DISSERTATION

To Study the Effect of Coal Rank and Porosity on the Optimization of ECBM Recovery

by

Mohammad Sazwan bin Ismail

Dissertation submitted in partial fulfilment of
the requirements for the
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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
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Approved by,

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May 2013

CERTIFICATION OF ORIGINALITY

It is hereby to certify that I am responsible for the work submitted in this report and all the sources of information used in this report have been fully acknowledged.

(MOHAMMAD SAZWAN BIN ISMAIL)

To my beloved parents,

all of my friends,

and the lecturers…

ABSTRACT

Coal Bed methane (CBM) is naturally occurring methane (CH_4) with small amounts of other hydrocarbon and non-hydrocarbon gases being adsorbed in coal seam reservoirs as a result of chemical and physical processes. CBM is often produced at shallow depths and often produced with large volumes of water at the early stage of production. There are several factors that influence the production of CBM like porosity, permeability, coal rank, initial gas content, and natural fracture system but this study will be focusing on the effects of different coal ranks and coal porosity on the optimization of ECBM recovery (CO_2 injection). The injection of carbon dioxide (CO_2) will enhance the recovery of CBM and at the same time a very attractive option for CO_2 sequestration.This project is done by simulating the data of CBM basins obtained from available published research papers. A reservoir simulator ECLIPSE(E300) developed by Schlumberger will be used in this project. The results later will be compared and further analyzed to conclude the project outcomes. Based on the study and literature review conducted, it is expected that the outcomes of the result will indicates that the higher coal rank will be having higher gas content whereas the porosity of coalbed may not be directly proportional to the increasing of coal rank (maturity) or burial depth. In certain cases, the less deep coalbed tend to has higher porosity compared to the deepest coalbed. The macropores of coalbed mostly are made up of natural fractures, called cleats which highly dependent on coalbed stress. This has effect on the porosity and the permeability of the coalbed.

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CHAPTER 1

INTRODUCTION

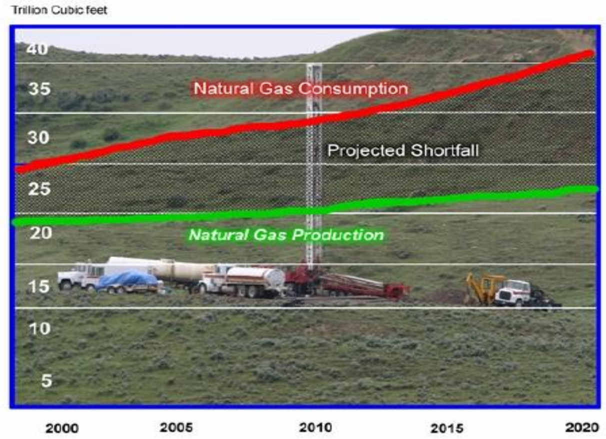
1.1 Background of Study

CBM is closely associated with coal seams that represent both the source rock and reservoir rock. Coal has immense amount of surface area which able to hold large volume of methane since coal seams have large internal surfaces to store six to seven times more gas than the equivalent rock's volume in a conventional gas reservoir (USGS, 1997). According to (Pinsker, 2002), coal can store six times the volume of natural gas found in conventional reservoirs. CBM exists in the coal seams in three basic states; as free gas, as the gas dissolved in the water in coal, and "adsorbed" gas on the surface of the coal. It consists mainly of methane (CH_4) with some amount of carbon dioxide, nitrogen, water vapour and heavier hydrocarbons like propane and butane.

CBM is considered as "sweet gas" as it does not contain hydrogen sulphide (H_2S) (Alberta Energy, 2007). CBM has become one of the important plays in the oil and gas industry since several decades back. CBM is also known as coal seam gas (CSG) or coal seam natural gas (CSNG). The names are used interchangeably which refer to any projects where coal is dewatered and the gas is produced to the surface but the coal is left underneath. During the second half of the 1990's CBM production has increased dramatically as an alternative new source of natural gas for many Western countries (CBM Primer, 2004).

Coals can contain up to seven times the amount of gas volume in conventional natural gas reservoir. Estimated reserves are about 7,500 Tcf globally, where 700 Tcf in United States alone (www.halliburton.com). According to (Ham and Kantzas, 2008), the total amount of CBM in-place reserves worldwide estimated to be between 3,500 to 95,000 Tcf (100 to 272 trillion m^3). This made CBM is to be considered one of the largest unconventional resources of fossil fuel. In the United States, total CBM in-place isestimated at 749 Tcf (21.4 trillion m³). As for Canada that has just begun producing gas from CBM, the estimated reserves are about 1,300 Tcf (37 trillion m³). As coal is a clean-burning energy source that suitable as fuel for electricity generation, residential or commercial heating, and vehicle fuel as in Compressed Natural Gas (CNG).

Figure 5 shows the natural gas consumption with respect to natural gas production in United States. CBM is expected to become more important as demand for natural gas is continuously increasing.



Over the next 20 years, U.S. natural gas consumption will grow by 50 percent. At the same time, U.S. natural gas production will grow by only 14 percent, if it grows at the same rate of the last 10 years.

Figure 1: U.S. Natural Gas Consumption and Production (CBM Primer, 2004)

The most common mineral to be found in coal for example illite clay, pyrite, quartz, and calcite are made up of the most common elements like oxygen, aluminum, silicon, iron, sulfur, and calcium. Minerals in coal commonly occur as single crystals or clusters of crystals that intermixed with organic matter that fill void spaces in the coal. The grains size range from submicroscopic to a few inches. In addition, methane-air mixture in the range of 5 to 15% would be explosive (Cervik, 1967).

1.1 Problem Statement

It is important to evaluate the potential of coalbed before it is put into commercial production in order to optimize the CBM recovery. The gas composition must be considered. For a CBM to be commercially marketable, the heating value must be around 1000 BTU/cuf. If the gas contains more than few percent of non-flammable gases such as Nitrogen (N_2) or Carbon Dioxide (CO_2), they need to be removed to achieve pipeline quality. Other than that, if the methane composition is less than 92% it may not commercially marketable (www.greenpowerenergy.com). This study will be focusing on the effect of different coal rank and coal porosity on the optimization of CBM recovery. Different coal ranks are having different porosity with respect to their depth and burial time (maturity). By knowing the effective porosity, we will be able to predict the storage capacity of the coalbed and its natural gas content. It is the best to evaluate the potential of coalbed with respect to their coal rank and porosity in other to optimize the production of CBM for marketable energy resource.

1.3 Objective and Scope of Study

The objectives of this study are:

- To study the effect of different coal rank on the optimization of ECBM recovery
- To investigate the impact of porosity on the optimization of ECBM recovery by using ECLIPSE (E300)simulator

The scope of study includes:

- Gathering data e.g. porosity, permeability, coal rank, coalbed depthfrom five different producing CBM basins around the world.
- Conducting a simulation by using ECLIPSE (E300)CBM model base on the data gathered
- Analyzing and interpreting the simulation results from ECLIPSE (E300)

CHAPTER 2

LITERATURE REVIEW

The study is focusing on the effect of different coal rank and porosity on the optimization of CBM recovery. Basically, this literature review will encompass the fundamental theory and concept related toCBM production on related fields.

2.0 Coal Formation

Coal formation began during the Carboniferous Period, known as the first coal age which spanned 360 million to 290 million years ago. The energy we get from coal today comes from the energy that plants absorbed from the sun million years ago. All living plants stored solar energy through a process known as photosynthesis. When the plants died, this energy is usually being released as the plants decayed. Under the conditions favorable to coal formation, the decaying process in interrupted, preventing the released of the stored energy, thus it is locked into the coal (worldcoal.org).

(Law and Rice, 1993) stated that coal is “the black rock that burns”. Coal is a sedimentary rock that had it origin on the surface of the earth as an accumulation of organic and inorganic debris. Coal starts off as peat (turf), an accumulation of partially decayed vegetation/plants like ancient woods, leaves, stems, twigs, seeds, spores, pollen, and other parts of aquatic and land plants. Later on, mare sediments are piled on the top of organic material, causing it to be buried and sank deeper into the sedimentary layer. These layer may be separated by clay or sand deposited during the breaks of accumulation cycle. Along the accumulation, organic processes begin to break the debris both physically and chemically.

Small insects, worms, and fungi break the debris into smaller pieces physically. As the peat solidifies, the small fragments formed are known as macerals. The peat is squeezed by overlying sediments, driving out its water content and being compacted into rock. Macerals are the particles of organic matter inherited from the remains of plant parts. This is important in determining coal quality.

Macerals are grouped into three main subdivisions: (1) vitrinite, (2) lipnitite, and (3) inertinite. These subdivisions are recognized by the American Society for Testing and Materials (ASTM, 1999).

Vitrinite which is the common maceral, results from the coalification of amorphous humic (decayed) plant material. It is also called pure coal, which sensitive to heat. It will become denser, tougher and more vitreous (glassy) as subjected to higher heat level deep inside the Earth. Index of the intensity of vitrinite has been used to determine the heat level or maturity of coals and organic matter. Liptinite develops from waxy or oily plant parts such as spores, algae, and resin. It is more enriched in hydrogen and produced larger amounts and higher grades of liquid fuel e.g. coal oil (kerosene) as it is rich in oily material, when subjected to destructive distillation than other coals. Inertinite consist of a group of common macerals formed from partially oxidized or burned plant cell walls. Fusinite or mineral charcoal is example of this group. Vitrinite-rich coals are shiny, black, clean, and subjected to conchoidal fracture like glass because of their even texture. Fusinite-rich coals, in contrast are similar to charcoal; dull, black, friable and dusty.

Chemically, the plants material is slowly transformed into simpler organic compounds that rich in carbon. These combined processes are called sedimentations as illustrated in Figure 1. After sedimentation, the peat is buried deeper and deeper while the pressure and heat continuously subjected to the formation. These slowly transform the peat into coal through the process of maturation or coalification. In general, to generate one foot of coal, it took approximately five feet of raw organic material.

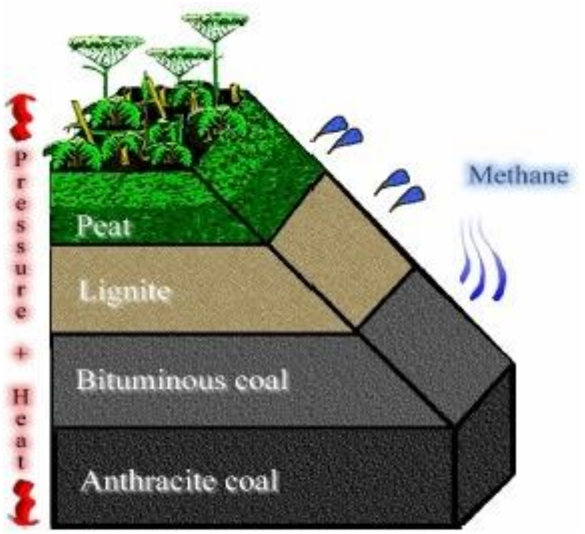


Figure 2: Sedimentation and Formation of Coal (CBM Primer, 2004)

2.1 Coal Rank

The type of plant materials, degree of metamorphism, and the range of impurity characterize the coal (Bates and Jackson, 1980). The degree of 'metamorphism' undergone by a coal, as it matures from peat to anthracite, which has an important bearing on the coal physical and chemical properties is referred as the 'rank' of the coal. Low rank coals, such as lignite and sub-bituminous is typically softer, friable materials with a dull, earthy appearance. They have high moisture levels and low carbon content, thus also low energy content. Higher rank coals are typically harder, often with black vitreous luster. Increasing in coal rank is alongside by a rise in the carbon and energy contents while the moisture content is decreasing. Anthracite is the top rank coal and has correspondingly higher carbon and energy content with lower level of moisture. The concept of coal rank is used to indicate the stage of alteration attained by a particular coal; the greater the alteration, the higher the coal rank. The transformation of peat to coal, known as "coalification" is a geothermal process and being dependent upon the effects of heat and pressure acting over periods of time. Figure 2 below illustrate the coalification processes.

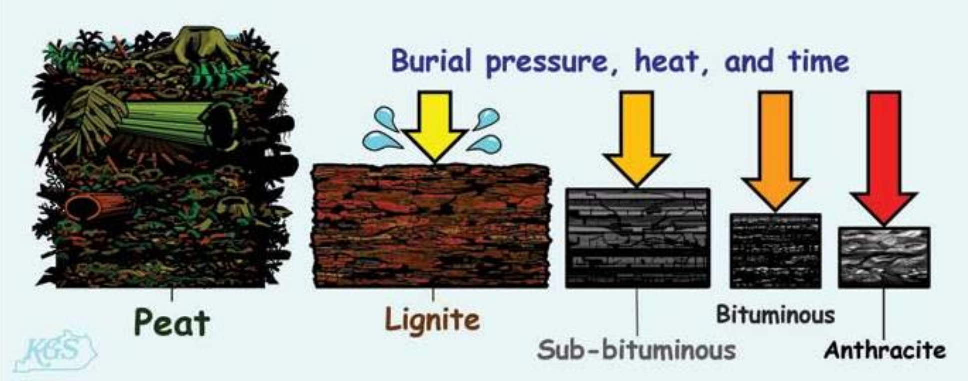


Figure 3: Classification and Rank of Coal (coal.infomine.com)

The figure above shows an increasing order of coal alteration. Coal starts off as peat. After a considerable amount of time, heat and burial pressure it is metamorphosed to lignite (brown coal immature). It is light in color and still soft. As the time passes, lignite increases in maturity by becoming darker and harder, classified as sub-bituminous coal. As the process continues, more chemical and physical changes occur and turn the coal into bituminous. The coal is now more dark and harder. Anthracite is the last stage where the coal has reaches ultimate maturation. This coal is very hard and shiny. Older coal tends to be on higher rank (mature) as they more likely to be buried more deeply for longer periods of time. To conclude, the higher the rank of a coal, the more deeply it was buried, therefore the higher the temperature and pressure it was subjected during and after burial. Each rank may be further subdivided as shown in Figure 3 above. Table 1 and Table 2 below described the physical and chemical properties of each coal rank.

Table 1: Physical Properties of Coal Rank (stovesonline.co.uk)

Coal Rank	Physical Properties
Peat	• Accumulation of partially decayed aquatic or land vegetation/plants • Soft formation and brownish in colour • The lowest rank of coal
Lignite (Brown coal)	• Brownish black • More like soil than a rock • Tends to disintegrate when exposed to weather
Sub-Bituminous	• More darker and harder than lignite • Also called black lignite
Bituminous	• Hard, dense, black coal • Bands of bright and dull material • The most common coal to be found
Anthracite	• Hardest, black and lustrous • The highest rank of coal

Table 2: Compositions of Coal Rank (undergroundcoal.com)

Coal Rank	Carbon Content (%)	Volatile Matter (%)	Calorific Value (kJ/kg)	Moisture Content (%)
Peat	60	>53	16 800	>75
Lignite (Brown Coal)	60 – 71	53 – 49	23 000	35
Sub-Bituminous	71 – 77	49 – 42	29 300	25 – 10
Bituminous	77 – 87	42 – 29	36 250	8
Anthracite	77 - 87	29 - 8	>36 250	< 8

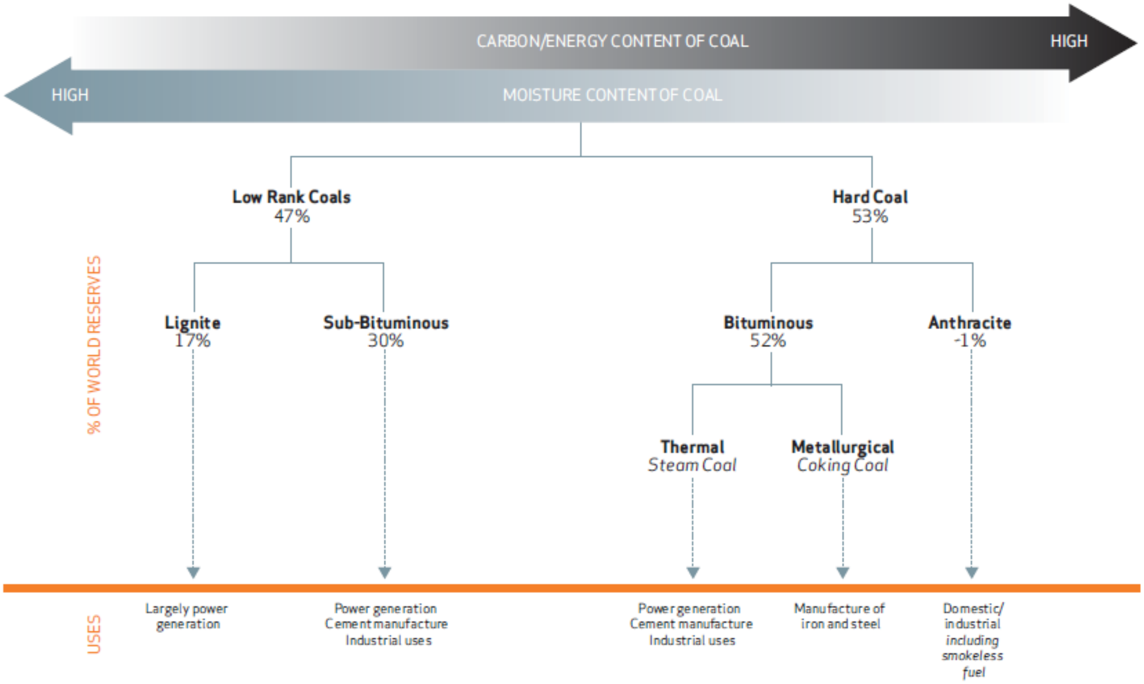


Figure 4: World's Coal Classification (worldcoal.org)

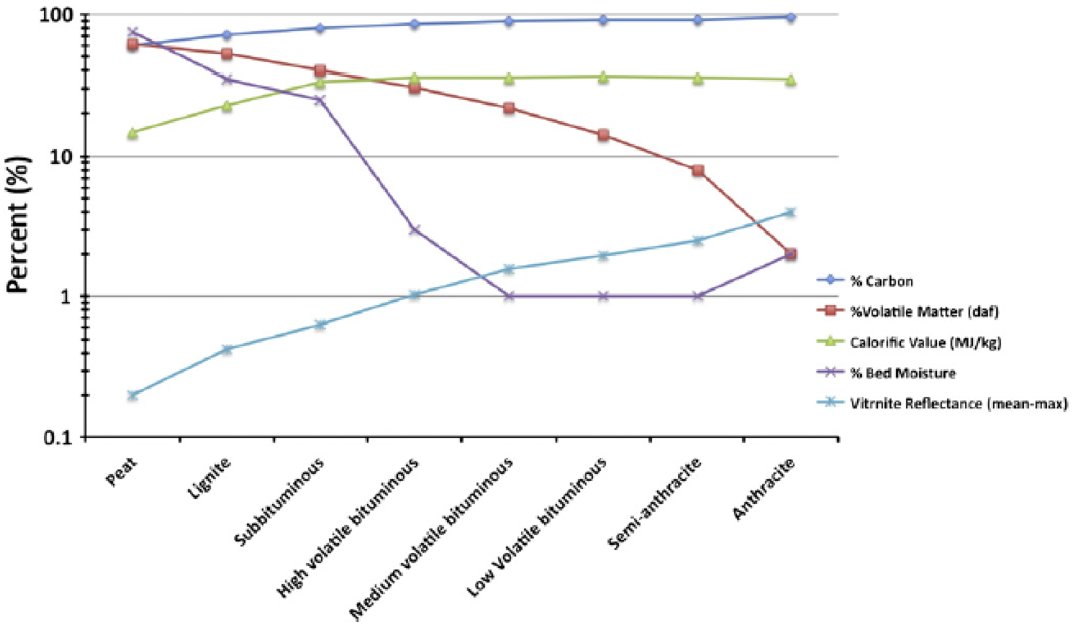


Figure 5: Coal Rank With Respect to Different Parameters (Moore, 2012)

There are many parameters can be used to estimate coal rank. Figure 5 shows some of the parameters that normally being used. By far the most accepted and preferable parameter is vitrinite reflectance, although this measurement can be influenced into giving incorrectly low or high readings because of original and secondary processes that acting on the coal (Newman and Newman, 1982).

As the rank of coal increases, the maximum gas holding capacity will also increase. This is due to lesser moisture content and higher porosity of the coal. However, the relationship between coal rank and gas properties neither be straightforward nor universal as there might be a doubt that rank is primarily influence on the maximum gas holding capacity of coal. General thought is that the mature the coal, the higher gas content (Hildenbrand et. al., 2006; Kim, 1977)shown in Figure 6.

Moisture content is very sensitive as the rank increases at the early stages of coalification (Figure 5). In common cases, moisture content decreases as the depth increases (Sivek et. al., 2010). It can be concluded that the higher gas holding capacity is due to the less moisture competing for methane adsorption sites at higher ranks (Bustin and Carkson, 1998; Crosdale et. al., 2008; Joulbert et. al., 1974; Ozdemir and Schroeder, 2009).For example in lignite, although it has abundant porosity, any gas produced (biogenically) would have less places to adsorb because the moisture content is relatively higher (>30%). Even slight changes in moisture content will significantly affect gas holding capacity.

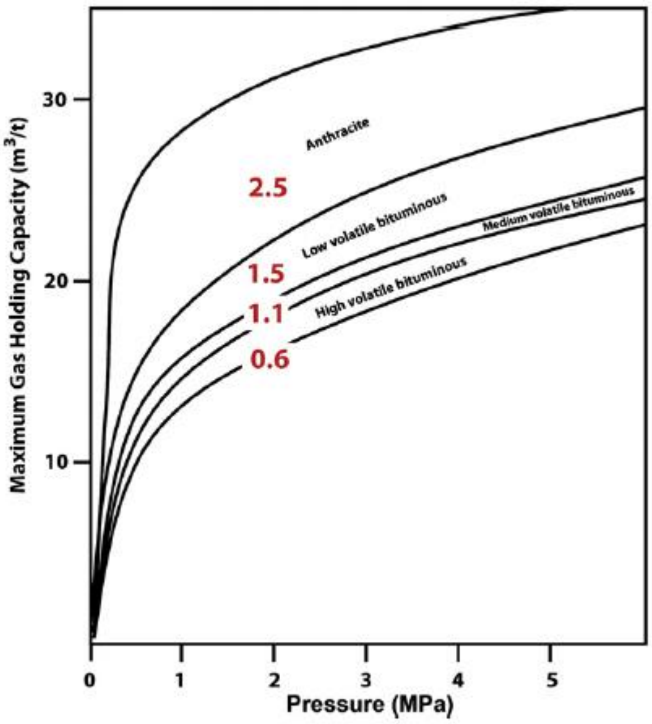


Figure 6: Adsorption Isotherms With Respect to Rank. Red Numbers Are Approximate Mean-maximum Vitrinite Reflectance (Kim, 1997)

2.3 Porosity

CBM is characterized by their unique dual porosity systems. They contain both primary (micropore and mesopore) and secondary (macropore) porosity systems (Law, 2002). Methane (CH_4) is trapped in coal pores either as a free gas or adsorbed in the matrix pores of the coal (Saleem et. al., 2012). The primary porosity system contains the most of the gas-in-place while the secondary porosity system provides the channel or conduit for gas movement into the wellbore. Methane (CH_4) is mainly stores in the primary gas storage by means of adsorption. It is trapped inside the porous media of the matrix. The matrix is relatively impermeable due to its fine size and the gas movement is dominated by diffusion.

The macropores or secondary storage is also known as the ‘cleat’. It can be subdivided into the face cleat, which is continuous throughout the coalbed and the butt cleat, which is discontinuous and terminates at the intersections with the face cleat (Syahrial E., 2005). Figure 7 shows the cleat orientation of the coal seams cleats.

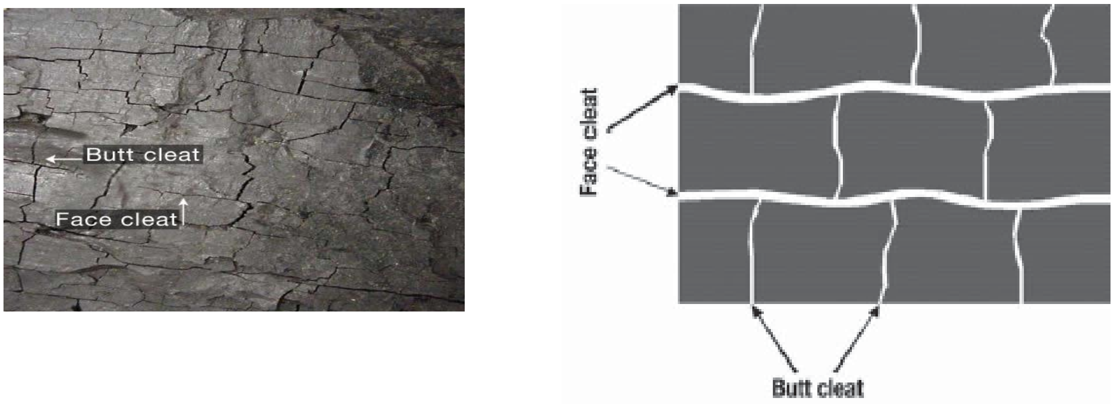


Figure 7: Cleats of the Coal Seams (undergroundcoal.com& Davidson et. al., 1995)

Underground coal is subjected to compression by overlying rock (overburden). This results in fractures or cleats within the coal. These cleats form an interconnected fracture network and allow water and gas to flow through the coal. Methane is held in place by the water pressure and when the water is produced, the gas will also flows through the fractures into wellbore and migrates to the surface (Youngson, 2007).

2.4 Estimated Gas Content

Prediction of gas content in coalbeds and the potential recovery has relied primarily on its relationship to coal’s rank, pressure, temperature, moisture and ash content, and methane adsorption capacity (Greg et. al., 1982). During the transformation of peat to lignite, a large quantity of biogenic methane is produced. From sub-bituminous through high-volatile bituminous, an additional 31cc/gm (1,000 cf/ton) of methane is generated. In the complete coalification of anthracite, 190-310 cc/gm (6,000-10,000 cf/ton) of methane is generated (Dolly &Meissner, 1977). In order to estimate the gas content, the adsorption capacity of specific rank of coal must be identified by constructing adsorption isotherms curves.

These curves as shown in Figure 8 were redrawn by (Kim, 1977) after correcting the temperature, ash and moisture content, and depth of burial was equated to pressure.

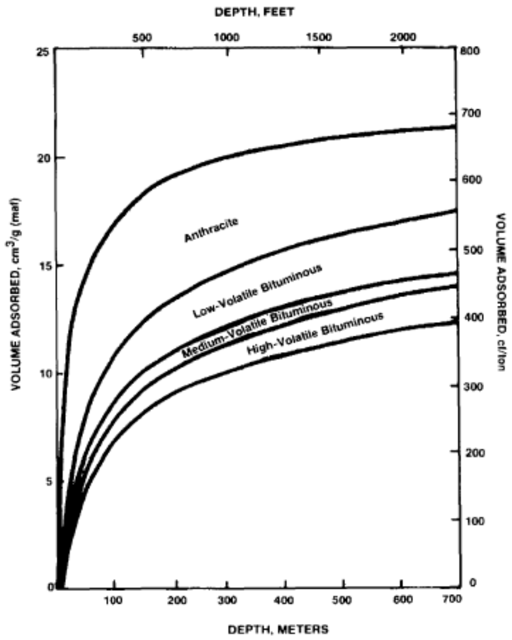


Figure 8: Estimated CH_4 Content According to Depth and Rank (Greg et. al., 1982)

Another method to determine the gas content is by “direct method” (Diamond & Levine, 1981) where the volume of gas in a coal sample is measured. A coal sample is collected, sealed in a container and the gas is measured as it desorbs. The lost gas of the sample from the time of coring until sealing can be calculated. After desorption is completed, the sample is crushed. The gas emitted is measured which is known as residual gas. An experiment was done to 397 coal samples and the percentage of residual gas from the total gas was calculated. The results are shown in Table 1 and plotted in Figure 9.

Table 3: Desorption Data Average (Greg et. al., 1982)

Coal Rank	Lost gas (cc/g)	Desorbed gas (cc/g)	Residual gas (cc/g)	Total gas (cc/g)	% Residual	No. of samples
Anthracite	0.98	8.10	0.61	9.69	6.31	9
Low-volatile bituminous	1.21	11.97	0.25	13.43	1.86	21
Medium-volatile bituminous	1.33	6.31	0.32	7.96	4.02	22
High-volatile A bituminous	0.21	2.77	1.38	4.36	31.65	217
High-volatile B bituminous	0.31	2.01	0.47	2.79	16.85	86
High-volatile C bituminous	0.12	1.09	0.07	1.28	5.47	42

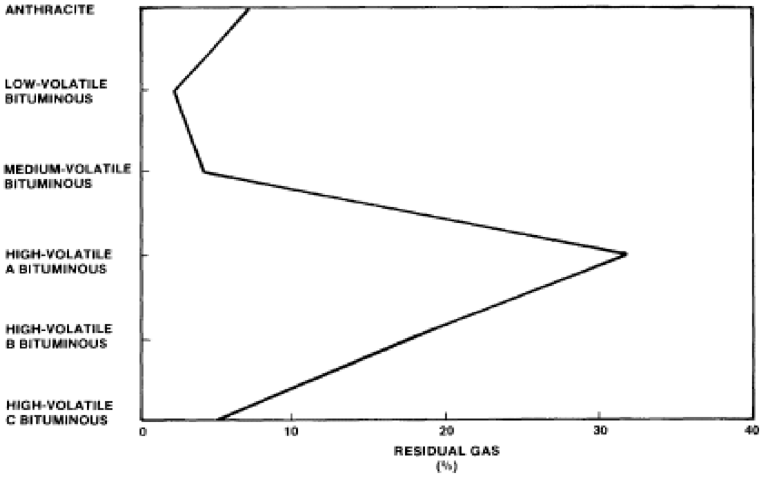


Figure 9: Residual Gas Content of Coal Rank (Greg et. al., 1982)

The best explanation of this correlation according to (Greg et. al., 1982) is that they are related to the porosity or internal surface area of the coal. Heat of wetting is used to measure the internal surface and it explains why the coal can contain more moisture and total gas as well as residual gas as the rank increases. If the internal surface area decreases above high-volatile A bituminous rank, then how can desorbed gas be greater or adsorption isotherms is higher for high rank coal. It is deduced that moisture content had interfered with desorption.

It has been shown to have an effect on adsorption isotherms (Joubert et. al., 1973). Moisture content up to 2.5% decreases the adsorption capacity as much as 40% in high-volatile bituminous coal, but only up to 15% in medium-volatile bituminous coal.

It is possible that the moisture content has caused higher residual gas content in high volatile A bituminous coal. This is probably due to change in internal structure of the coal. High-volatile A bituminous has reached the critical size or shape of pores which the moisture effectively block the pores. As the rank increases, the structure changes and the blocking effect decreases rapidly.

2.5 CBM Basins

In order to conduct the simulation study, there are some parameters and data need to be collected from different producing CBM basins around the world. This is later to be used when running the simulation model. Below are some backgrounds on the five chosen basins.

San Juan Basin

The San Juan Basin covers an area of about 7,500 square miles located near the Four Corners region of Colorado, New Mexico, Arizona and Utah (Figure 8). The basin measures roughly 100 miles in length in the north-south direction and 90 miles in width. The foremost coal-bearing unit in the basin is known as the Fruitland formation where CBM production occurs predominantly. Individual coalbeds average from 20 to over 40 feet thick. The total net thickness of the coalbeds ranges from 20 to over 80 feet across the basin. Typical CBM wells in the San Juan Basin range from 550 to 4,000 feet in depth, and about 2,550 wells are currently producing (COGCC and NM OCD, 2001). The San Juan Basin is the most productive CBM basin in the North America. The average production averages about 800 Mscf/day for each well (Stevens et. al., 1996). Production began in the late 1980's and rapidly expanded through the 1990's but no longer increasing. In 2000, the basin produced 0.78 Tcf of gas, which is 4% of total U.S natural gas production and 8% of the nation's CBM production.

It is the fastest growing field where large amounts of coal seams contain enormous amounts of methane due to unusual thickness (CBM Primer, 2004).

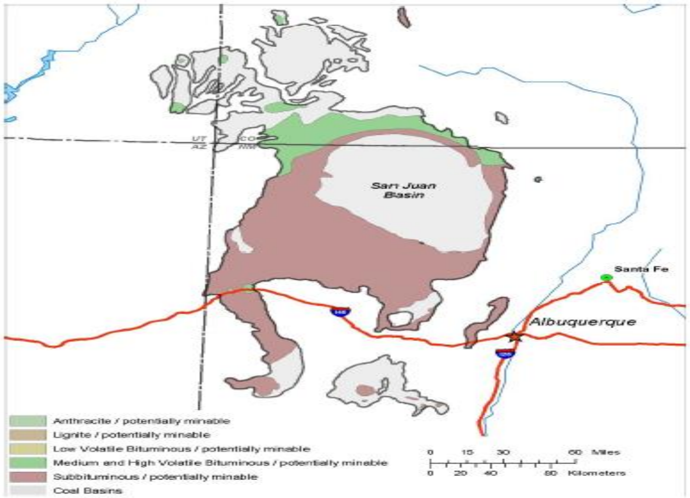


Figure 10: Location map of San Juan Basin (CBM Primer, 2004)

Powder River Basin

The Powder River Basin is located in north-eastern Wyoming and south-eastern Montana (Figure9). The basin covers an area of approximately 25,800 square miles, 75% is in Wyoming. 50% of the basin has the potential for CBM production. The coalbeds in this area are overlying with sandstones and shale. The basin formed mainly from Cretaceous and tertiary rocks although some Paleozoic and older Mesozoic rocks are also present. Some of the Upper Cretaceous and most of the tertiary strata are continental origin. Coal seams are developed on younger formations of the Fort Union (Paleocene) and Wasatch (Eocene) (Matthew, 2003). The majority of productive zones range from 150 feet to 1,850 feet underground (Randall, 1991). The uppermost formation is the Wasatch Formation, extending from surface to 1,000 feet depth. Most of the coalbeds are continuos but thinner (six feet or less). The Fort Union Formation lies directly below Wasatch Formation, about 3,000 feet. The coals in this formation are usually more plentiful in the upper portion, namely the Tongue River member.

The thickness of individual coal seams is over 150 feet. CBM production is predominantly from the Fort Union rather than Wasatch.According to (Matthew, 2003) coals in both formations are low sulphur and low rank (lignite-bituminous) and sorbed gas contents are usually lower than 100 scf/ton. The formations are naturally fractured and permeability are quite well. Absolute permeability estimation is high, about 10mD to several Darcys. The primary cleats system (face and butt) are often present.

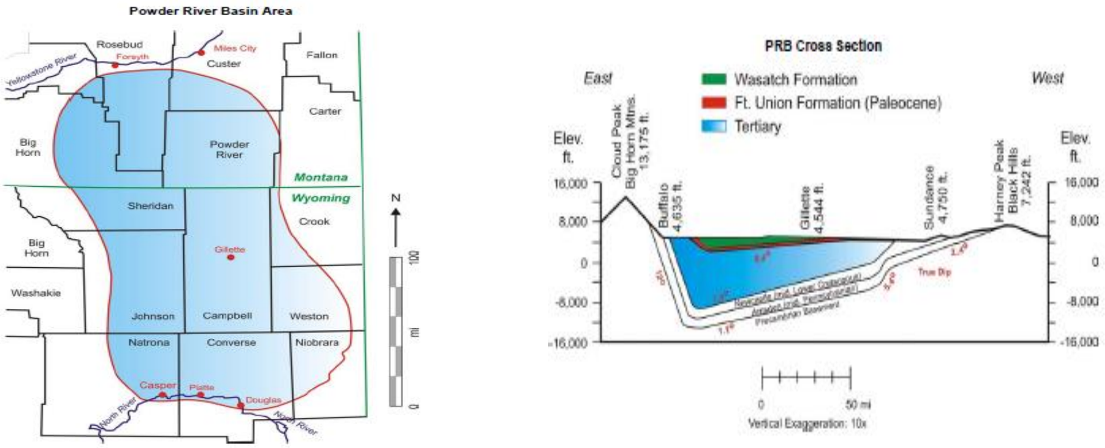


Figure 11: Powder River basin area and cross section (SPE 84427)

Qinshui Basin

At present, China is both the largest consumer and producer of coal in the world (Dai et al., 2012) and much attention has been focused on the origin, distribution, and production of coalbed methane (CBM). As China has gradually expanded its investment in the development of coalbed methane fields in recent years, the number of drilling and producing wells has increased markedly. From 1980 to 2004, only 287 CBM wells had been drilled (Sun, 2005). However, the number of drilled CBM wells by August 2010 had grown to 4657, among of which more than 3700 were producing wells (Sun et al., 2010). The Qinshui Basin was the earliest coal-bearing basin in China to be commercially developed for CBM, and currently the highest production in the country.

It is considered as basins with high-ranking of CBM in the world. The exploration is done by China United Coalbed Methane Co. Ltd., PetroChinaCoalbed Methane Company Ltd., and LanyanCoalbed Methane Co. Ltd. High recovery of CBM wells have been completed in Panzhuang, Sizhuang, and Fanzhuang I the souther area. The maximum production is up to 16,000 m³/d and a stable average production of 2,000 to 3,000 m³/d (CainengZou et. al., 2011).

The Qinshui Basin is located in the south-central part of Shanxi Province. In the carboniferous-Permian period, Indosinian movement especially Yanshan, elevated and denuded the strata after coal-bearing sediments were extensively deposited on the Permian HuabeiCraton. This results in a severalsLatepaleozoic residual basins, including Qinshui Basin. The Qinshui Basin covers an area of 23.5 × 10^3 km^2 and is bounded to the south by the Zhongtiaoshan Uplift, to the east by the Taihangshan Uplift, to the north by the Wutaishan Uplift, and to the west, the basin is separated from the Linfen Basin and the Lvliangshan Uplift by the Huoshan Uplift (Figure 9; Cai et al., 2011, Liu et al., 2010, Ye, 2009 and Zhang, 2004). The long axis of the basin is more than 330 km long and is generally aligned northeast-southwest and (Zhang, 2004). The basin is a large synclinorium with bilateral symmetry (Liu et al., 2010 and Zhang, 2004).

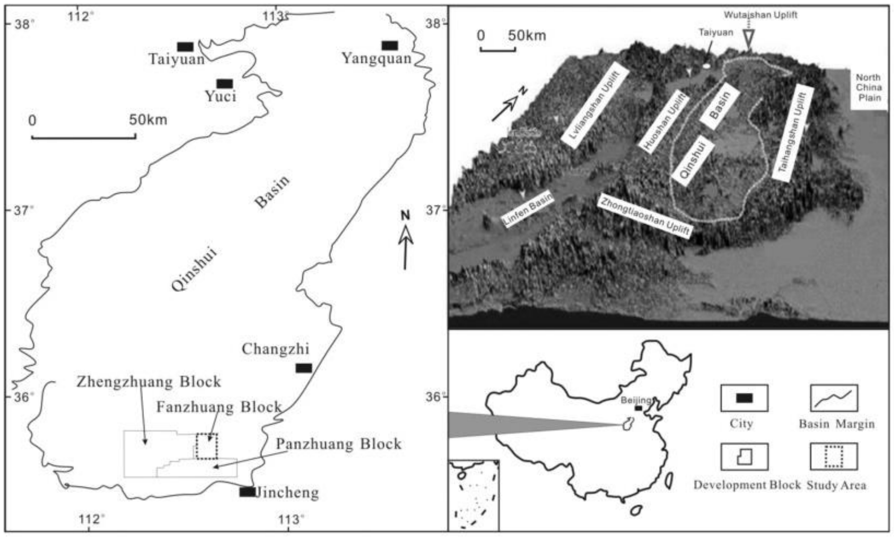


Figure 12: Qinshui Basin map (www.sciencedirect.com)

Zonguldak Basin

The **Zonguldak basin** of North Western Turkey has been mined for coal since the late 1800s. The basin takes its' name after Zonguldak (city and capital of Zonguldak Province). The Zonguldak is the only basin in Turkey with minable coal deposits. Geographically, the Zonguldak is roughly elliptical in shape with its long axis oriented roughly SW – NE, and is adjacent to the Black Sea. Three main regions have been recognized in the Zonguldak basin. These are the Armutcuk, the Zonguldak, and the Amasra from west to east respectively (Sinayuc&Gumrah, 2009).

The Zonguldak basin first experienced deposition in the Ordovician (Yalsin&Yilmaz, 2010). Deposition begins with the lower Ordovician Soḡuksu Formation. The Soḡuksu Formation ranges from 700 m to 1100 m thick. At its' base it consists of green shale and sandstone and coarsens upwards to arkosic conglomerates. The lower Ordovician Aydos Formation conformably overlies the Soḡuksu. It is a conglomerate of quartzitic sandstone and ranges in thickness from 50–200 m. The Findikli Formation was deposited during the upper Ordovician, Silurian, and lower most Devonian in the Zonguldak basin. It ranges from 300 – 450 m thick. Its' facies are indicative of a mixed siliclastic – carbonate shelf environment that is shallowing through time.According to (Sinayuc&Gumrah, 2008), Bartin-Amasra coal field was found convenient for enhanced coalbed methane (CBM) recovery among other fileds in Zonguldak Basin. The initial gas content were estimated using probabilistic simulations which resulted; possible reserve (P10): 72.92 bscf, probable reserve (P50): 47.74 bscf, and proven reserve (P90): 30.46 bscf. The Amasra reservoir is not saturated with water and almost 10% of the gas exists as cleat's free gas. Figure 11 shows the Zonguldak Basin structure.

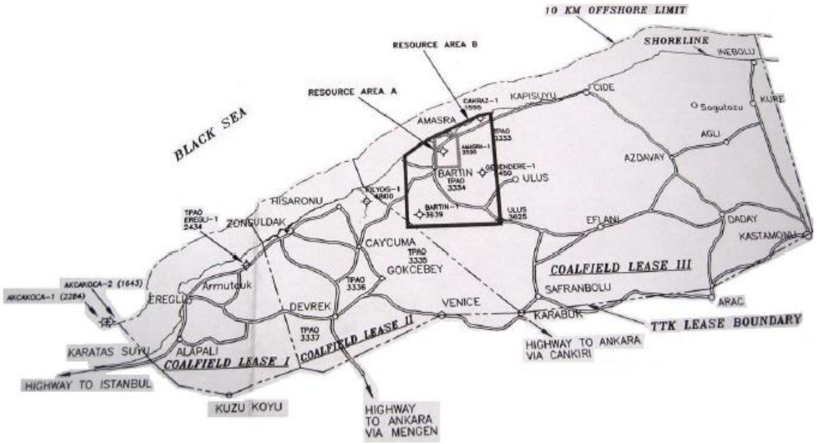


Figure 13: The Zonguldak Basin (Sinayuc & Gumrah, 2008)

Upper Silesian Basin

The most important coal basin in the region located around the town of Katowice in the North, Cracow (East) and the Czech border (South). The basin covers an area of 7,400 km² in southern Poland and in the Ostrava-Karvina region in the Czech Republic. The Poland's part is about 5,800 km². It is the most important coal basin in Poland and also one of the largest in Europe continent. Over 80% of coal deposits occur in this area. The basin was formed as a foredeep of the Moravo-Silesian fold zone. It also comprises a thick sequence of Upper Carboniferous sediments, up to 8,500 m. The upper part contains 60 coal seams while the lower part contains 250 coal seams. The thickness of coal seams ranges from 6-7 m (Volkmer& Freiberg, 2006).

Recently the RECOPOL ECBM Pilot project (Figure 11), a joint industry project (JIP) between TNO and Shell is located in the west central Upper Silesian Basin in the south of Poland near the Czech border. The pilot area consists of a small fault-block, which is triangular in shape. The deposits in the block dip 12° to the north with alternating layers of sandstone, clay, and coal having relatively low permeability, range of 0.5 to 2 mD (Wageningen& Maas, 2007).

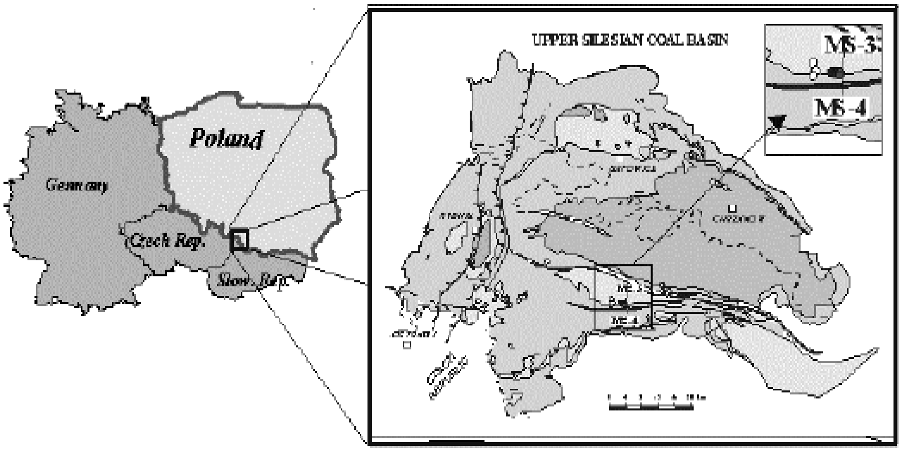


Figure 14: Recopol Pilotof Upper Silesian Basin (Wageningen& Mass, 2007)

All related parameters for each field is extracted and tabulated in **Table 5**. **Table 6** contains the selected uniform parameters from each field. The values of selected uniform parameters are portrayed later in bar chart for more detail comparison and analysis.

2.6 Production Profile of Coal Basin/Trend of Coal Production

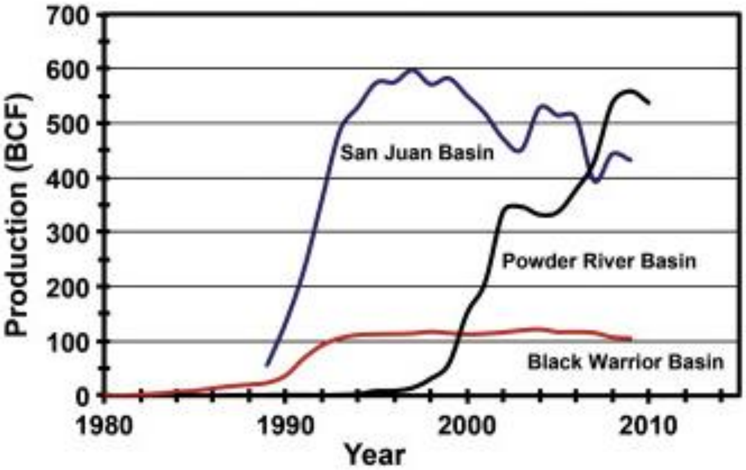
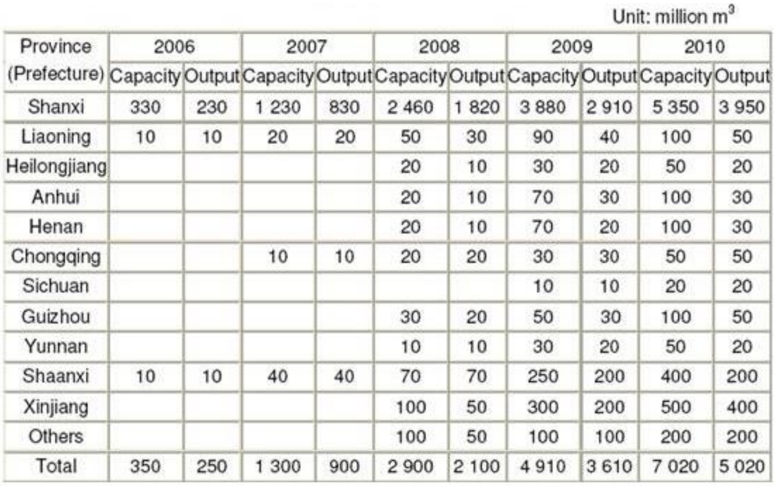


Figure 15: CBM production profile for San Juan Basin & Powder River Basin (www.sciencedirect.com)



Unit: million m^3

Province (Prefecture)	2006		2007		2008		2009		2010	
	Capacity	Output	Capacity	Output	Capacity	Output	Capacity	Output	Capacity	Output
Shanxi	330	230	1 230	830	2 460	1 820	3 880	2 910	5 350	3 950
Liaoning	10	10	20	20	50	30	90	40	100	50
Heilongjiang					20	10	30	20	50	20
Anhui					20	10	70	30	100	30
Henan					20	10	70	20	100	30
Chongqing			10	10	20	20	30	30	50	50
Sichuan							10	10	20	20
Guizhou					30	20	50	30	100	50
Yunnan					10	10	30	20	50	20
Shaanxi	10	10	40	40	70	70	250	200	400	200
Xinjiang					100	50	300	200	500	400
Others					100	50	100	100	200	200
Total	350	250	1 300	900	2 900	2 100	4 910	3 610	7 020	5 020

Table 4: CBM surface development plan in China, Qinshui & Ordos basins, Shanxi province (en.sxcoal.com)

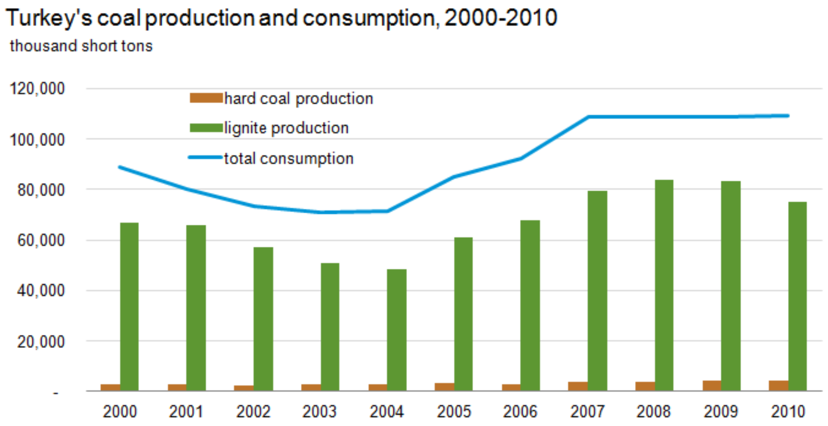


Figure 16: Turkey's coal production and consumption (www.eia.gov)

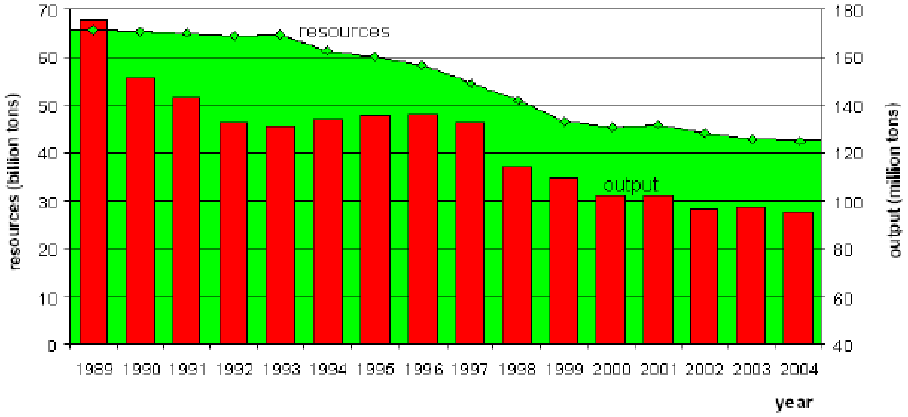


Figure 17: Hard coal resources and output in Poland (Volkmer, 2006)

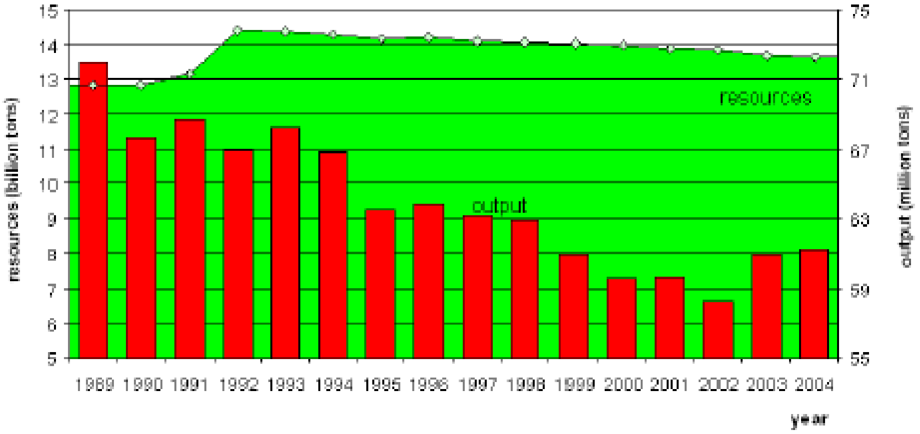


Figure 18: Lignite resources and output in Poland (Volkmer, 2006)

Table 5: Data from Different CBM Basins

San Juan Basin (Syahrial, E. 2005)		**Powder River Basin** (Matthew et. al. 2003)		**Qinshui Basin** (Zheng, S. & Xue, L. 2012)		**Zonguldak Basin** (Sinayuc, C. & Gumrah, F. 2008)		**Upper Silesian Basin** (Van Wageningen & Maas, J. G. 2007)	
Parameters	Value	Parameters	Value	Parameters	Value	Parameters	Value	Parameters	Value
Coal rank/quality	Sub-bituminous	**Coal rank/quality**	Sub-bituminous C	**Coal rank/quality**	Anthracite	**Coal rank/quality**	High-volatile A bituminous	**Coal rank/quality**	High-volatile bituminous
Coal seam thickness	29.527 ft	**Coal seam thickness**	64 ft	**Coal depth**	457.2 ft	**Average coal thickness**	3.0-26.0 ft	**Permeability**	0.5-2.0 mD
Absolute fracture permeability	3.65 mD	**Coalbed depth**	557 ft	**Coal thickness**	7.0 ft	**Coal depth**	1,788 ft	**Coal thickness**	3-20 ft
Natural fracture porosity	0.001	**Cleat porosity**	0.002-0.006	**Fracture porosity**	0.02	**Cleat porosity**	0.01, 0.02, 0.06	**Coal depth**	3,280 ft
Coal depth	4112.8 ft	**Absolute permeability**	10mD	**Fracture permeability**	3.0 mD	**Cleat permeability (range)**	0.01mD, 8.0mD, 100.0mD	**Average effective permeability**	1.3 mD
Initial reservoir temperature	113 °F	Initial reservoir pressure	152.5 psia	Coal density	1.3 g/cc	Coal density	1.54	**Cleat porosity**	0.005
Initial reservoir pressure	1109.5 psia	Initial reservoir temperature	113°F	Coal temperature	131 °F	Matrix porosity	0.04	Coal density	1.3 g/cc
Average coal density	1.43 g/cc	Coal density	1.33 g/cc	Initial reservoir pressure	2000 psia	Matrix permeability	0.01 mD (lateral), 0.001 mD (vertical)	Initial reservoir pressure	1300 psia
Average moisture content (by wt.)	0.0672	Ash content	0.044	Water saturation	0.92	Initial reservoir pressure	1500 psia	Initial reservoir temperature	90°F
Average ash content (by wt.)	0.156	Moisture content	0.27	Reservoir temperature	131°F	Initial reservoir temperature	94°F	Cleat spacing	0.08ft

From **Table 5**, the uniform parameters from every field have been selected as shown in **Table 6**below.

Table 6: Uniform Parameters for Each CBM Basin

CBM Basin	**Parameters**							
	Coal rank/quality	**Initial Water Saturation**	**Coal depth (ft)**	**Porosity (Tested)**	**Permeability (mD)**	**Coal density (g/cc)**	**Initial reservoir temperature (°F)**	**Initial reservoir pressure (psia)**
San Juan	Sub-bituminous	0.408	4,112.8	0.001 – 0.010	3.65	1.43	113	1,109.5
Powder River	Sub-bituminous C	0.408	557	0.001-0.010	10	1.33	113	152.5
Qinshui	Anthracite	0.08	457.2	0.01 – 0.10	3.0	1.60	131	2,000
Zonguldak	High-volatile A bituminous	0.01	1,788	0.01 - 0.10	8.0	1.54	94	1500
Upper Silesian	High-volatile bituminous	0.10	3,280	0.001 – 0.01	1.3	1.30	90	1300

From **Table 6**, the first five (5) parameters havebeen converted into respective **Table 7** and bar charts in order to have much details and clear analysis. The details are as below:

Table 7: Coal Basin and Quality

Coal Basin	**Coal Rank**
San Juan	Sub-bituminous
Powder River	Sub-bituminous C
Qinshui	Anthracite
Zonguldak	High-volatile A bituminous
Upper Silesian	High-volatile bituminous

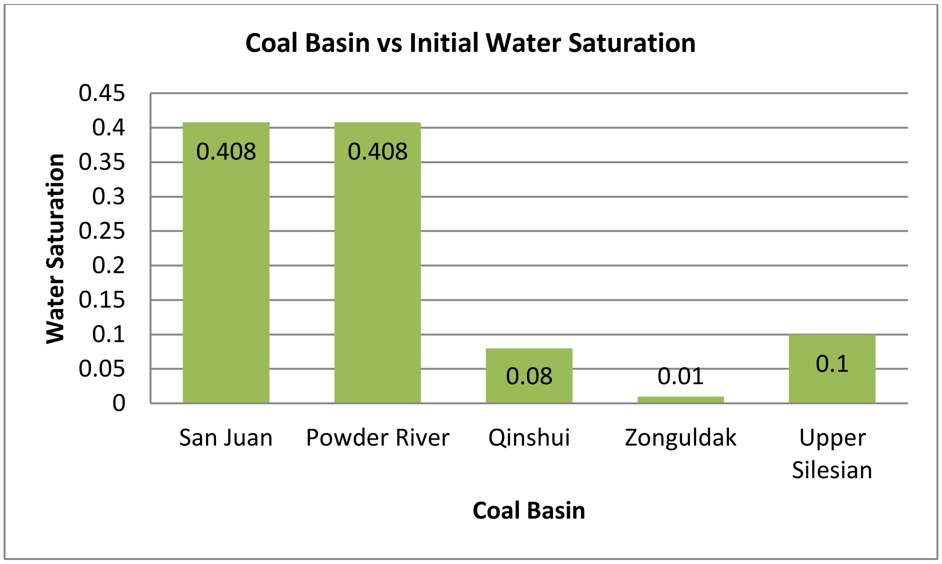


Figure 19: Coal Basin vs Initial Water Saturation

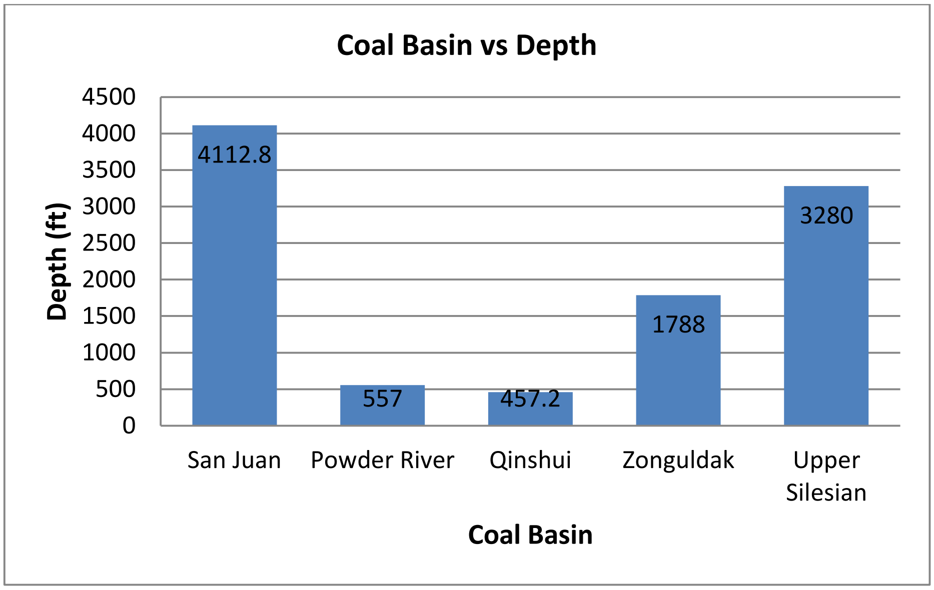


Figure 20: Coal Basin vs Depth

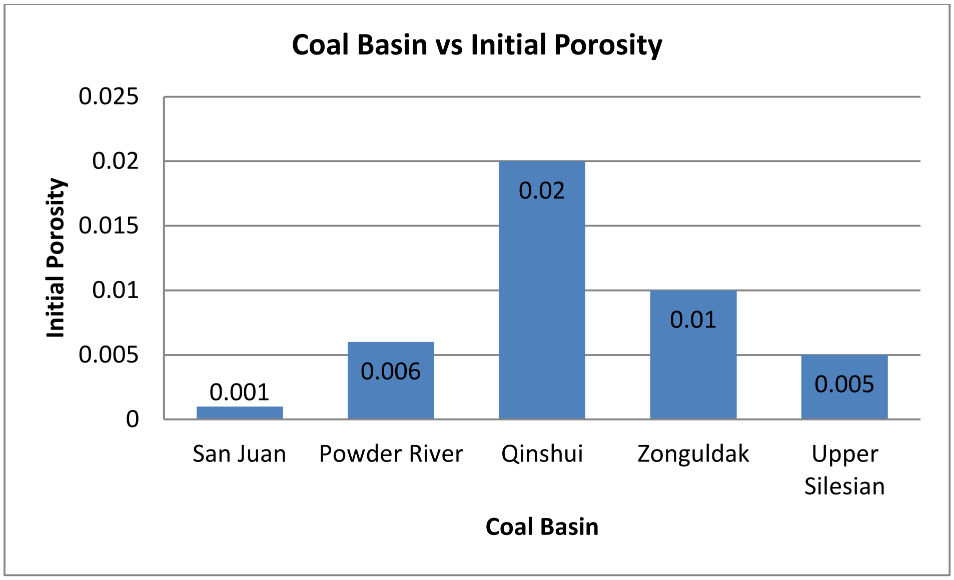


Figure 21: Coal Basin vsInitial Porosity

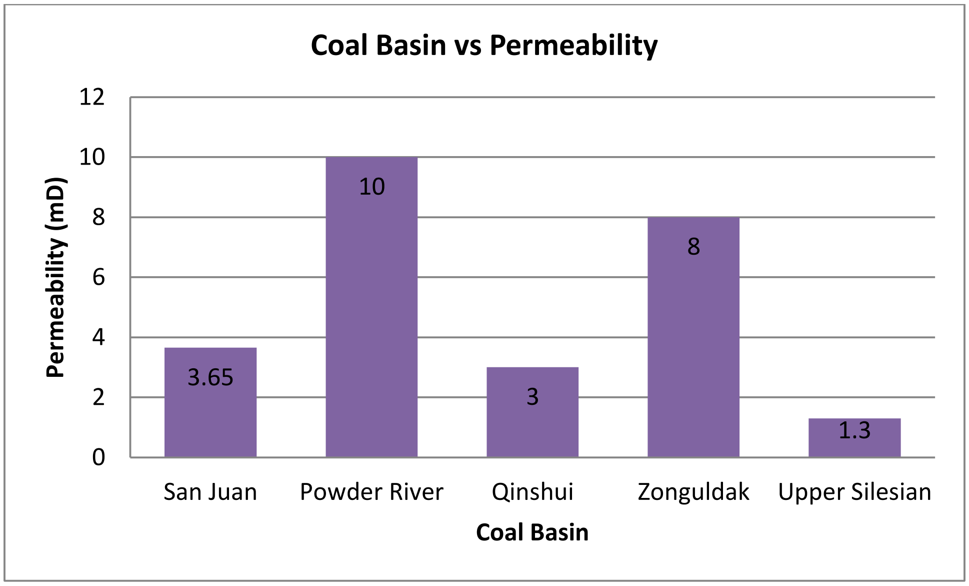


Figure 22: Coal Basin vs Permeability

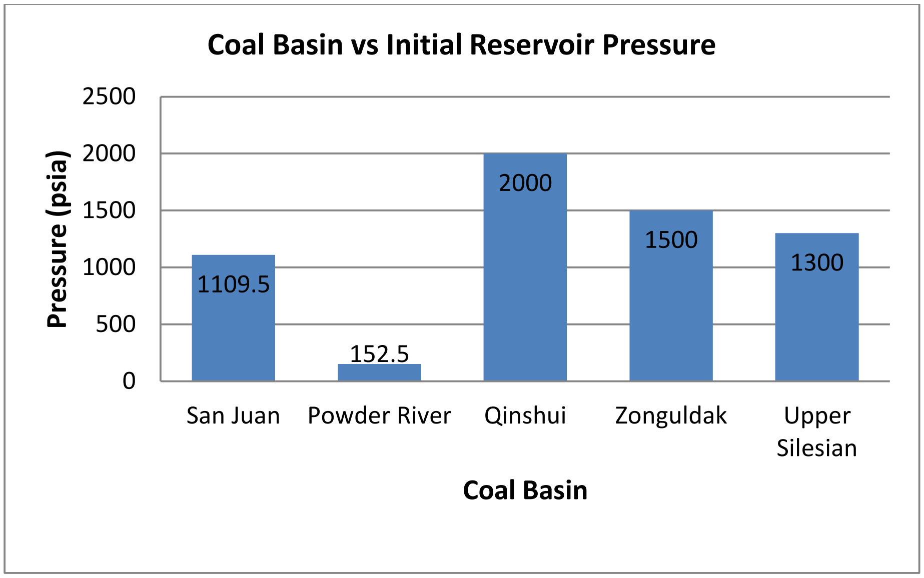


Figure 23: Coal Basin vsInitial Reservoir Pressure

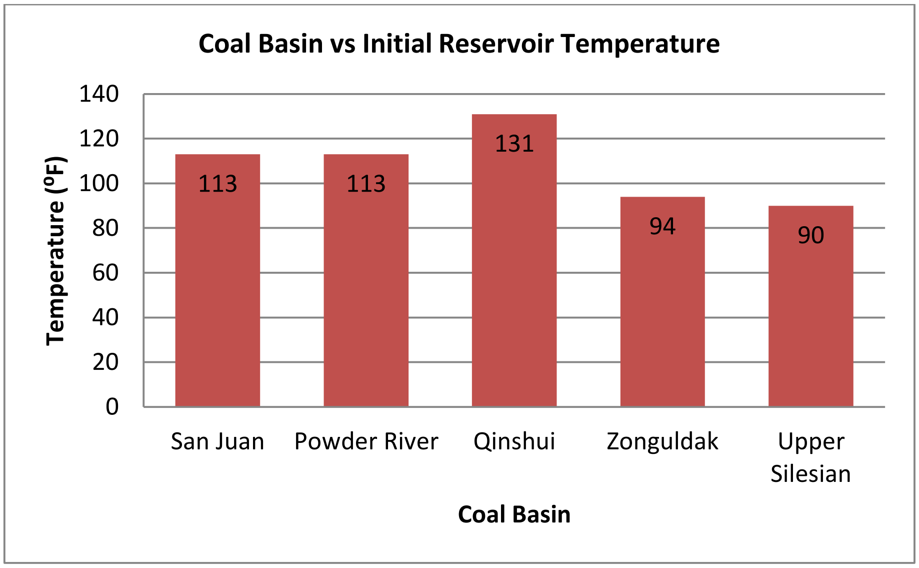


Figure 24: Coal Basin vs Initial Reservoir Temperature

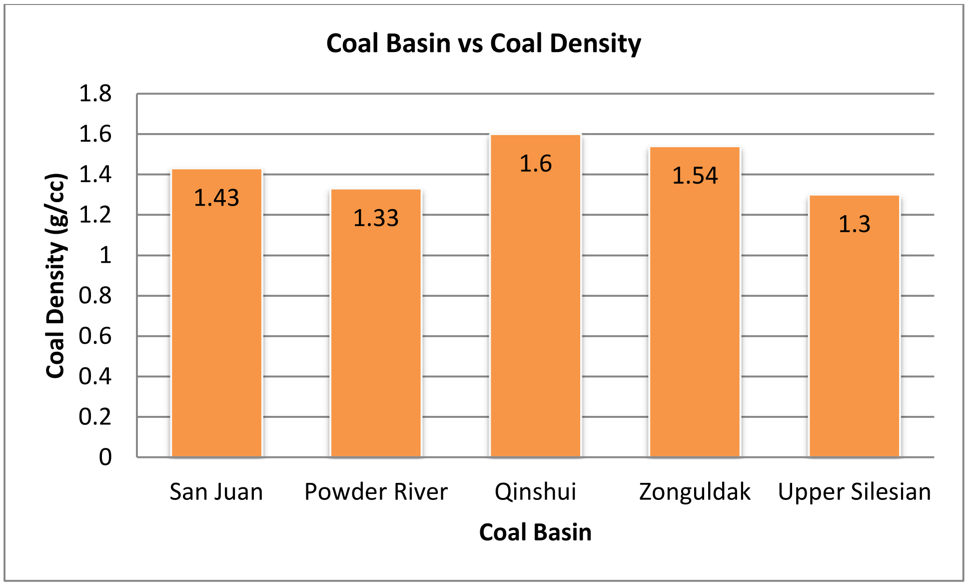


Figure 25: Coal Basin vs Coal Density

2.7 Analysis of the Graph

Each basin has been further analyzed according to the related parameters based on the bar charts given.

i. **San Juan Basin**

   The coal rank is sub-bituminous. The thickness of the coalbed is about 29.53 ft and the depth is 4,112.8 ft. It has porosity value of 0.001 while the absolute fracture permeability is 3.65mD. The coal density is 1.43 g/cc.

ii. **Powder River Basin**

   The coal rank is sub-bituminous C. The thickness of the coalbed is 64 ft and the depth is about 557 ft. The cleat porosity range from 0.002 to 0.006 while the absolute permeability is 10 mD. The coal density is 1.33 g/cc.

iii. **Qinshui Basin**

   The depth of coalbed is 457.2 ftwhich is shallower than San Juan but the coal rank is anthracite (highest rank). The thickness of the coalbed is around 7.0 ft which is the smallest with fracture porosity value of 0.02 and permeability is 3.0 mD.The coal density is 1.6 g/cc.

iv. **Zonguldak Basin**

   The depth of coalbed is 1,788 ft which is also shallower than San Juan but the coal has quality of high-volatile A bituminous. The average coal seams thickness is 3.0 ft to 26 ft. It has cleat porosity value range from of 0.01 to 0.06 and cleat permeability of 8mD.The coal density is 1.54 g/cc.

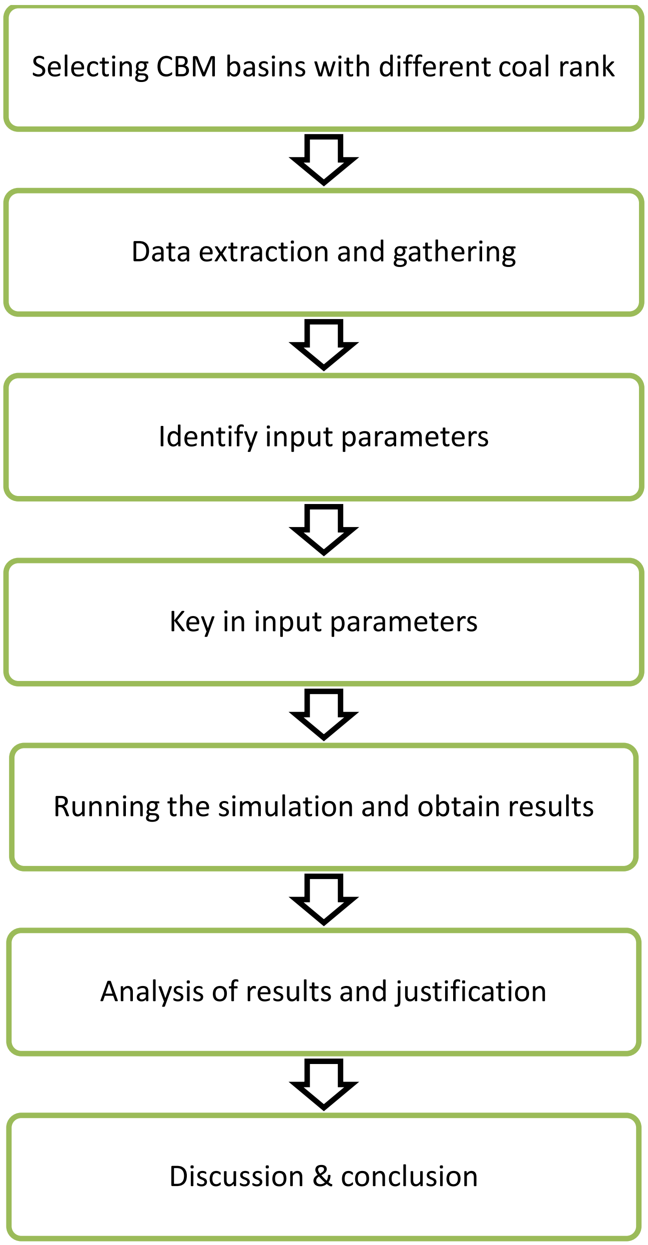
v. **Upper Silesian Basin**

   The coal rank is high-volatile bituminous. The coal seam thickness is range from 3 ft to 20 ft with the coal depth at 3,280 ft. The cleat porosity and average effective permeability value is0.005 and 1.3 mD respectively. The coal density is 1.3 g/cc.

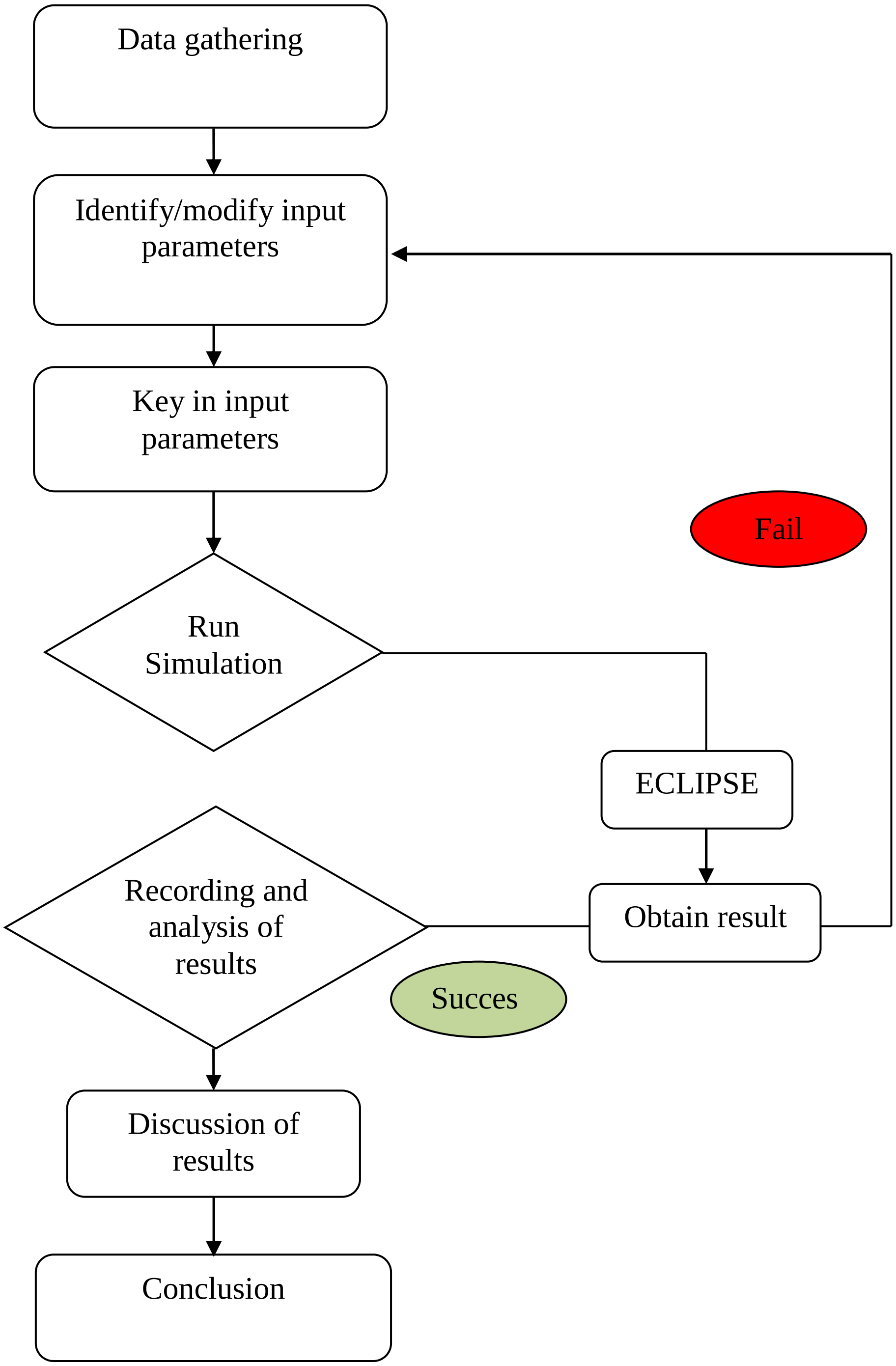
CHAPTER 3

METHODOLOGY

3.1 Project Methodology



3.2 Simulation Process Flowchart



3.3 Gantt Chart

Proposed Gantt Chart for the Project (Both FYP I and FYP II).

TOPIC	PROJECT ACTIVITIES	WEEKS																											
		Final Year Project 1														Final Year Project 2													
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	Project Scope Validation	🟨																											
	Project Introduction		🟨	🟨	🟨	🟨	🟨																						
	Submission of Extended Proposal						🟧																						
	Identify material and equipment						🟨	🟨																					
	Training on how to conduct experiment							🟨	🟨	🟨																			
	Proposal Defence									🟧																			
	Detail Study									🟨	🟨	🟨	🟨	🟨	🟨														
	Submission of Interim Draft Report														🟧														
	Finalized Procedure														🟨	🟨	🟨												
	Conducting Experiment															🟨	🟨	🟨	🟨	🟨									
	Result analysis and discussion																		🟨	🟨	🟨	🟨							
	Submission of progress report																						🟧						
	Preparation for Pre-SEDEX																						🟨	🟨	🟨	🟨			
	Pre-SEDEX																									🟧			
	Submission of draft report																									🟨	🟨		
	Submission of technical paper and dissertation																										🟧		
	Oral presentation																											🟧	
	Submission of project dissertation																												🟧

Proposed Gant Chart for the project (both FYP I and FYP II). Based on the Gant Chart, the project is feasible to be completed within the period of time.

CHAPTER 4

SIMULATOR PROGRAM

For this project, a reservoir simulator (ECLIPSE) has been selected to run the simulation. The simulatoris preferably selected due to their availability for academic purposes. Below are the summary of the simulator:

This study follows work done by (Law et. al., 2001). However, the numerical simulator used in this study is only E300 compositional simulator which follows black oil characteristics with additional features for CBM modelling and only capable to handle two gas components (e.g. CH_4 and CO_2 only). ECLIPSE does not incorporate the extended Langmuir isotherm theory in the CBM model, however it has a feature of relative adsorption for each gas component. This allows the simulator to take into account the “non-ideal” adsorption behavior of the two-gas mixture. Five different CBM basins have been selected to be tested in this study.

CBM models are characterized as a cleat system of equations. Most of the gas is stored in the coal matrix. Gas storage is dominated by adsorption according with Equation (1).

$$\text{GIIP} = A * h * \rho_b * G_c \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Adsorbed gas content,G_c, is calculated with the Langmuir equation as follows:

$$G_c = \frac{V_L + p}{p_L + p} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Gas desorbeds in the coal block and then drains to the fracture system by molecular diffusion (Fick’s law rather than Darcy’s law). The drainage rate (Fick’s law) from the coal block can be expressed using this equation:

$$q^* = \sigma \,.\, D_c \,.\, (c_m - c_f) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

For equation (3), q^*represents drainage rate per volume of reservoir. For CBM reservoir modeling, sorption time is related to the transfer factor, σ and the diffusivity term, D_c. Sorption time, τ, expresses the diffusion process by means of Equation (4):

$$\tau = \frac{1}{\sigma \, . \, D_c} \qquad \text{......................................(4)}$$

By definition, τ is the time at which 63.2% of the ultimate drainage occurs when maintained at constant surrounding pressure and temperature.

4.2 Description of Test Problems Set

The reference set used is CO_2-ECBM recovery process in an inverted five-spot pattern (see **Figure 4**). The basic features of E300simulator are as follow:

- Darcy flow of gas and water in the natural fracture system in coal
- Adsorption/desorption of two different gas components (CH_4 + CO_2) at the coal surface
- Instantaneously gas flow (diffusion) between the coal matrix and natural fracture system
- No coal matrix shrinkage/swelling due to gas desorption/adsorption
- No compaction/dilation of natural fracture system due to stresses
- No non-isothermal adsorption due to difference in temperatures between the coalbed and injected CO_2.

For each basin, 10 different porosity values are defined in the simulator to observe the behavior of CH_4 production rate when the porosity is changing in increasing order. A complete description of the test problem set is given in **APPENDIXII**.

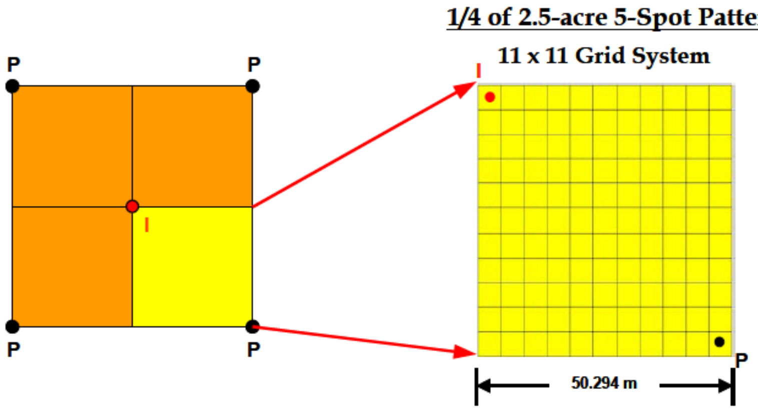


Figure 26: Schematic Diagram of Five-Spot Pattern (Law, 2002)

4.3 Typical Production Profile of CBM Well

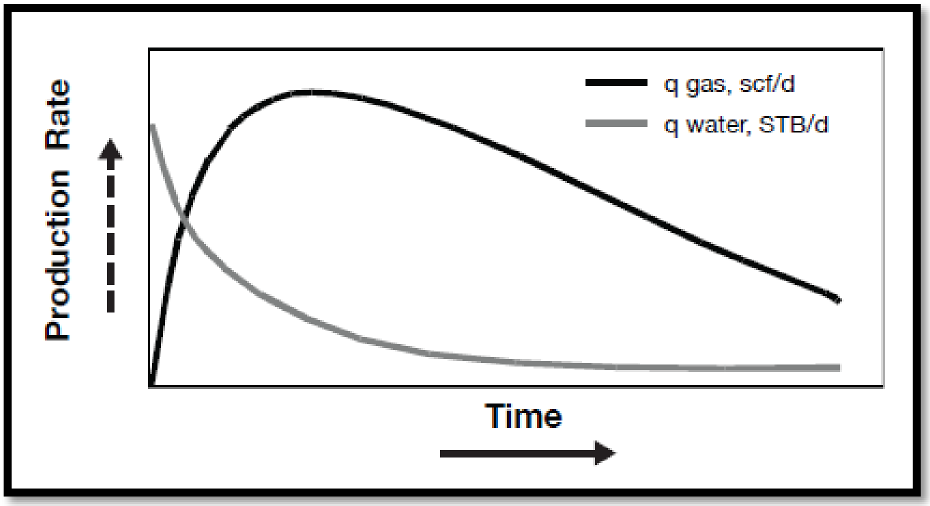


Figure 27: Typical production profile of CBM well (Mora and Wattenbarger, 2009)

The conventional primary CBM recovery process often begins with a production well that is often stimulated by hydraulic fracturing to connect the wellbore to the natural fracture of coal seams via the induced fracture created. In order for methane to be released and flow to take place, water is first pumped out from the well. The flow of water will decrease the pressure in the cleats thus making coal less capable of retaining methane in adsorbed form. Gas and water begin to move through the natural and induced fractures in the direction of decreasing pressure. As the natural fracture system pressure drops, gas molecules desorbed from the primary-secondary porosity interface and released to the secondary porosity system. The adsorbed gas concentration in the primary porosity near the natural fractures is reduced. A concentration gradient is established between the cleats and coal matrix which results in mass migration of methane by means of diffusion through the microporosity and mesoporosity.

Although the method quite simple, the estimated total methane recovery only around 50%. Hence, enhanced coalbed methane (ECBM) techniques have been developed to recover more portion of gas-in-place (GIP). According to Mitra and Harpalani, 2007 these techniques involve injecting another gas into the coal reservoir. The process can either be CO_2-ECBM where CO_2 displaces adsorbed methane from the coal matrix blocks, or N_2-ECBM where N_2 strips methane from coal matrix by reducing the partial pressure in the cleat system.

Carbon Dioxide (CO_2 Injection)

Carbon dioxide (CO_2) is more absorbable than CH_4. When CO_2 is injected into the coal natural fracture system during Enhanced Coalbed Methane (ECBM) recovery process, it is more preferably to be adsorbed into the primary porosity system. The CO_2 drives CH_4 from the primary porosity into the secondary porosity system. The secondary porosity pressure then increased due to the CO_2 injection, thus forced the CH_4 flows into the production well to be produced. The CO_2 is stored in-situ and is not produced unless the injected gas reaches the production well. This process basically is terminated when CO_2 breakthrough occurs.

CHAPTER 5

RESULTS OF EXPERIMENT

Figure 27 shows comparisons of CH_4 production rates for primary CBM (zero injection) and CO_2-ECBM recovery as functions of time for San Juan basin. It shows the enhancement in the CH_4 production due to the CO_2 injection. Generally, the enhancement of CH_4 recovery remains until CO_2 breakthrough occurs in the production. In this case, the CO_2 is continuously injected for 182.5 days. Due to higher initial gas saturation in every basin, the typical "negative decline" in CH_4 production rate in primary CBM recovery process due to "dewatering" process is not clearly observed.

The results of other basins are shown in **Figure 28, 29, 30,** and **31** respectively. The production data for each basin after tested with different porosity values is also recorded in **Table 8 and Table 9**. All well data presented are on a full-well basis and pattern results for the full 5-spot pattern consisting of four one-quarter producers and one full injector (see **Figure pg 36**).

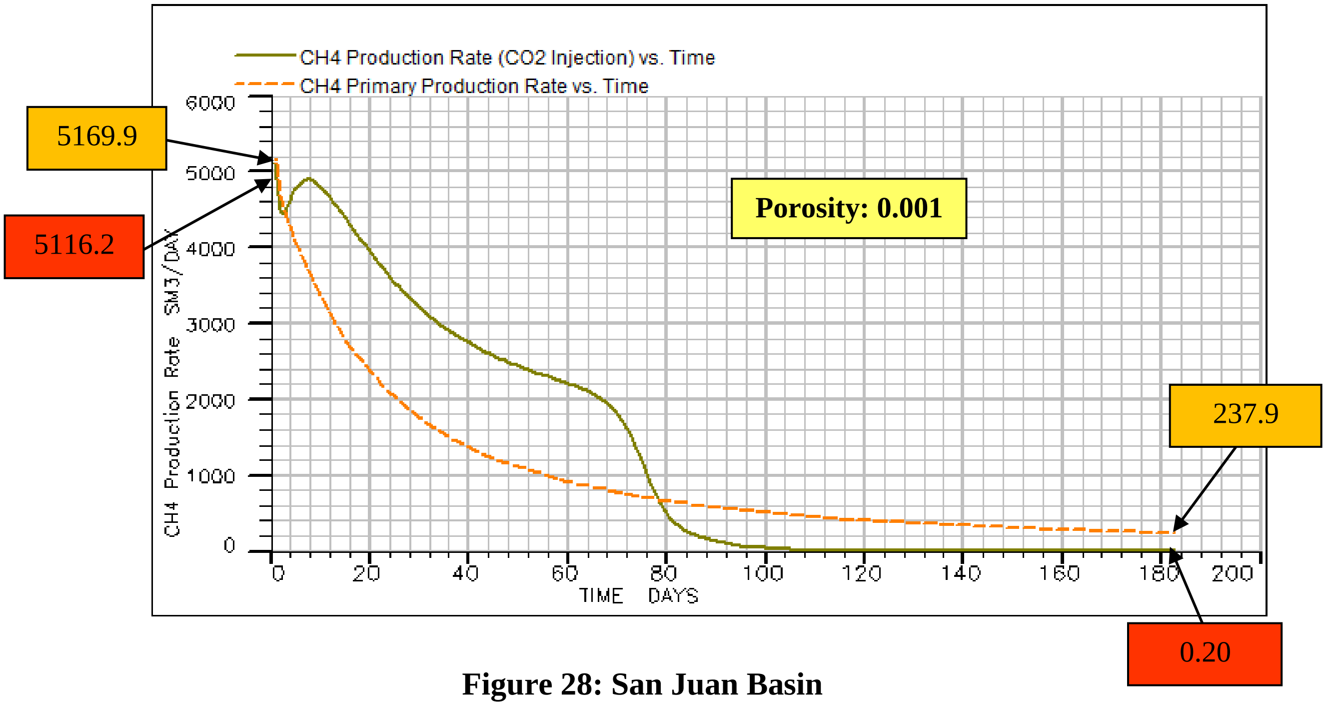


Figure 28: San Juan Basin

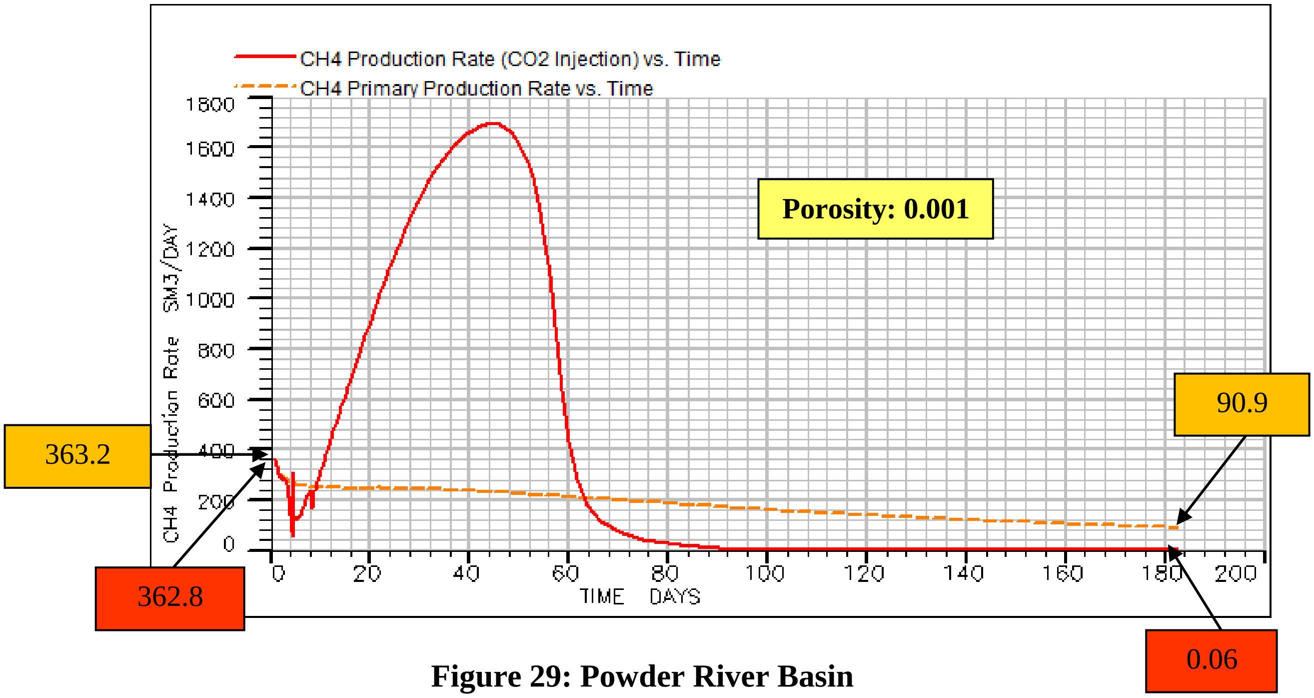


Figure 29: Powder River Basin

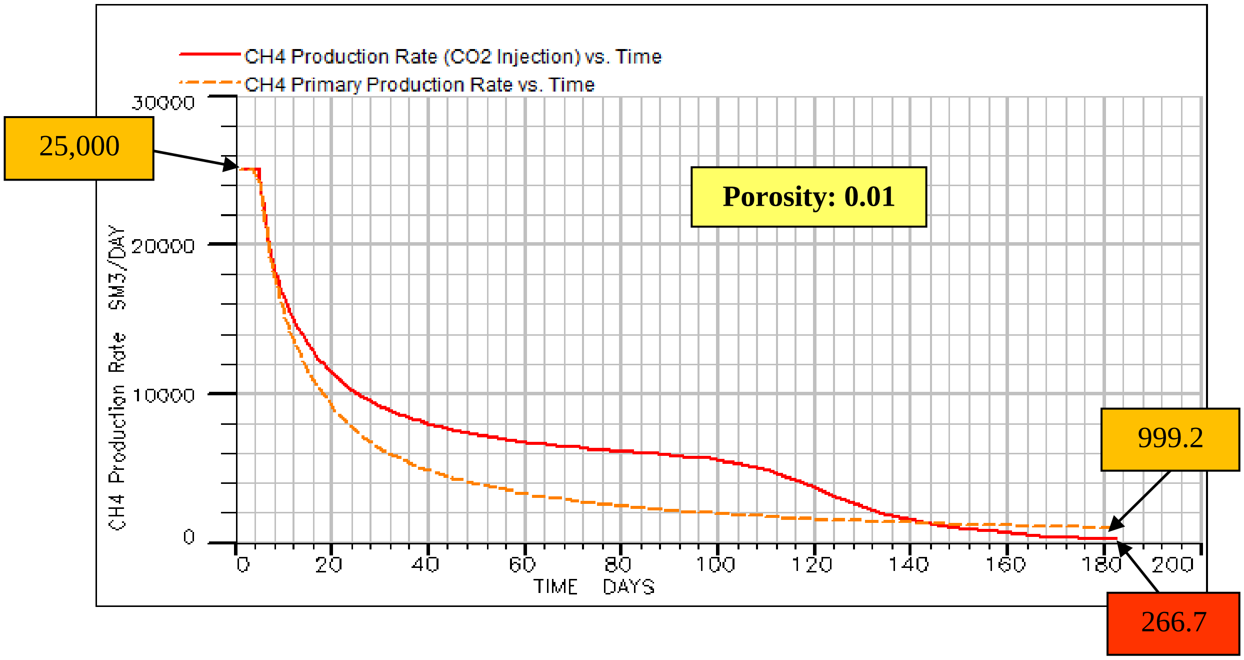


Figure 30: Qinshui Basin

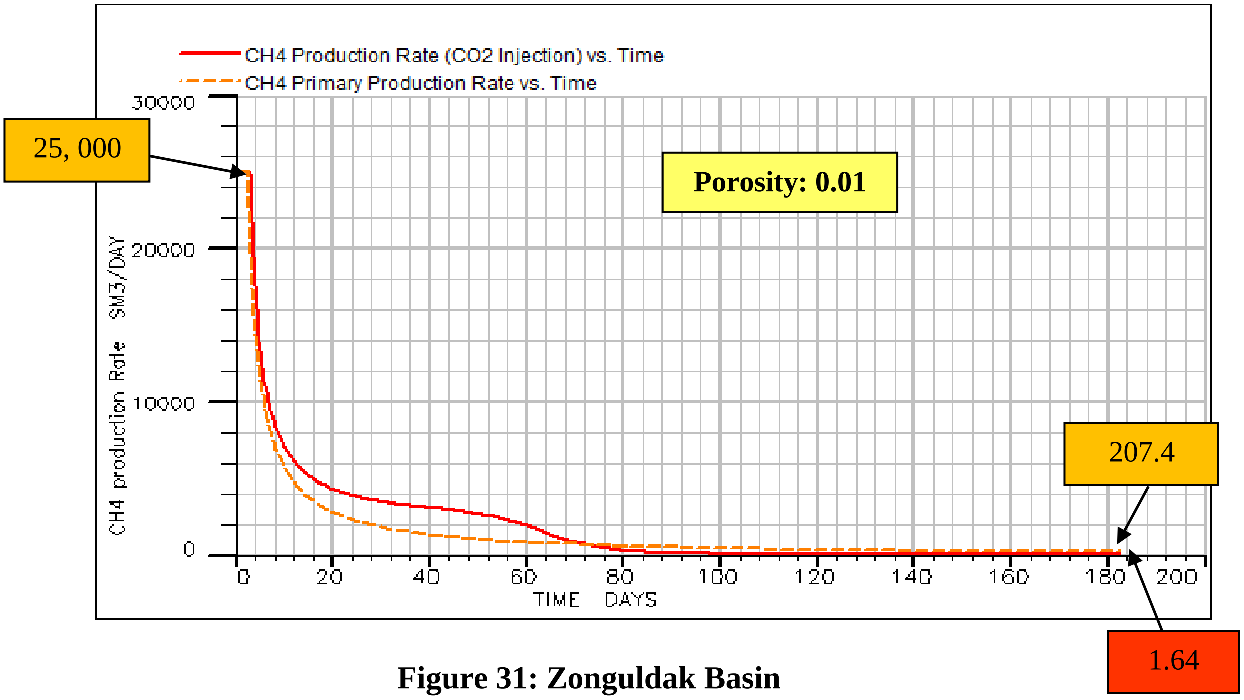


Figure 31: Zonguldak Basin

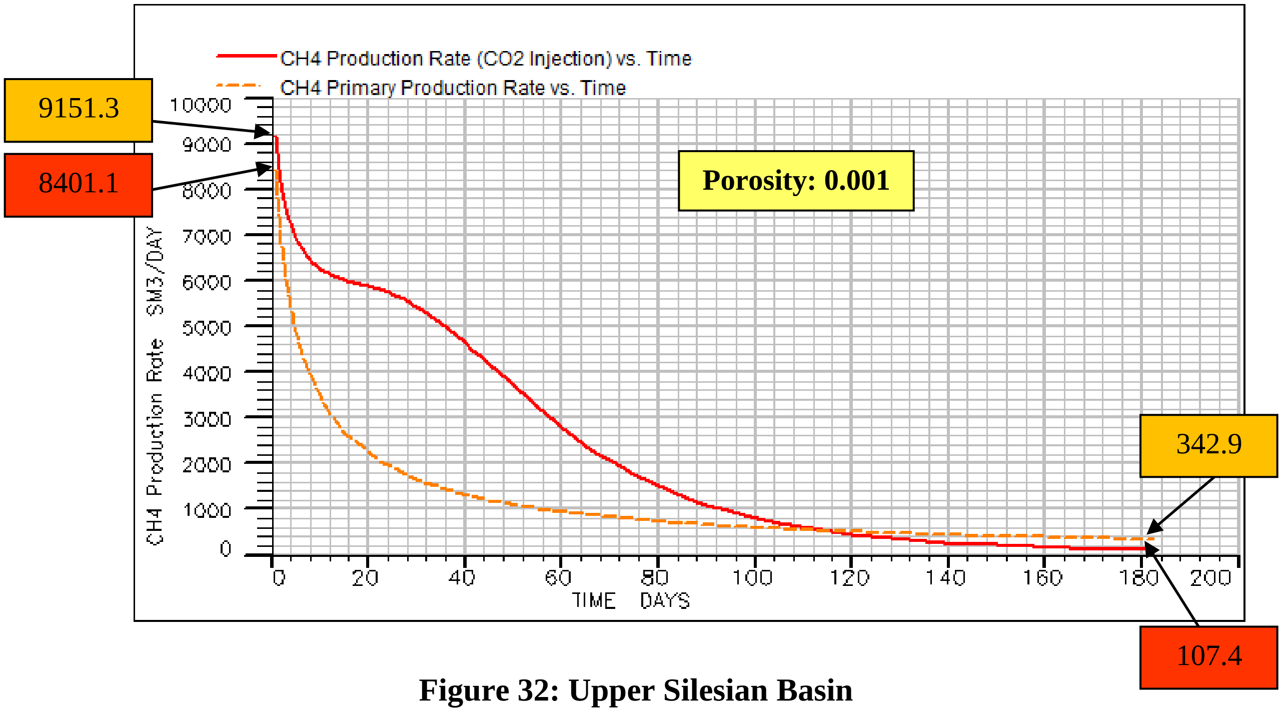
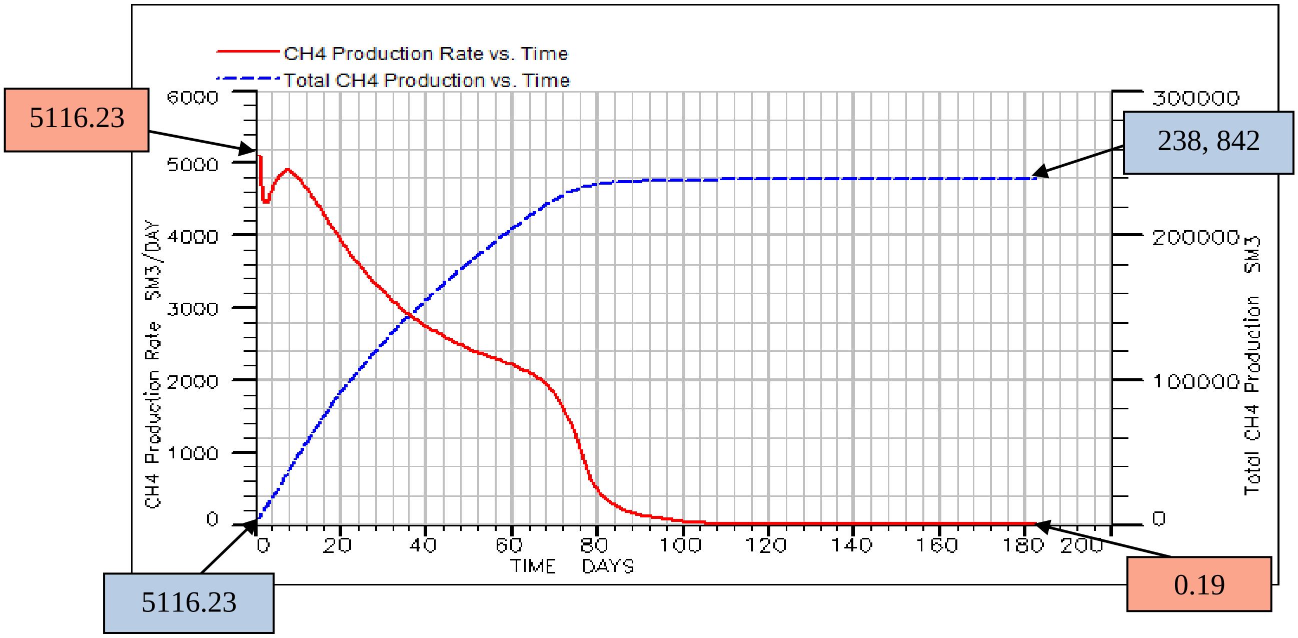


Figure 32: Upper Silesian Basin

Basin Name: San Juan, United States
Coal Type: Sub-bituminous

Test for Porosity: 0.001



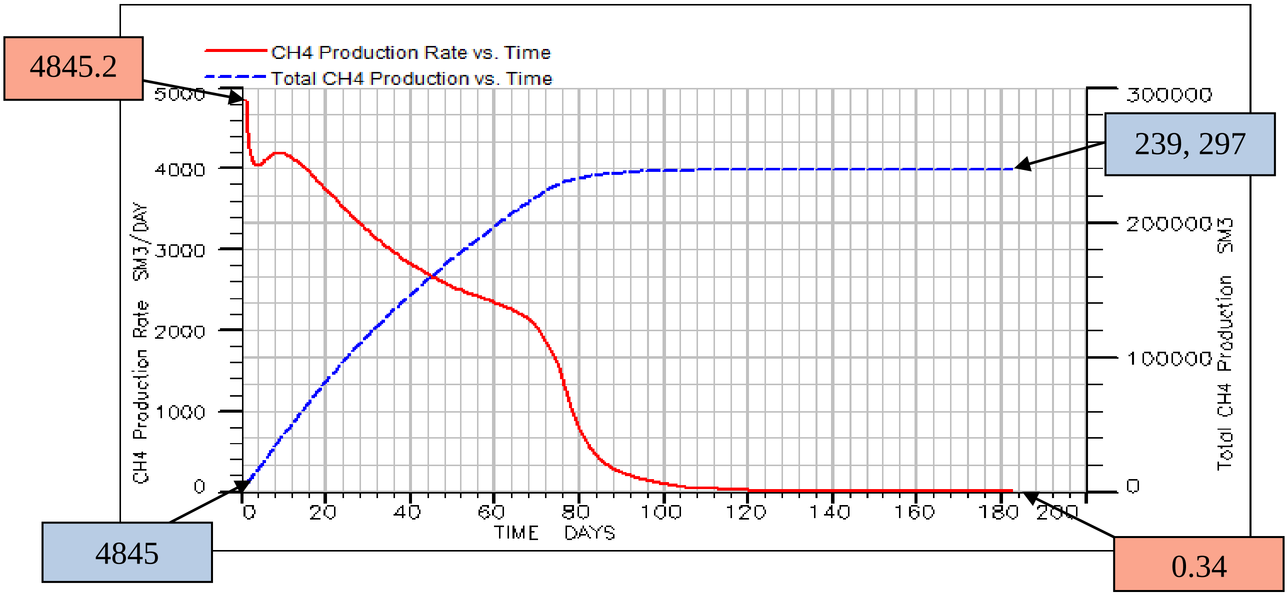
5116.23

238, 842

5116.23

0.19

Test for Porosity: 0.002



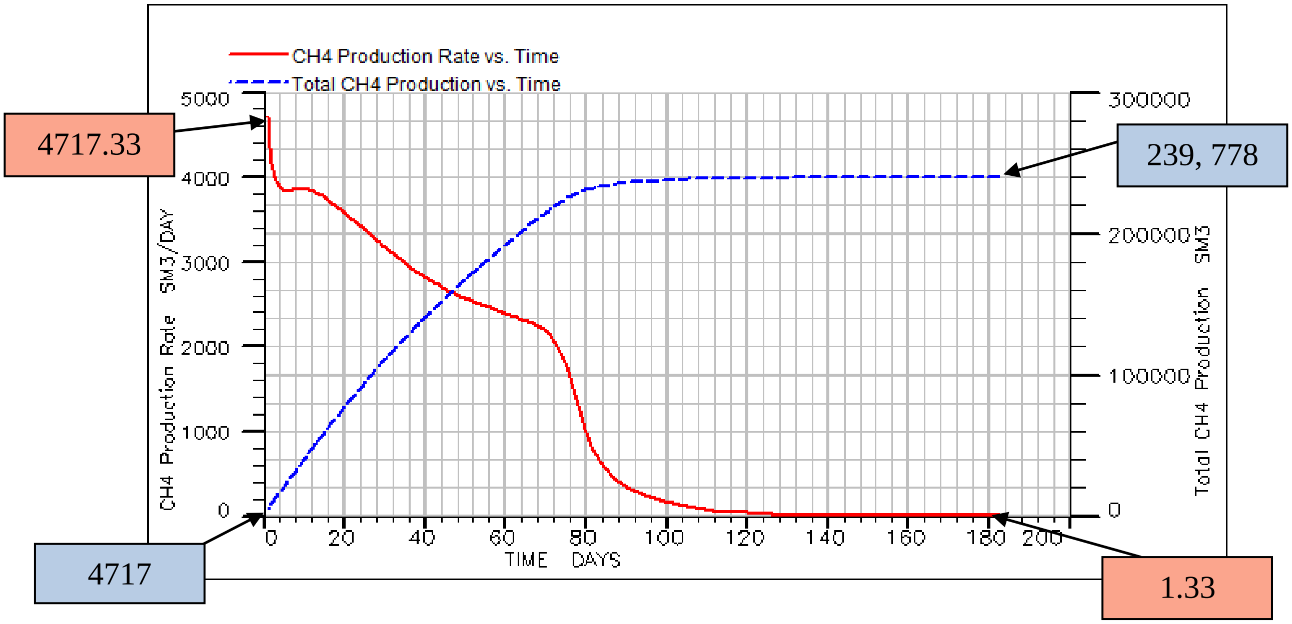
4845.2

239, 297

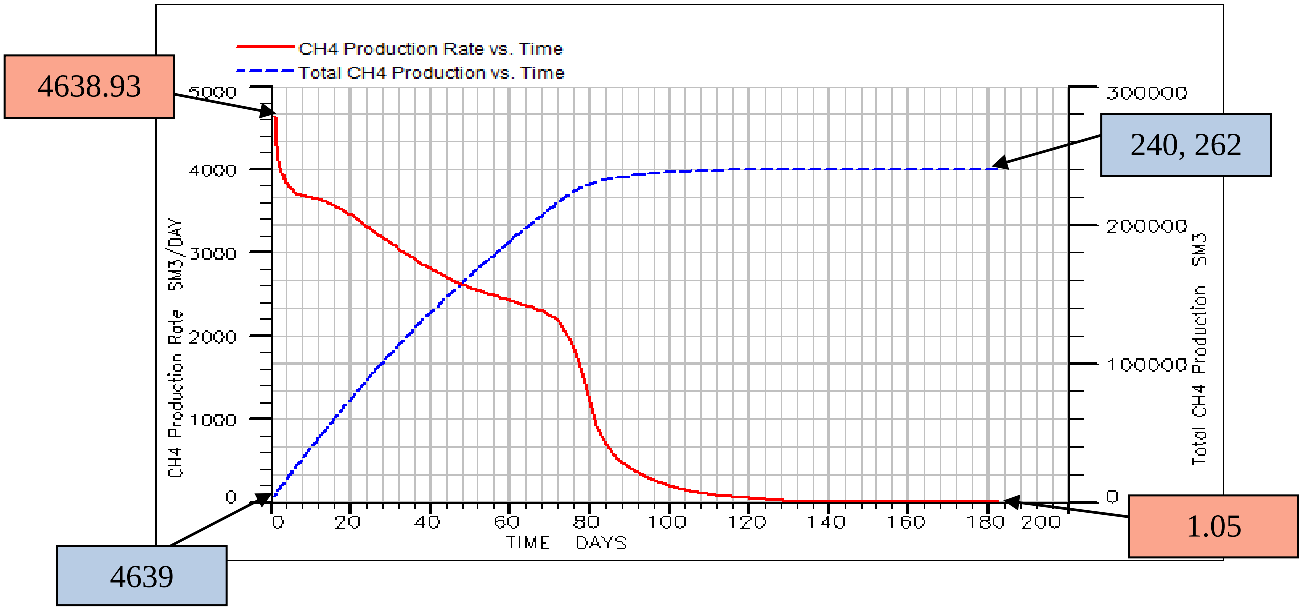
4845

0.34

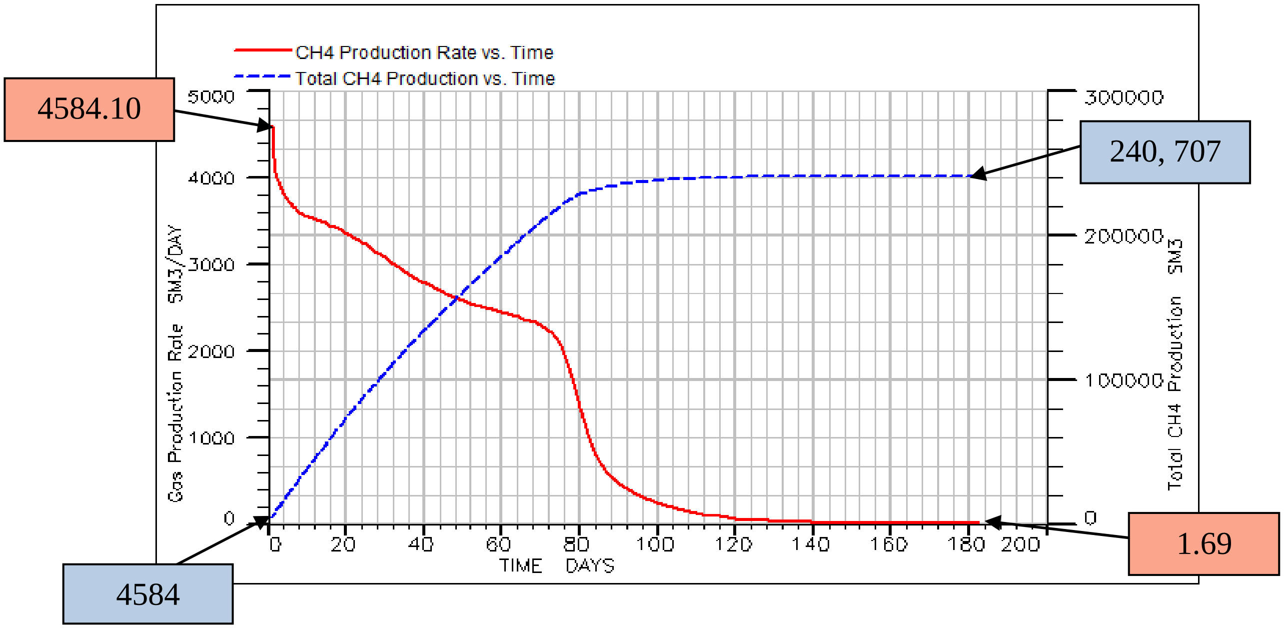
Test for Porosity: 0.003



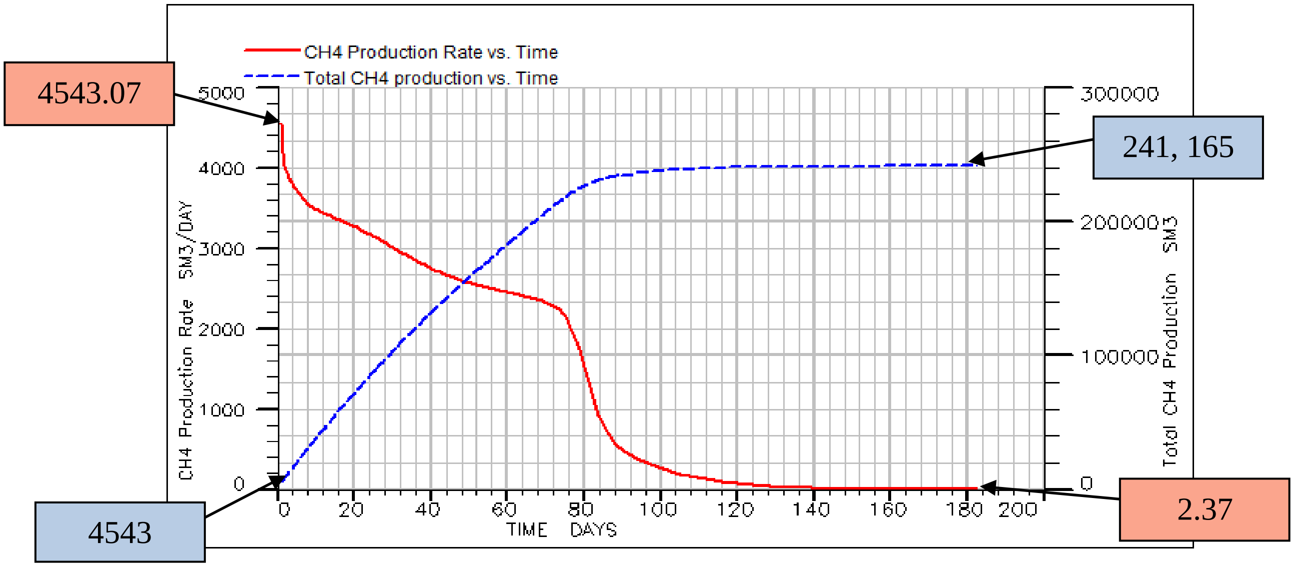
Test for Porosity: 0.004



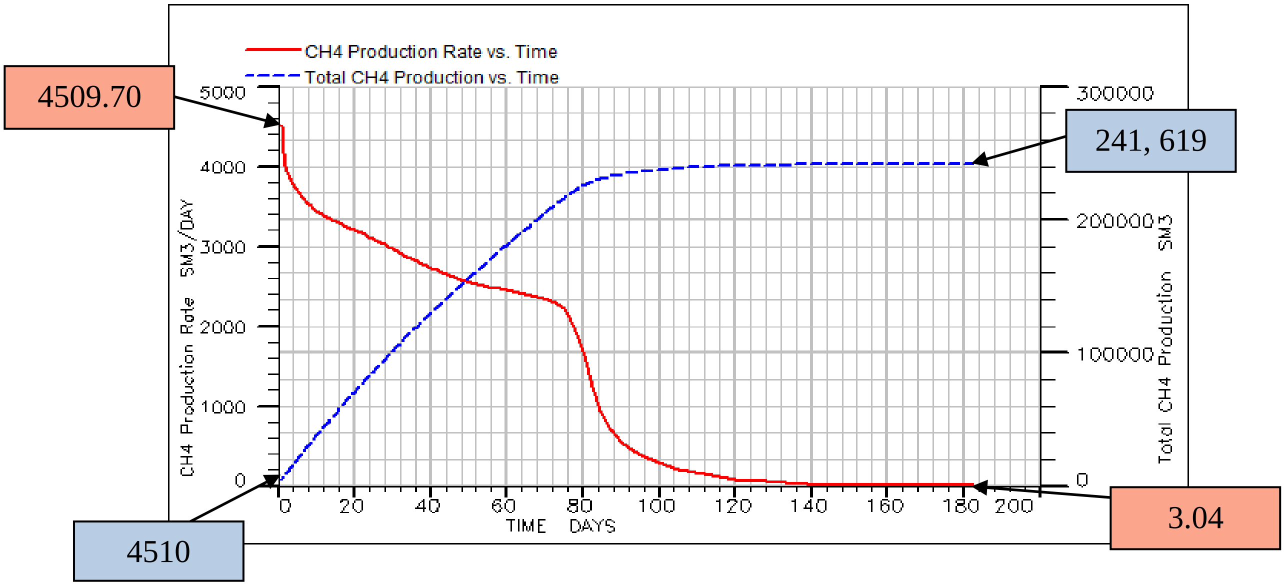
Test for Porosity: 0.005



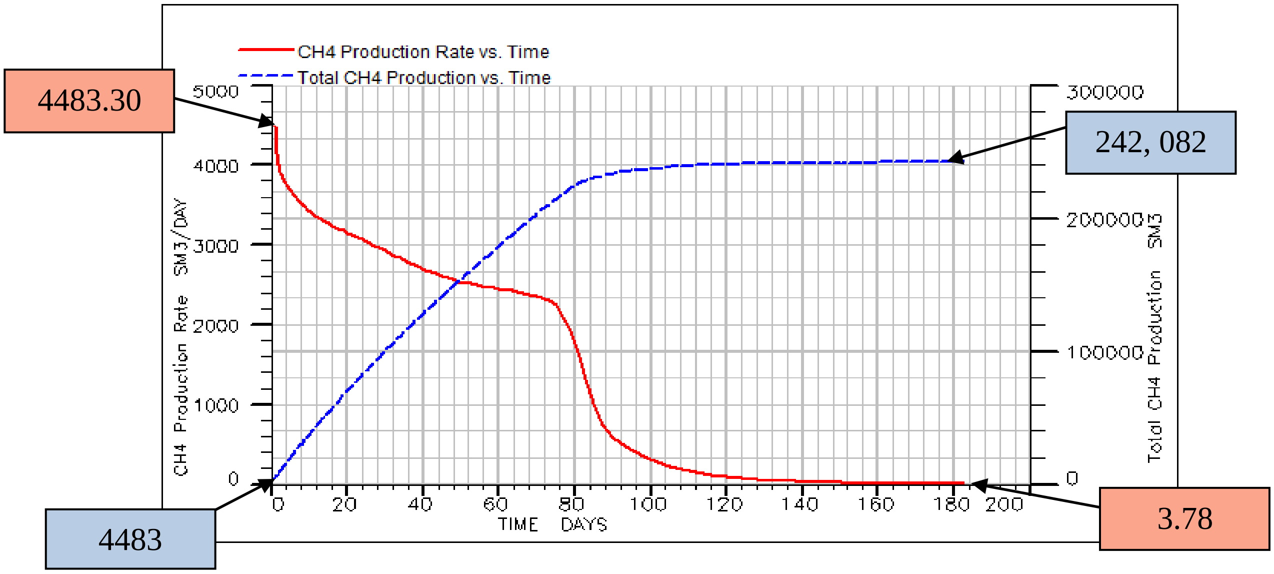
Test for Porosity: 0.006



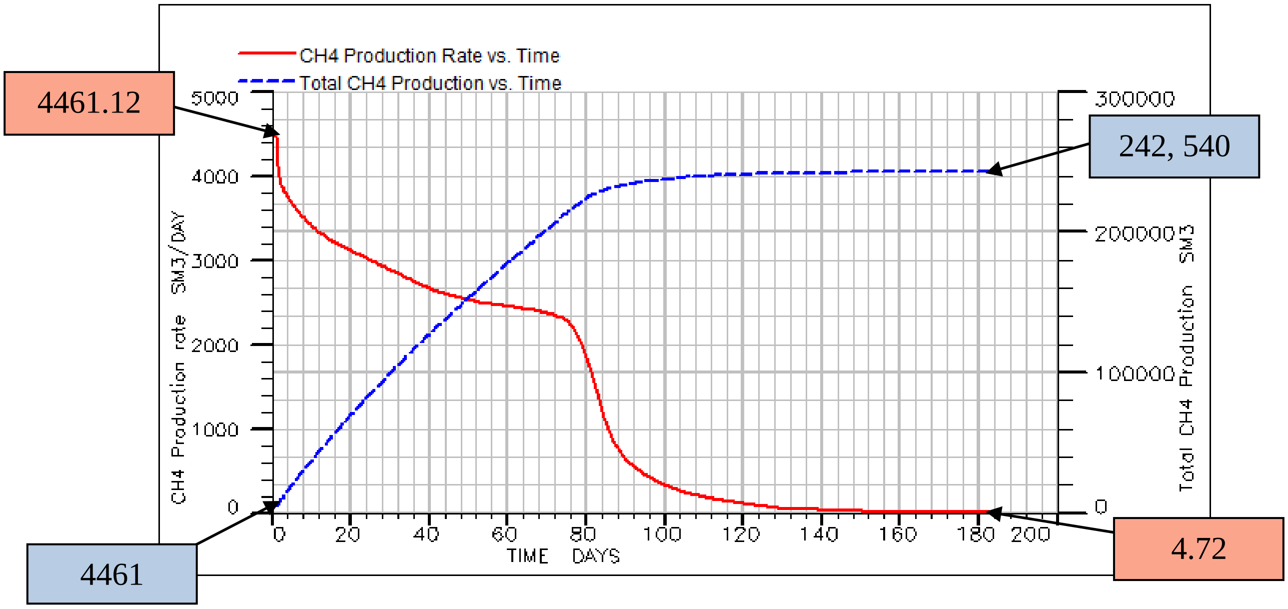
Test for Porosity: 0.007



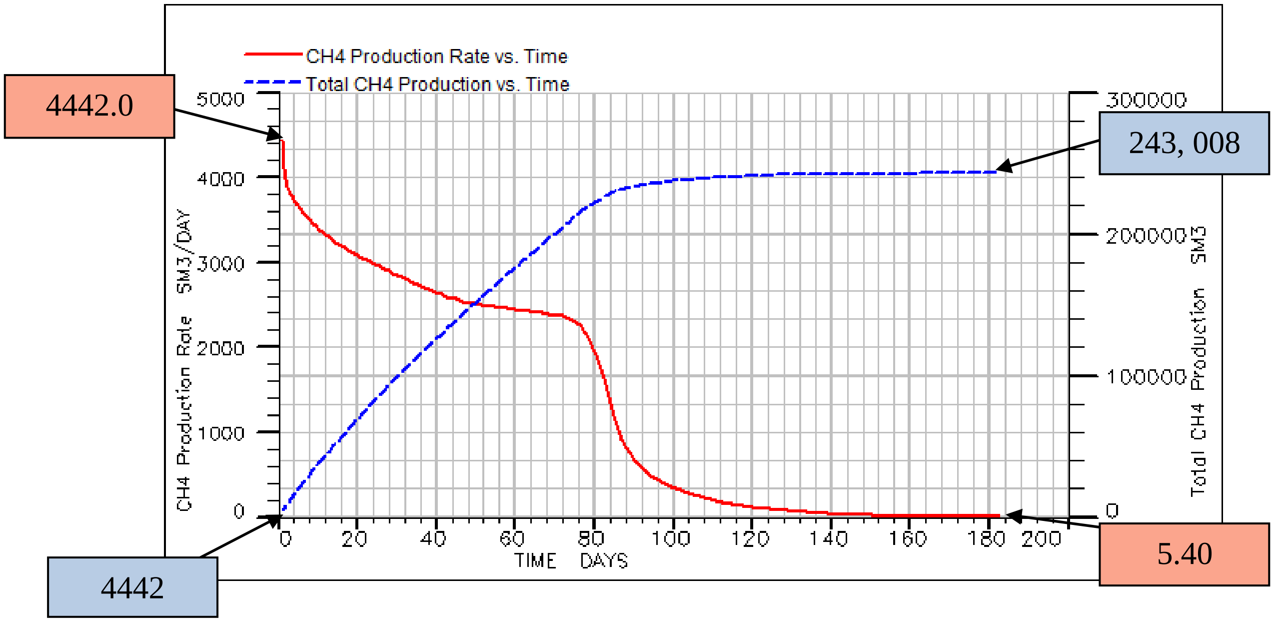
Test for Porosity: 0.008



Test for Porosity: 0.009

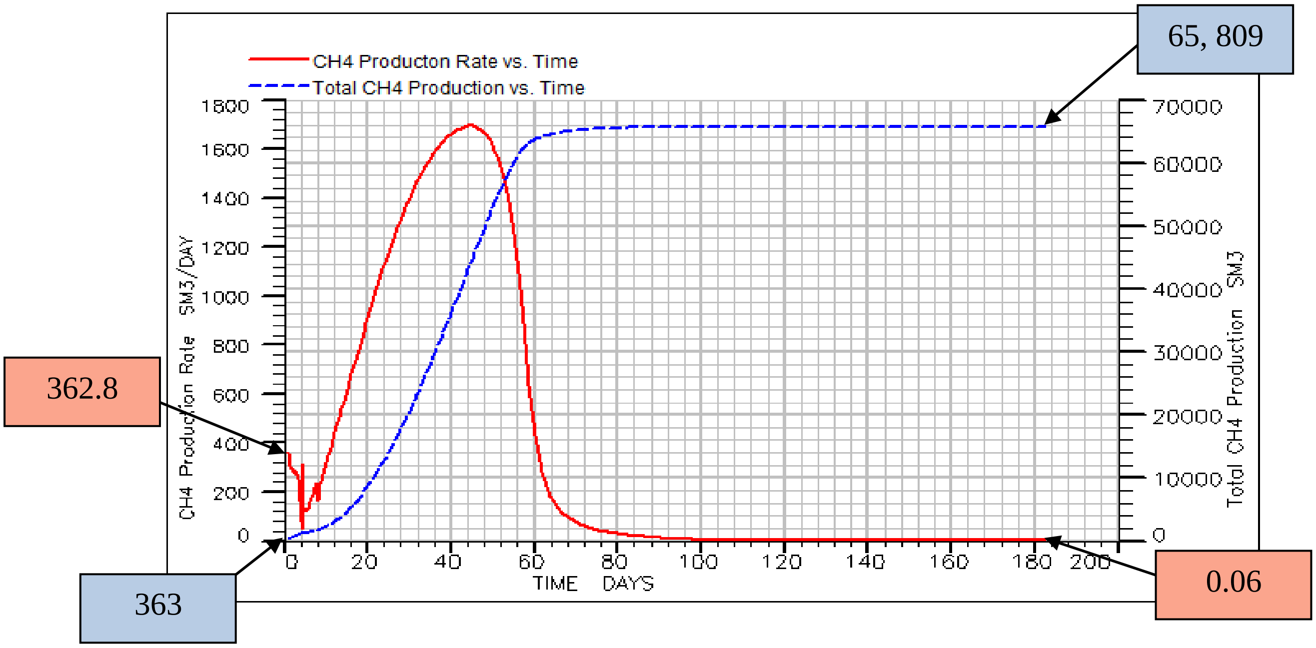


Test for Porosity: 0.010



Basin Name: Powder River, United States
Coal Type: Sub-bituminous C

Test for Porosity: 0.001



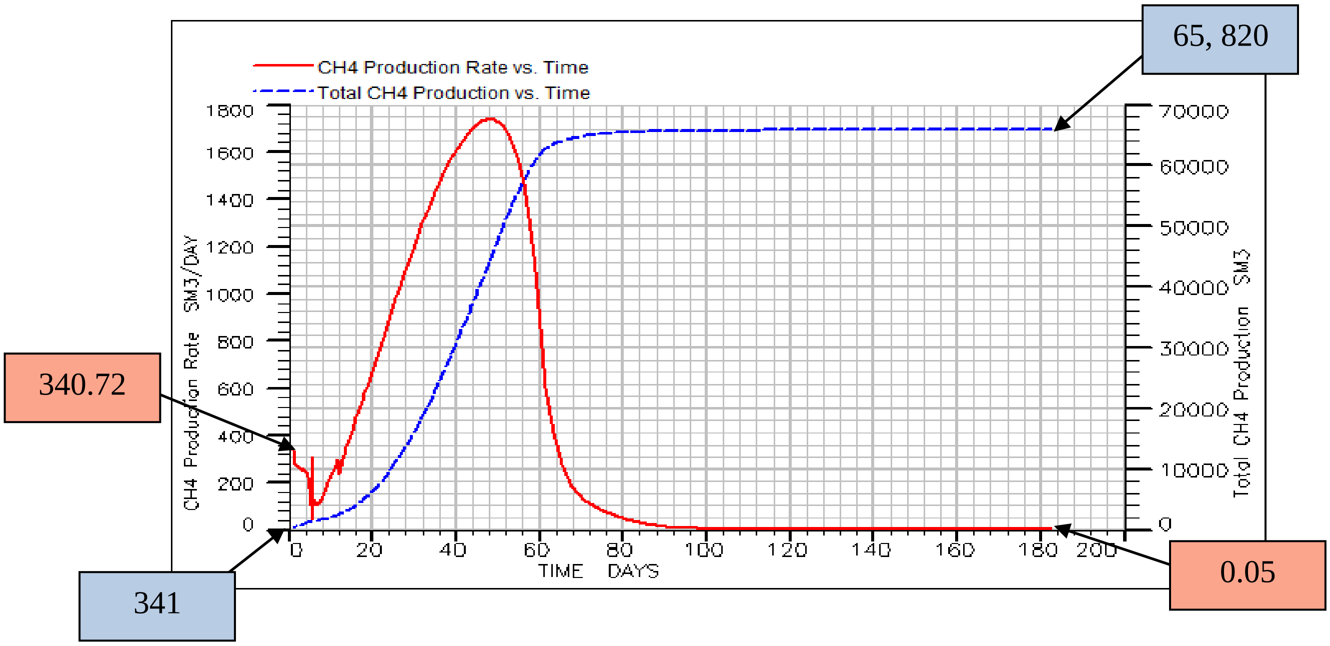
65, 809

362.8

363

0.06

Test for Porosity: 0.002



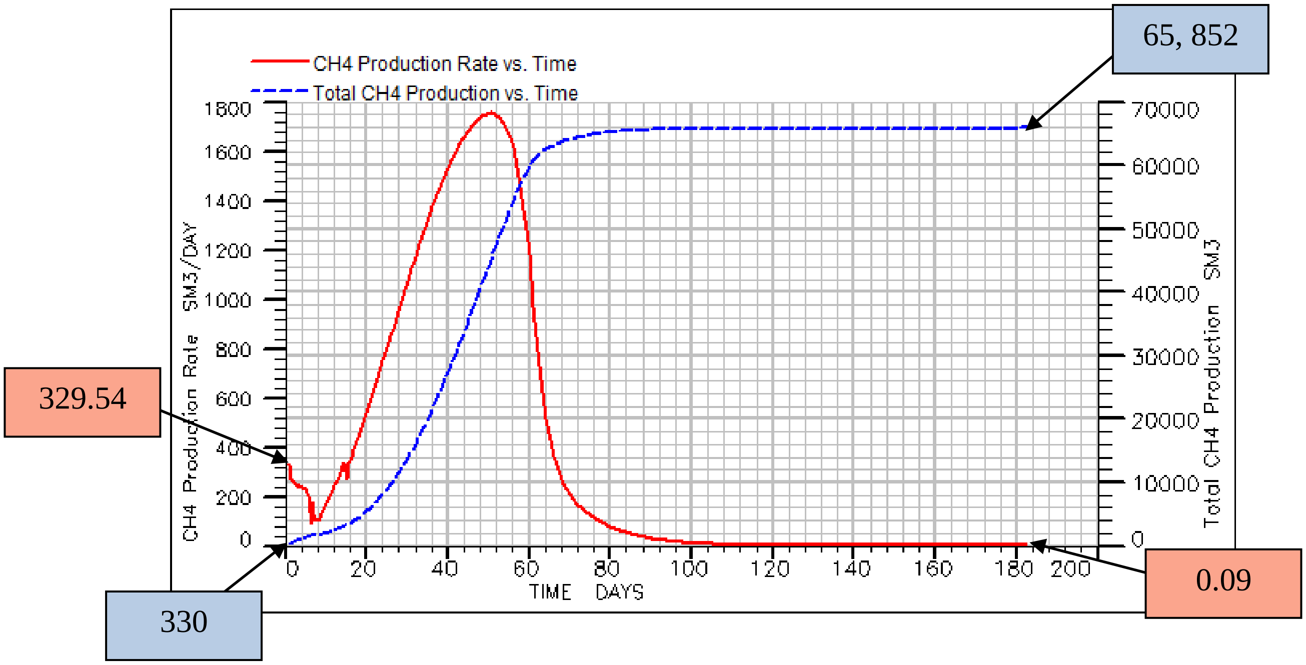
65, 820

340.72

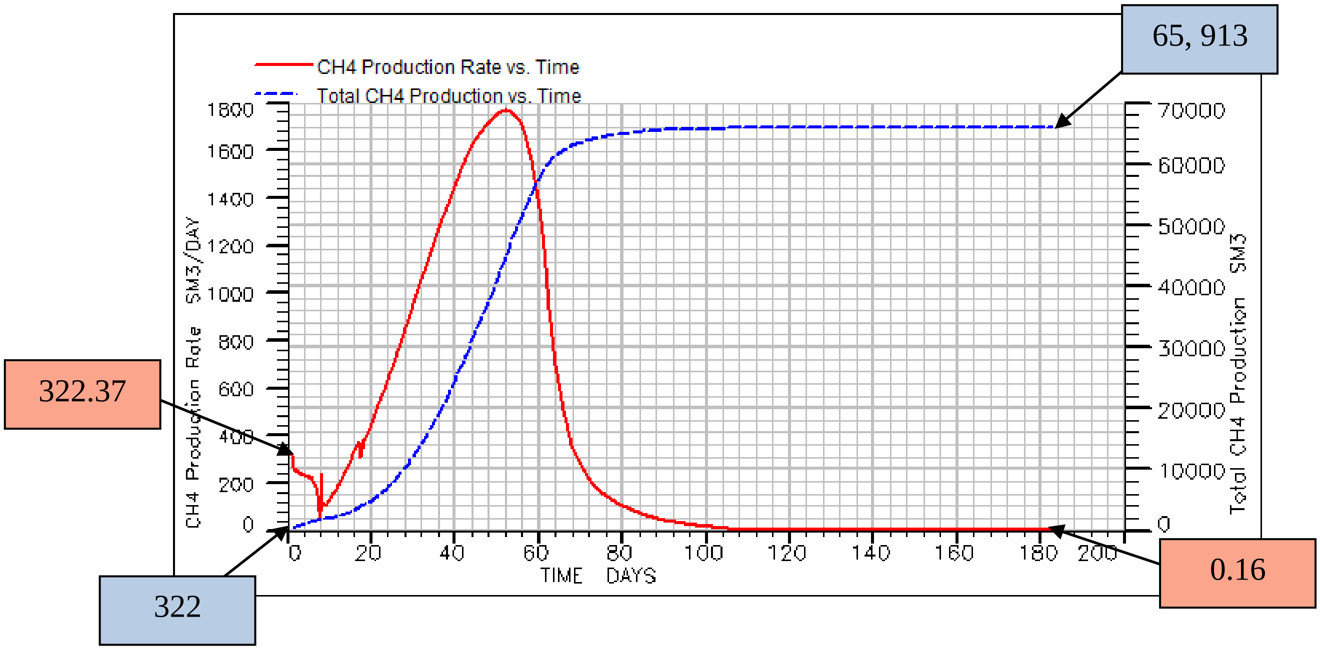
341

0.05

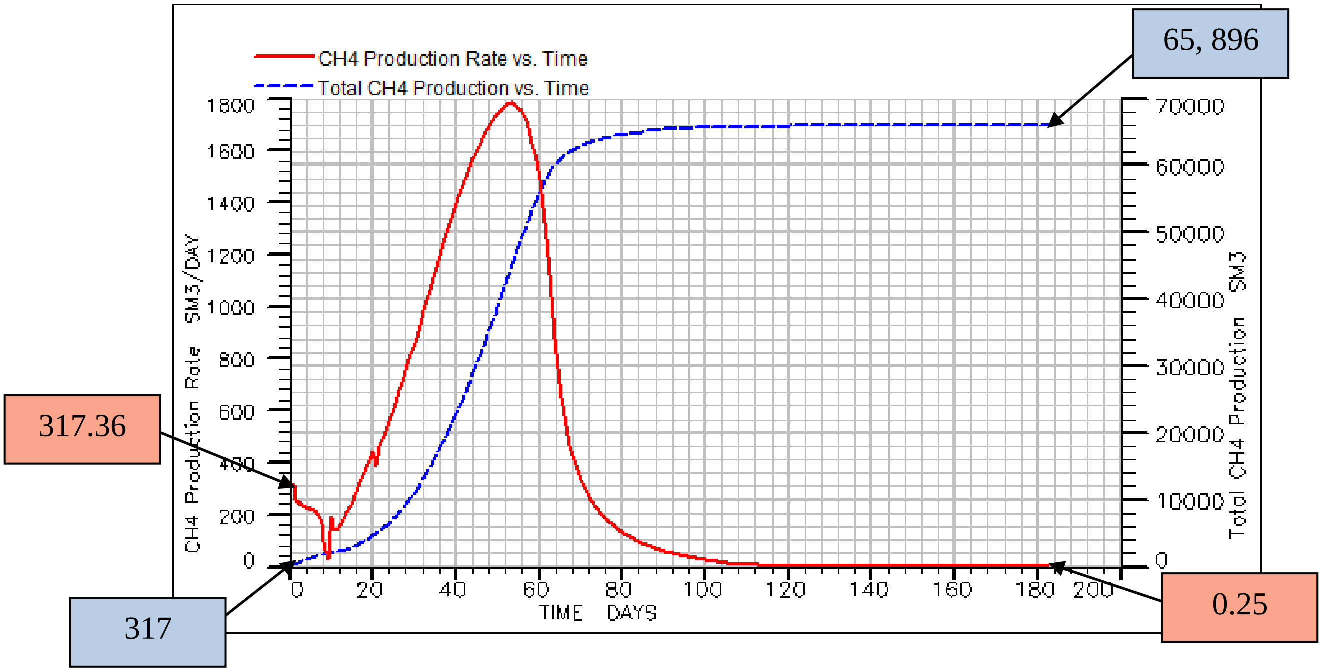
Test for Porosity: 0.003



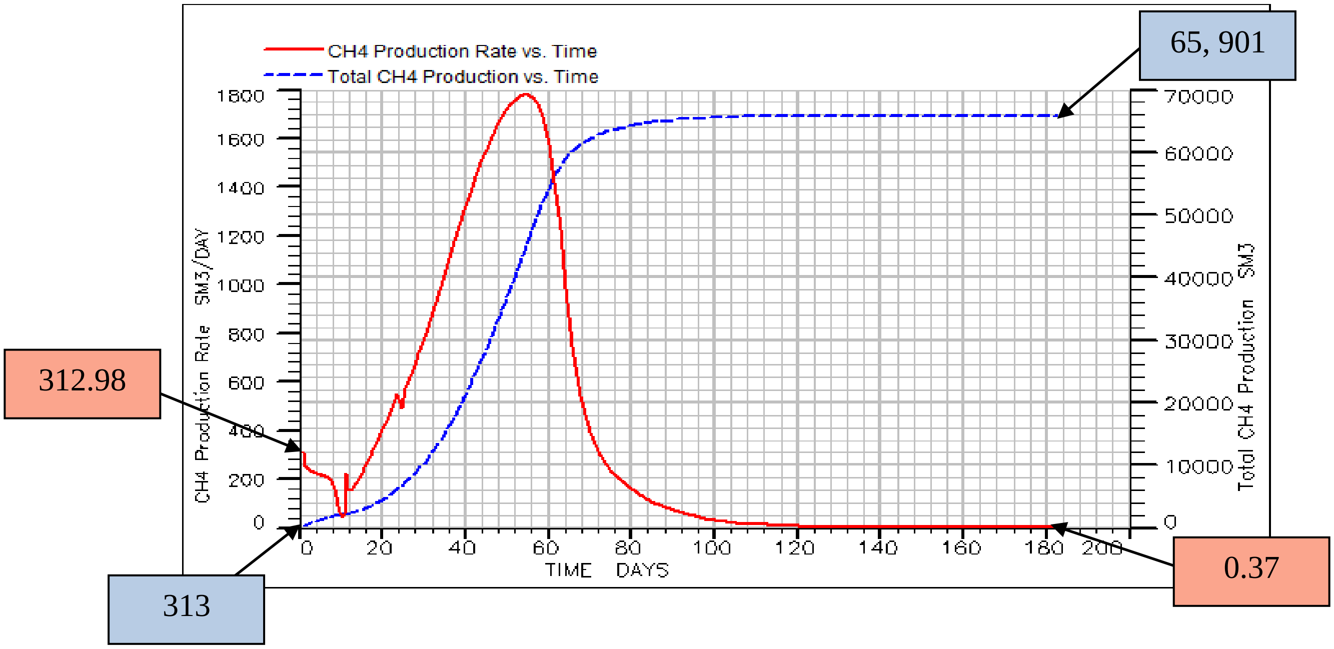
Test for Porosity: 0.004



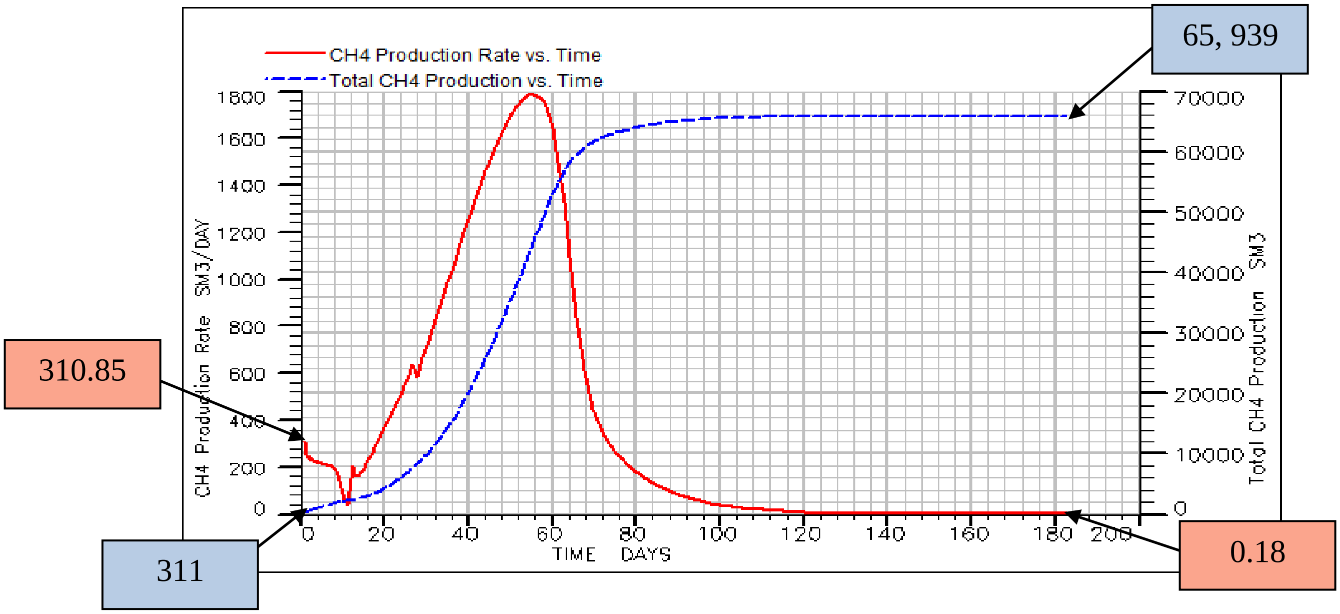
Test for Porosity: 0.005



Test for Porosity: 0.006



Test for Porosity: 0.007



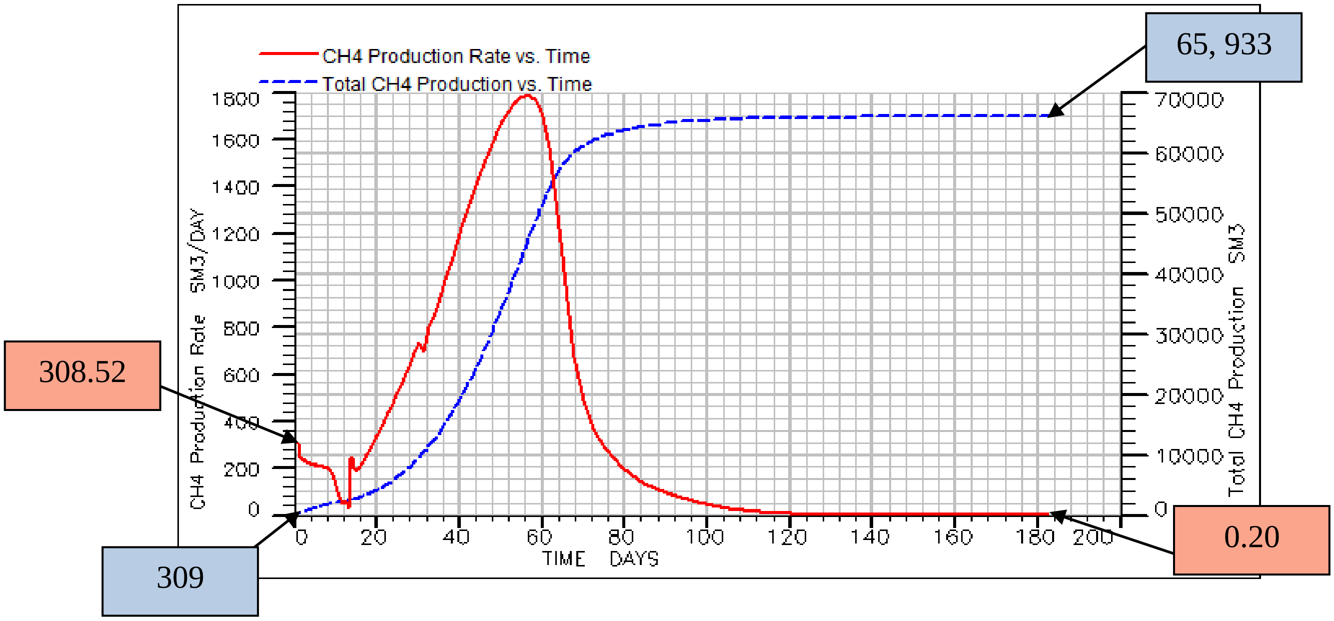
65, 939

310.85

311

0.18

Test for Porosity: 0.008



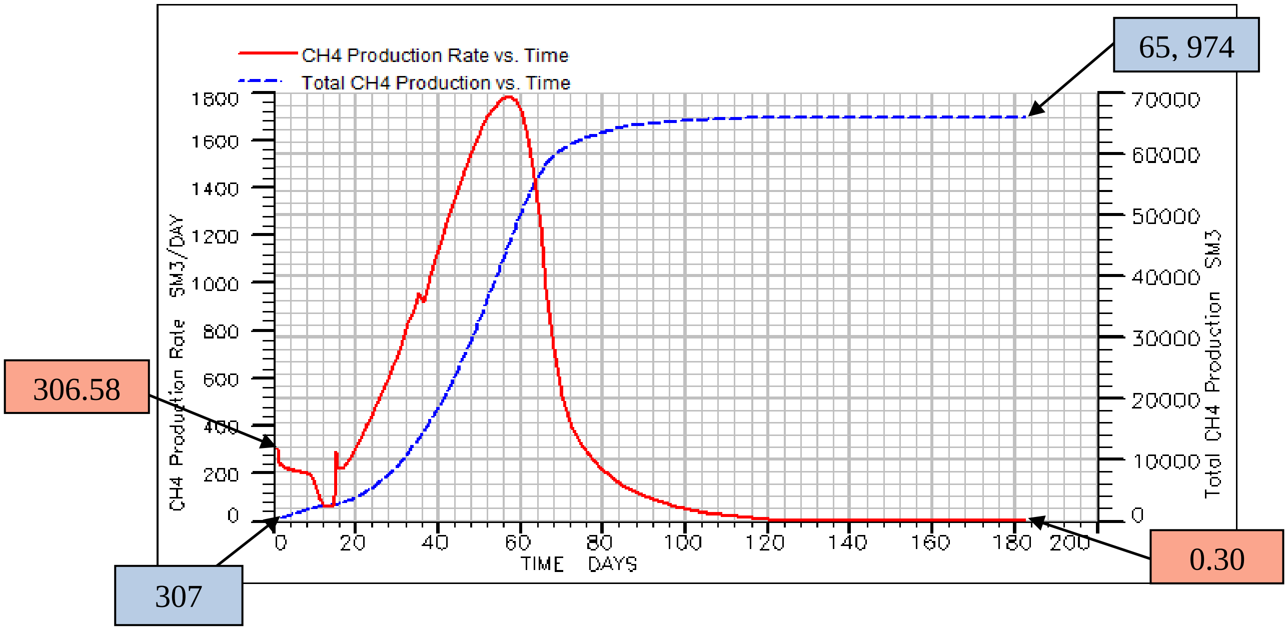
65, 933

308.52

309

0.20

Test for Porosity: 0.009



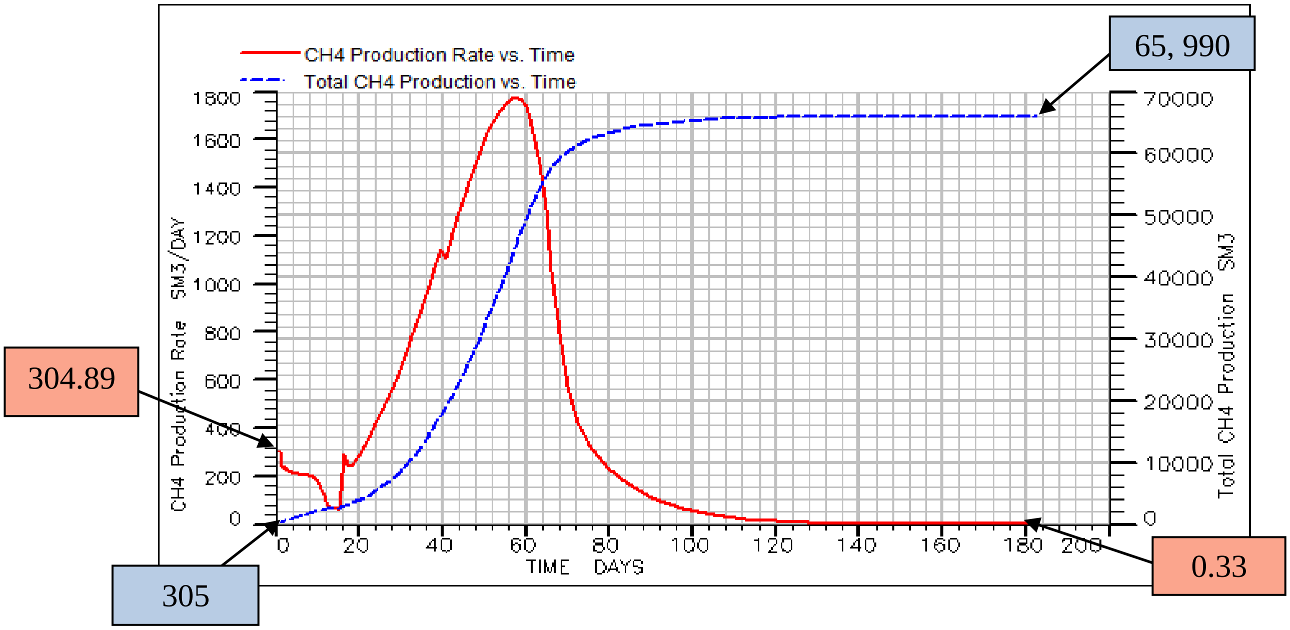
65, 974

306.58

307

0.30

Test for Porosity: 0.010



65, 990

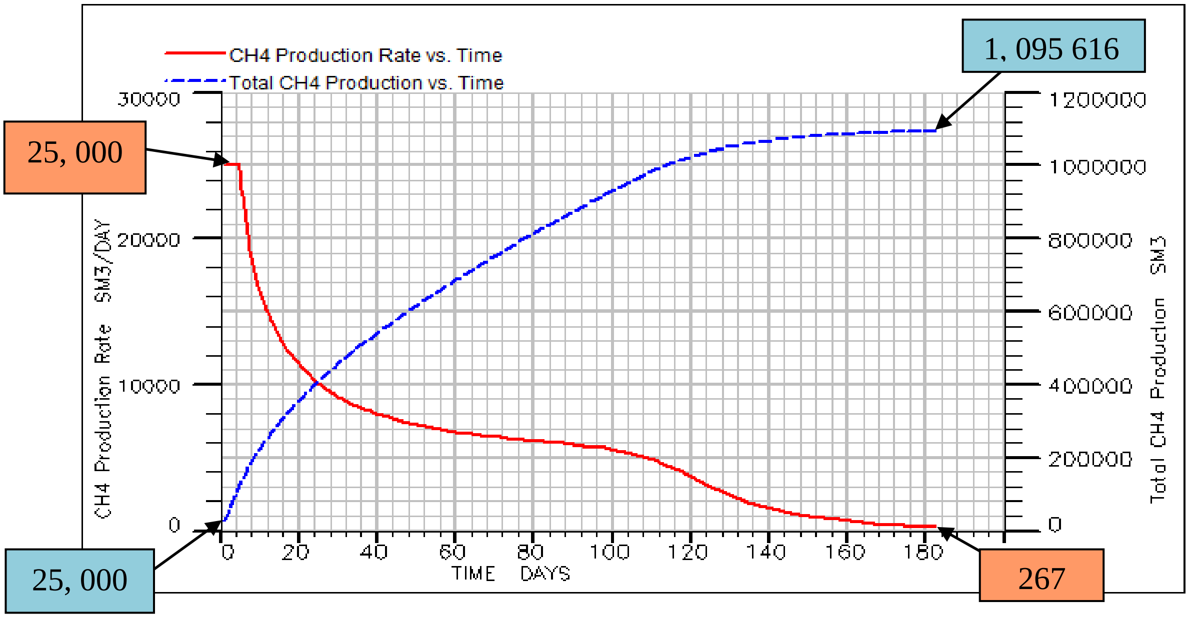
304.89

305

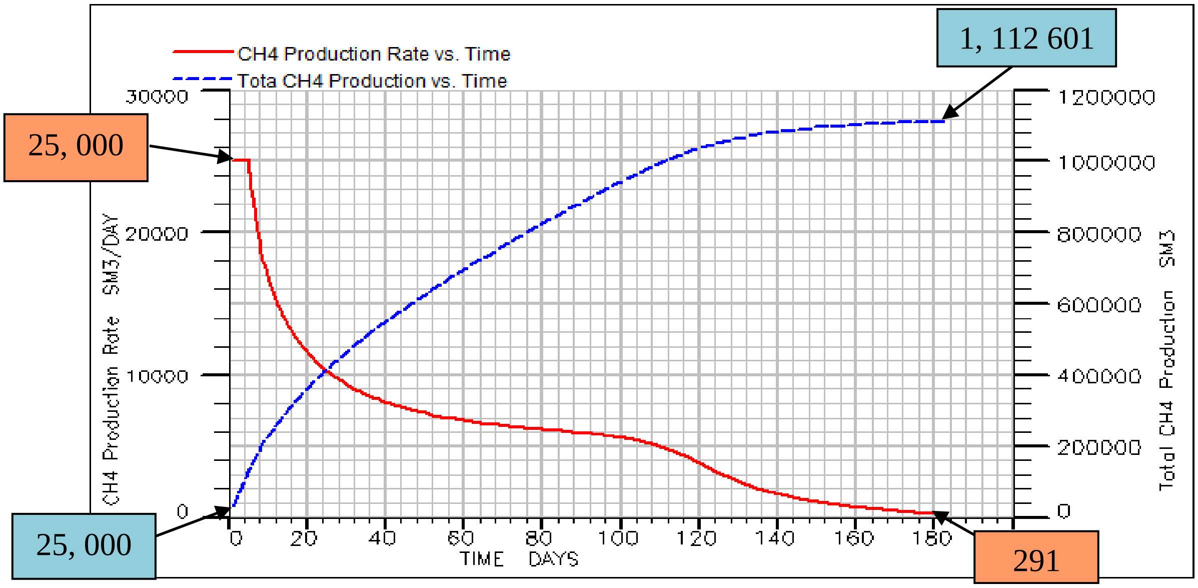
0.33

Basin Name: Qinshui, China
Coal Type: Anthracite

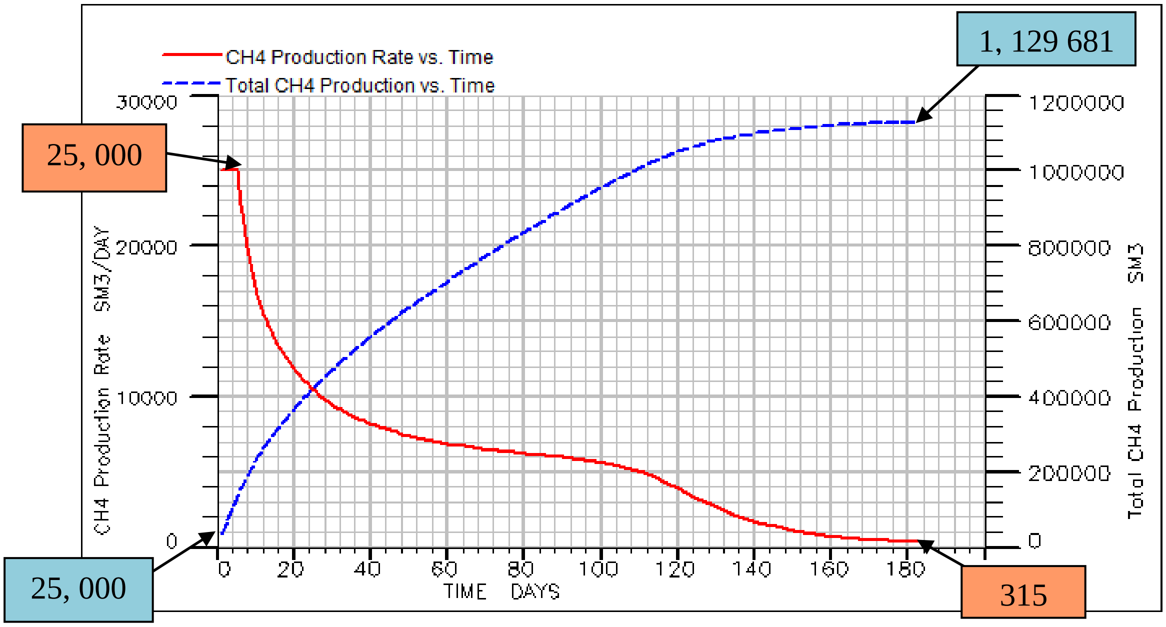
Test for Porosity: 0.01



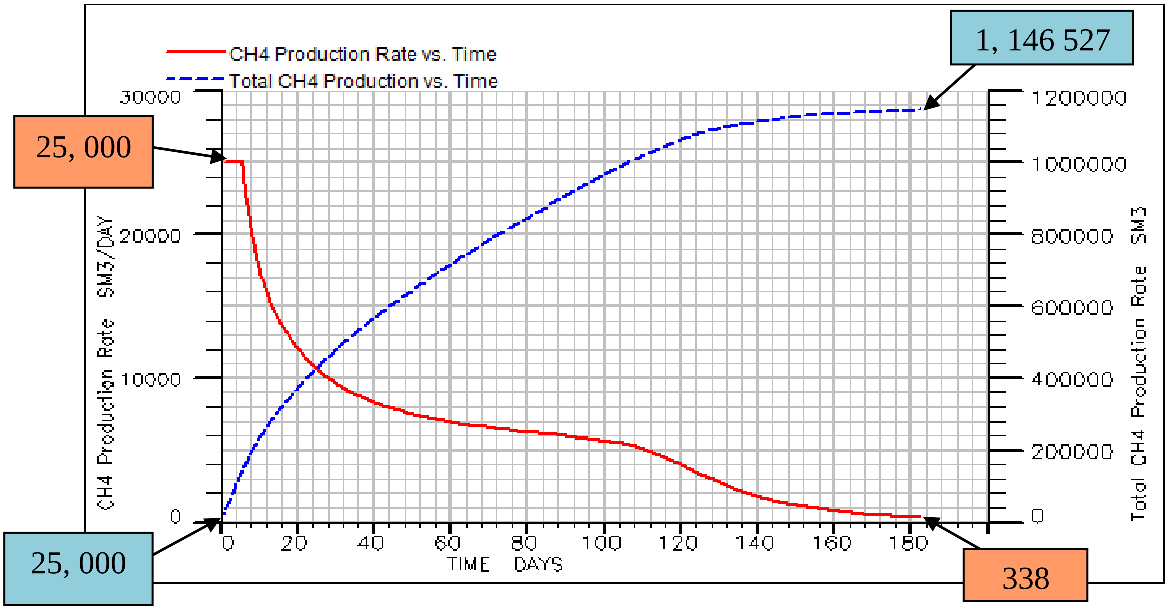
Test for Porosity: 0.02



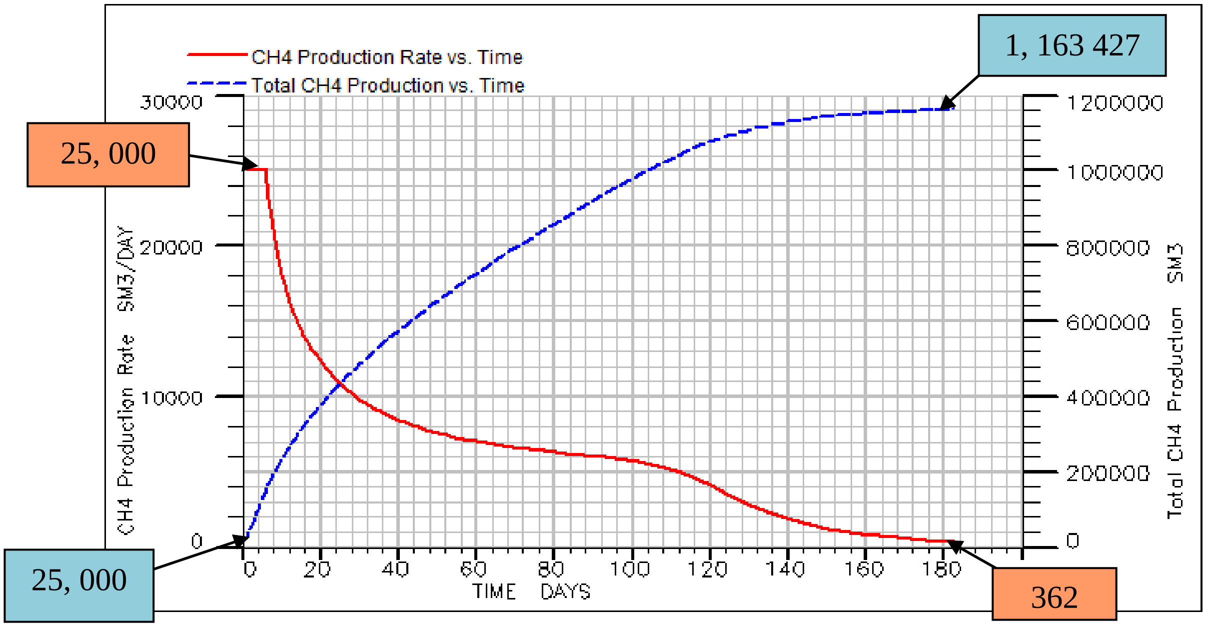
Test for Porosity: 0.03



Test for Porosity: 0.04



Test for Porosity: 0.05



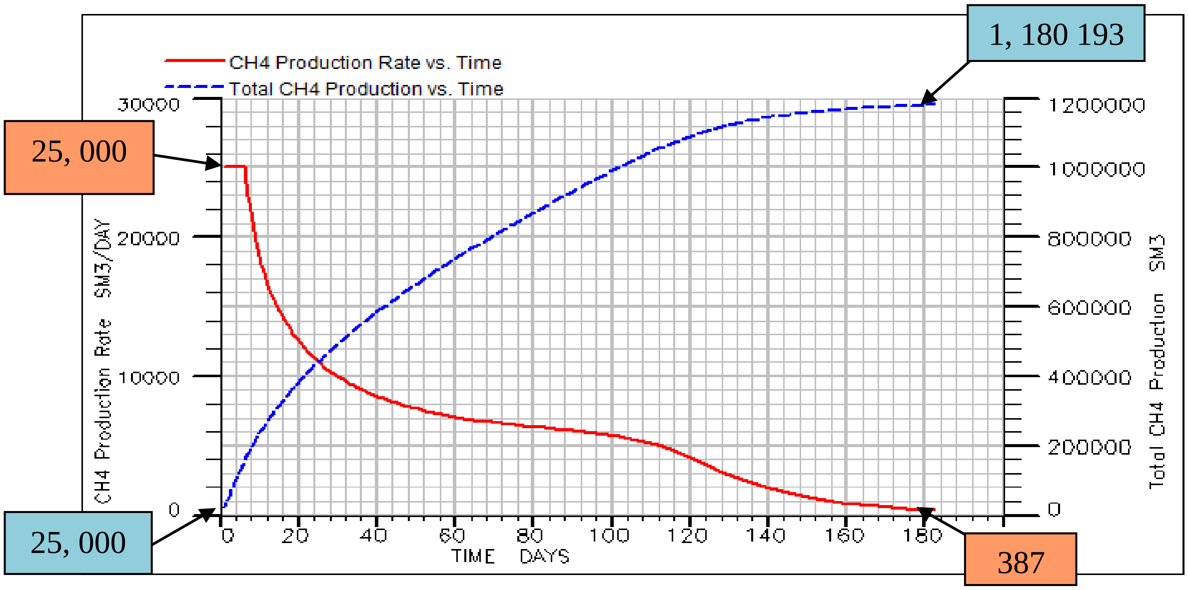
1, 163 427

25, 000

25, 000

362

Test for Porosity: 0.06



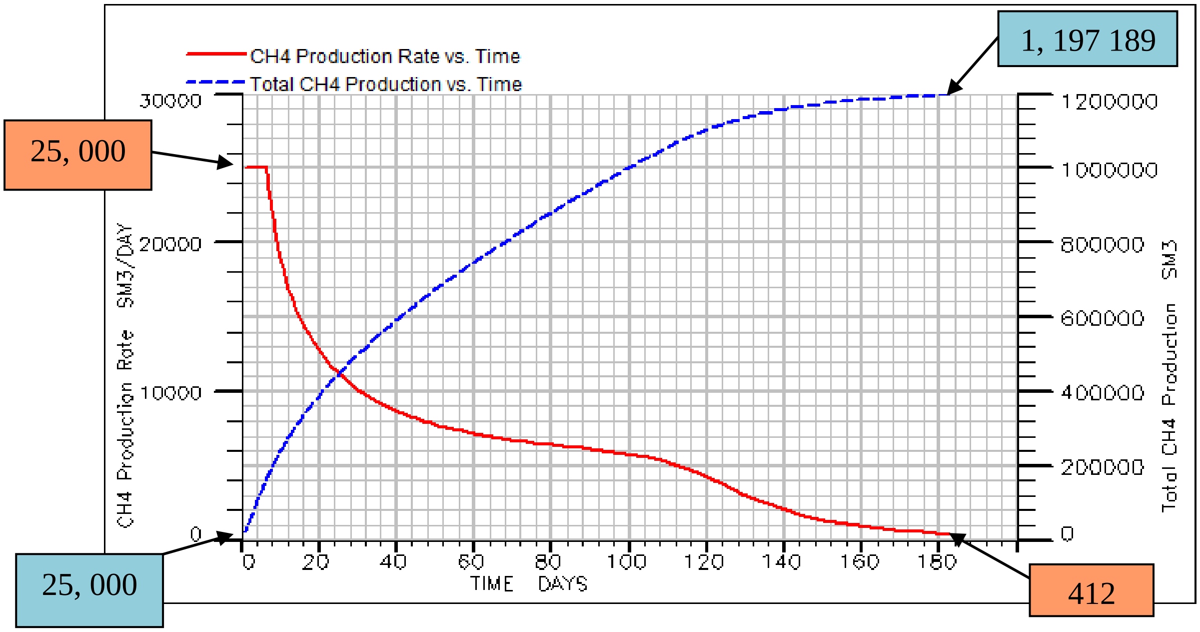
1, 180 193

25, 000

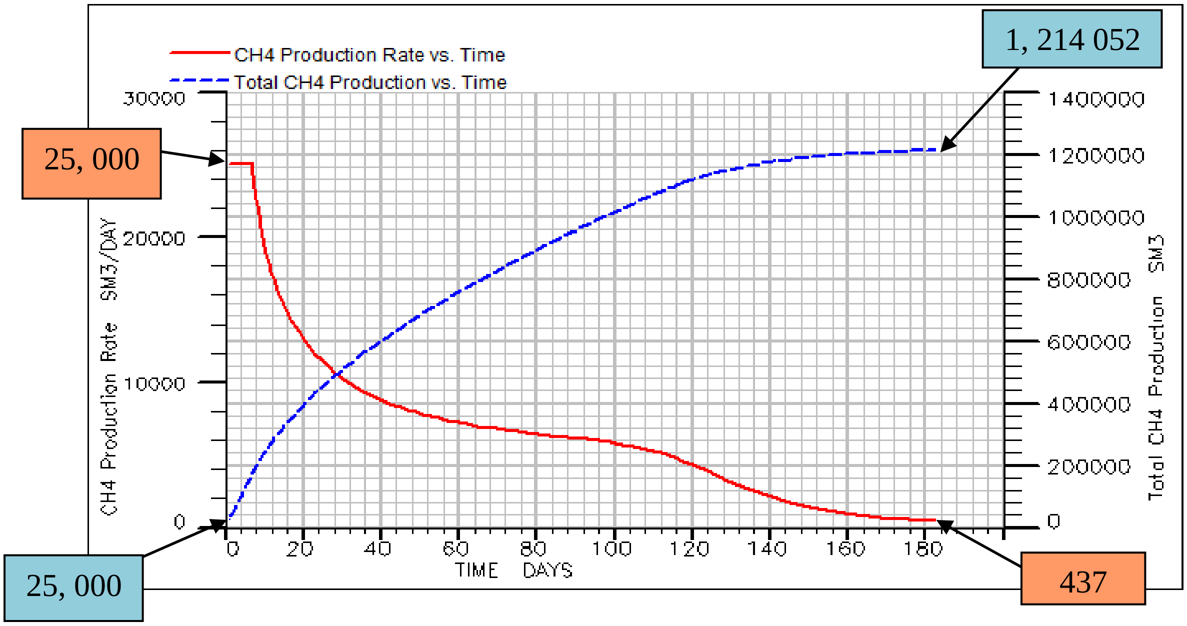
25, 000

387

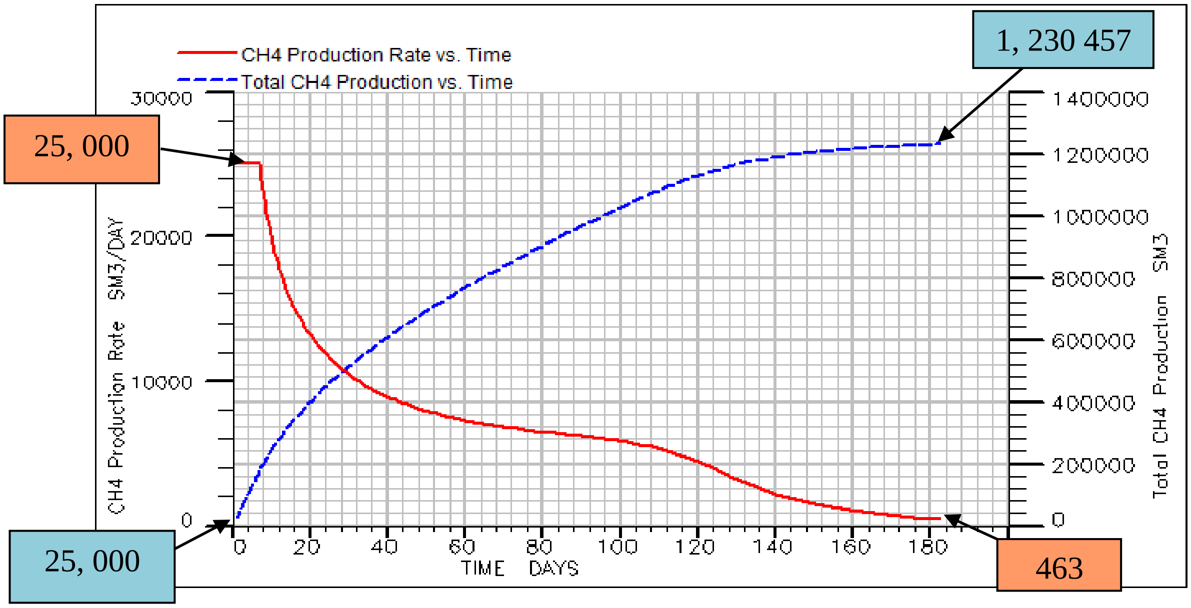
Test for Porosity: 0.07



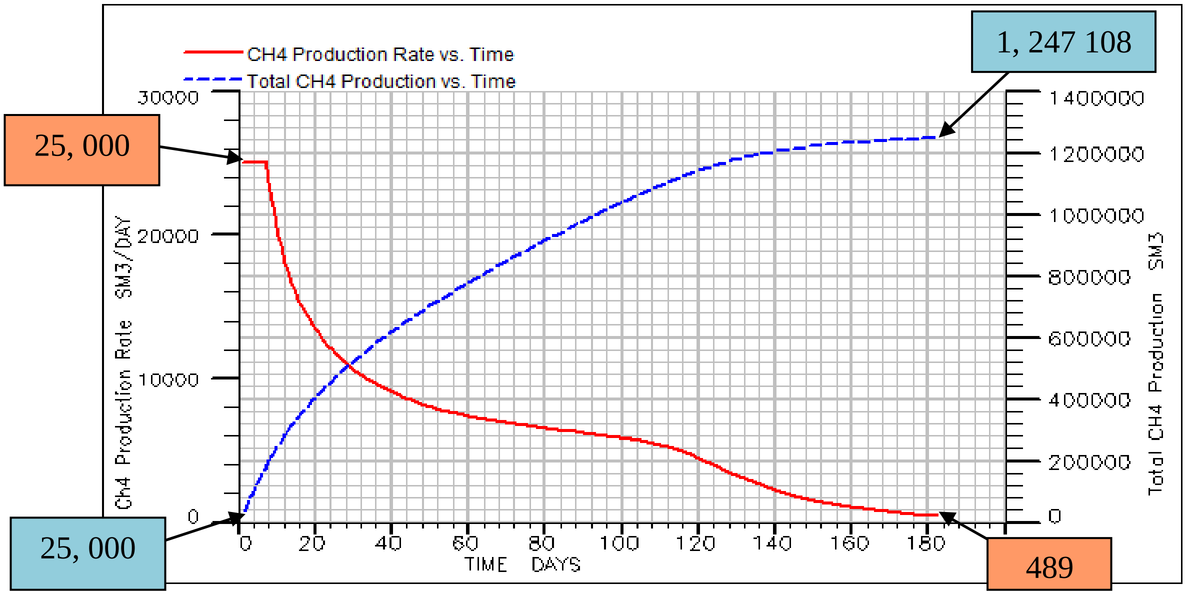
Test for Porosity: 0.08



Test for Porosity: 0.09

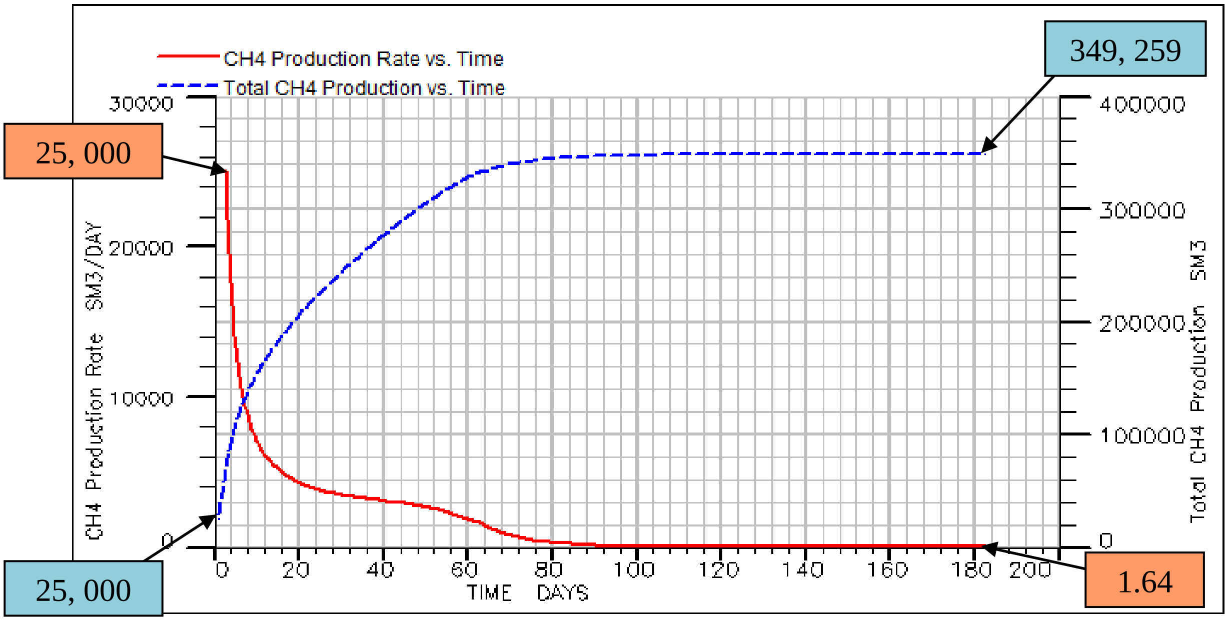


Test for Porosity: 0.10



Basin Name: Zonguldak, Turkey
Coal Type: High-volatile A bituminous

Test for Porosity: 0.01



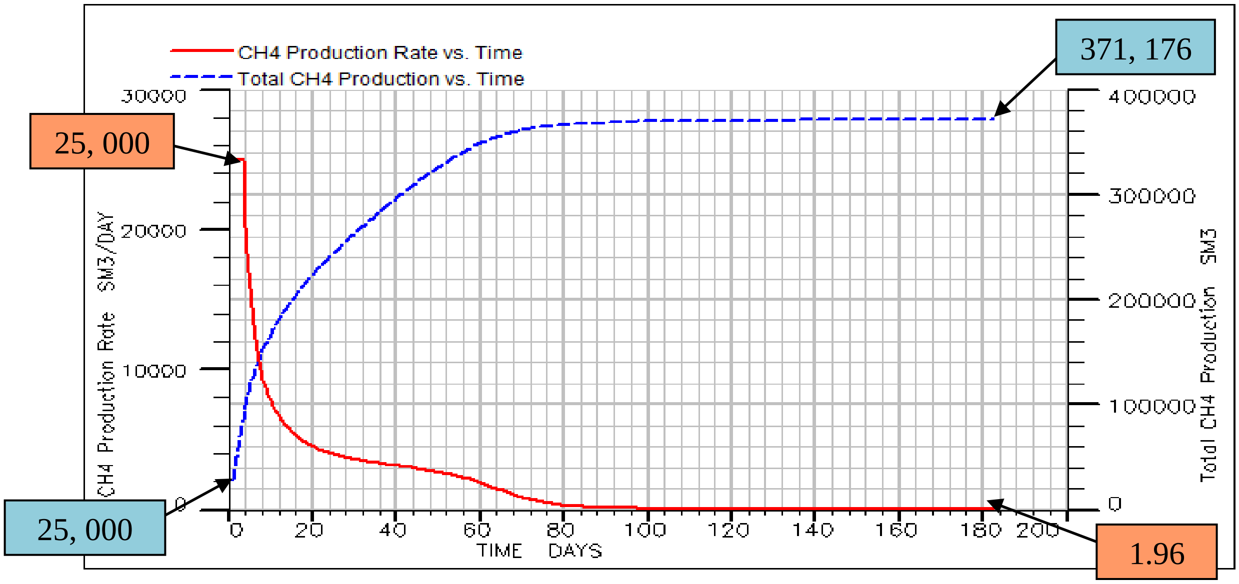
349, 259

25, 000

25, 000

1.64

Test for Porosity: 0.02



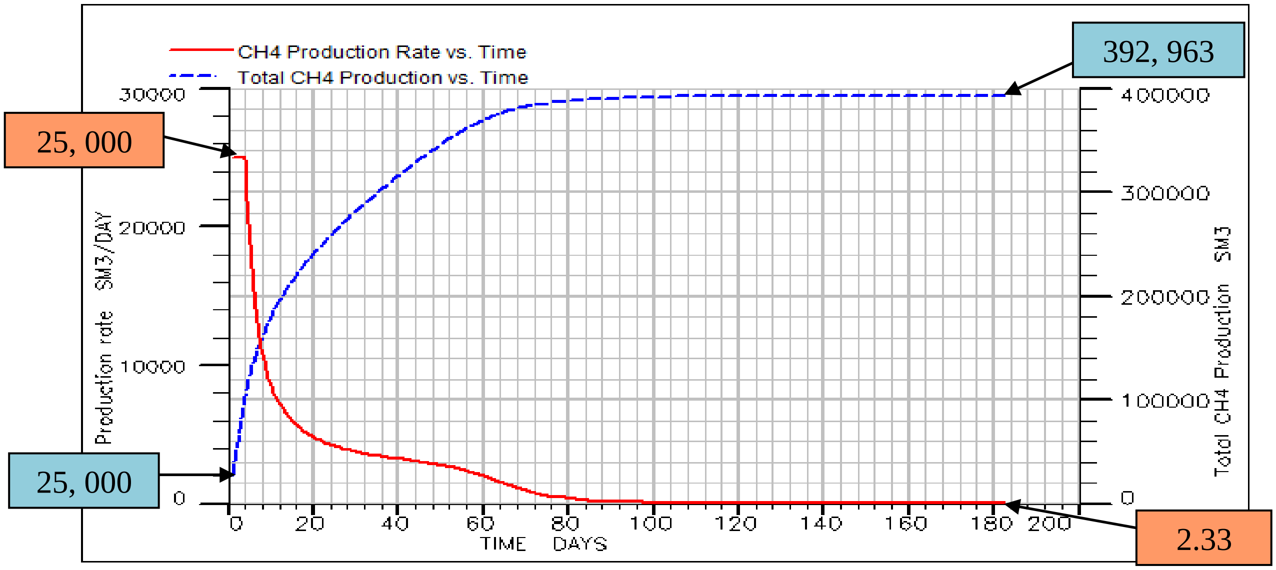
371, 176

25, 000

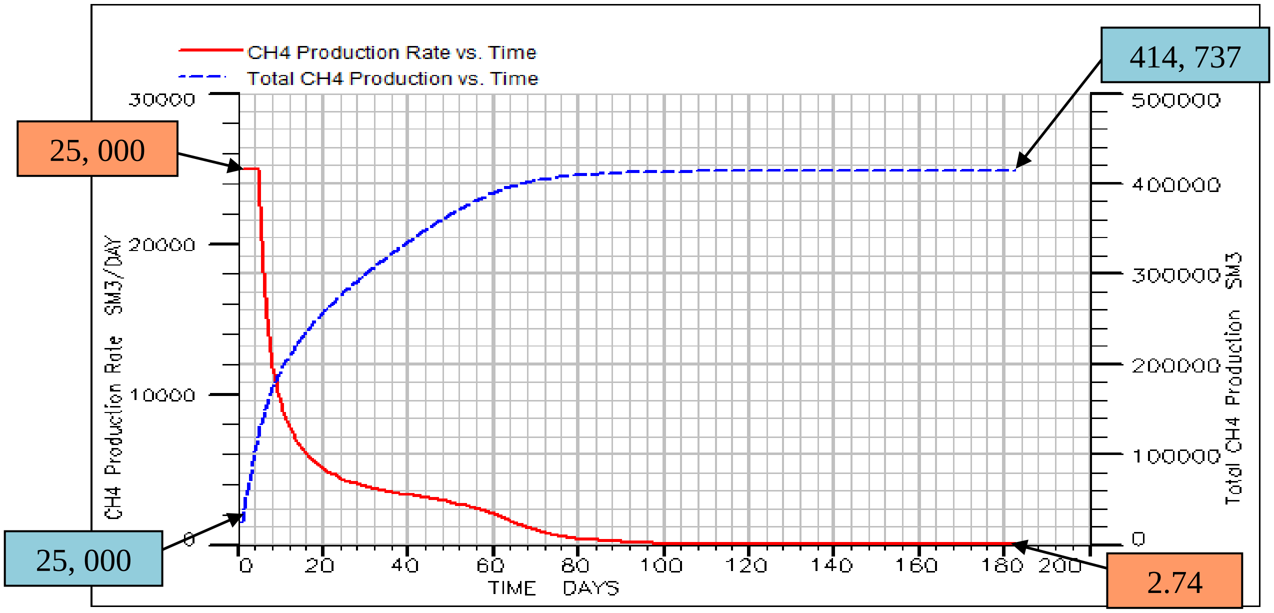
25, 000

1.96

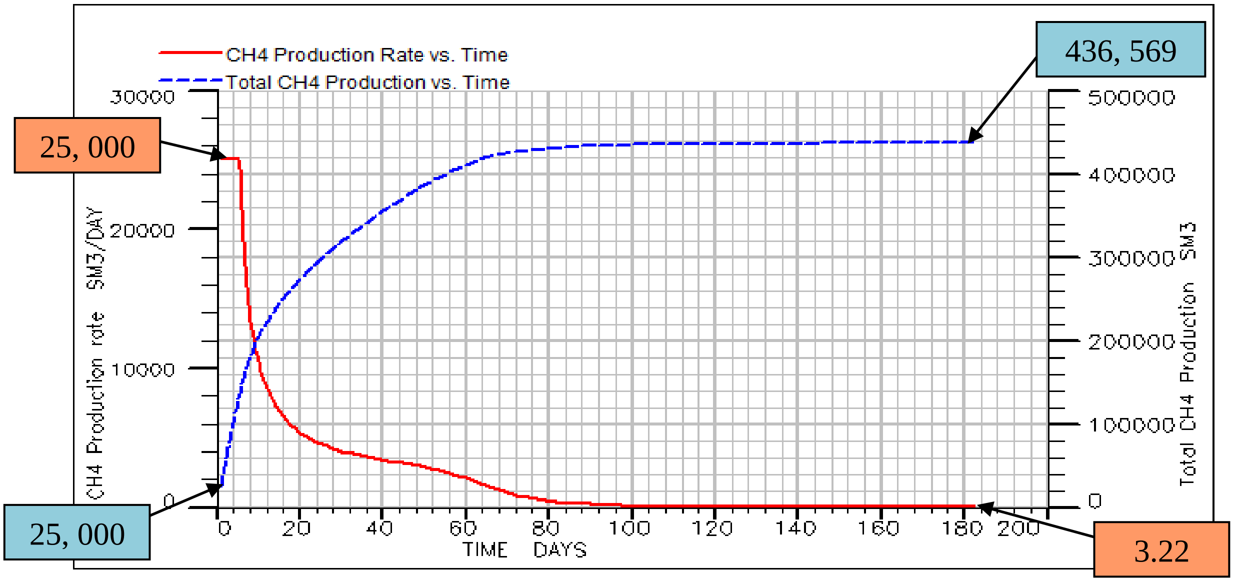
Test for Porosity: 0.03



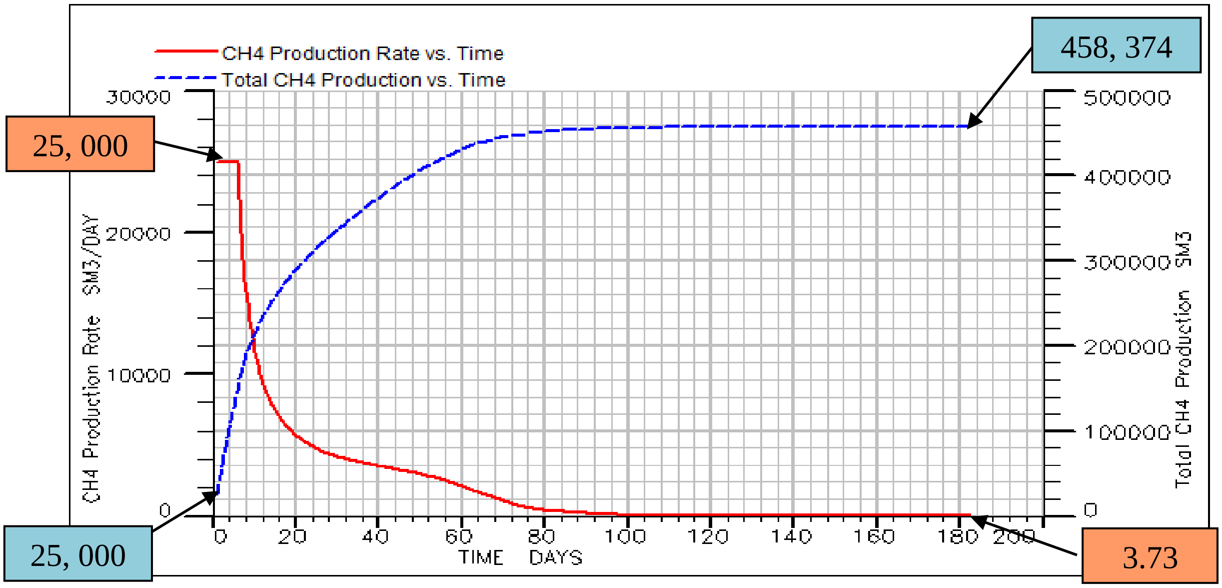
Test for Porosity: 0.04



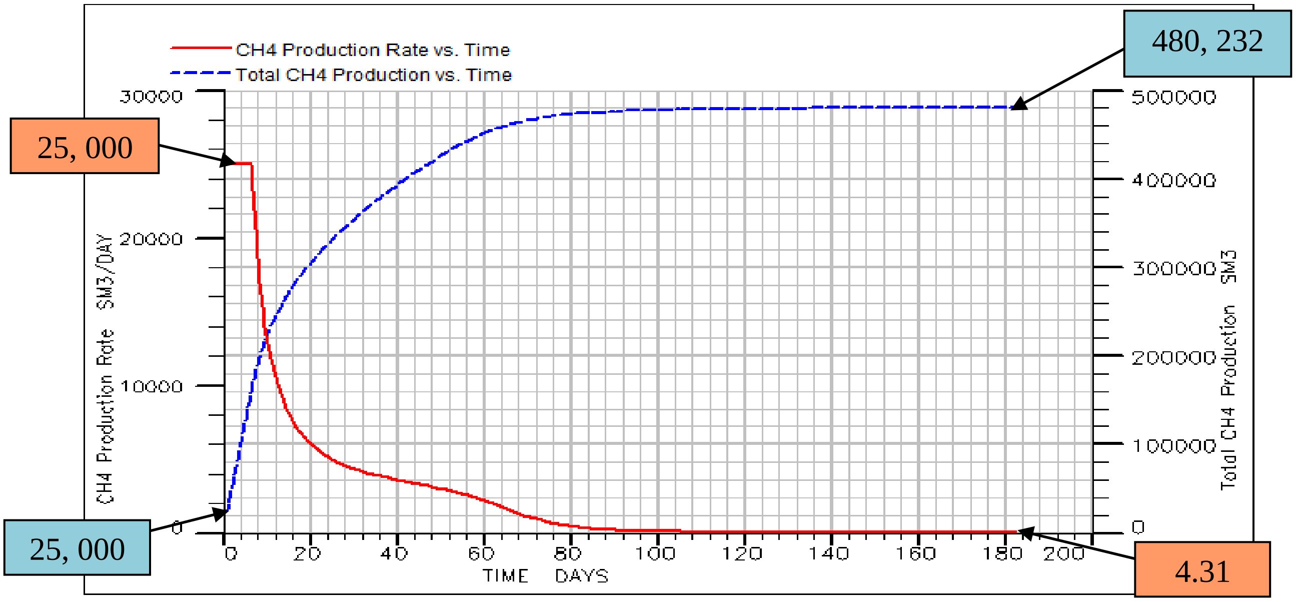
Test for Porosity: 0.05



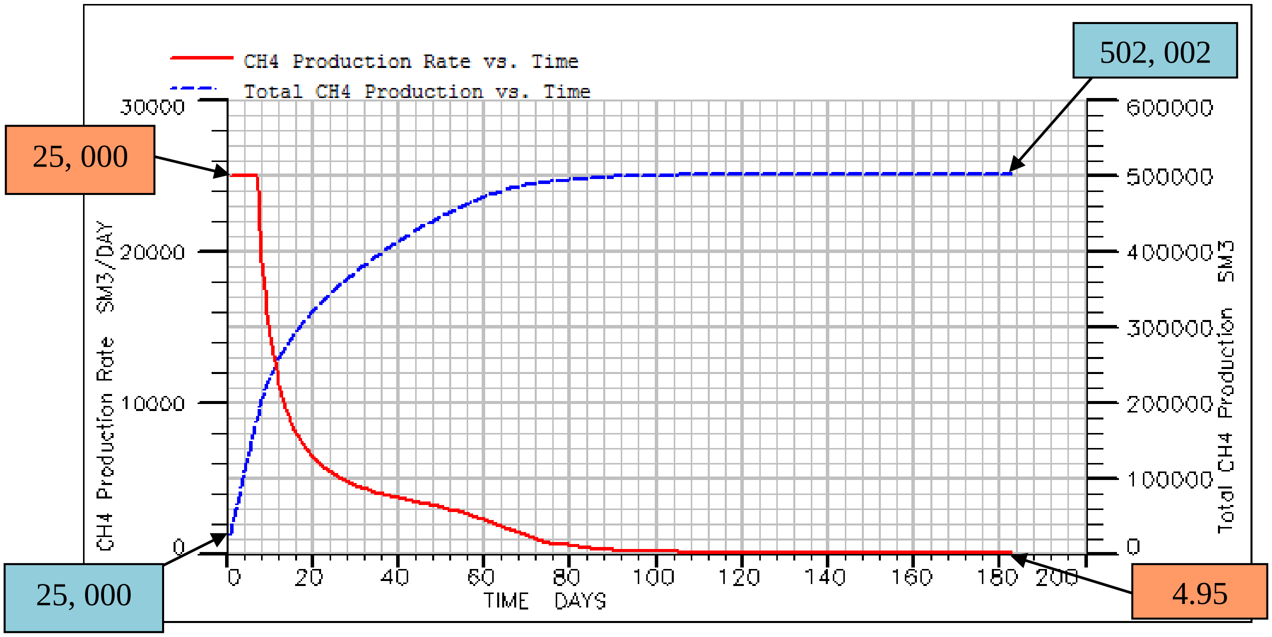
Test for Porosity: 0.06



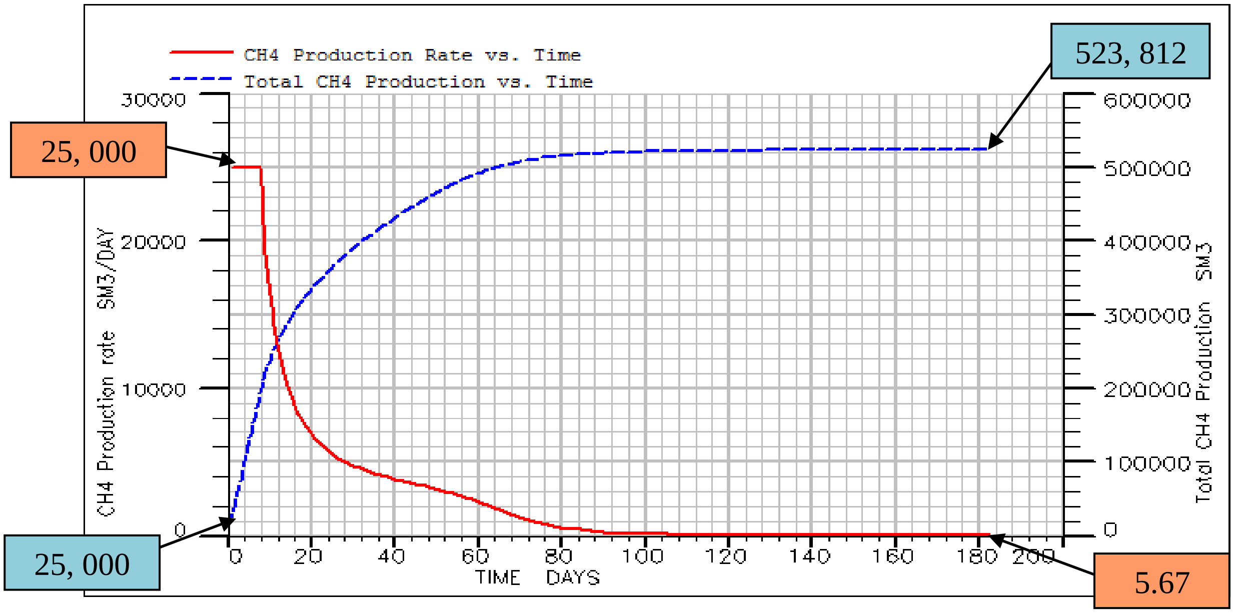
Test for Porosity: 0.07



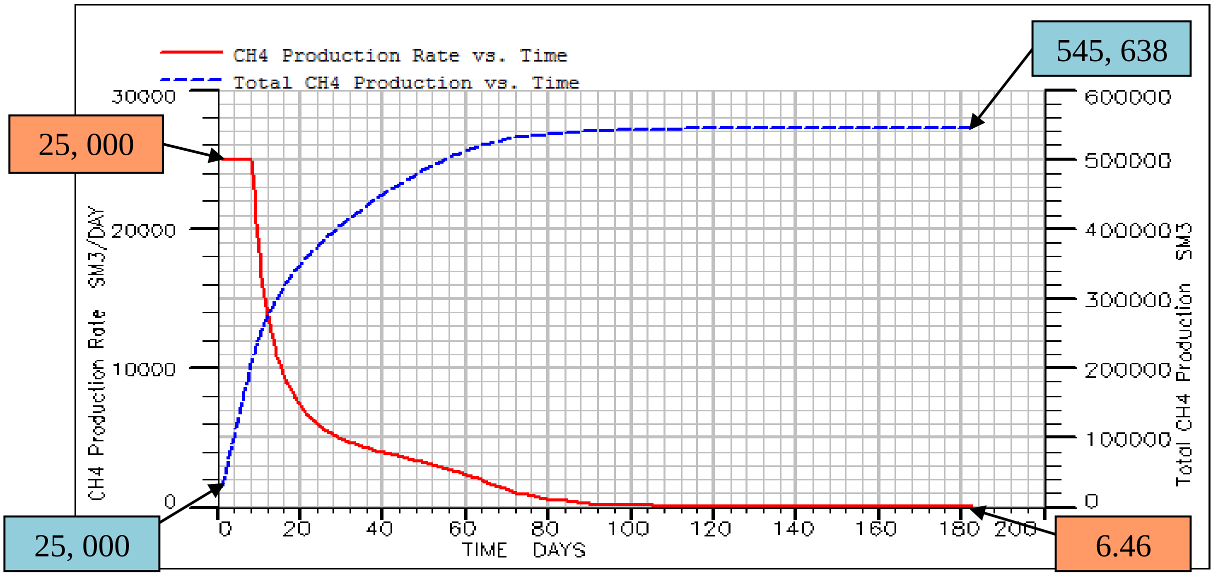
Test for Porosity: 0.08



Test for Porosity: 0.09

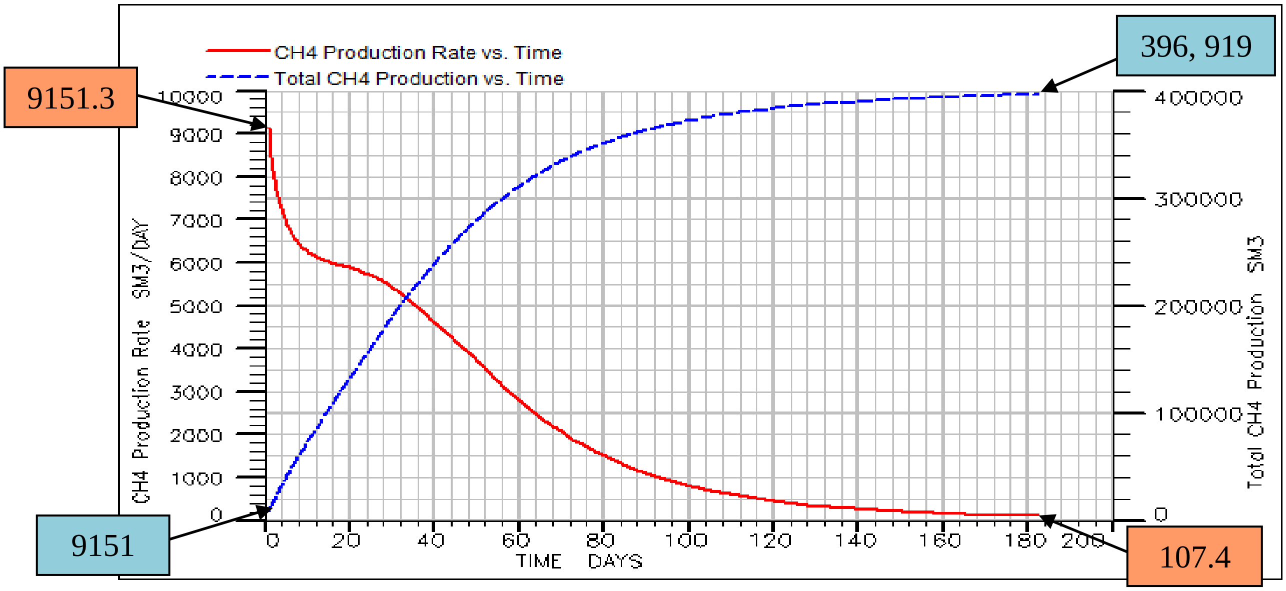


Test for Porosity: 0.10

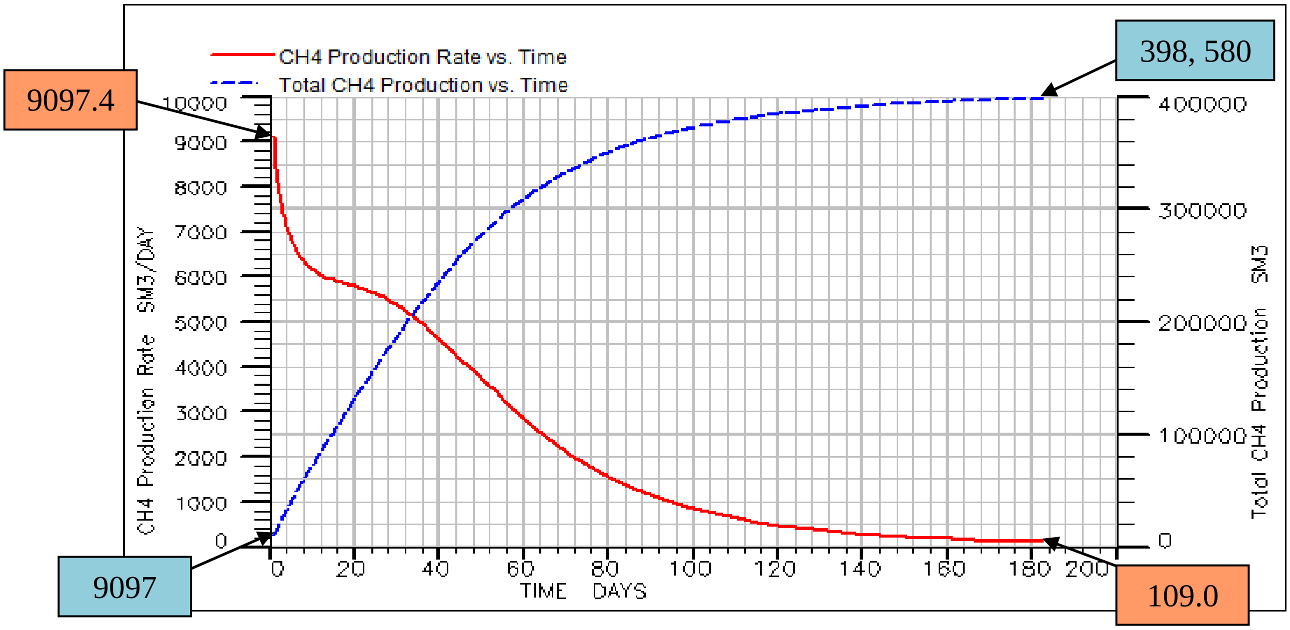


Basin Name: Upper Silesian (RECOPOL-Pilot), Poland
Coal Type: High-volatile bituminous

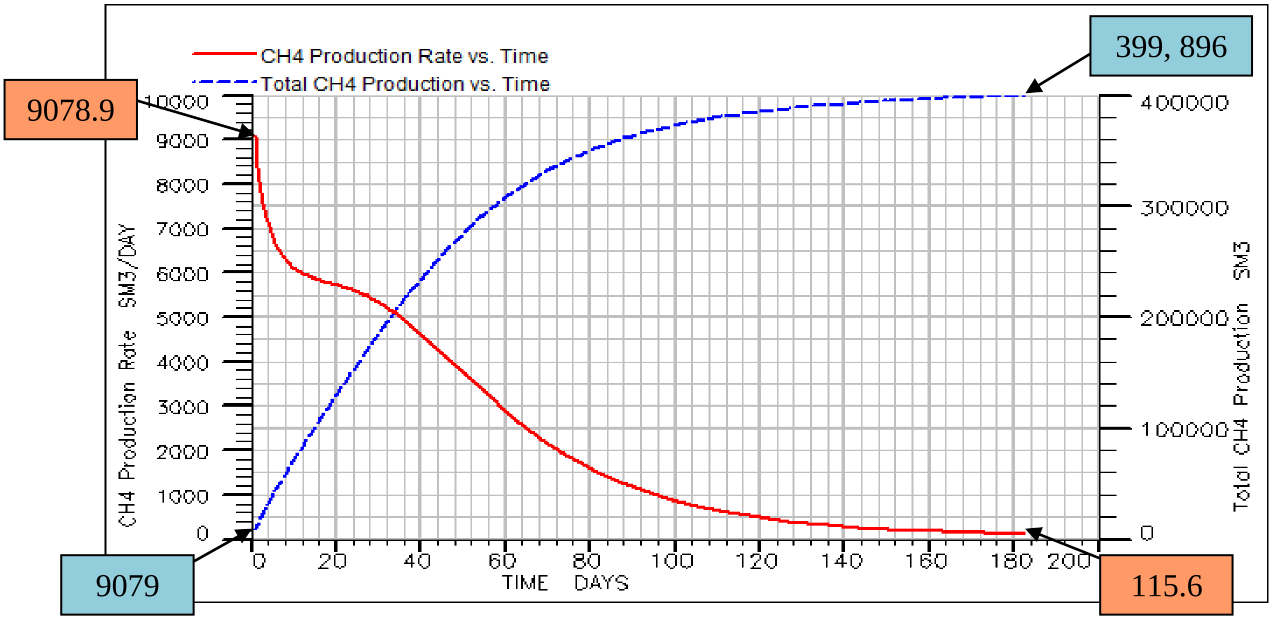
Test for Porosity: 0.001



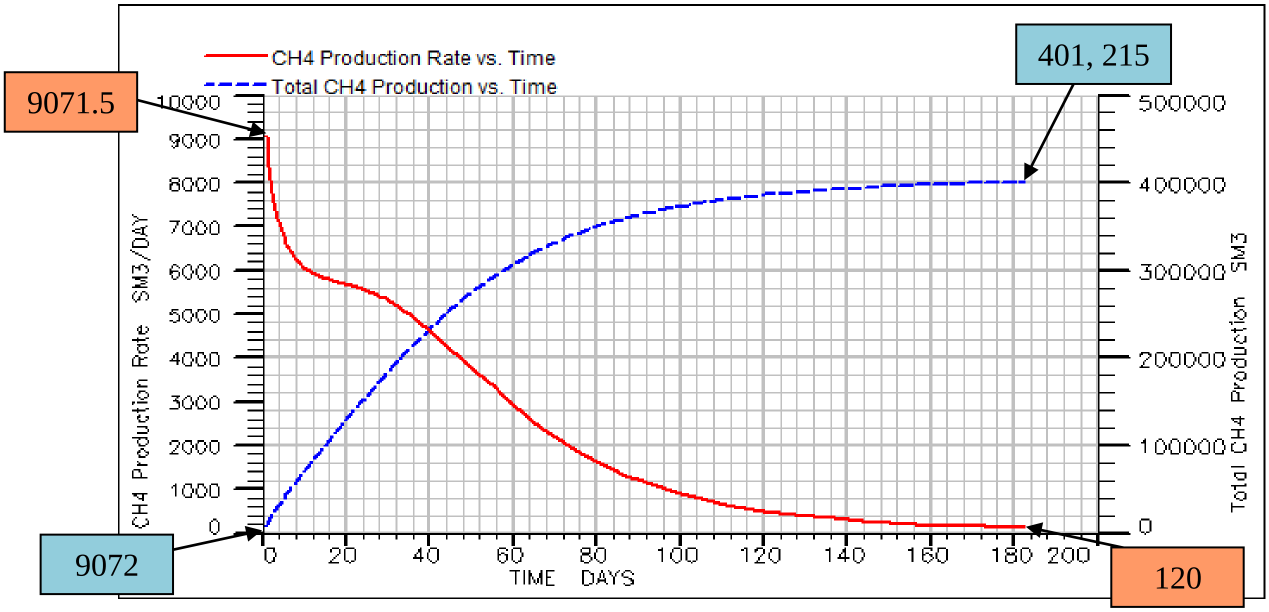
Test for Porosity: 0.002



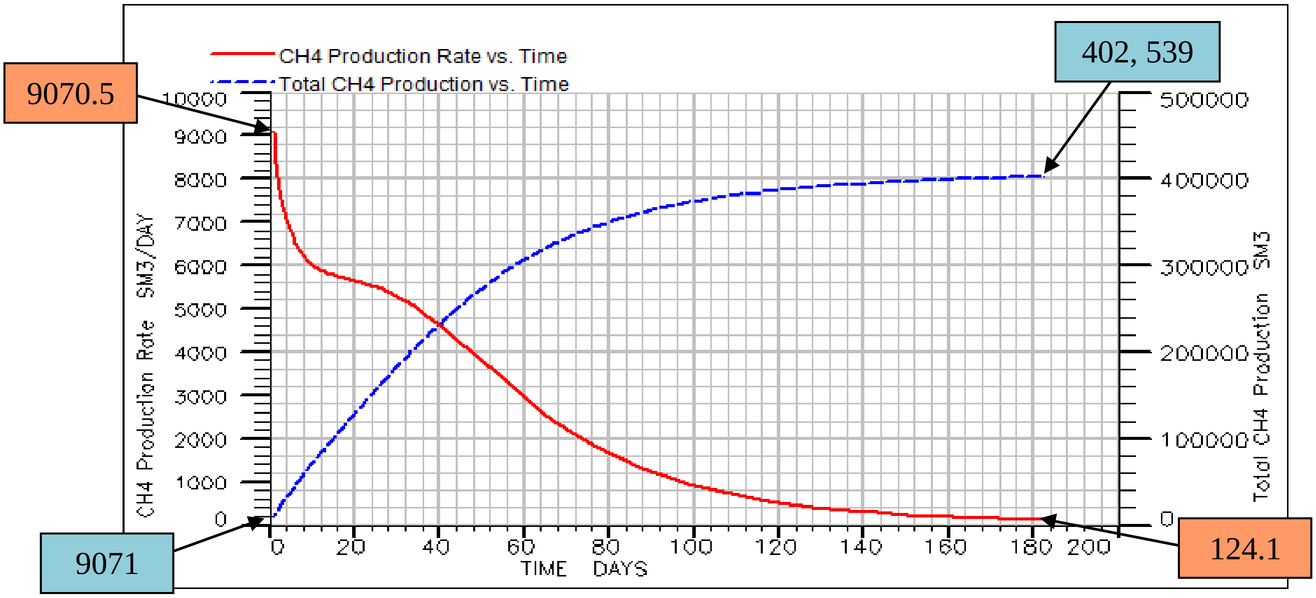
Test for Porosity: 0.003



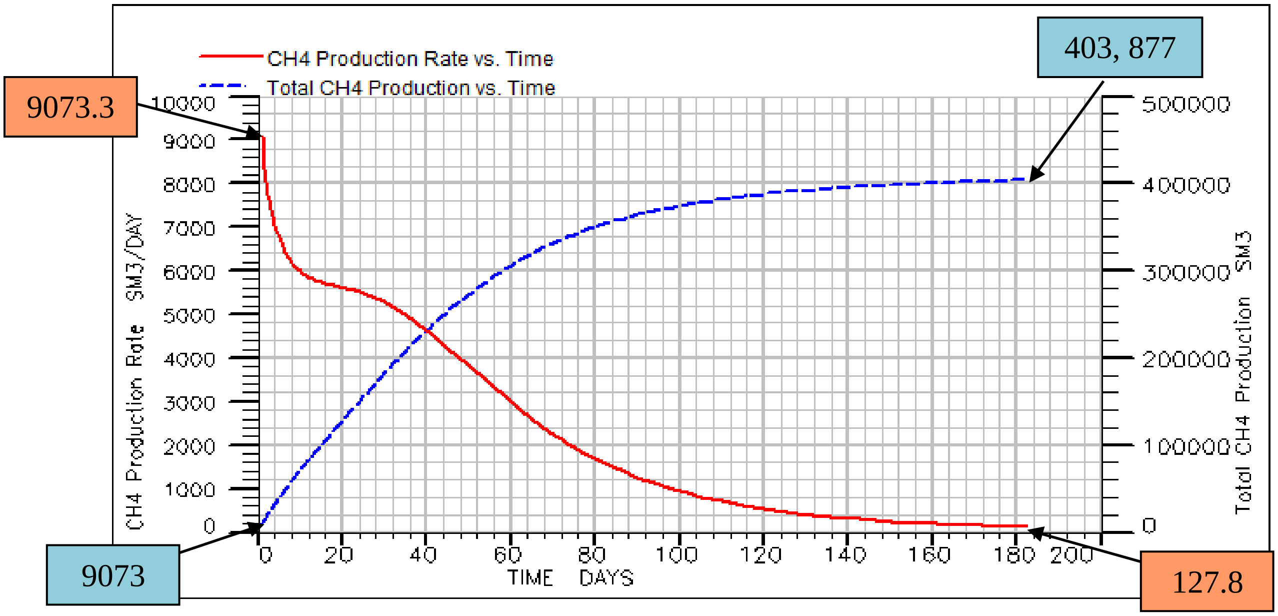
Test for Porosity: 0.004



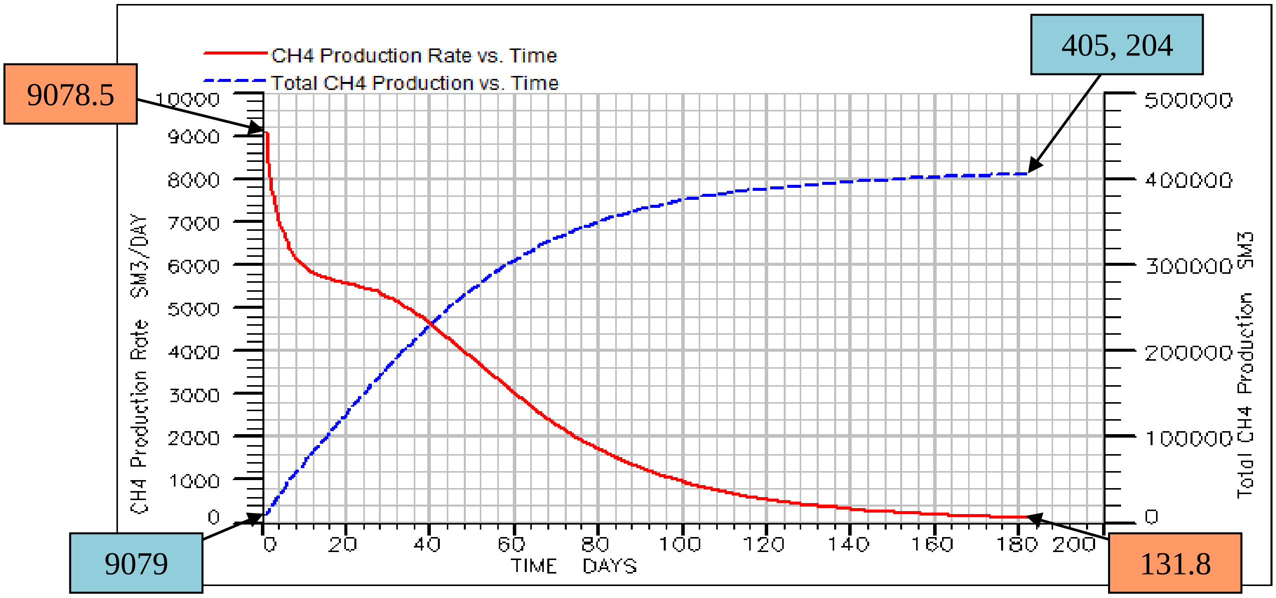
Test for Porosity: 0.005



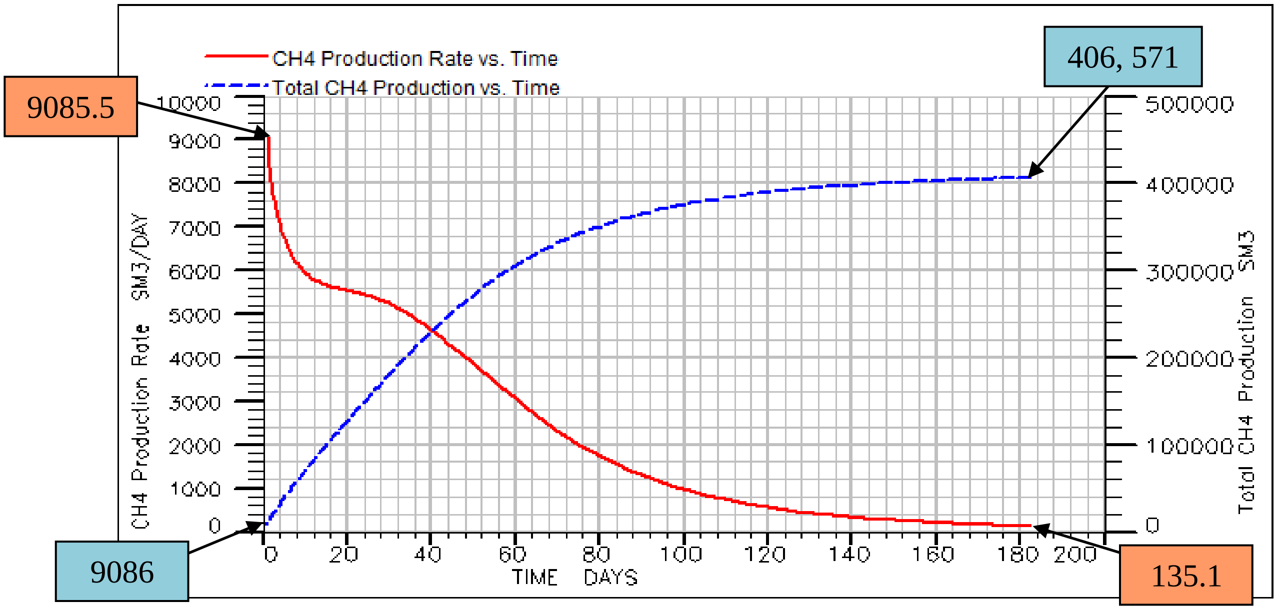
Test for Porosity: 0.006



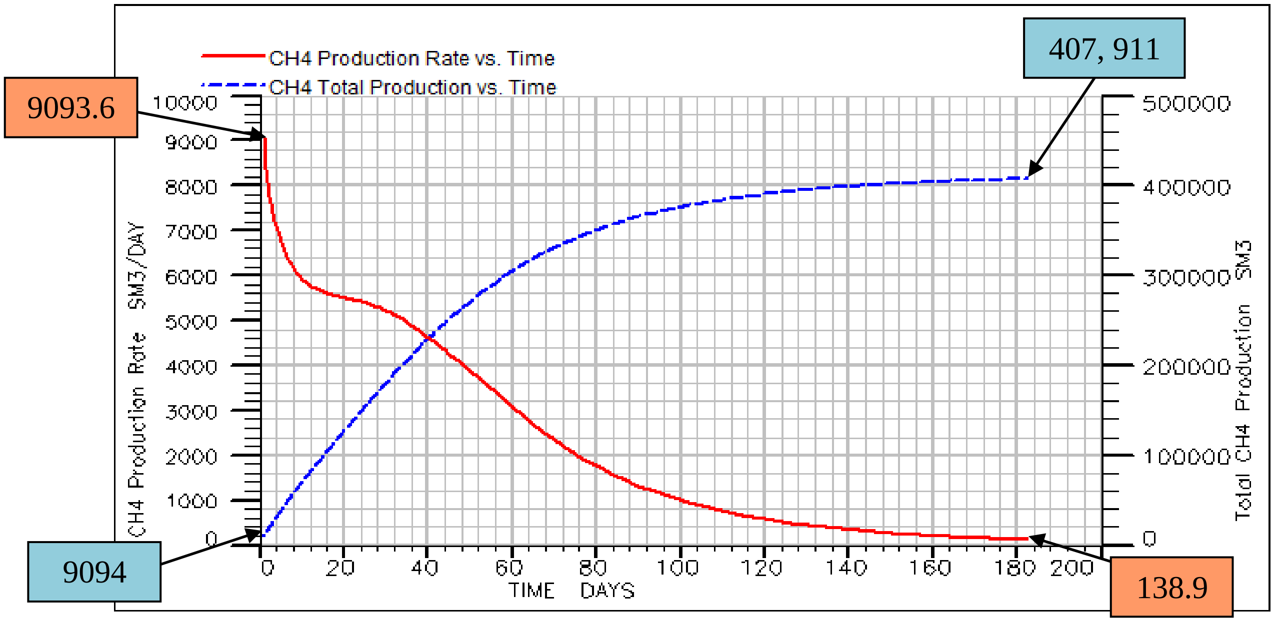
Test for Porosity: 0.007



Test for Porosity: 0.008



Test for Porosity: 0.009



Test for Porosity: 0.010

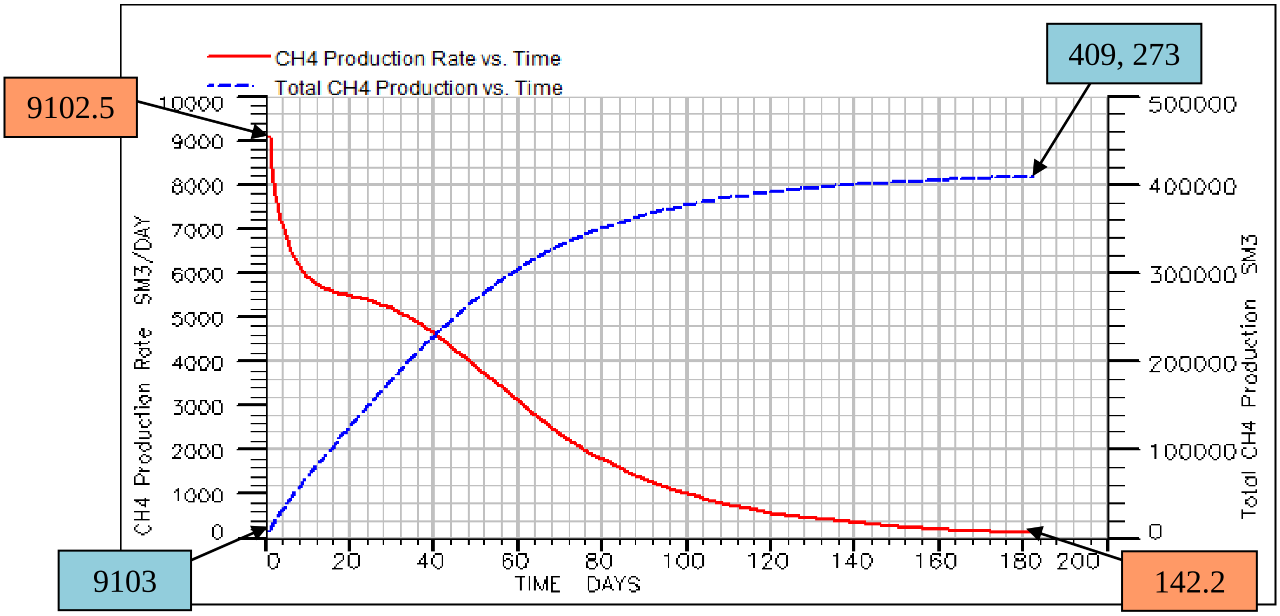


Table 8: Production Data of CBM Basins (Porosity 0.001-0.01)

Porosity Value	**CH_4 Production Rate (sm^3/day)**			**Total CH_4 Production (sm^3)**		
	San Juan (Sub-bituminous)	**Powder River (Sub-bituminous C)**	**Upper Silesian (High-volatile bituminous)**	**San Juan (Sub-bituminous)**	**Powder River (Sub-bituminous C)**	**Upper Silesian (High-volatile bituminous)**
0.001	5116 – 0.2	363 – 0.1	9151 – 107	5116 – 238, 842	363 – 65, 809	9151 – 396, 919
0.002	4845 – 0.3	341 – 0.1	9097 – 110	4845 – 239, 297	341 – 65, 820	9097 – 398, 580
0.003	4717 – 1.3	330 – 0.1	9079 – 116	4717 – 239, 778	330 – 65, 852	9079 – 399, 896
0.004	4639 – 1.1	322 – 0.2	9072 – 120	4639 – 240, 262	322 – 65, 877	9072 – 401, 215
0.005	4584 – 1.7	317 – 0.3	9071 – 124	4584 – 240, 707	317 – 65, 896	9071 – 402, 539
0.006	4543 – 2.4	313 – 0.4	9073 – 128	4543 – 241, 165	313 – 65, 901	9073 – 403, 877
0.007	4510 – 3.0	311 – 0.2	9079 – 132	4510 – 241, 619	311 – 65, 939	9079 – 405, 204
0.008	4483 – 3.8	309 – 0.2	9086 – 135	4483 – 242, 082	309 – 65, 950	9086 – 406, 571
0.009	4461 – 4.7	307 – 0.3	9094 – 139	4461-242, 540	307 – 65, 974	9094 – 407, 911
0.010	4442 – 5.4	305 – 0.3	9103 - 142	4442 – 243, 008	305 – 65, 990	9103 – 409, 273

Table 9: Production Data of CBM Basins (Porosity 0.01-0.10)

Porosity Value	CH_4 Production Rate (sm^3/day)		Total CH_4 Production (sm^3)	
	Qinshui (Anthracite)	Zonguldak (High-volatile A bituminous)	Qinshui (Anthracite)	Zonguldak (High-volatile A bituminous)
0.01	25, 000 – 267	25, 000 – 1.6	25, 000 – 1, 095 616	25, 000 – 349, 259
0.02	25, 000 – 291	25, 000 – 2.0	25, 000 – 1, 112 601	25, 000 – 371, 176
0.03	25, 000 – 315	25, 000 – 2.3	25, 000 – 1, 129 681	25, 000 – 392, 963
0.04	25, 000 – 338	25, 000 – 2.7	25, 000 – 1, 146 527	25, 000 – 414, 737
0.05	25, 000 – 362	25, 000 – 3.2	25, 000 – 1, 163 427	25, 000 – 436, 569
0.06	25, 000 – 387	25, 000 – 3.7	25, 000 1, 180 193	25, 000 – 458, 374
0.07	25, 000 – 412	25, 000 – 4.3	25, 000 – 1, 197 189	25, 000 – 480, 232
0.08	25, 000 – 437	25, 000 – 5.0	25, 000 – 1, 214 052	25, 000 - 502, 002
0.09	25, 000 – 463	25, 000 – 5.7	25, 000 – 1, 230 457	25, 000 – 523, 812
0.10	25, 000 – 489	25, 000 – 6.5	25, 000 – 1, 247 108	25, 000 – 545, 638

CHAPTER 6

DISCUSSION OF RESULTS

6.1 DISCUSSION

From **Figure 27 to Figure 31**, it is clearly shown that the production rate of methane gas (CH_4) is increased with CO_2-ECBM. This results in higher total production of CH_4. The initial production and final production rate without CO_2 injection and with CO_2 injection shows some changes and the overall production rate for CO_2-ECBM is much higher.

Base on the porosity test results, the initial CH_4 production rate for **San Juan**,**Sub-bituminous**coalis decreasing as the porosity value increased from 0.001 to 0.01.However, the later production rate is increased and the total production of CH_4 is also increased. The **Powder River basin** also shows the same trend as San Juan basin, however the production rate and total production is lower than San Juan basin. This is because Powder River basin has lower coal rank than San Juan basin which is **Sub-bituminous C**.

As for **Upper Silesian** basin, with coal rank of **High-volatile bituminous** the production rate slightly decreased from porosity value 0.001 to 0.005. Later the production rate increased until porosity value of 0.01. The final production rates keep on increasing as well as total CH_4 production.

Qinshui and Zonguldakbasins have the same initial production rate for each porosity values (0.01 to 0.10). The only different is the final production rate for Qinshui basin is higher than Zonguldak basin, although both of their rates increased. This is due to the **Anthracite** coal of **Qinshui** basin which is the highest rank, compared to **High-volatile A bituminous** of **Zonguldak** basin. The total CH_4productions for both basins are increased.

The methane (CH_4) production from CBM reservoir can be enhanced and optimized by means of injecting Carbon dioxide (CO_2) to recover more gas. CBM reservoir with high porosity value and high coal rank is the excellent candidate for greatest methane (CH_4) production by using CO_2 injection.

6.2 CONCLUSIONS

From this study, it shows that as the porosity value increases, the production rate and total production of CH_4 will also increases for all basins. However, this effect is very significant in higher coal rank reservoir which gives the highest production.The highest production of CH_4 is from Qinshui basin, follows by Zonguldak, Upper Silesian, San Juan and Powder River as the least production which follows the decreasing of coal rank from anthracite, high-volatile A bituminous, high-volatile bituminous, sub-bituminous, and sub-bituminous C. In real condition the porosity of CBM reservoir usually ranging from 0.1% to 10%. Therefore, the objectives of this study are achieved.

6.3 RECOMMENDATIONS

This study can be further improved by using basins with lower coal rank e.g. peat and lignite to achieve a wide range of results. Besides, available data from other CBM basins with the same coal rank in this study can be used and tested to make a comparison. Other available simulators can also be used like CMG, GEM, COMET2, SIMED II, GCOMP etc.Later the results from each simulator can be made as a comparison study. This will help to verify the reliability or consistency of the test results. Other than that, experimental study also can be performed to test the coal samples of related ranks.

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APPENDIX I

Problem Set: 5-spot CO_2-ECBM recovery process

Grid system: Rectangular (x-y-z) grid system; 11 x 11 x 1 (see Figure 4)

Area = ¼ of a 2.5 acres pattern

Pattern half width = 50.294m [165ft]

Operating Conditions

Well locations:

Injection well: (i = 1, j = 1, k = 1)

Production well: (i = 11, j = 11, k =11)

Well radius (2 7/8" well): 0.0365 m [0.11975 ft]

Well skin factor = 0

182.5-day continuous CO_2 injection/production period (0 – 182.5 days):

- CO_2 injection rate (full well) = 23, 316.82 sm^3/day
  [1 x 10^6 scf/day]
- Maximum bottom-hole pressure = 15, 000 kPa
  [2175.6 psia]
- Minimum bottom-hole pressure = 25 kpa
  [39.885 psia]