.1	40	8.32%
10/4/1996	365	34	42	297.4	95.8	358.5	30.2	42	8.65%
10/5/1996	337	30	44	307.6	96.7	354.5	29.4	44	8.94%
10/6/1996	395	29	46	319.7	97.6	350.6	28.6	46	9.30%
10/7/1996	397	29	48	331.8	98.5	346.6	27.8	48	9.65%
10/8/1996	342	28	50	342.2	99.3	342.8	27.1	50	9.95%
9/9/1996	358	25	52	353.1	100.1	338.9	26.4	52	10.27%
10/10/1996	327	27	54	363.1	100.9	335.1	25.7	54	10.56%
9/11/1996	347	28	56	373.7	101.8	331.4	25	56	10.87%
10/12/1996	365	26	58	384.8	102.5	327.7	24.4	58	11.19%
9/1/1997	316	25	49	394.5	103.3	324.4	24.1	49	11.47%
9/2/1997	340	22	48	404.8	104	321	23.6	48	11.77%
11/3/1997	345	23	41	415.4	104.7	317.8	23.2	41	12.08%
11/4/1997	340	23	42	425.7	105.4	314.6	22.7	42	12.38%
11/5/1997	364	21	43	436.8	106	311.3	22.2	43	12.70%

11/6/1997	353	22	53	447.6	106.7	307.9	21.5	53	13.02%
11/7/1997	299	22	50	456.7	107.4	304.8	21.1	50	13.28%
11/8/1997	293	20	58	465.7	108	301.4	20.5	58	13.54%
10/9/1997	311	19	42	475.1	108.6	298.9	20.5	42	13.82%
11/10/1997	299	20	46	484.3	109.2	295.8	20	46	14.08%
10/11/1997	317	19	54	493.9	109.7	292.7	19.4	54	14.36%
11/12/1997	299	19	43	503.1	110.3	290.1	19.2	43	14.63%
10/1/1998	340	19	43	513.4	110.9	287.4	18.9	43	14.93%
10/2/1998	291	18	57	522.3	111.4	284.2	18.2	57	15.19%
12/3/1998	283	16	56	530.9	111.9	281.4	17.9	56	15.44%
12/4/1998	280	17	55	539.5	112.5	278.8	17.6	55	15.69%
12/5/1998	295	15	50	548.5	112.9	276.3	17.4	50	15.95%
12/6/1998	267	15	42	556.6	113.4	274	17.2	42	16.18%
12/7/1998	262	17	47	564.6	113.9	271.4	16.8	47	16.42%
12/8/1998	298	17	44	573.7	114.4	269	16.6	44	16.68%
11/9/1998	270	15	54	581.9	114.9	266.3	16.1	54	16.92%
12/10/1998	286	15	58	590.6	115.3	263.7	15.7	58	17.17%
11/11/1998	299	13	47	599.8	115.7	261.7	15.7	47	17.44%
12/12/1998	249	15	47	607.4	116.2	259.4	15.4	47	17.66%
11/1/1999	283	13	53	616	116.6	256.9	15	53	17.91%
11/2/1999	253	15	50	623.7	117	254.8	14.8	50	18.14%
13-03-1999	250	13	53	631.3	117.4	252.5	14.5	53	18.36%
13-04-1999	260	12	47	639.3	117.8	250.5	14.4	47	18.59%
13-05-1999	265	12	49	647.3	118.2	248.4	14.1	49	18.82%
13-06-1999	259	12	60	655.2	118.5	245.9	13.7	60	19.05%
13-07-1999	239	13	41	662.5	118.9	244.5	13.8	41	19.26%
13-08-1999	262	13	42	670.5	119.3	242.4	13.6	42	19.50%
12/9/1999	270	12	54	678.8	119.7	240.1	13.2	54	19.74%
13-10-1999	255	11	54	686.5	120	238.1	13	54	19.96%
12/11/1999	226	11	58	693.4	120.4	236	12.7	58	20.16%

13-12-1999	252	11	52	701.1	120.7	234.3	12.6	52	20.39%
12/1/2000	236	12	57	708.3	121.1	232.2	12.3	57	20.60%
12/2/2000	254	11	41	716.1	121.4	231	12.4	41	20.82%
13-03-2000	219	11	45	722.7	121.7	229.1	12.2	45	21.01%
13-04-2000	244	11	57	730.2	122.1	226.9	11.8	57	21.23%
13-05-2000	257	11	54	738	122.4	225.2	11.7	54	21.46%
13-06-2000	241	10	51	745.4	122.7	223.6	11.6	51	21.67%
13-07-2000	238	10	48	752.6	123	222	11.4	48	21.88%
13-08-2000	244	9	45	760.1	123.3	220.4	11.3	45	22.10%
12/9/2000	222	10	43	766.8	123.6	218.8	11.2	43	22.30%
13-10-2000	215	10	54	773.4	123.9	216.8	10.9	54	22.49%
12/11/2000	229	10	44	780.4	124.2	215.6	10.9	44	22.69%
13-12-2000	207	10	45.3	786.7	124.5	214	10.7	45.3	22.88%
12/1/2001	217	9	46.6	793.3	124.8	212.4	10.5	46.6	23.07%
12/2/2001	205	9	47.9	799.6	125.1	210.8	10.4	47.9	23.25%
14-03-2001	217	9	49.1	806.2	125.3	209.2	10.2	49.1	23.44%
14-04-2001	208	8	50.4	812.5	125.6	207.7	10.1	50.4	23.63%
14-05-2001	230	9	51.7	819.6	125.8	206.2	9.9	51.7	23.83%
14-06-2001	209	8	53	825.9	126.1	204.6	9.8	53	24.02%
14-07-2001	225	9	47	832.8	126.4	203.4	9.7	47	24.22%
14-08-2001	189	8	49	838.6	126.6	201.9	9.6	49	24.38%
13-09-2001	204	8	54	844.8	126.9	200.3	9.4	54	24.57%
14-10-2001	211	9	49	851.2	127.1	199.1	9.3	49	24.75%
13-11-2001	193	8	55	857.1	127.4	197.5	9.1	55	24.92%
14-12-2001	212	8	47	863.6	127.6	196.5	9.1	47	25.11%
13-01-2002	186	8	46	869.2	127.9	195.2	9	46	25.27%
13-02-2002	203	7	48	875.4	128.1	193.8	8.9	48	25.46%
15-03-2002	198	8	57	881.5	128.3	192.2	8.7	57	25.63%
15-04-2002	207	7	41	887.8	128.5	191.5	8.8	41	25.82%
15-05-2002	184	8	46	893.4	128.8	190.1	8.6	46	25.98%

15-06-2002	178	7	60	898.8	129	188.2	8.3	60	26.14%
15-07-2002	184	8	59	904.4	129.2	187	8.2	59	26.30%
15-08-2002	186	7	52	910.1	129.4	186.1	8.2	52	26.46%
14-09-2002	177	7	51	915.5	129.7	184.9	8.1	51	26.62%
15-10-2002	187	6	57	921.2	129.8	183.5	8	57	26.79%
14-11-2002	181	6	41	926.7	130	182.9	8.1	41	26.95%
15-12-2002	193	7	42	932.6	130.2	181.8	8	42	27.12%
14-01-2003	175	7	41	938	130.5	180.7	7.9	41	27.28%
14-02-2003	180	7	50	943.4	130.7	179.2	7.7	50	27.43%

Begin Forecast

Date DD-MM-YYYY	qg (Mscfd)	Qw (bbl/d)	Gp (MMscf)	Wp (Mbbl)	Recovery factor
14-02-2003	179.2	7.7	1003.2	138	29.17%
14-03-2003	176.8	7.3	1003.6	138.1	29.18%
14-04-2003	175.4	7.2	1008.6	138.3	29.33%
14-05-2003	174.3	7.1	1013.8	138.5	29.48%
14-06-2003	173.1	7	1019.2	138.7	29.64%
14-07-2003	172	6.9	1024.4	138.9	29.79%
14-08-2003	170.9	6.9	1029.7	139.1	29.94%
14-09-2003	169.8	6.8	1035	139.3	30.10%
14-10-2003	168.7	6.7	1040.1	139.5	30.24%
14-11-2003	167.7	6.7	1045.3	139.7	30.40%
14-12-2003	166.6	6.6	1050.3	139.9	30.54%
14-01-2004	165.6	6.5	1055.4	140.1	30.69%
14-02-2004	164.5	6.5	1060.6	140.3	30.84%
14-03-2004	163.6	6.4	1065.3	140.5	30.98%
14-04-2004	162.5	6.3	1070.4	140.7	31.13%
14-05-2004	161.6	6.3	1075.2	140.9	31.26%
14-06-2004	160.6	6.2	1080.2	141.1	31.41%
14-07-2004	159.6	6.2	1085	141.3	31.55%
14-08-2004	158.7	6.1	1090	141.5	31.70%
14-09-2004	157.7	6	1094.9	141.7	31.84%
14-10-2004	156.8	6	1099.6	141.9	31.97%
14-11-2004	155.9	5.9	1104.4	142	32.11%
14-12-2004	155	5.9	1109.1	142.2	32.25%
14-01-2005	154	5.8	1113.9	142.4	32.39%
14-02-2005	153.2	5.8	1118.6	142.6	32.53%

14-03-2005	152.3	5.7	1122.9	142.7	32.65%
14-04-2005	151.5	5.7	1127.6	142.9	32.79%
14-05-2005	150.6	5.6	1132.2	143.1	32.92%
14-06-2005	149.8	5.5	1136.8	143.3	33.06%
14-07-2005	148.9	5.5	1141.3	143.4	33.19%
14-08-2005	148.1	5.4	1145.9	143.6	33.32%
14-09-2005	147.2	5.4	1150.5	143.8	33.45%
14-10-2005	146.4	5.3	1154.9	143.9	33.58%
14-11-2005	145.6	5.3	1159.4	144.1	33.71%
14-12-2005	144.8	5.3	1163.8	144.2	33.84%
14-01-2006	144	5.2	1168.2	144.4	33.97%
14-02-2006	143.2	5.2	1172.7	144.6	34.10%
14-03-2006	142.5	5.1	1176.7	144.7	34.22%
14-04-2006	141.8	5.1	1181.1	144.9	34.34%
14-05-2006	141	5	1185.3	145	34.47%
14-06-2006	140.3	5	1189.7	145.2	34.59%
14-07-2006	139.5	4.9	1193.9	145.3	34.72%
14-08-2006	138.8	4.9	1198.2	145.5	34.84%
14-09-2006	138	4.9	1202.5	145.6	34.97%
14-10-2006	137.3	4.8	1206.6	145.8	35.09%
14-11-2006	136.6	4.8	1210.9	145.9	35.21%
14-12-2006	135.9	4.7	1214.9	146.1	35.33%
14-01-2007	135.2	4.7	1219.2	146.2	35.45%
14-02-2007	134.5	4.7	1223.3	146.3	35.57%
14-03-2007	133.9	4.6	1227.1	146.5	35.68%
14-04-2007	133.2	4.6	1231.2	146.6	35.80%
14-05-2007	132.5	4.5	1235.2	146.8	35.92%
14-06-2007	131.8	4.5	1239.3	146.9	36.04%
14-07-2007	131.2	4.5	1243.3	147	36.15%
14-08-2007	130.5	4.4	1247.3	147.2	36.27%
14-09-2007	129.9	4.4	1251.3	147.3	36.39%
14-10-2007	129.2	4.4	1255.2	147.4	36.50%
14-11-2007	128.6	4.3	1259.2	147.6	36.62%
14-12-2007	128	4.3	1263.1	147.7	36.73%
14-01-2008	127.3	4.3	1267	147.8	36.84%
14-02-2008	126.7	4.2	1271	148	36.96%
14-03-2008	126.1	4.2	1274.6	148.1	37.06%
14-04-2008	125.5	4.1	1278.5	148.2	37.18%
14-05-2008	124.9	4.1	1282.3	148.3	37.29%

14-06-2008	124.3	4.1	1286.1	148.5	37.40%
14-07-2008	123.7	4.1	1289.9	148.6	37.51%
14-08-2008	123.1	4	1293.7	148.7	37.62%
14-09-2008	122.5	4	1297.5	148.8	37.73%
14-10-2008	121.9	4	1301.2	149	37.84%
14-11-2008	121.4	3.9	1304.9	149.1	37.94%
14-12-2008	120.8	3.9	1308.6	149.2	38.05%
14-01-2009	120.2	3.9	1312.3	149.3	38.16%
14-02-2009	119.7	3.8	1316	149.4	38.27%
14-03-2009	119.2	3.8	1319.4	149.5	38.37%
14-04-2009	118.6	3.8	1323	149.7	38.47%
14-05-2009	118.1	3.8	1326.6	149.8	38.58%
14-06-2009	117.5	3.7	1330.2	149.9	38.68%
14-07-2009	117	3.7	1333.8	150	38.78%
14-08-2009	116.4	3.7	1337.4	150.1	38.89%
14-09-2009	115.9	3.6	1341	150.2	38.99%
14-10-2009	115.4	3.6	1344.5	150.3	39.10%
14-11-2009	114.9	3.6	1348	150.5	39.20%
14-12-2009	114.3	3.6	1351.5	150.6	39.30%
14-01-2010	113.8	3.5	1355	150.7	39.40%
14-02-2010	113.3	3.5	1358.5	150.8	39.50%
14-03-2010	112.9	3.5	1361.7	150.9	39.60%
14-04-2010	112.3	3.5	1365.2	151	39.70%
14-05-2010	111.9	3.4	1368.5	151.1	39.79%
14-06-2010	111.4	3.4	1372	151.2	39.90%
14-07-2010	110.9	3.4	1375.3	151.3	39.99%
14-08-2010	110.4	3.4	1378.8	151.4	40.09%
14-09-2010	109.9	3.3	1382.2	151.5	40.19%
14-10-2010	109.4	3.3	1385.5	151.6	40.29%
14-11-2010	108.9	3.3	1388.8	151.7	40.38%
14-12-2010	108.5	3.3	1392.1	151.8	40.48%
14-01-2011	108	3.2	1395.5	151.9	40.58%
14-02-2011	107.5	3.2	1398.8	152	40.67%
14-03-2011	107.1	3.2	1401.8	152.1	40.76%
14-04-2011	106.6	3.2	1405.1	152.2	40.86%
14-05-2011	106.2	3.2	1408.3	152.3	40.95%
14-06-2011	105.7	3.1	1411.6	152.4	41.05%
14-07-2011	105.3	3.1	1414.8	152.5	41.14%
14-08-2011	104.9	3.1	1418	152.6	41.23%

14-09-2011	104.4	3.1	1421.3	152.7	41.33%
14-10-2011	104	3.1	1424.4	152.8	41.42%
14-11-2011	103.5	3	1427.6	152.9	41.51%
14-12-2011	103.1	3	1430.7	153	41.60%
14-01-2012	102.7	3	1433.9	153	41.70%
14-02-2012	102.3	3	1437.1	153.1	41.79%
14-03-2012	101.9	3	1440	153.2	41.87%
14-04-2012	101.4	2.9	1443.2	153.3	41.97%
14-05-2012	101	2.9	1446.2	153.4	42.05%
14-06-2012	100.6	2.9	1449.3	153.5	42.14%
14-07-2012	100.2	2.9	1452.3	153.6	42.23%
14-08-2012	99.8	2.9	1455.4	153.7	42.32%
14-09-2012	99.4	2.8	1458.5	153.8	42.41%
14-10-2012	99	2.8	1461.5	153.8	42.50%
14-11-2012	98.6	2.8	1464.6	153.9	42.59%
14-12-2012	98.2	2.8	1467.5	154	42.67%
14-01-2013	97.8	2.8	1470.6	154.1	42.76%
14-02-2013	97.4	2.8	1473.6	154.2	42.85%
14-03-2013			1476.2	154.3	42.93%