

RESERVOIR ENGINEERING FOR GEOLOGISTS

Coalbed Methane Fundamentals

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Historically, gas emissions from coal have been a nuisance and a safety hazard during coal mining operations, causing numerous explosions and deaths. But today, coalbed methane (CBM) is an increasingly important source of the world's natural gas production with many countries, including Canada, actively developing this unconventional energy source.

Currently, CBM accounts for 10% of U.S. natural gas production with the size of the resource (OGIP) estimated at 700 TCF. The most active areas of production are the San Juan Basin in New Mexico, the Powder River Basin in NE Wyoming/SE Montana, and the Black Warrior Basin in Alabama.

In Canada, CBM is still in the early stages of development, yet it already accounts for about 1% of total gas production. The Western Canada Sedimentary Basin contains the majority of Canada's estimated 600 TCF of CBM resource potential. Formations of greatest interest are the Mannville, which tends to produce water as well as gas (a "wet" coal) and the Horseshoe Canyon, which usually produces gas with virtually no water (a "dry" coal).

In general, coal is classified into four main types depending on the quantity and types of carbon it contains as well as the amount of heat energy it can produce. These are:

1. Lignite (brown coal) – the lowest rank of coal; used as fuel for electric power generation.
2. Sub-bituminous coal – properties range between lignite and bituminous coal.
3. Bituminous coal – a dark brown to black, dense mineral; used primarily as fuel in steam-electric power generation.
4. Anthracite – the highest rank; a harder, glossy, black coal used primarily for residential and commercial space heating; it may be divided further into petrified oil, as from the deposits in Pennsylvania.

Note that graphite, which is metamorphically altered bituminous coal, is technically the highest rank of coal. However, it is not commonly used as fuel because it is difficult to ignite.

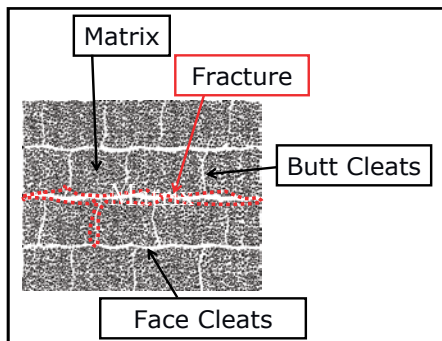


Figure 1. Coal is a dual porosity system.

COAL CHARACTERISTICS

Coals are recognized on geophysical logs because of several unique physical properties. The coals typically have very low gamma, low density, and high resistivity values.

Similar to conventional naturally fractured reservoirs, coal is generally characterized as a dual-porosity system because it consists of a matrix and a network of fractures (Figure 1). For both groups, the bulk of the in-place gas is contained in the matrix. However, matrix permeability is generally too low to permit the gas to produce directly through the matrix to the wellbore at significant rates.

In a naturally fractured system, most of the produced gas makes its way from the matrix to the fracture system to the wellbore. If the well has been hydraulically frac'd, gas may

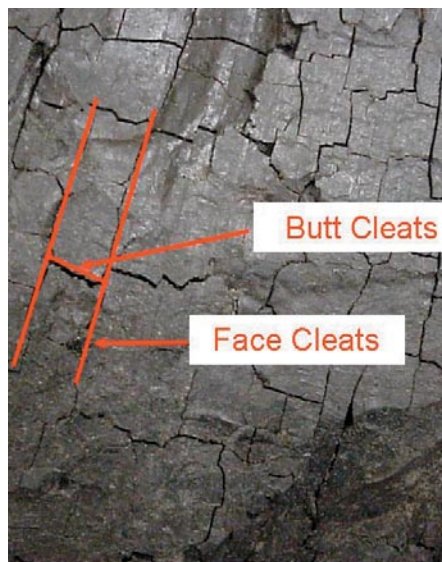


Figure 2. Example of coal cleat structure.

also travel from the natural fracture system to the man-made fracture system to the wellbore. With both conventional naturally fractured reservoirs and CBM reservoirs, the natural fracture system has high permeability, relative to matrix permeability, but very limited storage capacity.

In coal terminology, natural fractures are called "cleats". The cleat structure consists of two parts: face cleats and butt cleats (Figure 2). Face cleats are typically continuous fractures that go across the reservoir. They are considered the main pathway for gas production.

Butt cleats are discontinuous, perpendicular to the face cleats and generally act as a feeder network of gas into the face cleats.

The effective porosity, permeability, and water saturation are all properties of the coal "cleat" system. Since coal permeability is a property of the cleat space, it is affected by the structure and characteristics of the cleat network, e.g., the dominant fracture orientation, fracture continuity, frequency, and width.

The effective permeability of the cleat system is also influenced by the contrast between face and butt cleat permeability. CBM reservoirs are generally considered to be anisotropic systems, where the effective permeability is the geometric average of face and butt cleat permeability. Permeability anisotropy creates elliptical drainage areas and should be taken into account when placing wells in CBM development projects.

DIFFERENCES WITH CONVENTIONAL RESERVOIRS

A good starting point to understanding the production characteristics of coalbed methane reservoirs is by considering the differences to conventional gas production. The most significant differences are:

- In a conventional reservoir, the majority of the gas is contained in the pore space but in a CBM reservoir, the majority of the gas is adsorbed (bonded to the coal molecules) in the matrix.
- In a conventional reservoir, reservoir gas expands to the producing wells in direct response to any production-induced

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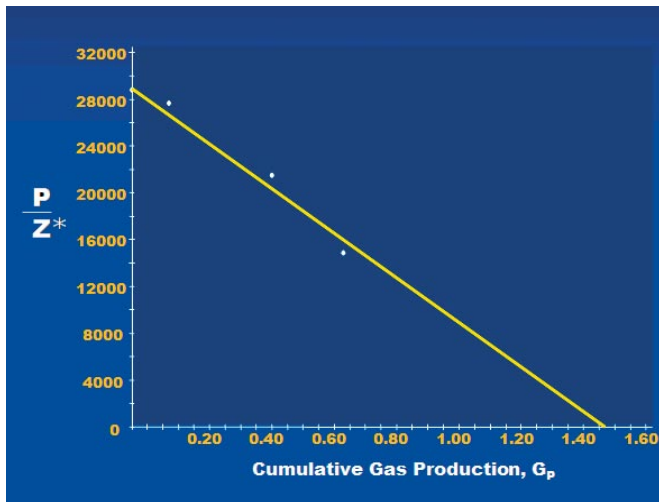


Figure 3. Conventional gas P/Z plot.

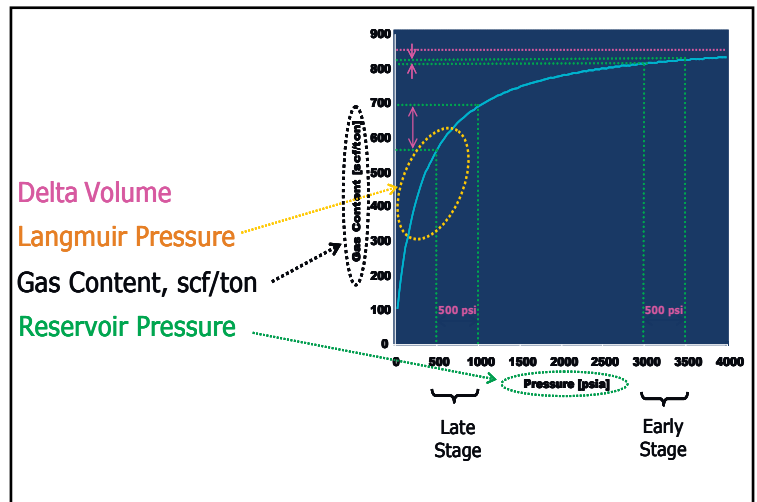


Figure 4. Comparison of desorption volumes with changes in reservoir pressure.

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pressure gradient. But CBM reservoirs generally require that reservoir pressure be below some threshold value to initiate gas desorption.

- In a CBM reservoir, a gas molecule must first desorb and diffuse through the coal matrix to a cleat. It can then move through the cleated fracture system and the hydraulic frac-stimulation to the wellbore via conventional Darcy flow.

CBM GAS STORAGE CAPABILITY

The primary storage mechanism in CBM reservoirs is adsorption of gas by the coal matrix. Matrix surface area, reservoir pressure, and the degree to which the coal is gas saturated are the factors that determine the in-place gas volume of a coal. Note that the smaller the coal particle size, the larger the surface area.

The complete gas-in-place volumetric equation for a CBM reservoir is:

$$OGIP = A \cdot h \cdot \rho_b \cdot GC_i + \frac{A h \phi_i (1 - S_{wi})}{B_{gi}}$$

Where:

- A is drainage area,
- h is net pay,
- ρ_b is bulk density,
- GC_i is initial Gas Content,
- ϕ_i is porosity,
- S_{wi} is initial water saturation
- B_{gi} is initial formation volume factor.

The first term represents the adsorbed gas in the matrix while the second term is the free gas in the cleats. Since the pore volume in CBM reservoirs is in the order of 1% of the total volume, the free gas contribution to the total in-place gas volume is negligible.

As with all volumetric estimates, uncertainty

in the input data creates a range of possible outcomes for OGIP. Some common areas of uncertainty for CBM projects include:

- The gas content of the coal,
- The degree of heterogeneity and complexity contained in CBM reservoirs,
- The impact of modelling complex multi-layer coal/non-coal geometries with simple one- or two-sequence models.

CBM GAS DESORPTION

While the relationship between pressure decline and gas production is essentially a straight line in a conventional reservoir (Figure 3), the depletion profile in a CBM reservoir is distinctly non-linear. For a given pressure drop, a CBM reservoir will desorb significantly more gas when the starting reservoir pressure is low compared to when reservoir pressure is high (Figure 4).

If the initial reservoir pressure is significantly greater than the pressure required to initiate desorption (the coal is under-saturated), and water is initially present in the cleat system, then the initial production period may produce only water without any gas (Figure 5). Depending on the degree of under-saturation, dewatering can last from a few months to two or three years and can significantly affect the economics of the prospect.

If initial reservoir pressure is equal to the critical desorption pressure (the coal is gas-saturated), then gas production will start as soon as reservoir pressure begins to decrease. This situation most often applies to “dry” coals but can also apply to saturated “wet” coals.

The equation that is commonly used to describe the relationship between adsorbed

gas and free gas as a function of pressure is known as the Langmuir isotherm. The isotherm is determined experimentally and measures the amount of gas that can be adsorbed by a coal at various pressures. The Langmuir isotherm is stated as:

$$V = V_L \frac{P}{P_L + P}$$

Where:

- V_L , the Langmuir Volume, is the gas content of the coal when reservoir pressure approaches infinity.
- P_L , the Langmuir Pressure, is the pressure corresponding to a gas content that is half ($1/2$) of the Langmuir volume. The steepness of the isotherm curve at lower pressures is determined by the value of P_L .

CBM gas consists primarily of methane (CH_4) but may also contain lesser percentages of carbon dioxide (CO_2) and nitrogen (N_2). As coal has the strongest affinity for nitrogen and the weakest affinity for carbon dioxide, the three gases adsorb/desorb at different rates from coal (Figure 6). Thus, it is not uncommon for the CO_2 content of the produced gas to decrease as gas is produced and reservoir pressure depletes.

CBM GAS TRANSPORT MECHANISMS

After desorbing from the coal, gas in a CBM reservoir uses diffusion to travel through the coal matrix to the cleat system. The time required to diffuse through the matrix to a cleat is controlled by the gas concentration gradient, the gas diffusion coefficient, and the cleat spacing. In general, greater concentration gradients, larger diffusion coefficients, and tighter cleat spacing all act to reduce the required travel time.

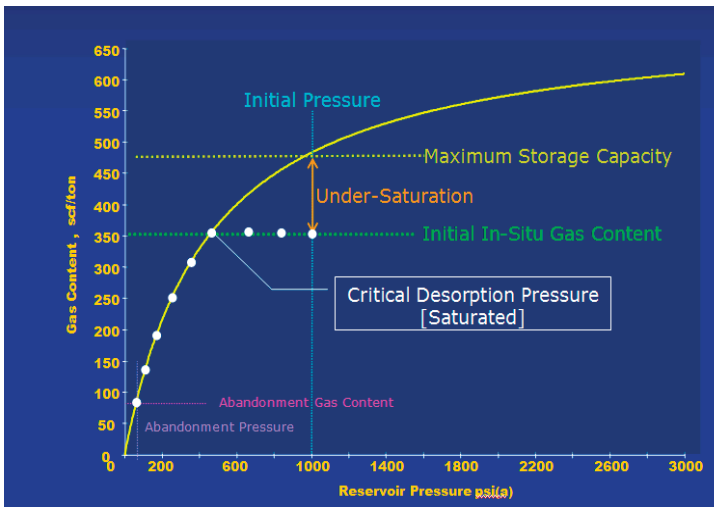


Figure 5. Desorption behaviour of under-saturated CBM reservoirs.

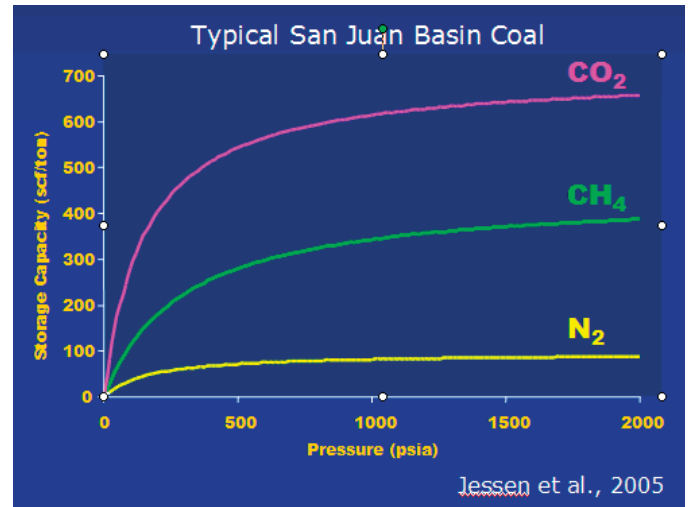


Figure 6. CBM gas storage capacities for N₂, CH₄, and CO₂.

On reaching a cleat, gas then travels the remaining distance to the wellbore by conventional Darcy flow. Since flow in a CBM reservoir is generally two-phase flow, fluid saturation changes in the cleat system and consequent changes in relative permeabilities become important.

As the gas is produced from a CBM reservoir, two distinct and opposing phenomena occur that affect the absolute permeability of the cleat system:

1. As reservoir pressure decreases, it reduces the pressure in the cleats. Cleat effective stress (which is the difference between overburden stress and pore pressure) increases and compresses the cleats, causing cleat permeability to decrease.
2. As gas desorbs from the coal matrix, the matrix shrinks. Shrinkage causes the space within the cleats to widen and the permeability of the cleats increases.

From the Langmuir isotherm (Figure 4), the amount of gas desorbed for a given pressure drop is relatively small at high pressures. Thus in the early stages of production, the compaction effect is the dominant factor and cleat permeability will tend to decrease slightly. As production continues and gas recovery becomes significant, matrix shrinkage will dominate and increase cleat permeability.

In “wet” coals, changes in the relative permeability of the cleat system with changes in water and gas saturation must be considered in the Darcy flow equation to correctly predict well performance. As illustrated by a typical set of relative permeability curves (Figure 7), the relative permeability to gas increases with decreasing water saturation and vice versa.

CBM WELL PERFORMANCE

The production of CBM wells can be

generally divided into three separate phases (Figure 8):

- Dewatering phase (for under-saturated reservoirs): In this phase, no gas is produced (excepting in the transient near wellbore region or in complex reservoirs)
- Negative decline: Water production continues to decline while gas production increases.
- Production in this phase is generally dominated by the relative permeability of gas and water.
- Decline phase: Declining reservoir pressure is now the dominating factor although its impact is mitigated to some extent by a shrinking matrix and increasing cleat permeability. Nonetheless, the gas production rate declines as in conventional gas reservoirs, albeit at a slower rate of decline.

The water production forecast looks similar

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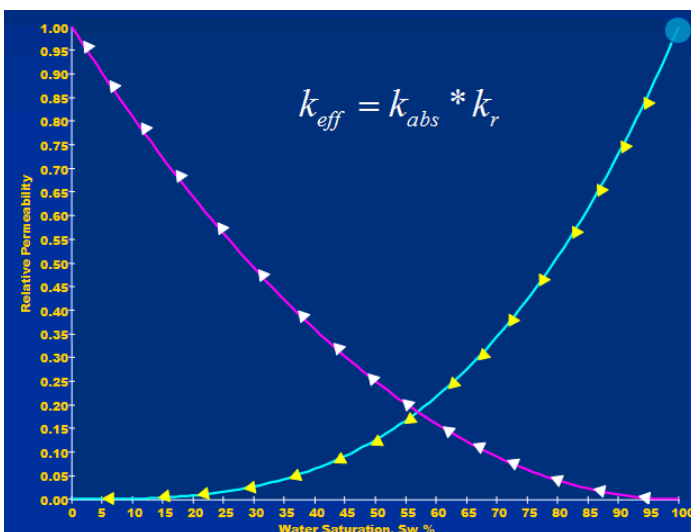


Figure 7. Relative permeability to gas and water.

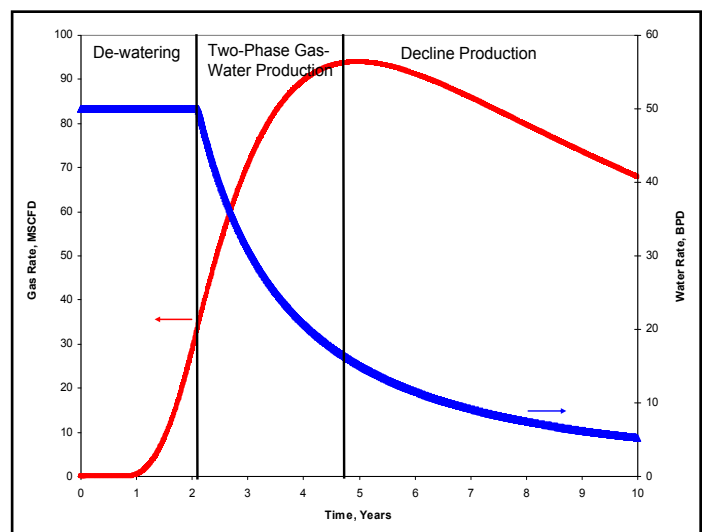


Figure 8. CBM well production profile.

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to a production forecast for a conventional water producing reservoir. Maximum water production rates are achieved initially but decline thereafter through a combination of reservoir pressure depletion and decreasing relative permeability to water.

The gas production profile displays both the initial, dormant period followed by an increasing production rate till it reaches a peak and then declines. Although reservoir pressure is monotonically declining through the life of the simulation well, it is counteracted during the inclining production period by increases in the relative permeability to gas and in the absolute permeability of the cleats.

As the water saturation approaches its minimum value, declining reservoir pressure dominates and the well goes into the decline phase of its producing life. During this time period, the declining production trend resembles conventional gas production. Note that a "dry" CBM reservoir exhibits only the declining portion of the production pattern.

Given the scope and complexity of the

inputs for CBM reservoirs, simulation is generally required to predict the deliverability and cumulative production of CBM wells. As improvements in drilling, completion and production techniques advance, CBM will continue to be an increasingly important source of natural gas.

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This article was contributed by Fekete Associates, Inc. For more information, contact Lisa Dean at Fekete Associates, Inc.



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