Simulating the Effect of the Coal Density on Methane Recovery for CBM Study

By

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Dissertation submitted in partial fulfilment of

the requirements for the

Bachelor of Engineering (Hons)

(Petroleum Engineering)

May 2013

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgement, and that the original work contained here have not been undertaken or done by unspecified sources or persons.

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(NORSYUHADA BT AB RAZAK)

ABSTRACT

Unconventional coal bed methane (CBM) reservoirs have a huge future potential to production but difficult to develop due to their complexity. Analyzing production performance and estimating original gas in place somewhat complicated and has led to numerous methods of approximating production performance. Hydrocarbon reservoirs are known to react to changes in their properties, particularly coal density. Therefore, it is important to study the effect of coal density changes towards production and gas in place of CBM. The production rates of four CBM fields which are Qinshui Basin, San Juan Basin, and Western Canada Basin will be simulated and analyzed, with coal density being the manipulated variable. Simulation will be performed using the ECLIPSE E300 model, with several assumptions made. From the result, it is clear to see that coal density enhances the production of methane gas from CBM fields. An increase in coal density leads to higher production rates and a prolonged maximum production time as well as gas in place. High reservoir pressure, Langmuir isotherms, gas content and coal density are favorable for CBM production.

ACKNOWLEDGEMENTS

First of all, the author would like to convey her greatest praise and gratitude to Allah the Almighty for His Mercy for giving the strength and capability to complete this report of Final Year Project throughout this final semester. Special thanks to FYP II supervisor, Ms. Siti Sarah Salehuddin and FYP I supervisor, AP Aung Kyaw, Co-Supervisor, Mr Umer Shafiq from Universiti Teknologi PETRONAS (UTP) for the constant guidance towards the completion of this report.

The author also would like to take this opportunity to thank all parties involved for the respective professionalism and contribution to the project particularly to Mr Adam Rahim, Production Technologist from PETRONAS Carigali, KLCC for his contribution and also to her friends for their continuous support. Besides that, the author would like to express the deepest appreciation to Mr Saleem Qadir Tunio, Petroleum Engineering Lecturer in whose encouragement, guidance and support from the initial to the final stage of this project in developing a good understanding in coal bed methane.

Thank you once again from the author and without their guidance and persistent help, this project would not have been possible.

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INTRODUCTION

1.1 Background of Study

Coal beds are an attractive prospect for development because of the ability to retain large amounts of methane. CBM has grown from an unconventional gas play that most operators stayed away from 20 years ago into a commercially important, mainstream natural gas source. CBM production is commercially well established in several countries. Interestingly, successful CBM production is occurring from a wide range of coal types, ages, and geologic settings. However, in all cases the keys to commercial success are favorable geologic conditions (good coal thickness, gas content/saturation, and permeability); as well as other parameter such as coal rank initial pressure, coal density, porosity and sorption time. Figure 1 below shows the global production from four countries. The USA still dominates the production followed by Australia, China and Indonesia. Challenging geologic condition and high cost have failed to commercialize. The operators need to enhance their technology to develop this unconventional reservoir. With more and more coal bed fields being discovered, and demand of energy ever increasing, the need to produce this unconventional gas seems more of a necessity. These country have potential to develop.

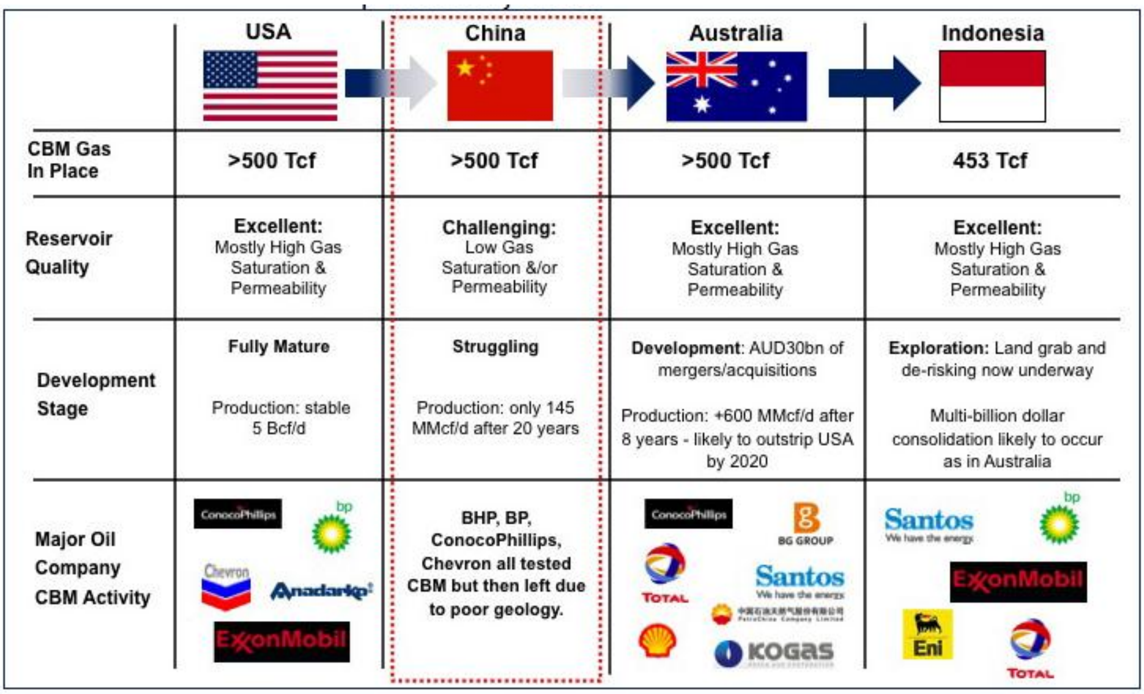


Figure 1 : Global coal bed methane development history

A successful production strategy that increases the methane production will depend on a variety factors including coal density. There are four types of coal rank which are anthracite, bituminous, subbituminous and lignite. Each of them has different range of density. Each of coal rank will give different value in production performance as well as gas in place due to its maturity, reservoir pressure and reservoir temperature. Production decline curve was used to forecast the future behavior of the wells. They represent one of the important tools for future revenue evaluation, recovery factor assessments, and well performance. This study focused only on methane production and gas in place rather than the combined impact of gas and water production. And the best tool that takes in account all the parameters and mechanisms that control CBM production in order to predict the performance is a numerical reservoir simulator. Eclipse 300 was used because it is an economical and simple tool to predict and analyze gas production for CBM.

1.2 Problem Statement

Forecasting the production performance for coal bed methane (CBM) reservoirs is important because of their huge future potential to develop. These reservoirs are also have large reserves but difficult to develop. By forecasting the production performance and calculating gas in place, we can estimate the real amount of gas in reservoir at once can optimize the cost of CBM production. Previous study in calculating gas in place simply used a value of density in 1.32 g/cc to 1.36 g/cc can lead to erroneous result (Nelson, 1999). Hence, more research has to be done regarding the effect of coal density towards production rates. To gauge on this potentiality for a CBM field, the production rates should be comparable to that of renowned CBM producing fields. This project will provide a future references in helping to forecast the production performance in terms of manipulated variable of coal density.

1.3 Objective and Scope of study

1.3.1 Objective

The objectives of this study are

i. To study the change in gas production rate, cumulative production and gas in place with the change in coal density of the reservoir.
ii. To compare and contrast between the production performance of three CBM fields.
iii. To study the effect of coal rank on production performance.

The CBM locations are the Qinshui Basin, San Juan Basin, and Western Canada (Alberta) Basin. The scope of study is limited to use only one simulation software and only published data will be used.

1.3.2 The relevancy of the project

The project will weighted more on research project which will lead to less optimization in mechanical equipment usage. However due to its dependency in collecting and studying reservoir physical characteristic and its economical aspect, it will consume most of the time given in executing the project. Apart from that, less concern will be on the cost and budget allocation for the project as most of the resources (software and lab facilities) is provided by the UTP.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview of CBM

Coal bed methane (CBM) is a form of natural gas extracted from coal beds. This naturally fractured reservoir is characterized as a system of matrix blocks with each matrix block surrounded by fractures (cleats). Coal bed methane production data is considered a complex and difficult to analyze especially at the early stages of the recovery. CBM reservoir performance is influenced by the interrelationship of a set of reservoir, geologic, and operation parameters. K.Aminian (n,d) found that coal is a heterogeneous and anisotropic porous media which is characterized by two distinct porosity (dual porosity) systems: macro pores and micro pores. Macro pores was identified as cleats which are constitute the natural fractures common to all coal seams while micro pores, or the matrix, contain the vast majority of the gas. Ibrahim (2009) explain the process of gas desorption for the dual porosity system in Figure 2.

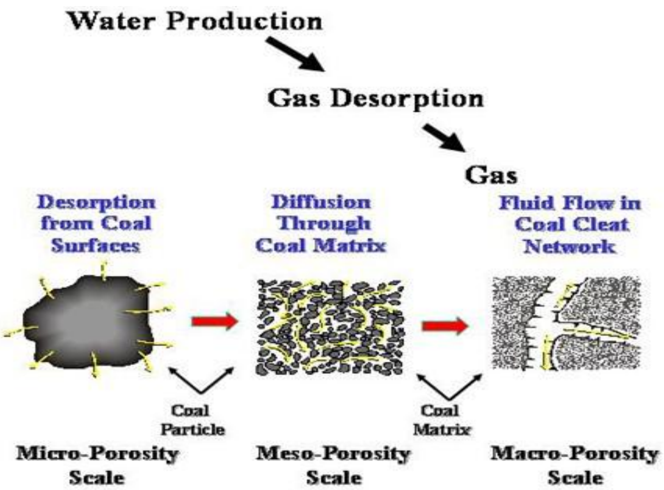


Figure 2 : The process of gas desorption for dual porosity system

Consequently, the gas storage mechanism differs significantly from the conventional gas reservoirs. The majority of the gas is held in the matrix adsorption and a very small percentage is in a free state flowing in the cleats. Moreover, at initial conditions the system is usually water saturated so, in order to produce gas, the water has to be removed from the cleat system first by lowering hydrostatic pressure. This key parameter influences the gas production rate and producible reserve potential of coal bed gas reservoirs. Before gas start to produce, CBM reservoir will go through a dewatering period. These may cause the production process can be difficult to model. During dewatering process, the gas desorbs from the coal, gas rate increases and water saturation decreases. Wei et al (2006) explained in his paper that desorption process is described by the Langmuir isotherm, which relates the adsorbed gas volume to the pressure of the gas phase. The Langmuir isotherm varies widely for each coal reservoir. . This reduction in pressure allows the gas to be released from the matrix by desorption. Then, the rate of desorption will influence the value of gas in place calculation. Thus, the water rate experiences a decline while the gas rate increases. The dewatering period is one of the most sensitive and non-uniform stages in CBM production. The dewatering process can take a few days or several months. Eric (2012) stated in his study that, the water production greatly decline until the gas rate reaches the peak value. This time-to-peak-gas is a critical parameter since the gas production starts declining after the peak has been reached. After reaching peak rate, produced gas decreases with time and follows production trend of conventional gas reservoirs. R.Guo (2008) also described that CBM is a dual porosity, antistrophic medium and multiphase flow system and gas production directly influenced by (gas in place, desorption time, permeability, Langmuir sorption isotherm) especially at the earlier stage and indirectly influenced by coal density.

2.2 Type of coal rank

Coal is classified into four general categories, or "ranks." They range from lignite through subbituminous and bituminous to anthracite, reflecting the progressive response of individual deposits of coal to increasing heat and pressure. The carbon content of coal supplies most of its heating value, but other factors also influence the amount of energy it contains per unit of weight. Coal density can be affected by the type of coal rank. Hatt, (2009) found that the properties of the coal rank which are influences by pressure, heat and time. The formation of coal from a variety of plant materials via biochemical and geochemical processes is called coalification. The nature of the constituents in coal is related to the degree of coalification, the measurement of which is termed rank. Rank plays a direct role when determining how much methane can be stored within the coal. Darling (2011) explained that the higher the rank of the coal, the more methane it is able to store. Seidle (2011) also stated in his book that rank also plays an important role for gas. In CBM, there are four types of coal rank which are lignite, subbituminous, bituminous and anthracites. However there is no clear demarcation between them and coal is also further classified as semi anthracite, semi bituminous and sub bituminous. Karine (2010) found that the residual gas increases as rank increases, reaches a maximum at the rank of high-volatile. A bituminous and decreases rapidly as rank increases to medium-volatile. Anthracite is the oldest coal from geologic perspective. It is a hard coal composed mainly of carbon with little volatile content and practically no moisture. Lignite is the youngest coal from geological perspective .It is hard coal composed mainly of carbon with little volatile matter and moisture content with low fixed carbon. Fixed carbon refers to carbon in its free state, not combined with other elements. Volatile matter refers to those combustible constituents of coal that vaporize when coal is heated. Table 1 below shows the properties of coal rank.

Table 1: The properties of coal rank

	Lignite	Subbituminous	Bituminous	Anthracites
Picture of coal				
Heat content	4000-8300	8500-13000	11000-15000	13000-15000
Ranking	Fourth (youngest and wettest)	Third	Second	First (oldest and hardest)
Carbon content	25-35%	35-45%	45-85%	>85%
Coal Density	0.7-1.5 g/cm^3	1.2-1.75 g/cm^3	1.2-1.5 g/cm^3	1.4-1.8 g/cm^3
Ash	10-50%	< 10%	3-12%	10-20%
Sulfur	0.4-1.0%	< 2%	0.7-4.0%	0.6-0.8%

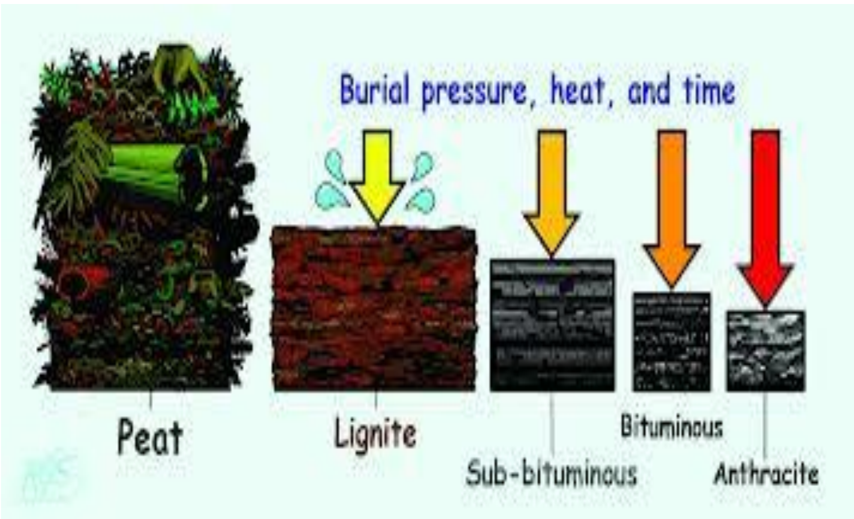


Figure 3: The coal rank depends on burial pressure, heat and time

2.3 Coal bed methane production

As stated previously, coal bed methane is a dual porosity system where the gas is stored by the adsorption of the in the coal matrix. This in turn causes the pressure volume relationship is described by sorption isotherm which relates the gas storage capacity of a coal to pressure. The typical sorption isotherm is shown in Figure 4.The common relationship between gas storage capacity and pressure can be described by an equation presented by Langmuir: This figure shows the amount of gas sorbed per unit increase in pressure decreases with increasing sorption pressure and the sorbed gas eventually reaches a maximum value which is represented by Langmuir volume constant (V_L). Langmuir pressure constant (P_L) represents the pressure at which gas storage capacity equals one half of the maximum storage capacity (V_L).

$$G_s = \frac{V_L P}{P_L + P} \tag{1.1}$$

Where: G_s= Gas storage capacity, scf/ton

P = Pressure, psia

V_L= Langmuir volume constant, scf/ton

P_L= Langmuir pressure constant, psia

Equation (1) assumes pure coal in the field. In order to account for ash and moisture contents of the coal, the equation is modified:

$$G_s = (1 - f_a - f_m)\frac{V_L P}{P_L + P} \tag{1.2}$$

Where: f_a= Ash content, fraction

f_m=Moisture content, fraction

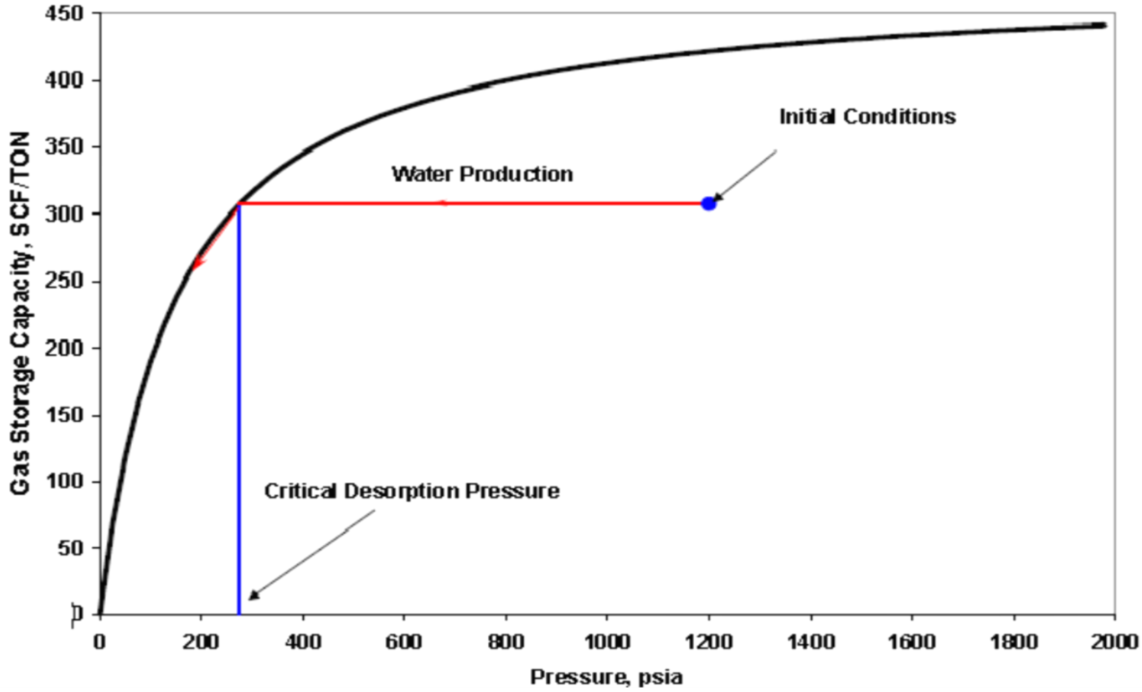


Figure 4 : An Example of Langmuir Isotherms

According to Aminian (n,d), most of the coal bed methane reservoir initially only produced water as the cleats is filled with water. Water must be produced continuously in order to reduce reservoir pressure and release the gas. The author added that once the pressure in the cleat system is lowered by water production to the critical desorption pressure gas will be desorbed from the coal matrix. The critical desorption matrix is defined by the author as the pressure on the sorption isotherm that corresponds to the initial gas content. As the desorption process continues, a free methane gas saturation builds up within the cleat system and once the gas saturation has been exceeded, the desorbed gas will flow along with water through the cleat system to the production well.

As the desorption process continues, both the gas saturation and the flow of methane increases and becomes more dominant. Thus, the water production will decline rapidly until it reached a point where the gas rate reached peak value and water saturation approaches the irreducible water saturation. Figure 5 shows a typical coal bed methane reservoir production.

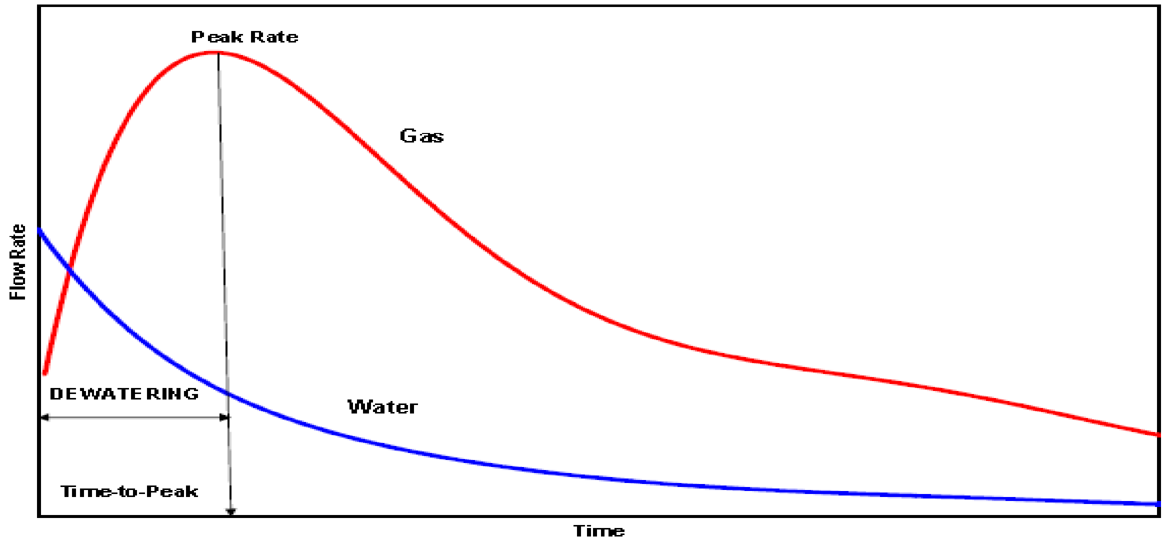


Figure 5 : A Typical Production History of a Coal Bed Methane Reservoir

According to Lin (2010), to recover the methane gas from the reservoir, certain conditions must be fulfilled to initiate the desorption of the gas:

1. Decrease of the reservoir pressure
2. Presence of a more absorbable gas (example carbon dioxide, CO_2)
3. Reduction in the methane partial pressure

Lin also reported most of the coal bed methane production in the world is using primary recovery method in an open holed production wells. During the production, down hole submersible pumps are used to move formation water up the tubing which decreases the reservoir pressure. Methane in turn, will be desorbed from the coal surface, diffuse to the cleats or fracture network and flows to the wellbore.

However, the author added that there are certain limitations of primary recovery. An example provided by Stevens et al (1998) is primary recovery by depressurization typically recovers less than half of the resource underground. Rawn-Schatzinger (2003) also added environmental problems and operational issues during primary recovery.

2.4 Coal density affected production performance and gas in place

The density of coal is a function of its composition. Generally, all other compositional factors being equal, coal density will be directly correlated with the mineral matter content. This is due to the mineral matter component of coal has a significantly higher density than the bulk organic matter. A major source of in situ density analysis error is the assumption that the compositional properties of coal bed reservoirs are homogeneous. Coal composition and density properties are not uniform throughout the bulk rock comprising a coal bed reservoir but vary both vertically and laterally as a function of such geologic variables as depositional environment, overlying and underlying rock lithology, coal rank, equilibrium moisture content, mineral matter content, mineral composition.

A common practice in coal bed reservoir gas-in-place analysis is to use a rule-of-thumb value of 1.32 to 1.36 g/cm3 for the in-situ reservoir rock density.1,6,7 For vitrinite-rich bituminous rank coal, the organic matter density is about 1.295 g/cm3 and the mineral matter density is about 2.497 g/cm3.20 The rule-of-thumb density value range of 1.32 to 1.36 g/cm3 would only be appropriate for use with bituminous rank coal having an in-situ moisture content of about 1.5% and a mineral matter content range of about 5 to 10%.20

Gas in place is the amount of gas in a reservoir at any time, calculated at standard conditions. The calculation of gas in place is useful to estimate gas reserves for economic purposes. The summation between adsorbed gas and gas in fracture system can be defined as amount of gas in coal. The parameters needed for estimating gas in place in a CBM reservoir are average in situ gas content, coal thickness, reservoir or well drainage area, and average in situ coal density. Density is an important coal property that determines the potential of gas resources in CBM reservoir.

There are several types of analysis techniques for gas in place calculation which are dry and ash free calculation, deliverability, static material balance, conventional, forecasting, numerical models, diffusion, decline curve analysis, modified hyperbolic analysis and agarwal-gardner rate time type curve. Adsorption Isotherm is defined as amount of gas that is adsorbed on solid surface as a function of pressure at constant temperature. There are several sorption isotherms which have been developed such as Freundlich's, Langmuir's, Henry's and Brunaner's theory.

Among these theories, Langmuir's theory is the most frequently used for coalbed methane. The Langmuir isothrem relates the coverage or adsorption of molecules on a solid surface to gas pressure or concentration of a medium above the solid surface at a fixed temperature. The assumption for this theory are one gas molecule is adsorbed at a single adsorption site, an adsorbed molecule gas does not affect the molecule on the neighboring site, site are indistinguishable by the gas molecules and adsorption is on an open surface and there is no resistance to gas access to adsortiopn sites. Below is the langmuir isotherm which assumes that the reservoir is at a constant temperature and defines the quantity of gas adsorbed as (James, 2008):

$$OGIP = O.031214AhVmyp(\frac{bPi}{1+bPi}) \qquad (1.3)$$

where:

OGIP = Original gas in place (SCF)

A = Drainage area in ft

h = Thickness of the coal in ft

Vm = Gas content of coal (SCF/ton)

y = Mineral-matter free mass fraction of total coal (fraction)

ρ = Density (g/cc)

b = Langmuir shape factor (psi-1)

Pi = Initial reservoir pressure (psia)

The equation 3 can also yield remaining gas by substituting current reservoir pressure for initial reservoir pressure since the other parameters are reservoir characteristics that don't change substantially over the life of a well. As we know that, every coal rank has different maturity, pressure and temperature.

$$V_{adsorbed} = \frac{V_L P}{P_L + P} \quad (1.4)$$

The amount of gas in place can then be defined as:

$$GIP = V_{adsorbed} A h \rho_B \quad (1.5)$$

CHAPTER 3

METHODOLOGY

3.1 Research methodology

To achieve the objective, a methodology consisting of the following two steps was employed:

1. Development of a base model for coal bed methane production in all each basin.
2. Variety of CBM production type curve

3.1.1 Development of a base model for coal bed methane production in

The study was started with a literature review about CBM reservoir and geological characteristics on each basin. In order to construct reliable CBM base model, information and wide range of data was compiled. Wide sets of data were run to visualize and understand the parameter that influence the coal density parameter on the performance of CBM wells. The main inputs were compiled:

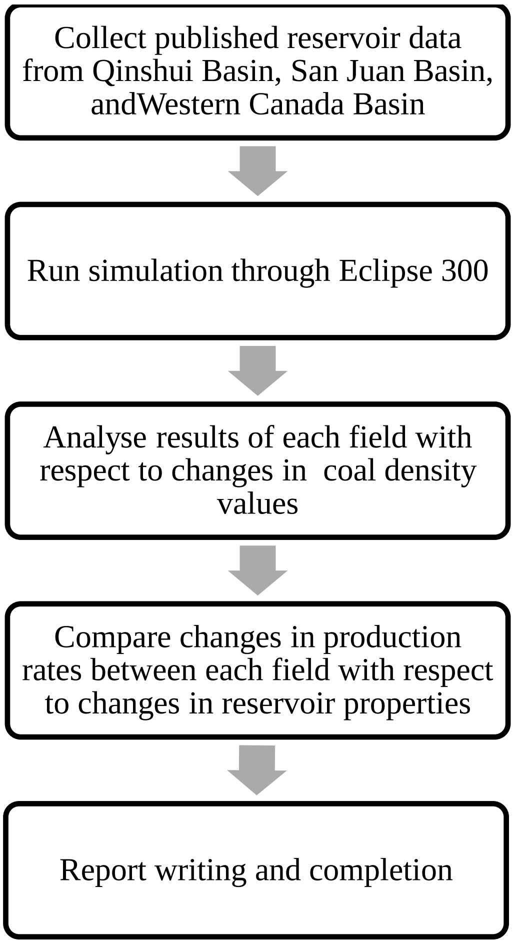
1. Permeability
2. Porosity
3. Thickness
4. Reservoir pressure
5. Reservoir temperature
6. Period of production
7. Rock compressibility
8. Sorption time
9. Water and gas saturation

3.1.2 Variety of CBM production type curve based on manipulated parameter coal density.

Three type of CBM production curve was performed which are the methane production rate, total methane production and gas in place. These performance were tested varies with production time, 180 days. The parameter of coal density was manipulated while others parameter was compiled as constant on each basin.

3.2 Project Activities

The basic flow for the research would be:



The effect of coal density towards CBM production will be studied and simulated using ECLIPSE software, using the E300 model. Four different fields will be selected for this simulation, in which are selected based on different coal ranks. The four CBM locations are San Juan Bain (Fruitland Coal), Western Canada Basin (Horseshoe Canyon), Qinshui Basin. Simulation is run several times for each field with different coal density values (manipulated variable), which will differ from case to case. The results will then be compared, first within the same field and the analysis of how coal density affects production of CBM. Secondly, the fields will be inter-compared.

To further ease the simulation process, a few assumptions were made. Firstly, it is assumed that the rate of CO_2 injection is constant for all fields. Secondly, it is assumed that gas diffusion between the coal matrix and the natural fracture system occurs instantaneously. Thirdly, coal shrinkage and swelling completely neglected. Fourth, it is assumed that the reservoir pressure is uniform throughout; hence the model would also have equal pressure everywhere.

3.3 Gantt Chart

No	Details/Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Continue consultation with SV														
2	Research for published reservoir data to be used in simulation														
3	Perform simulation using Eclipse, E300														
4	Consult supervisor regarding obtained result														
5	Start work on progress report and Submission														
6	Conduct further simulation work if needed														
7	Start write up of Final Draft Report and consultation with SV														
8	Start write up of technical paper														
9	Submission of Dissertation (Soft Bound) and technical paper														
10	Preparation for Pre- Sedex (poster)														
11	Make necessary amendments to final draft report														
12	Pre-Sedex presentation														
13	Oral presentation														
14	Submission of Dissertation (Hard Bound)														

3.4 Key Milestones

Key Milestones: Week 3 – Find published CBM reservoir data

Week 5 – Perform Simulation

Week 11 – Submission of Dissertation and Technical Report

Week 13 – Oral Presentation

Week 14 – Submission of Dissertation (Hard Bound)

Tools and material needed for research:

i. ECLIPSE software
ii. Published data

CHAPTER 4

RESULTS & DISCUSSIONS

The general objective of this study was focused towards the changes in gas production rate, cumulative production and gas in place when coal density of the reservoir changes as well as compare and contrast between the production rates, cumulative production and gas in place of three CBM fields. In order to develop this research, Eclipse, E300 was used to construct the variety type of production curve. The model was constructed with 5 spot patterns which is an injection pattern in which four production wells are located at the corners of a square and the injector well sits in the center. The well was injected with gas CO_2 to boost the production performance.

A large number of simulation were run while varying the main parameters of coal density and holding the rest of the inputs constant that based on each basin. The simulation will be divided into three different cases, where case 1 is Qinshui Basin, case 2 is San Juan Basin, and case 3 is Western Canada Basin.

Below is the table for data gathering from three basins:

Table 2: Data Gathering for all basin

	Qinshui Basin	San Juan Basin (Fruitland)	Western Canada Basin (Horshoe Canyon)
Coal Rank	Anthracite	High Volatile A Bituminous	Subbituminous
Range of coal density	1400kg/m3-1800kg/m3	1200kg/m3-1500kg/m3	1200kg/m3-1750kg/m3
Tops of coal seam	2005 ft	4112.8 ft	3005 ft
Reservoir thickness	50 ft	44.2 ft	754 ft
Porosity	0.05 %	0.1 %	0.1%
Cleat permeability	2.3 mD	3.65 mD	1 mD
Gas content	29m3/t	24m3/t	17m3/t
Initial pressure	822 psia	1109.5 psia	204 psia
Coal Density	1500kg/m3	1385 kg/m3	1314 kg/m3
Reservoir temperature	42.222 F	113 F	71 F
Coal compressibility	30x 10^-6 1/psia	25x 10^{-6} $psia^{-1}$	12 x 10^-6 1/psia
Langmuir pressure	217.6 psi	323 bar	586 psi
Langmuir volume	28.08 m3/ton	13.76 m3/ton	9m3 /ton

Due to unavailability of published data regarding water saturation coal compressibility and, the values used are estimates, hence it is assumed to be 50% saturated with water. The coal density will be manipulated based on the coal rank.

4.1 Case 1: Qinshui Basin

Case 1a : Qinshui Basin (coal density = 1400kg/m3)

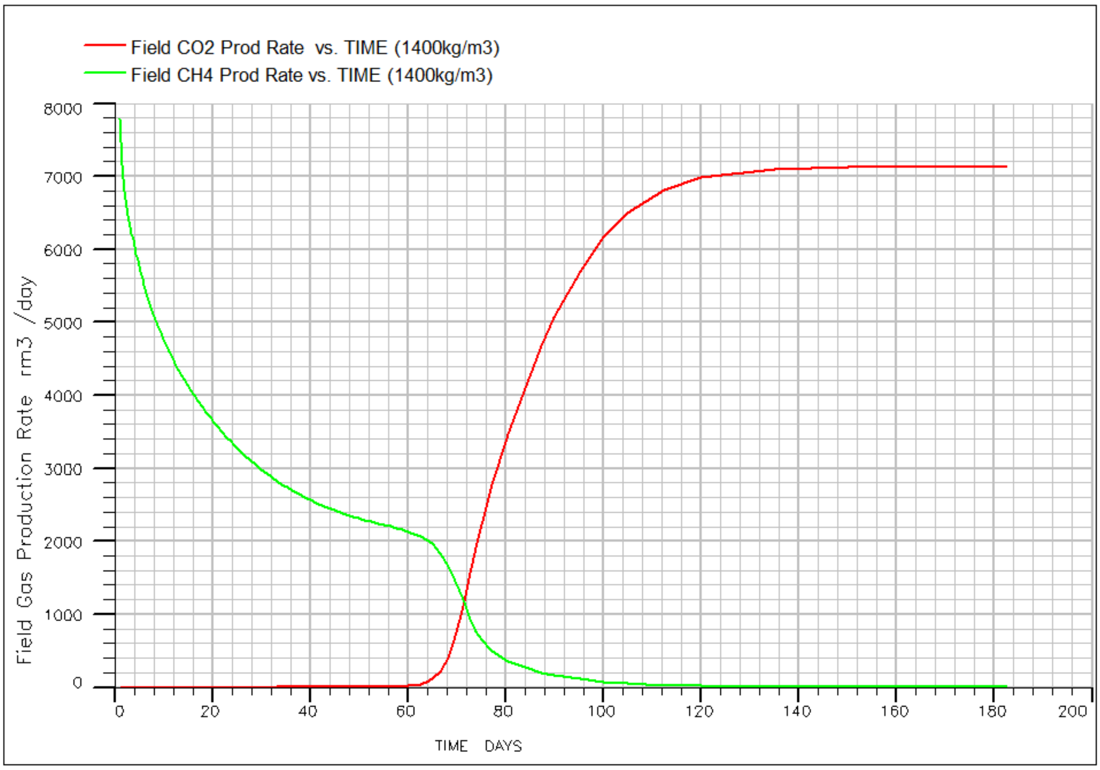


Figure 6 : Field Production Rate Co2 vs CH4, Coal Density 1400kg/m3, Qinshui Basin

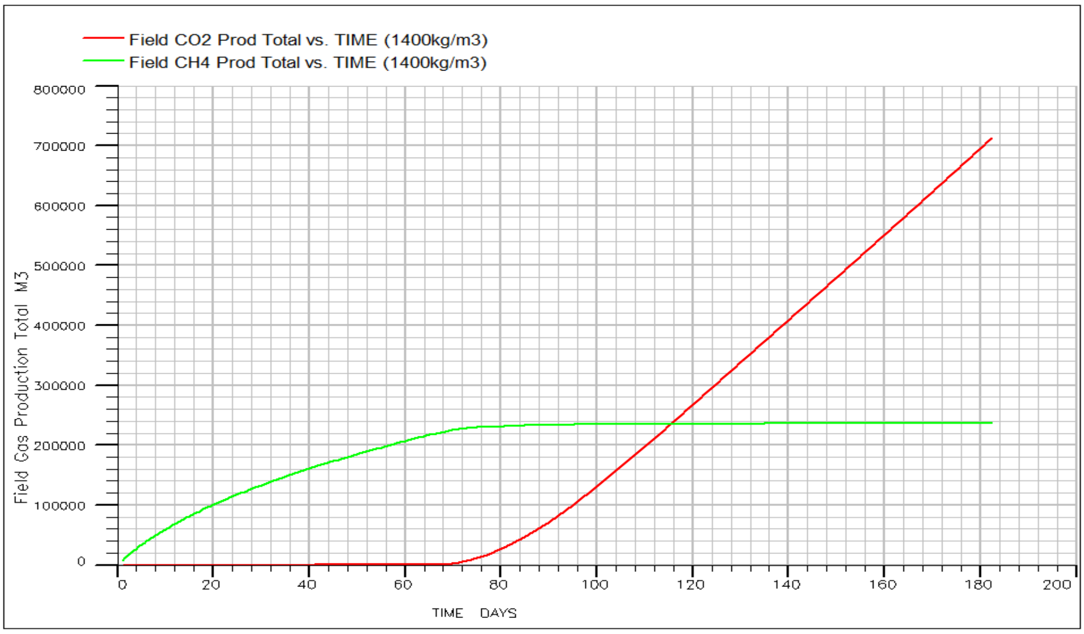


Figure 7 : Field Gas Production Total Co2 vs CH4, Coal Density 1400kg/m3, Qinshui Basin

Case 1b: Qinshui Basin (original case= 1500kg/m3)

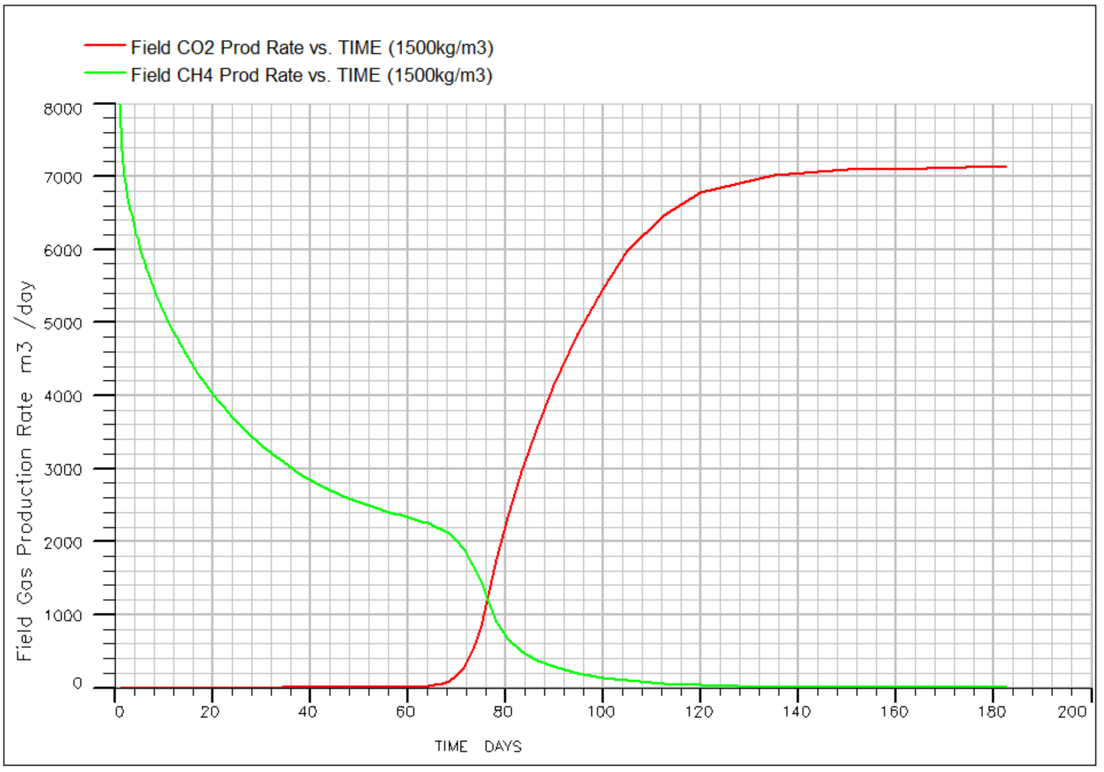


Figure 8 : Field Production Rate CO2 vs CH4, Coal Density 1500kg/m3, Qinshui

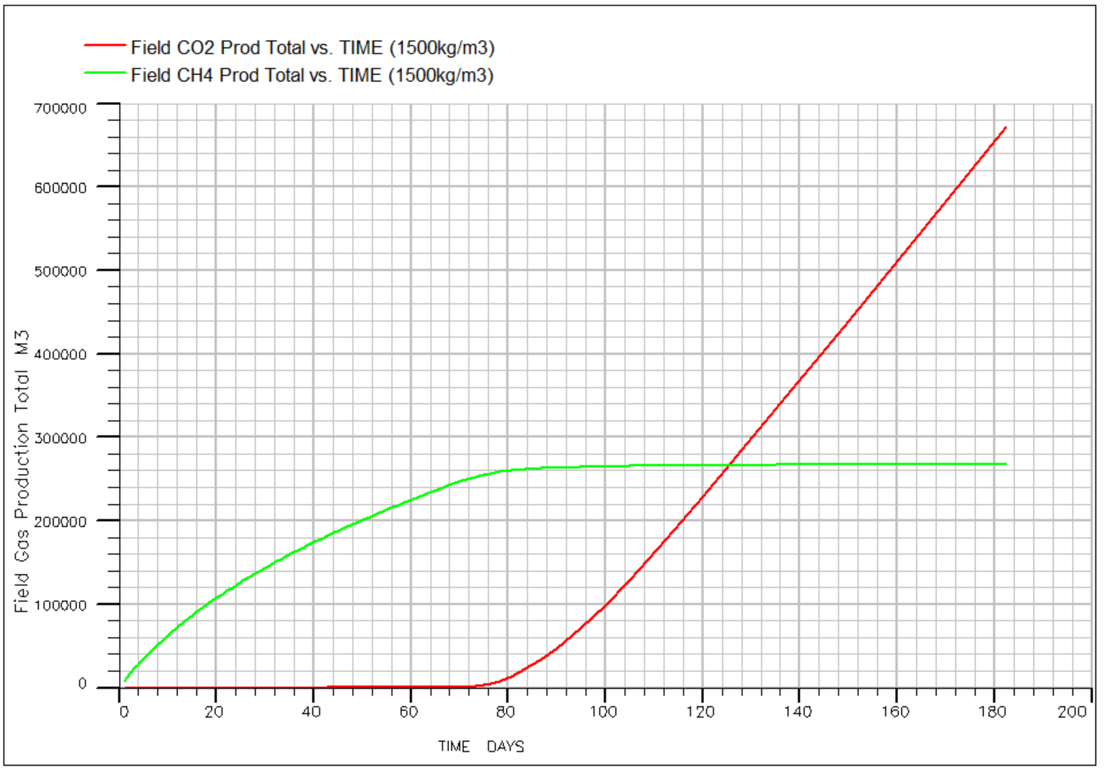


Figure 9 : Field Gas Production Total, Coal Density 1500kg/m3, Qinshui Basin

Case 1c: Qinshui Basin (coal density = 1600kg/m3)

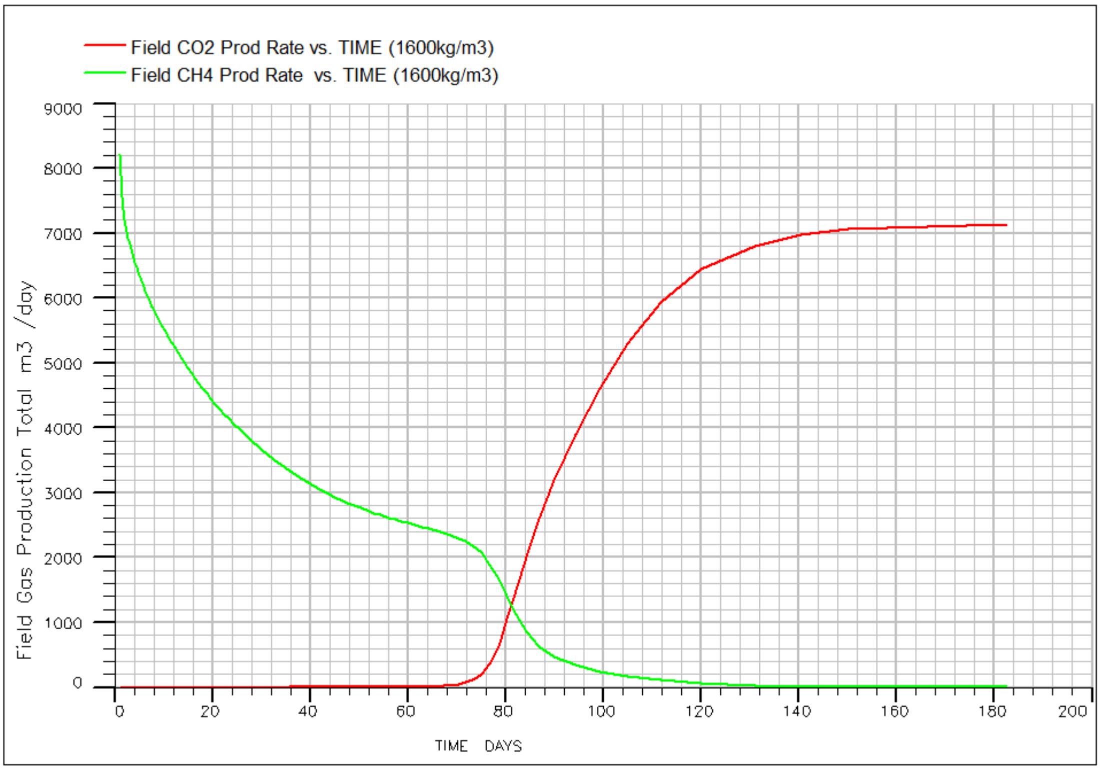


Figure 10 : Field Production Rate CO2 vs CH4, 1600kg/m3

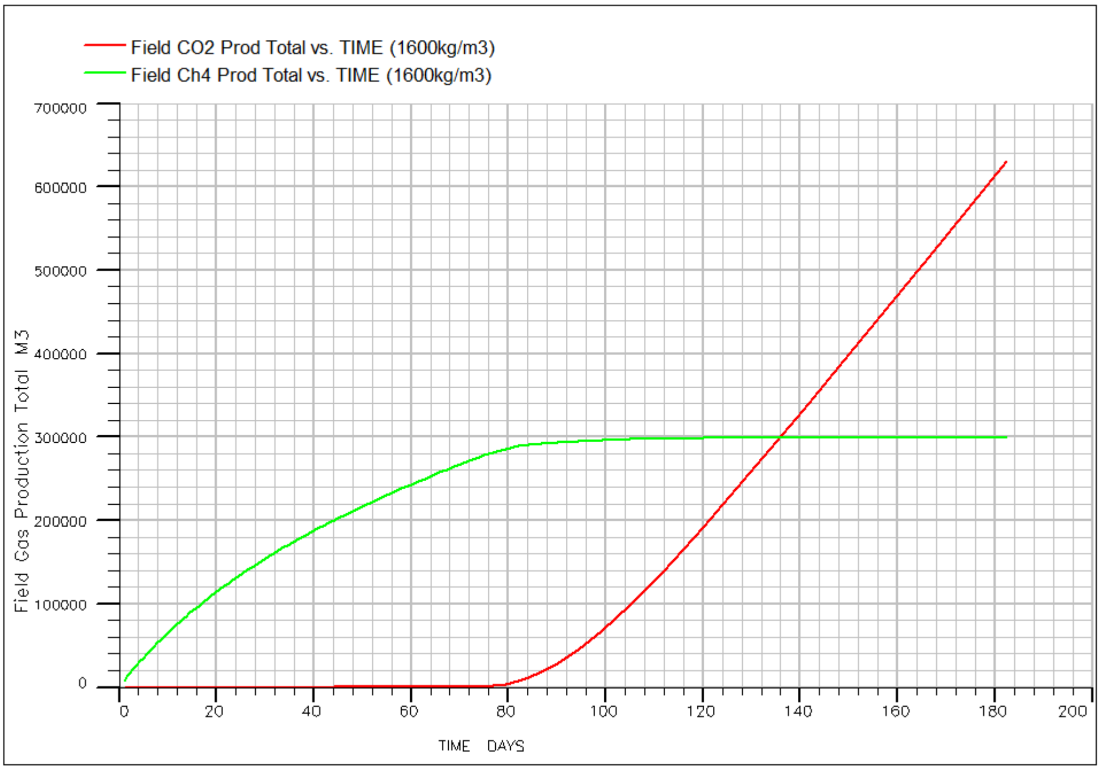


Figure 11 : Field Gas Production Total,Coal Density 1600kg/m3, Qinshui Basin

Case 1d: Qinshui Basin,(coal density =1700kg/m3)

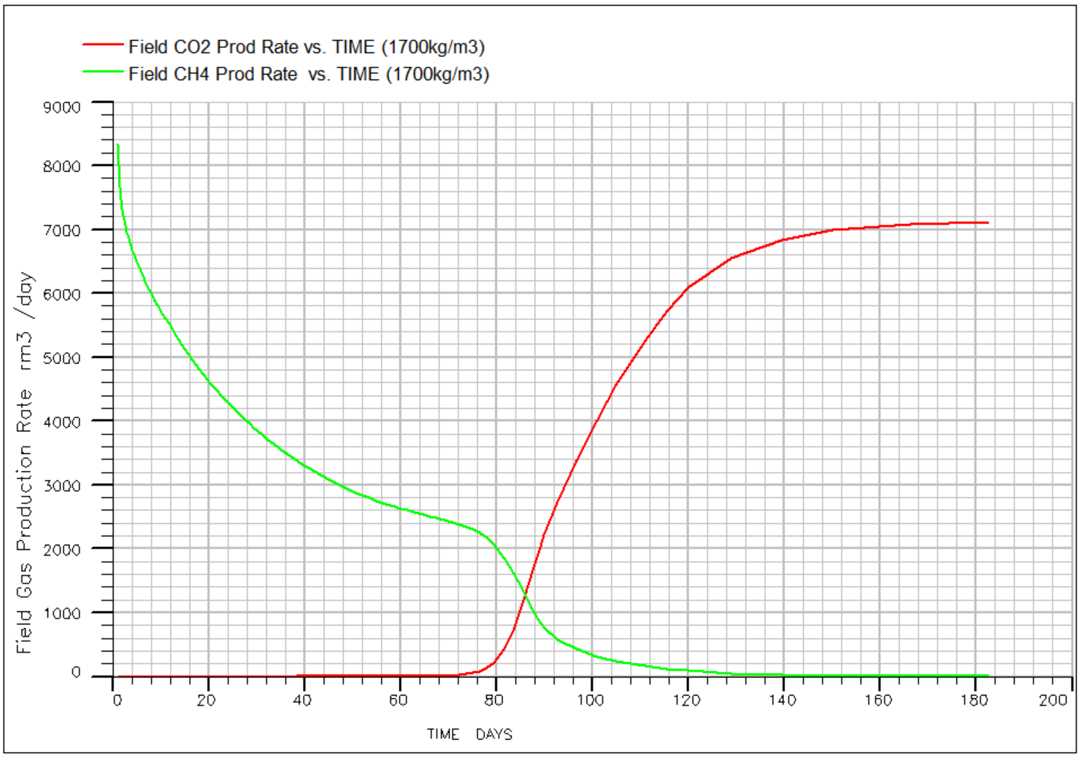


Figure 12 :Field Gas Production Rate CO2 vs CH4,Coal Density 1700kg/m3, Qinshui Basin

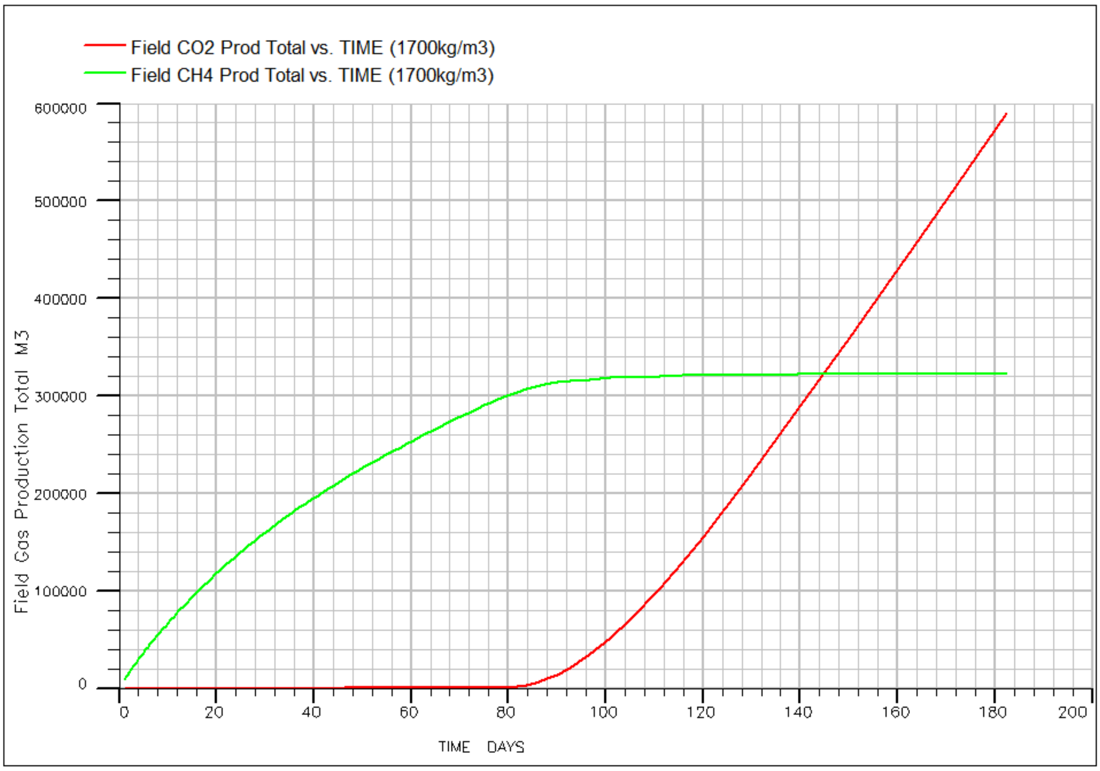


Figure 13 : Field Gas Production Total, Coal Density 1700kg/m3, Qinshui Basin

Case 1e: Qinshui Basin, (coal density = 1800kg/m3)

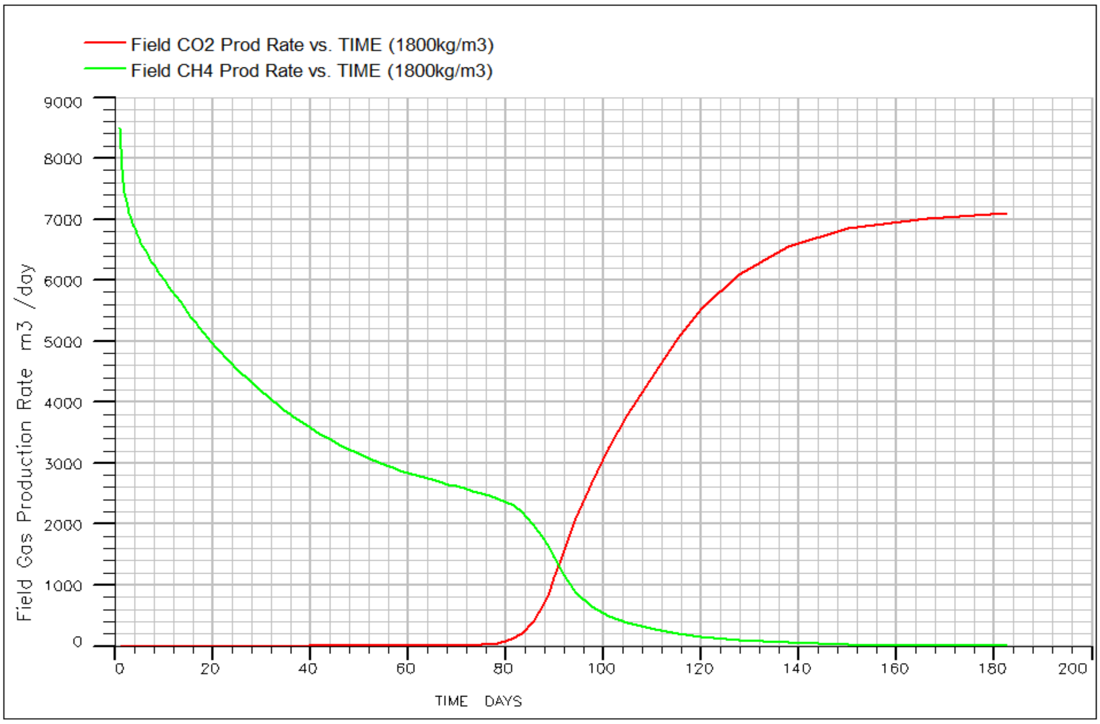


Figure 14 : Field Gas Production Rate CO2 vs CH4, Coal Density1800kg/m3, Qinshui Basin

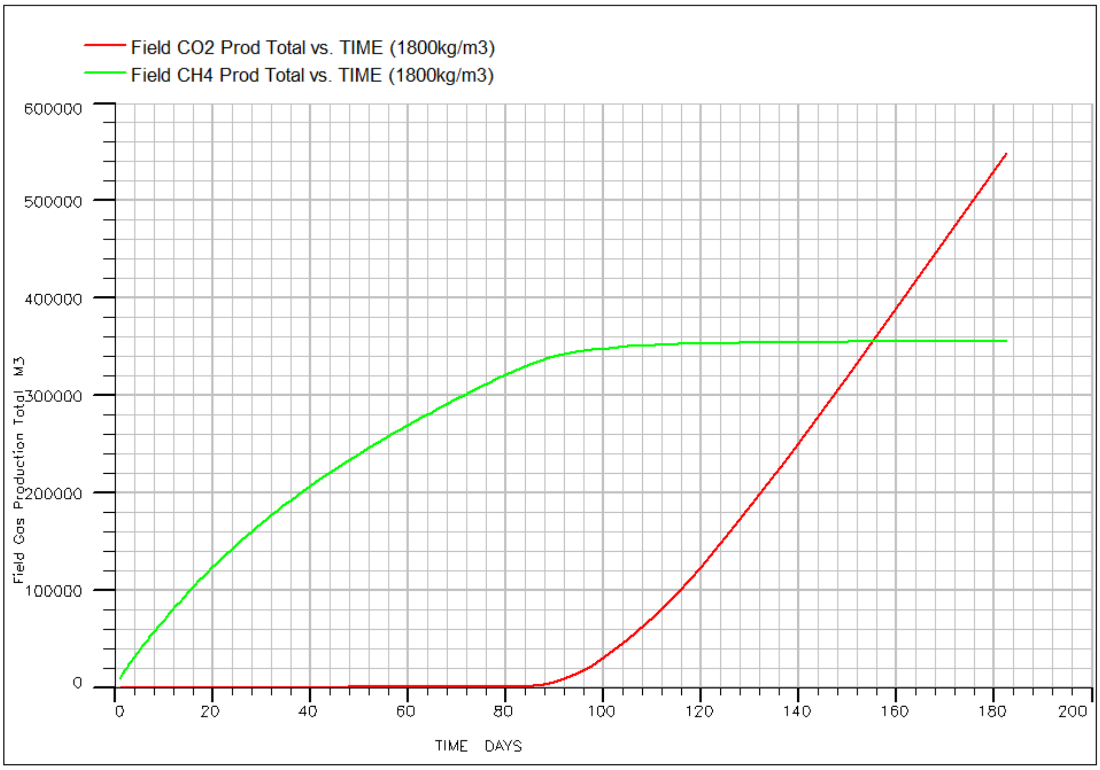


Figure 15 : Field Gas Production Total, Coal density 1800kg/m3, Qinshui Basin

Table 3: Analysis Result of Qinshui Basin

No	Coal Density (kg/m3)	Analysis
1	1400kg/m3	. i. As with other production rates from previous fields, methane production rates increases rapidly over a one day period. This can be attributed by the instantaneous diffusion rates between coal matrixes to the natural fractures of the coal. However, one major difference of this coalfield to other fields mentioned above is that the target production rate of 5000 m3/day is reached. This is due to the high initial reservoir pressure and the high Langmuir Pressure. ii. Maximum methane production rate is at 7782.245 m3/day. iii. After the initial spike in production rates, methane gas drops in rate dramatically. For methane, the decline rate reduces at day 60 at rate 2133.79740 after which point the production rate continue to level off. iv. This one not varies with the total gas production, however, the leveling-out period is at 70 days. Then it reached 6009 M3 for maximum produced methane.
2	1500kg/m3	i. A rise in the coal density of the coal formation results in a rise of the gas production rate rather than previous case. Gas production rate reached a peak of 8000 m3/day, likewise, at this time, methane produced is 8000 M3. ii. As time goes by, both production rates dwindled down significantly until it reaches zero production rate as the reservoir pressure declines. However, at around 68 days until 78 days, there is a slight raise in the rate production of methane.

4	1600kg/m3	i. When coal density is increased to 1600kg/m3, the target rate of gas production of 5000 m3/day is met. Maximum gas production rate reached 8506 m3/day. The increase in coal density allows more absorbed gas through the coal fractures, hence an increase in its production rate. ii. The same phenomenon as the previous case can be seen during the latter stages of production, where methane production rate increases slightly. A closer look at the graph shows that methane production rates alternates between drops slightly in production rate, as seen between days 50 through 70. iii. Maximum cumulative gas production is still unchanged at just under 300000 M3 between days 120 through day 180.
5	1700kg/m3	i. The gas production rate of 8331m3/day be reached when coal density is increased to 1700kg/m3, which is also the maximum production rate. After the peak is reached, both production rates decreased significantly until production rate is zero. ii. For produced methane, 321320 M3 was reached for maximum production.
6	1800kg/m3	i. Target gas production rate is also met when coal density is increased further to 1800kg/m3. ii. However, methane production rate reached a maximum of 8100 m3/day, a slight decrease from the previous case.

To see the trends of gas in place, gas production rate and cumulative volume as coal density increases, the sequences of gas in place, production rates and cumulative production with increasing coal density is illustrated in figure 16, 17 and 18.

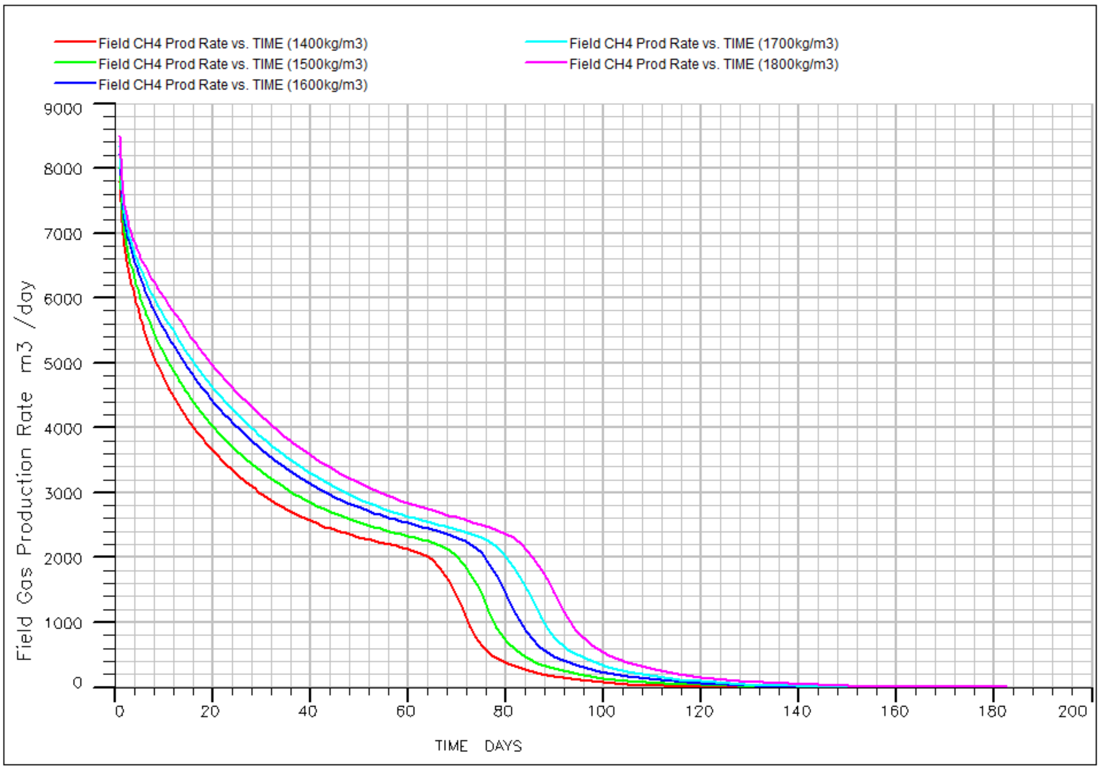


Figure 16 : Field Gas Production Rate, Qinshui Basin

In figure 16, the gas production curves of five cases start the early production rate with higher rate (>8000M3) rather than two upcoming other basin. This is because the production starts with the high initial reservoir pressure. This is logical since anthracite is high coal rank that has high value in reservoir pressure and the graph also presenting the temporal characteristics of gas production in the high rank coal bed methane fields.

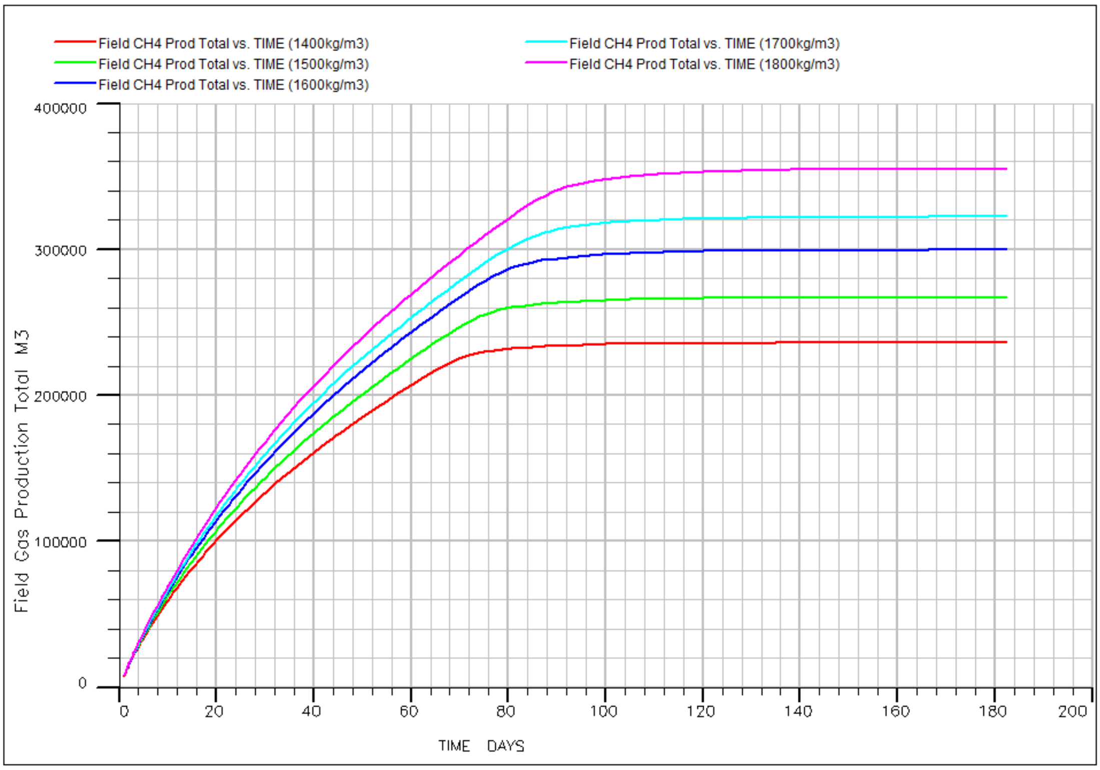


Figure 17: Field Gas Production Total, Qinshui Basin

In figure 17, as the coal density increases the total of total methane production is also increase. As we can see, when we increase the coal density, the early productivity also increases but then it gives slow in maximum production varies time.

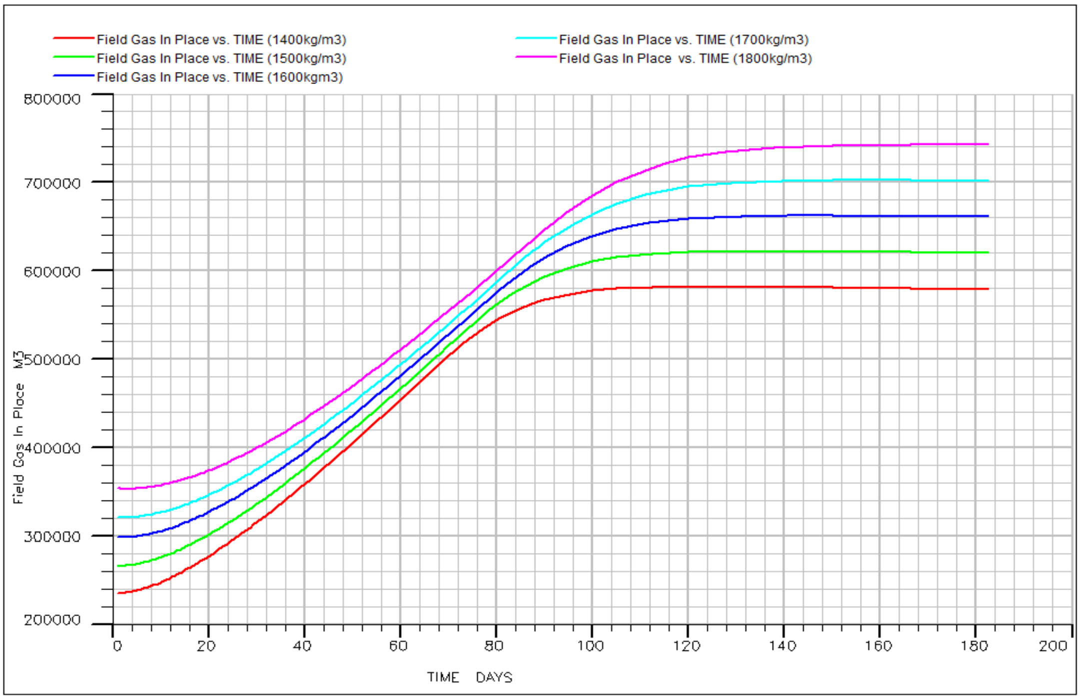


Figure 18 : Field Gas In Place, Qinshui Basin

In figure 18, as the coal density increases, the gas in place also increases. This is logical since in formula that stated in literature review part that the higher the coal density the higher the gas in place. The maximum gas in place at the end of sorption time is day 180. So to develop the gas reserves, time factors also need to be considered.

4.2 Case 2: San Juan Basin

Case 2a: San Juan Basin, (coal density = 1200kg/m3)

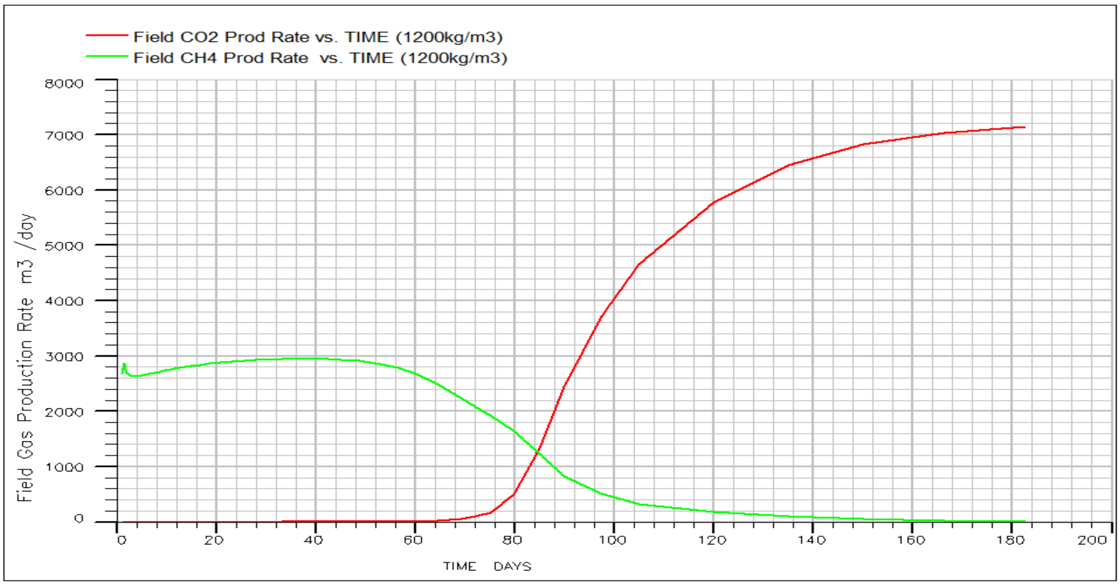


Figure 19 : Field Gas Production Rate CO2 vs CH4,Coal Density 1200kg/m3, San Juan Basin

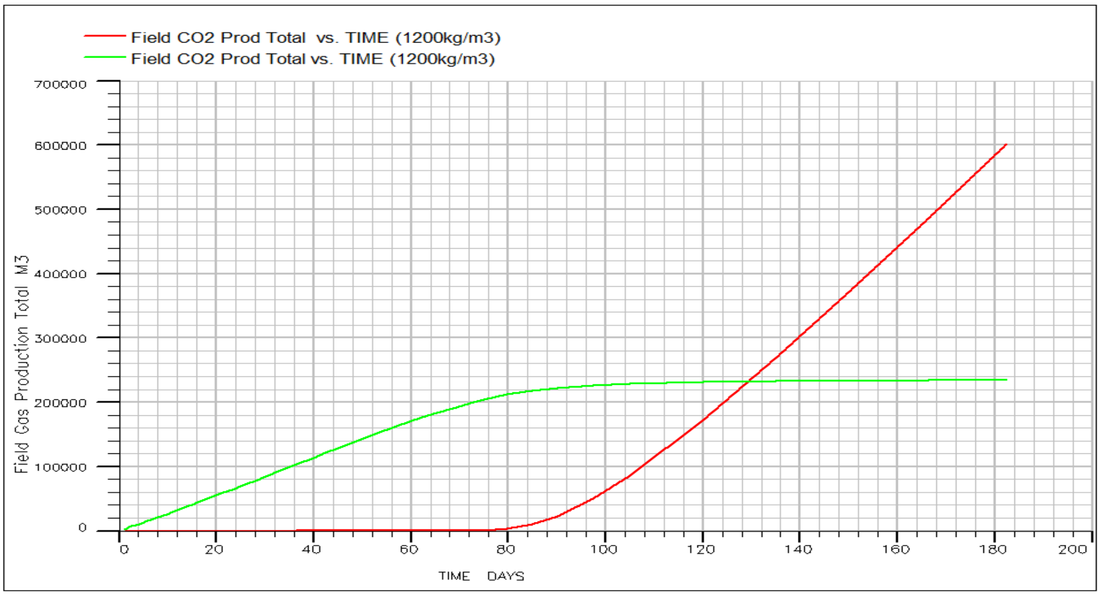


Figure 20 : Field Production Total CO2 vs CH4, Coal Density 1200kg/m3, San Juan Basin

<u>Case 2b: San Juan Basin, (coal density= 1350 kg/m3)</u>

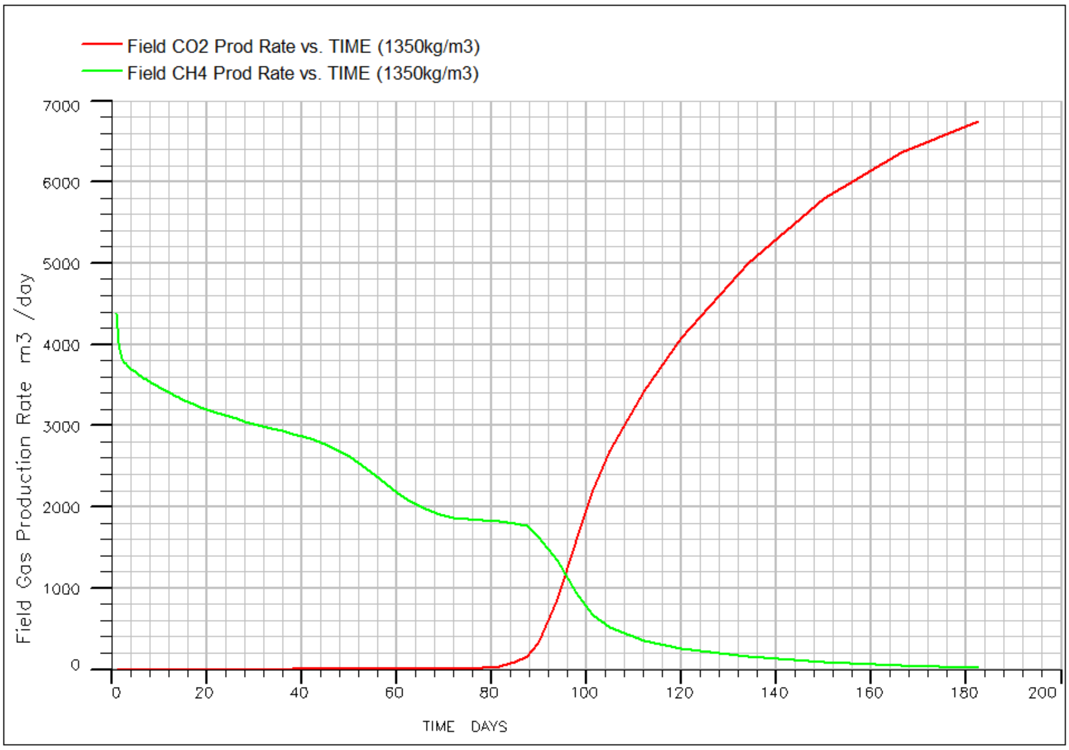


Figure 21 : Field Gas Production Rate CO2 vs CH4, Coal Density 1350 kg/m3, San Juan Basin

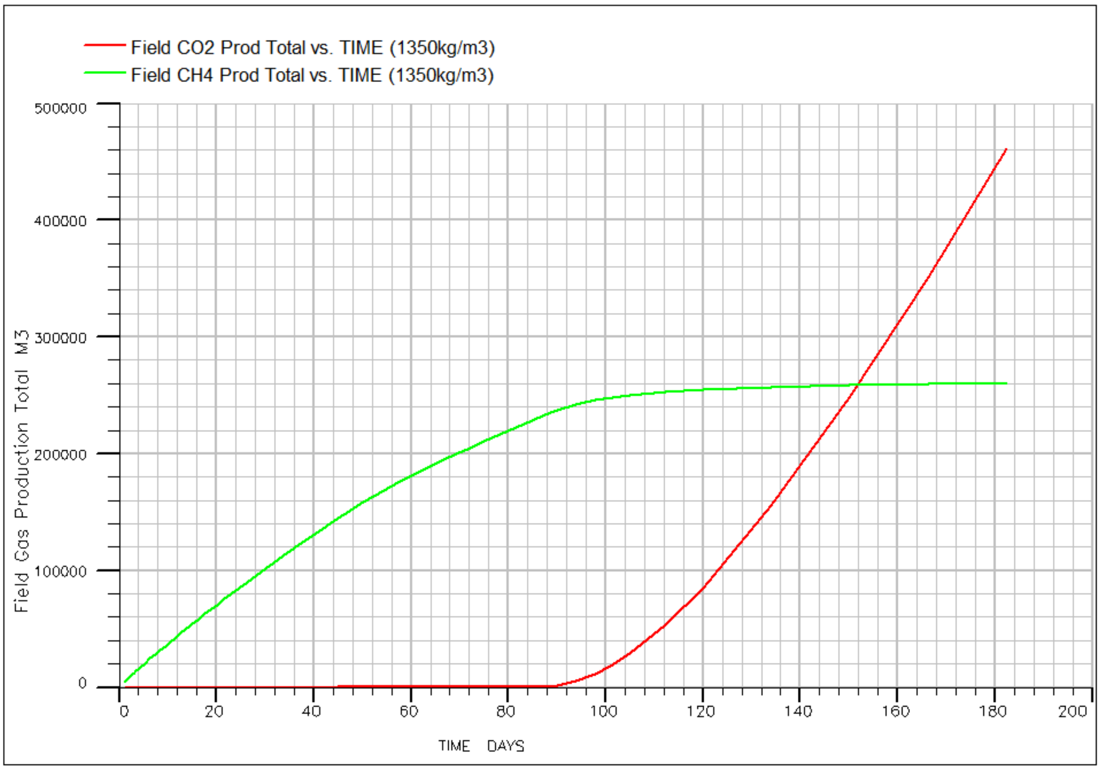


Figure 22: Field Gas Production Total, Coal Density 1350kg/m3, San Juan Basin

<u>Case 2c: San Juan Basin, (coal density = 1385kg/m3)</u>

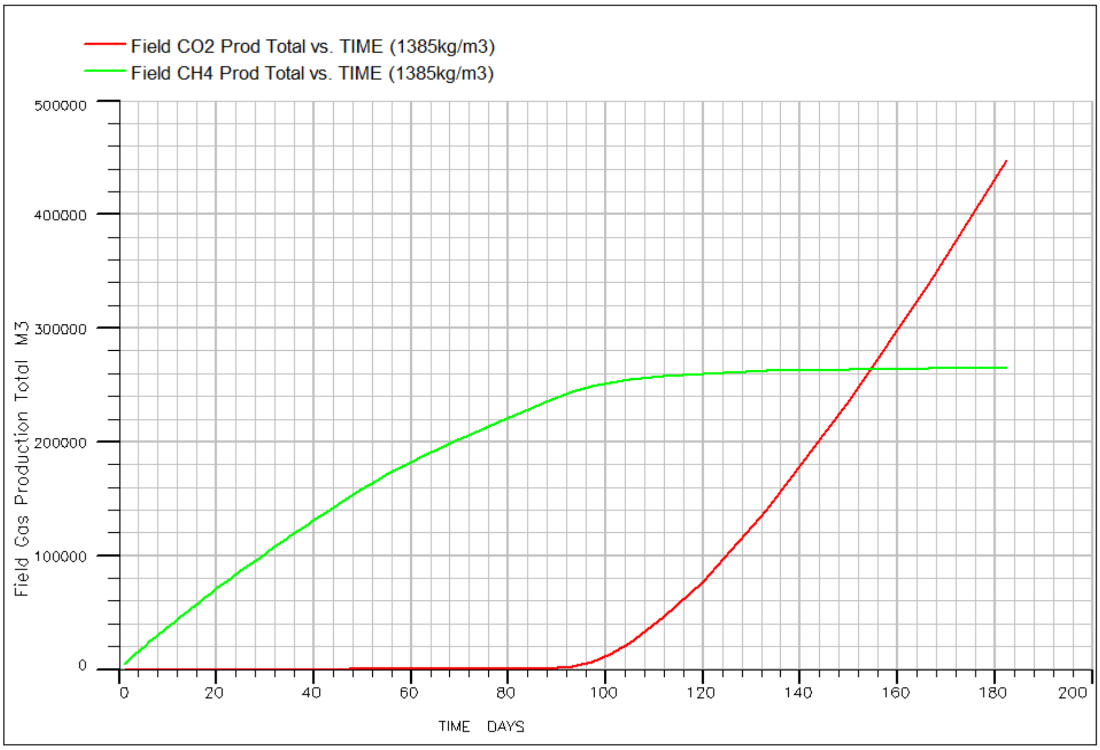


Figure 23 : Field Gas Production Total, Coal Density 1385 kg/m3, San Juan Basin

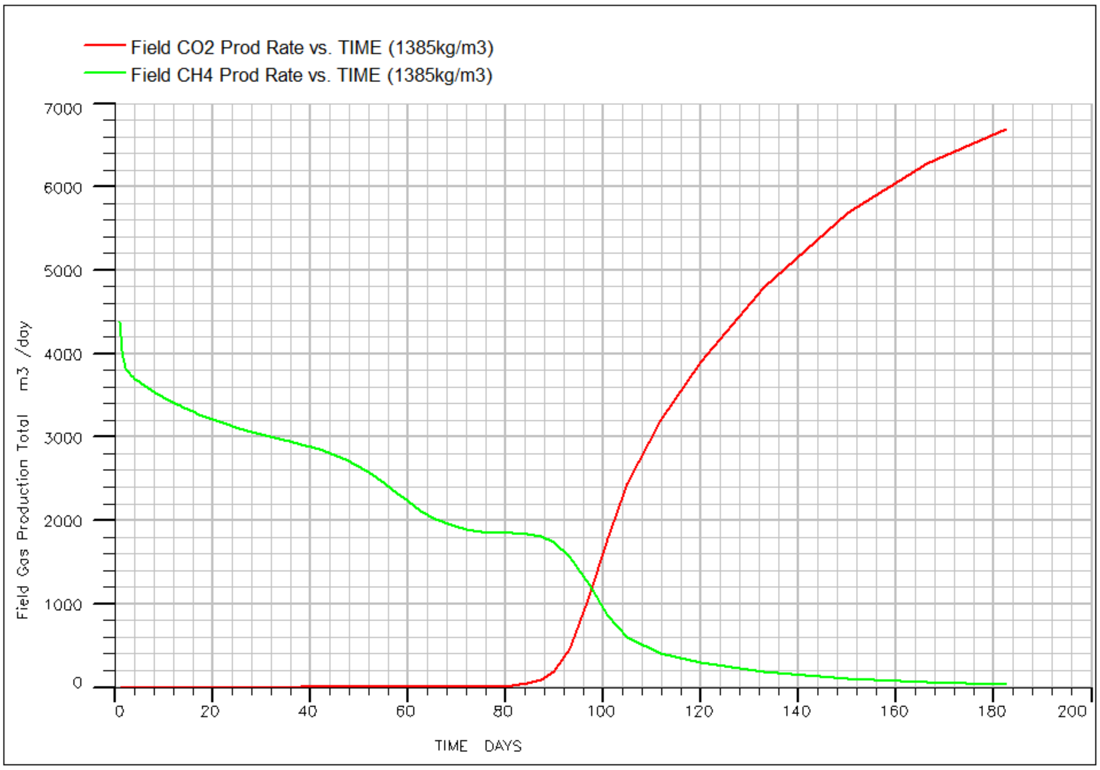


Figure 24 : Field Gas Production Rate, Coal Density 1385 kg/m3, San Juan Basin

Case 2d: San Juan Basin, (coal density = 1500kg/m3)

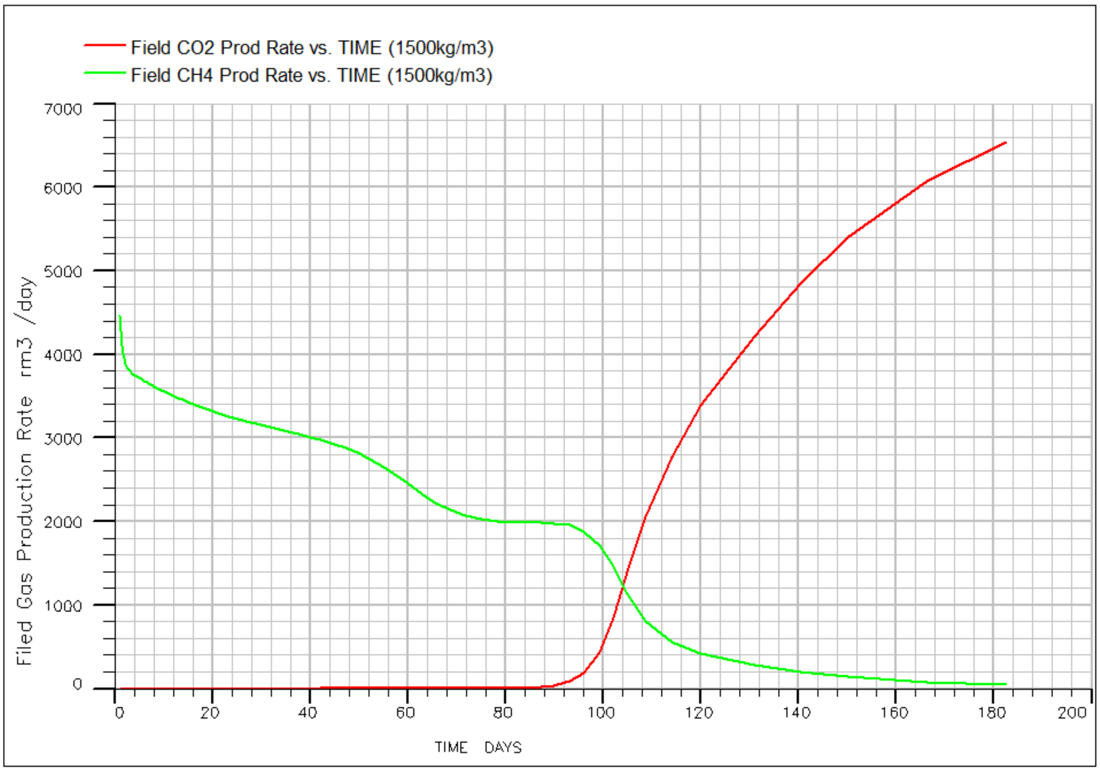


Figure 25 : Field Gas Production Rate, Coal Density 1500kg/m3, San Juan Basin

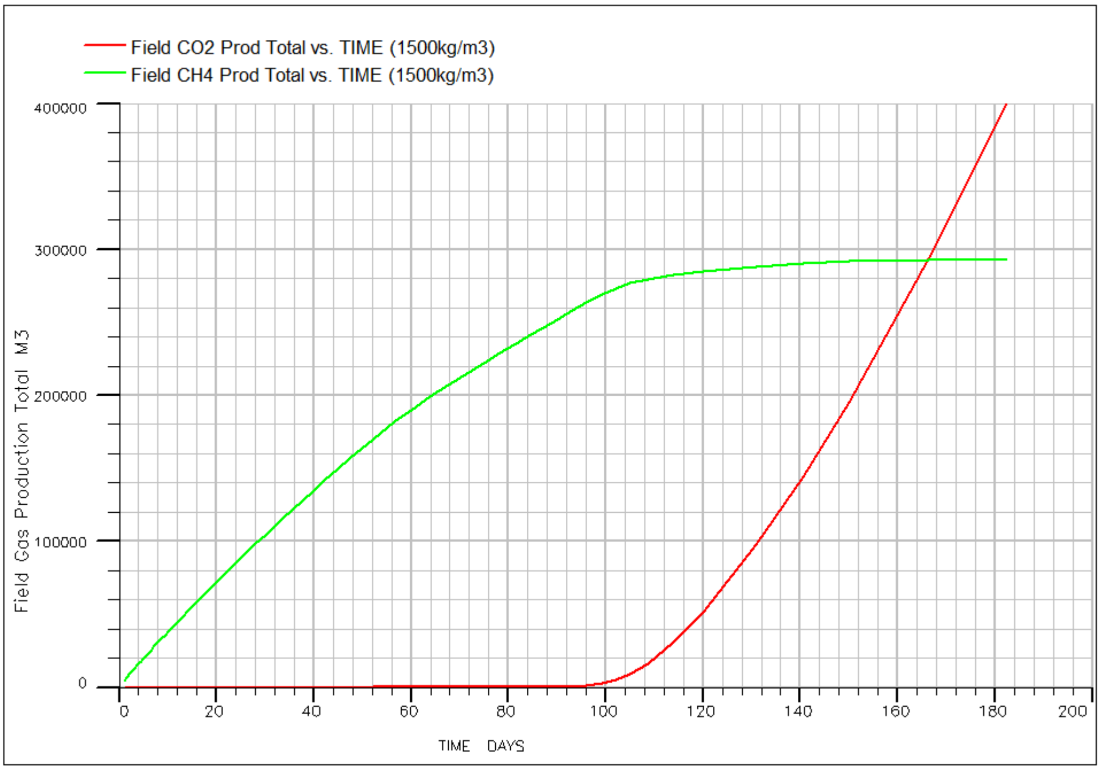


Figure 26 : Field Gas Production Total, Coal Density 1500kg/m3, San Juan Basin

<u>Case 2e: San Juan Basin,(coal density = 1750kg/m3)</u>

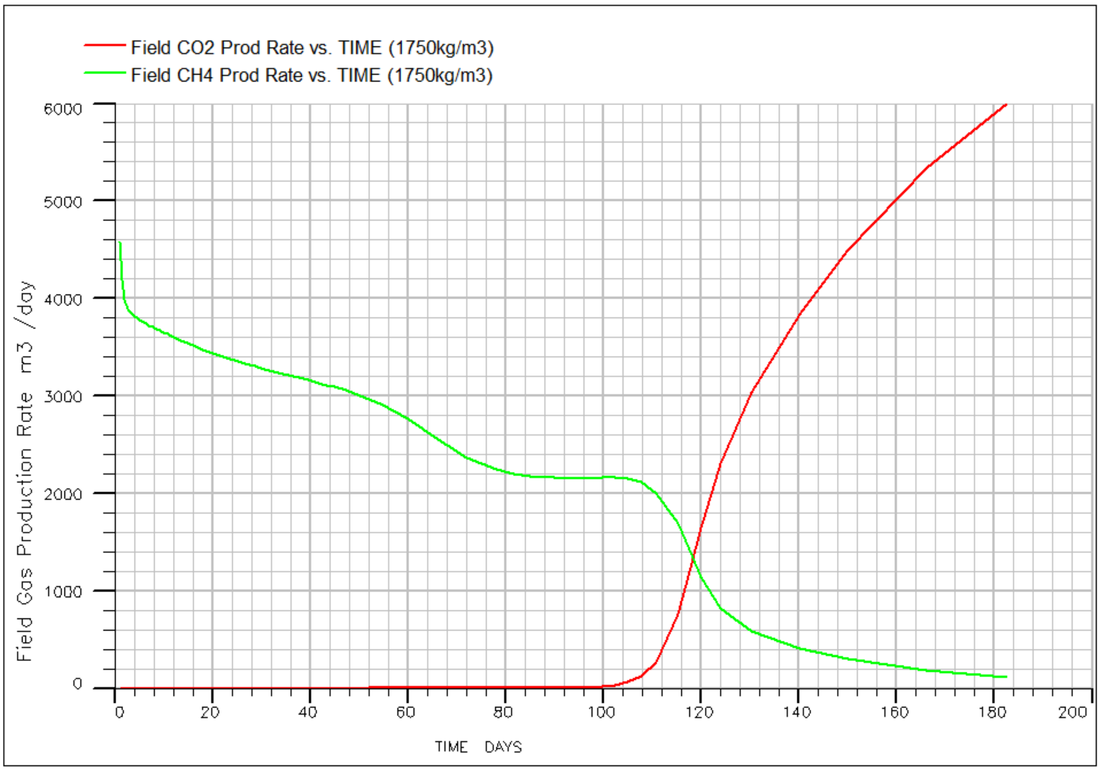


Figure 27 : Field Gas Production Rate, Coal Density 1750 kg/m3, San Juan Basin

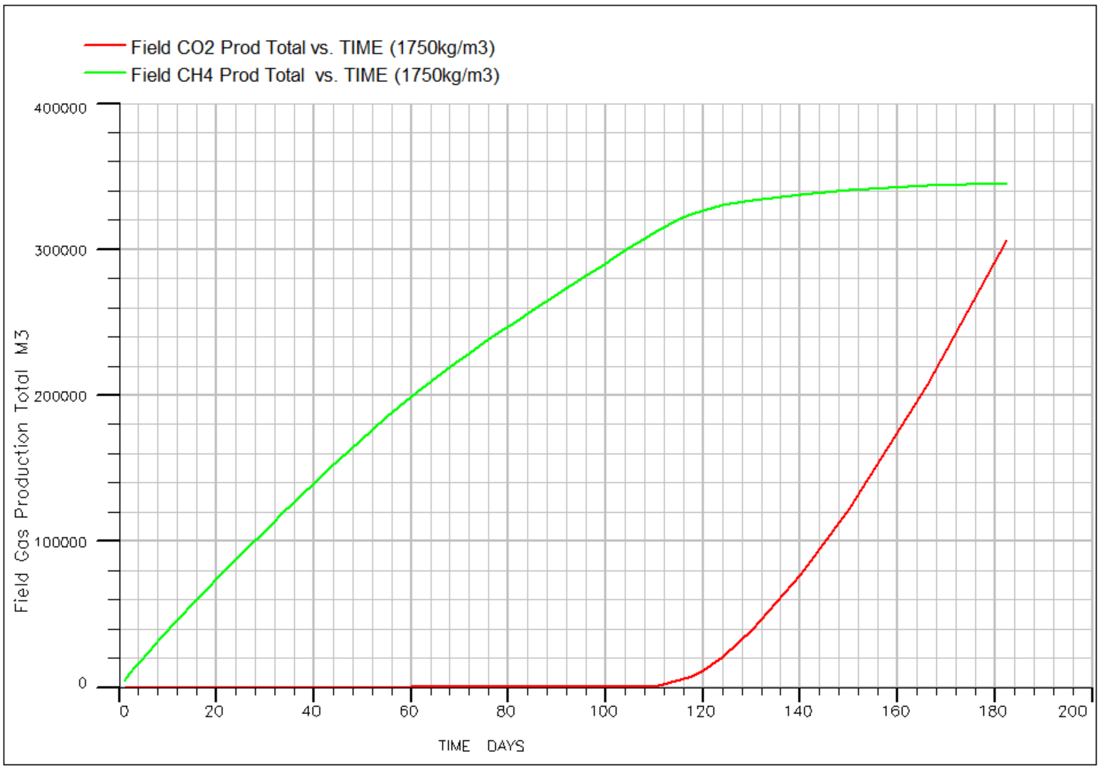


Figure 28 : Field Gas Production Total, Coal Density 1750kg/m3, San Juan Basin

Table 4 : Analysis Result of San Juan Basin

No	Coal Density (kg/m3)	Analysis
1	1200kg/m3	i. Maximum methane production rate of 2956 m3/day between day 36 and day 37.At this time, there is no production of CO2. When CO2 start to inject at day 72, production rate decline until 1780 m3/day. ii. The production rate of methane starts to decline at day 50, with no injection. iii. At day 1, the production rate of methane starts with 2674.728 m3/day. The production rate increase until 2882.2581 m3/day, then it decline until 2633.8523m3/day. iv. Methane production rate and CO2 production rate intercept between day 90 and day 89 with 874.5m3/day and 2320 m3/day.

		v. Total methane production reached a plateau of 234000M3 which continued for three days. This is due to the maximum production limit set during running of the simulation. vi. Production inclines rate start at day 1 until day 80 with 5x10^5 M3. The production starts to slow down flat after the day 80 due to reduction in reservoir pressure.
2	1350kg/m3	i. Methane production rate peaked at day 1 about 4373.64 m3/day and then drops after one day. The methane production rate decreases steeply until about 5 days. Thereafter, CO2 production rates starts to level out at day 90 but then it still cannot boost the methane production rate. ii. Production of methane gas peaked and plateaued for a longer period, which is about 88 days compared to only two days before in the previous case. Gas production stay in plateau period until day 182 with 234150 M3.
3	1385kg/m3	i. Maximum methane production rate increases to 4373.63818 M3. ii. Gas production increase in straight line from day 1 until day 50 which are prolonged at 4384.87M3 until 160000M3. After that it starts to give in plateau period until the end of sorption time.
4	1500kg/m3	i. Methane production rate peaked at 4460 m3/day thereafter decreases rapidly until about 80 days when the production rate starts to level out and

		decrease again until 182 day. ii. When production rate give 2782.40 m3/day, the methane gas production give value at 166900M3. iii. Initial rapid gas cumulative production can be seen from the graph that they have higher saturations and higher reservoir pressure. After 115 days, gas cumulative production starts to slow down.
5	1750kg/m3	i. Methane production rate maximizes at 1 day at a rate of 4576 M3. After this period, methane production increase rapidly until day 120. ii. Meanwhile rate of production decline eventually reduces at 4 days. iii. Like previous cases, methane gas production continued to increase at a rate of 57.5 m3/day until 4140.5 m3/day for 115 days and then reduces in production rate. After 3 days, rate of decline reduces and eventually ends at zero production rates.

It can be seen that there are common trends with all the graphs. In figure 30, when coal density increases, the period of which maximum gas production occurs in prolonged. Firstly, gas production rate spiked very quickly. This can be attributed to the instantaneous diffusion of fluids from coal matrix into the fractures of the coal. After this spike, all results showed a decline in production rate and then eventually evened off to zero production. In other words, the higher the coal density, the longer the maximum production period.

From the cumulative production graphs, it can be said that when coal density rises, total production also rises. However, there is an exception for the gas production in which at day 1 until day 80 where the plot show same trend. After day 80, the production start to give different value in production total varies with time. At coal density of 1750kg/m3, the gas was absorbed more to the coal and diffuse out from coal into the well more quickly, hence resulting in faster depletion of the total gas content of the coal, as well as it will give greater cumulative gas production. Due to this, the limiting factor is the Langmuir volume, which is the maximum gas content of the coal. The high coal density result is faster production of gas, which in turn results in faster depletion of the gas content.

To see the trends of gas production rate and cumulative volume as coal density increases, the sequences of production rates and cumulative production with increasing coal density is illustrated in figure 29,30 and 31.

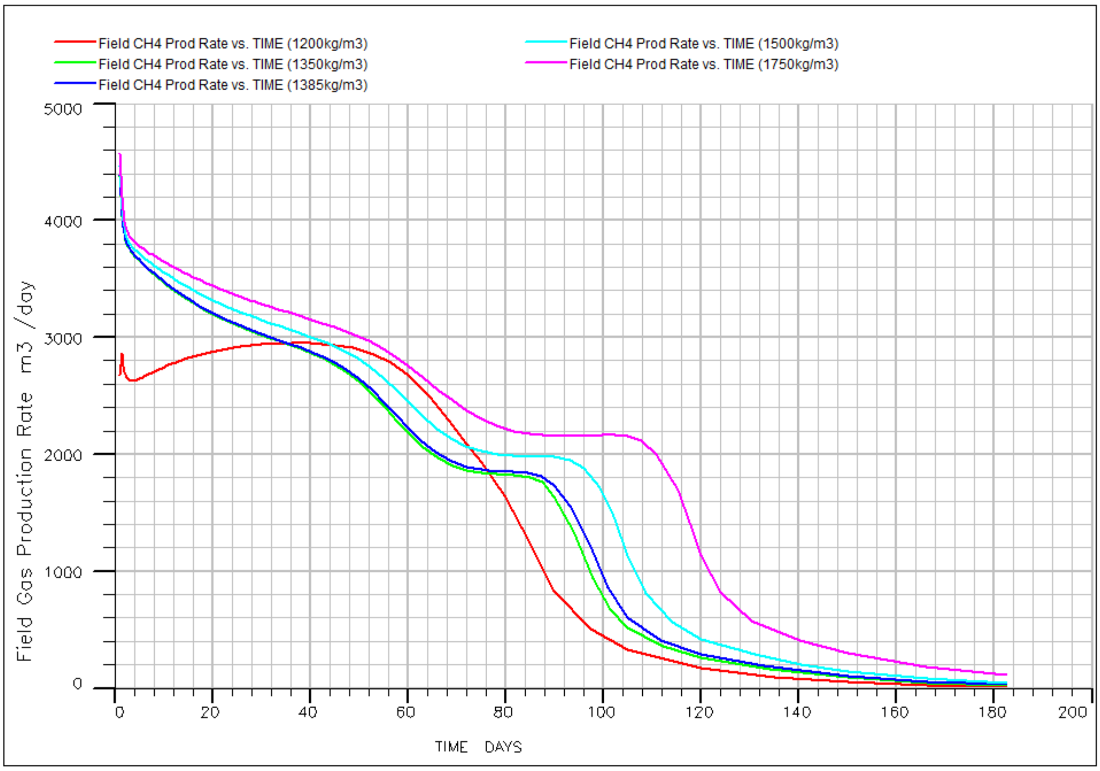


Figure 29 : Field Gas Production Rate, Coal Density All Case, San Juan Basin

The gas production rate curve for the first case is quite different. This is due to the less value of density. It can be concluded that the density of 1200 kg/m3 is not reliable to use in this case.

All these gas production curves had an apparent peak production and reached that peak during the first 5 days and then the production rate dropped to around 3000m3/day after the first 40 days.

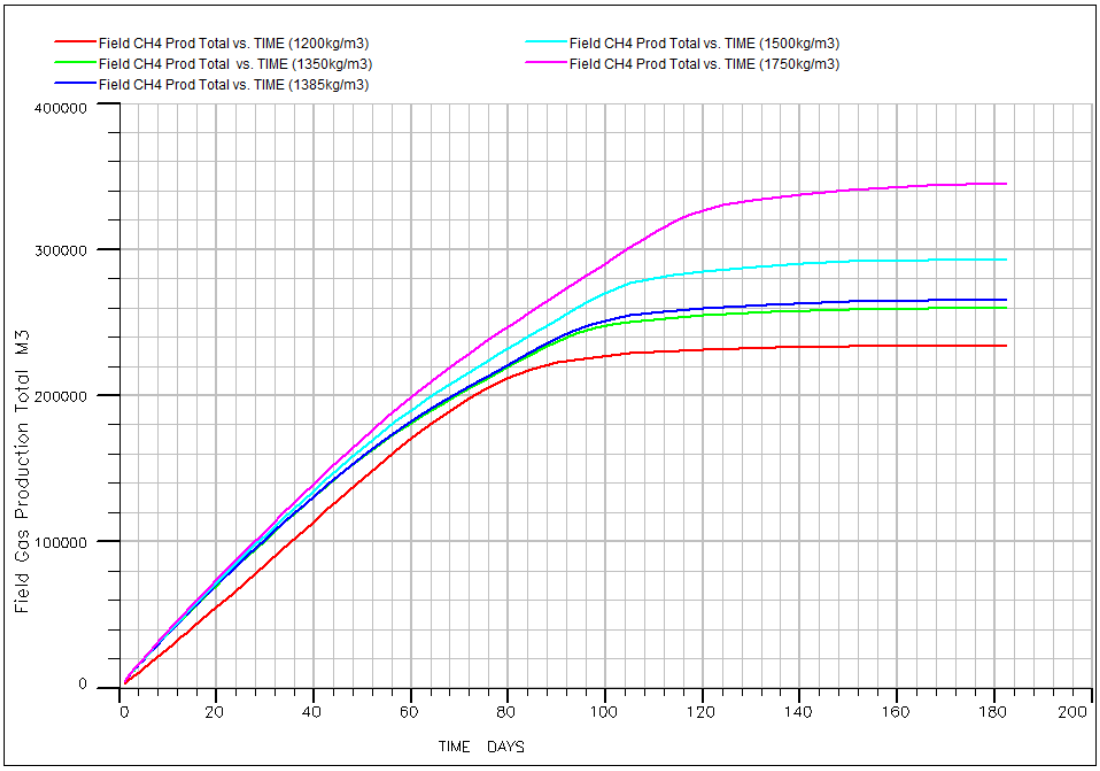


Figure 30 : Field Gas Production Total, Coal Density All Cases, San Juan Basin

From figure 31, we can say that high density will give resulted in high gas in place. Since the mineral matter component of coal has significantly higher density than the bulk organic matter. In general coal density directly correlated with the mineral content. As San Juan Basin is High Volatile A- Bituminous it gives high value in gas content that contributes to the value of coal density.

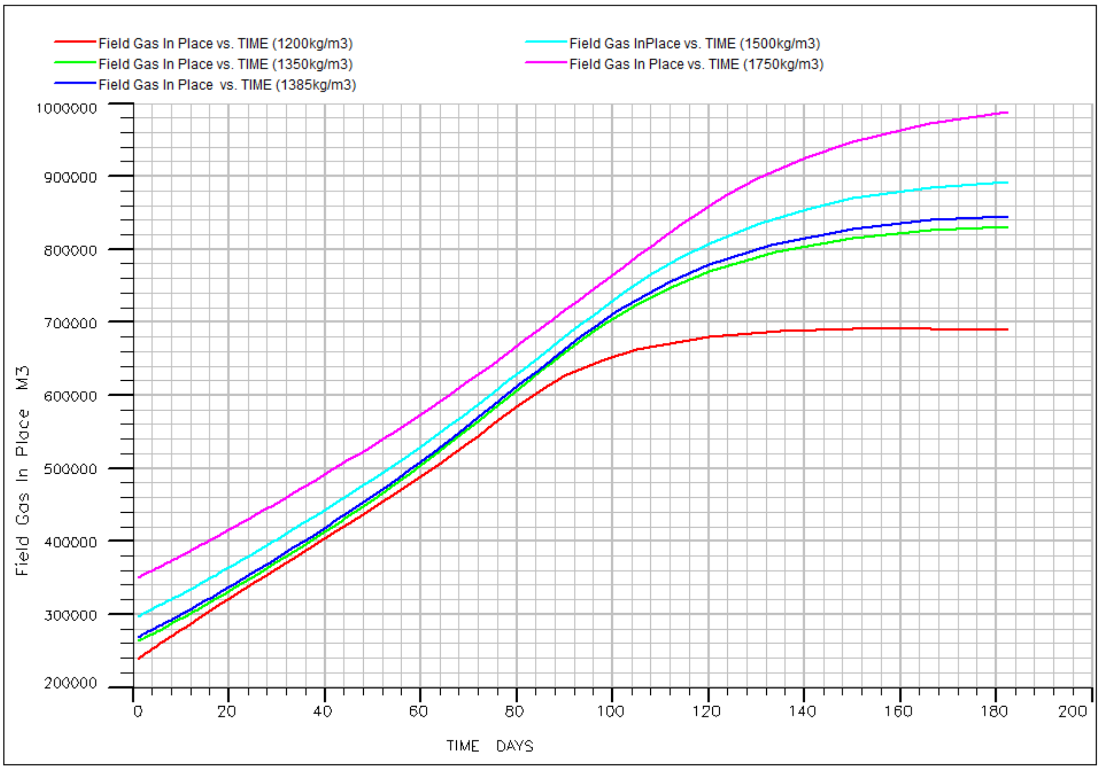


Figure 31 : Field Gas In Place, Coal Density All Cases, San Juan Basin

4.3 Case 3: Western Canada Basin

<u>Case 3a :Western Canada Basin,(coal density = 1200kg/m3)</u>

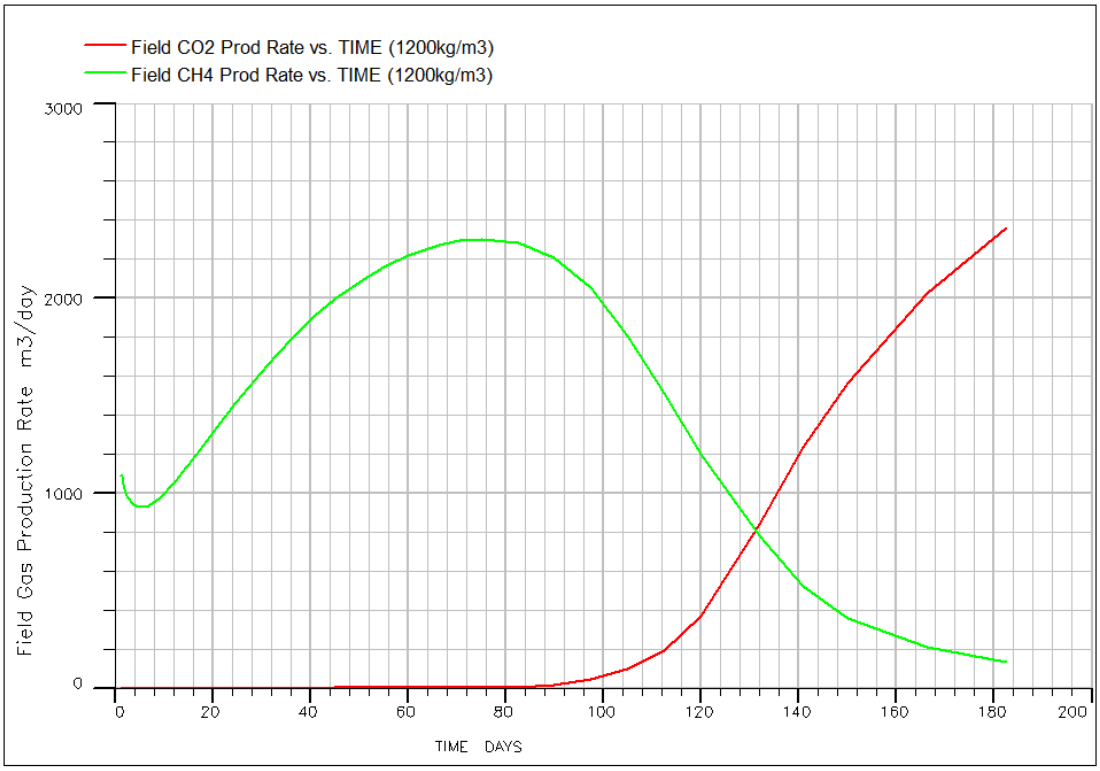


Figure 32 : Field Production Rate, Coal density 1200kg/m3, Western Canada Basin

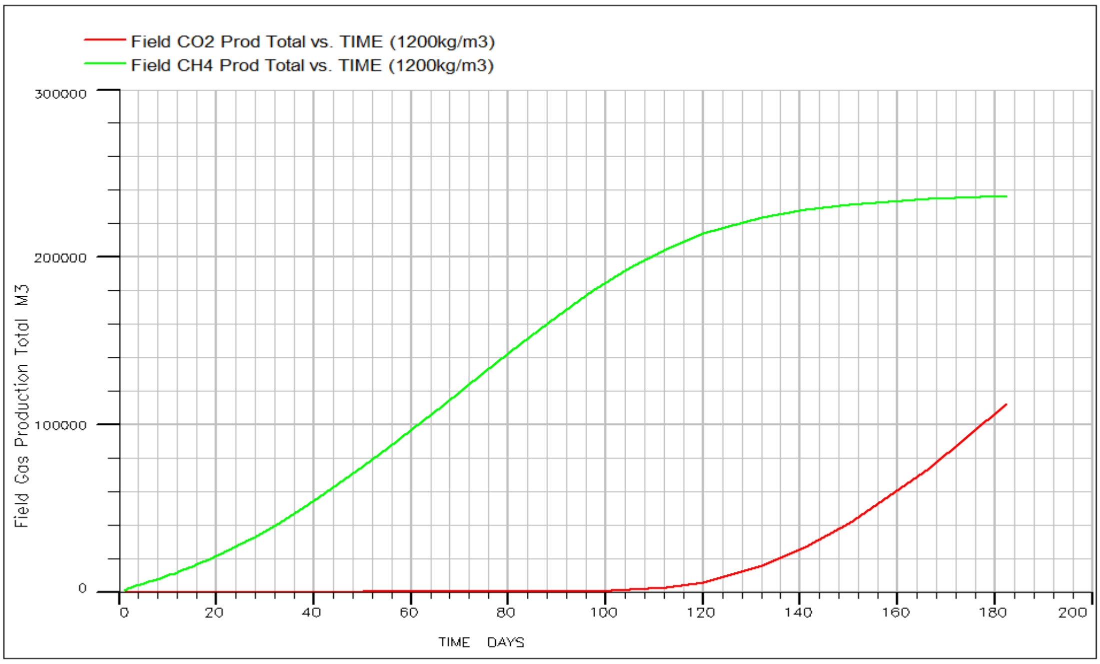


Figure 33 : Field Production Total of CH4, Coal Density 1200 kg/m3, Western Canada Basin

Case 3b : Western Canada Basin, (original case = 1314 kg/m3)

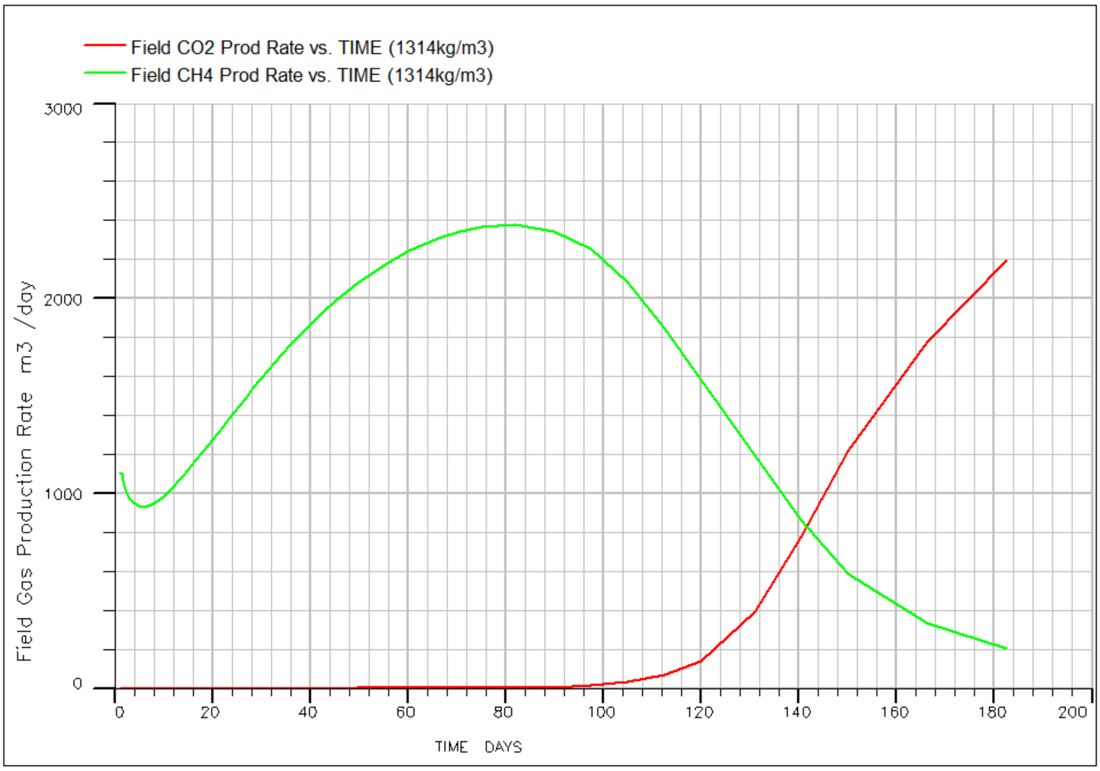


Figure 34 : Field Production Rate, Coal Density 1314kg/m3, Western Canada Basin

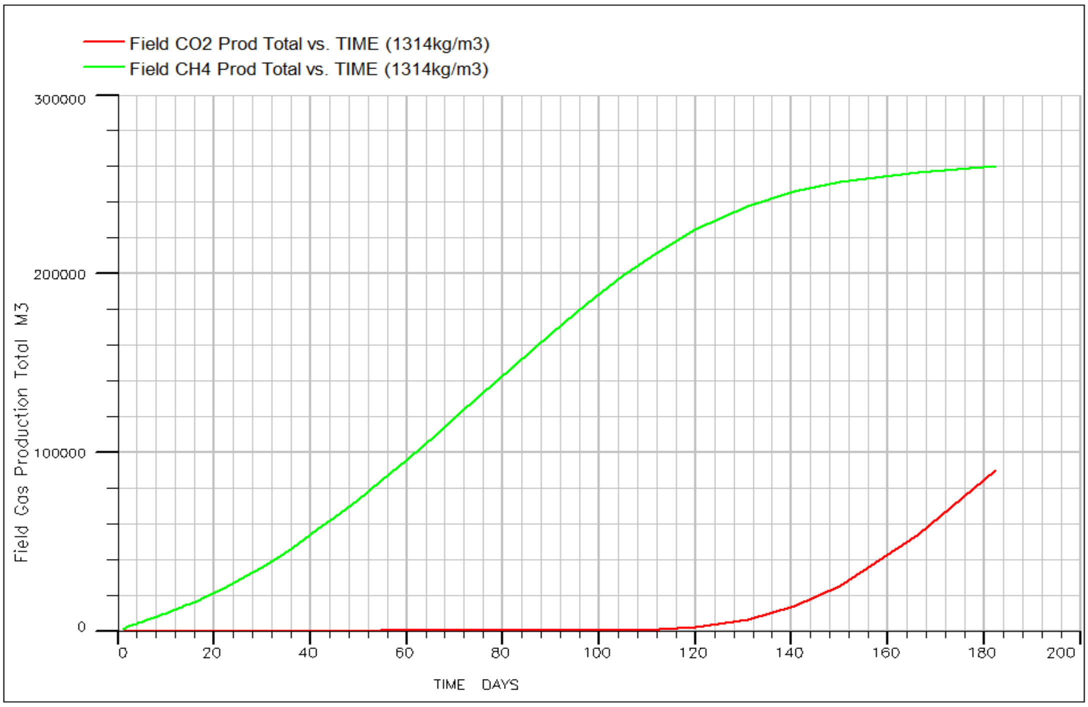


Figure 35 : Field Production Total of CH4, Coal Density 1314 kg/m3, Western Canada Basin

Case 4c : Western Canada Basin, (coal density = 1500kg/m3)

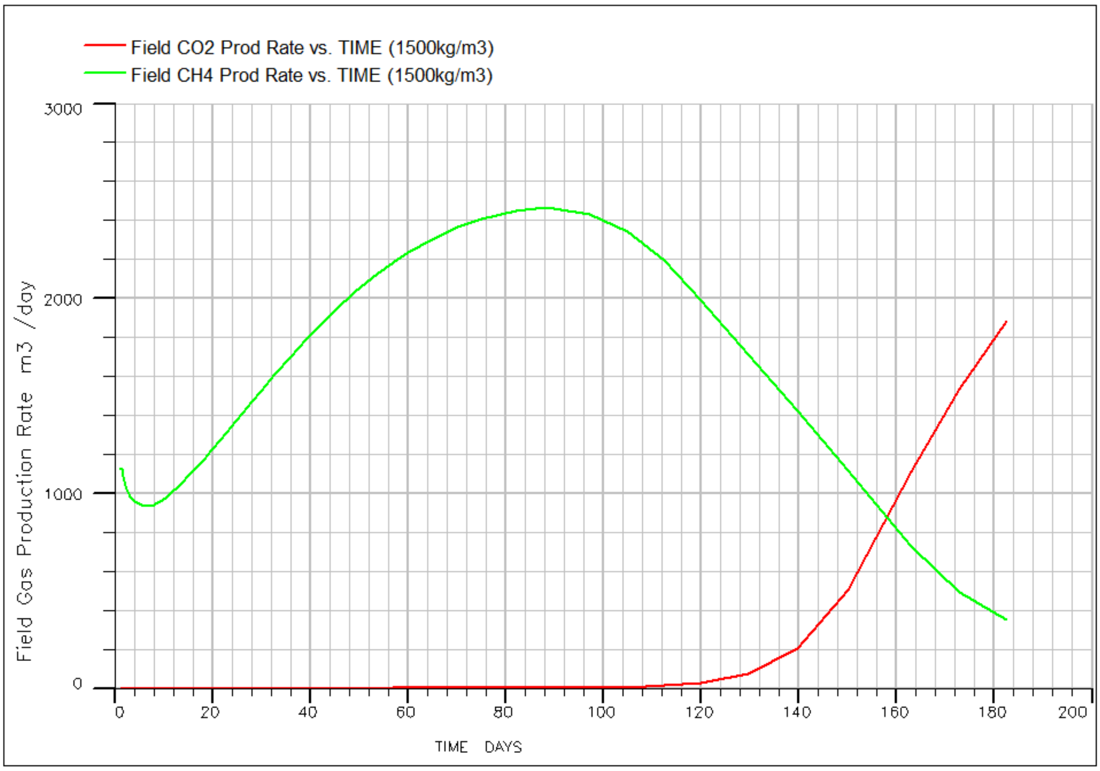


Figure 36 : Field Production Rate, Coal Density 1500kg/m3, Western Canada Basin

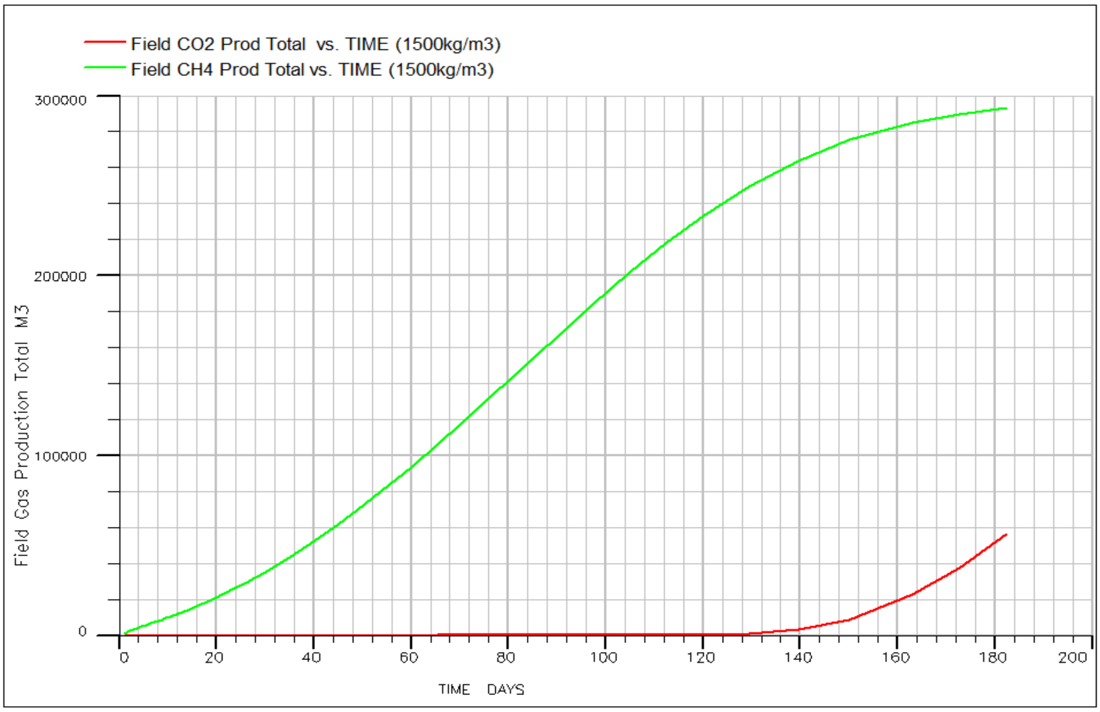


Figure 37 : Field Production Total of CH4, Coal Density 1500 kg/m3, Western Canada Basin

Case 3d: Western Canada Basin, (coal density = 1750kg/m3)

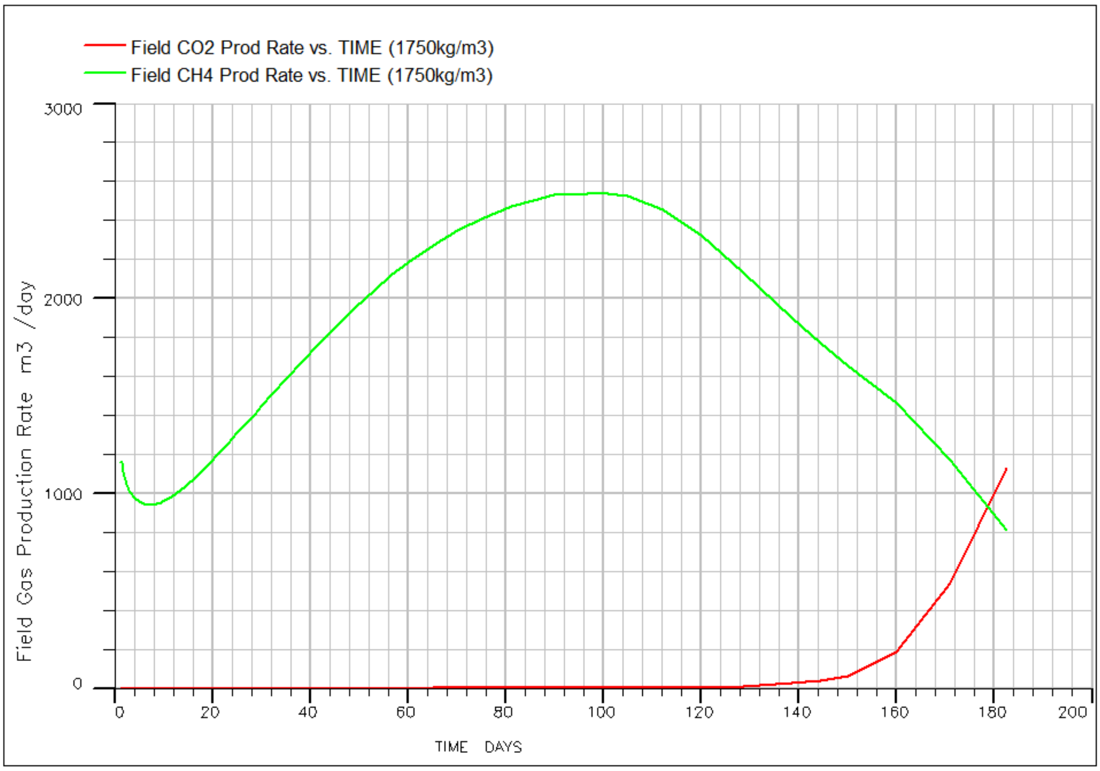


Figure 38 : Field Production Rate, Coal Density 1750kg/m3, Western Canada Basin

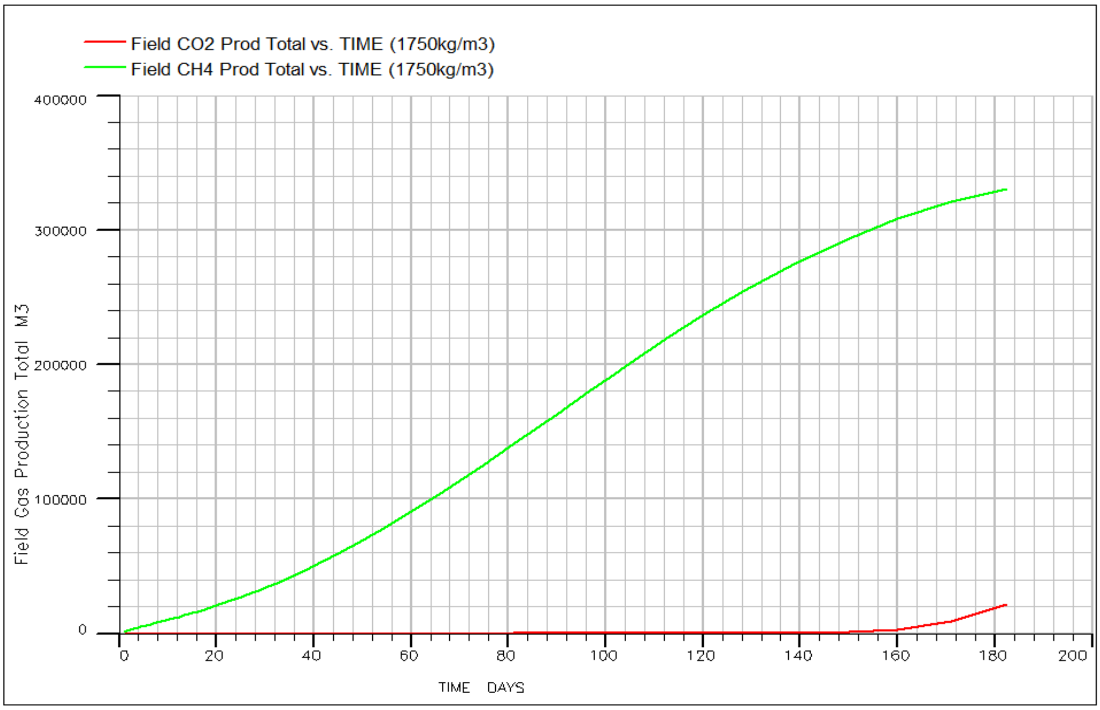


Figure 39 : Field Production Total of CH4, Coal Density 1750 kg/m3, Western Canada Basin

Table 5 : Analysis Result of Western Canada

No	Coal Density (kg/m3)	Analysis
1	1200kg/m3	i. Methane production increases very rapidly. This production reached a peak rate of 2304 m3/day with total production at this stage is 131023 M3. After this maximum production, production rate decreases gradually, until about day 140. ii. Methane gas production reaches maximum production until 236930 M3 at the end of sorption time with slow production rate, 134.5 m3/day. iii. At 2361.554 m3/day, the CO2 was fully injected to give maximum methane production.
2	1314kg/m3	i. When the coal density was change, the peak rate was change at day 81 with higher rate which is 2378.625 m3/day. ii. Meanwhile at this stage, the methane production produces 140500 M3 in value. iii. At early stage, methane production rate start at day 1 with 1101.2532 m3/day. Then it drops slowly during the plateau production rate of gas at day 6. iv. At day 107, with production rate, 2024.4 m3/day it give optimum point of total production which is 202440M3.
4	1500kg/m3	i. Methane production maxed at plateau period between day 86 until day 90, 2462 m3/day. Gas production at this stage also remains unchanged 160000 M3. ii. At first, total methane production shows higher than this case but then at day 92,

		methane production rise higher than previous case. However, the dip in production rate of methane after one day is greater than the previous case. Different production rate between these cases is 23 m3/day. The subsequent temporary rise of methane production is also steeper as compared to the previous case. This is also caused by the changes in the coal density. iii. In graph total methane production between this case and previous case, there is a different value in both production due to different gas adsorption capacity. The effect of the gas adsorption capacity on coal density is stronger when CO_2 gas presented in coal.
5	1750kg/m3	i. Methane production rates starts according to the trend in which the total production start increase varies with methane production rate. However, one major difference that can be observed is that methane production rate only peaked at almost day 98, then after the methane gas production rate has dropped to below its maximum methane production. ii. Maximum production rate is still 2539.35 m3/day; however it took a longer time to reach that point. iii. With the CO_2 injection, help the production to be fully level out. iv. Coal density, 1750kg/m3 is a high value for subbituminous. Since this value give highest

		production, it shows that high density will give high production. Usually this high density come from minerals and it have much greater deviation than low density due to heterogeneous distribution of the minerals deposited in coal. iv. The higher coal density of the coal formation also plays a role in this phenomenon.

It can be observed that for all coal density values, methane is initially produced at high rates, until a certain point is reached, thereafter production rate slightly drops. However, as coal density values rises, methane production rates drops slightly, and starting at day 1 until day 6, CO2 production rate does not change at all, remain at zero stage. After day 6, CO2 gas was level out and methane production rate increase too. Since the density of coal is different, the adsorption capacity to methane and CO2 are different. From the figures above, we can see that after coal density value changes, methane production is boosted by CO2 injection. Prior to that, the total production for methane has a dramatic increase compared to those for CO2 flow. This effect is due to the higher affinity of methane to coal than CO2. So, methane has more adsorption capacity than CO2.

The coal density also influenced by gas content. Higher gas content surely will give high in coal density value. Theoretically, the force of attraction between the two solid coal surfaces will be replaced by that between two adsorbed gas films weaker Van Der Wall's field than the original solid coal surface (Aziz and Ming Li, 1999). Consequently, the strength of coal would be reduced. The adsorption of coal is strictly dependent on the composition of coal. Different maceral present in the coal affect its adsorption capacity and therefore the strength of the coal.

To give a clearer insight into the trends of production rate and cumulative production with respect to changes in coal density, the following figures are presented.

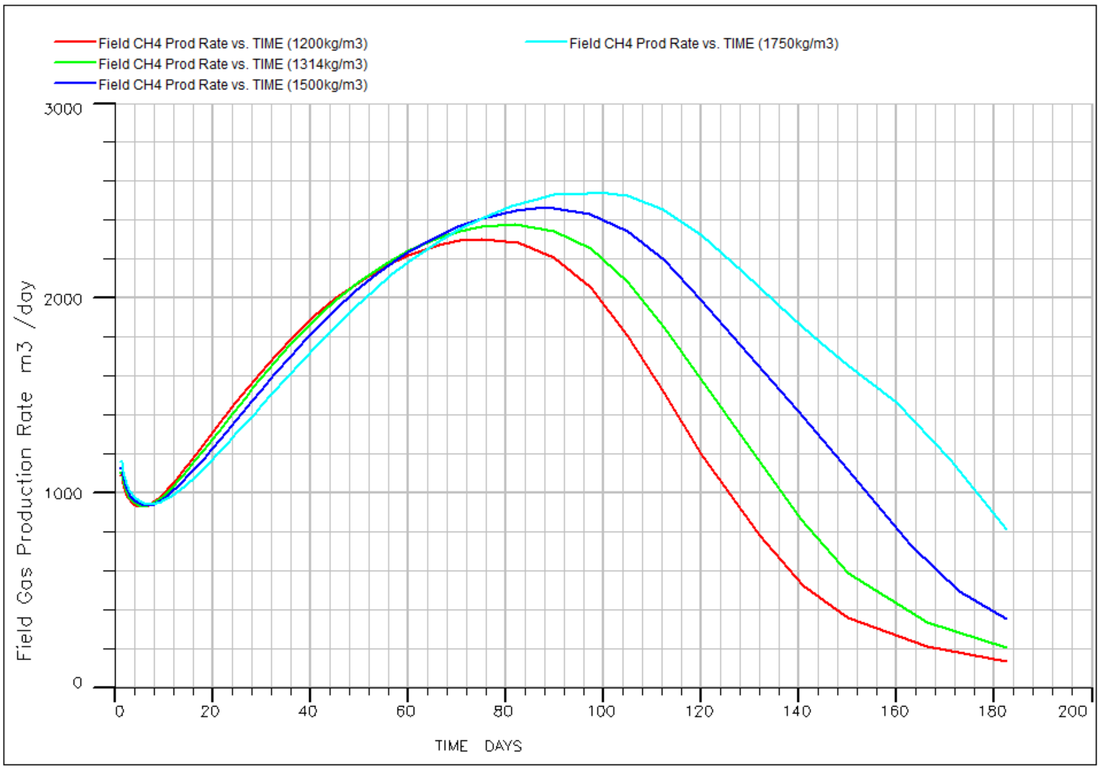


Figure 40 : Field Gas Production Rate, Coal Density All Cases, Western Canada Basin

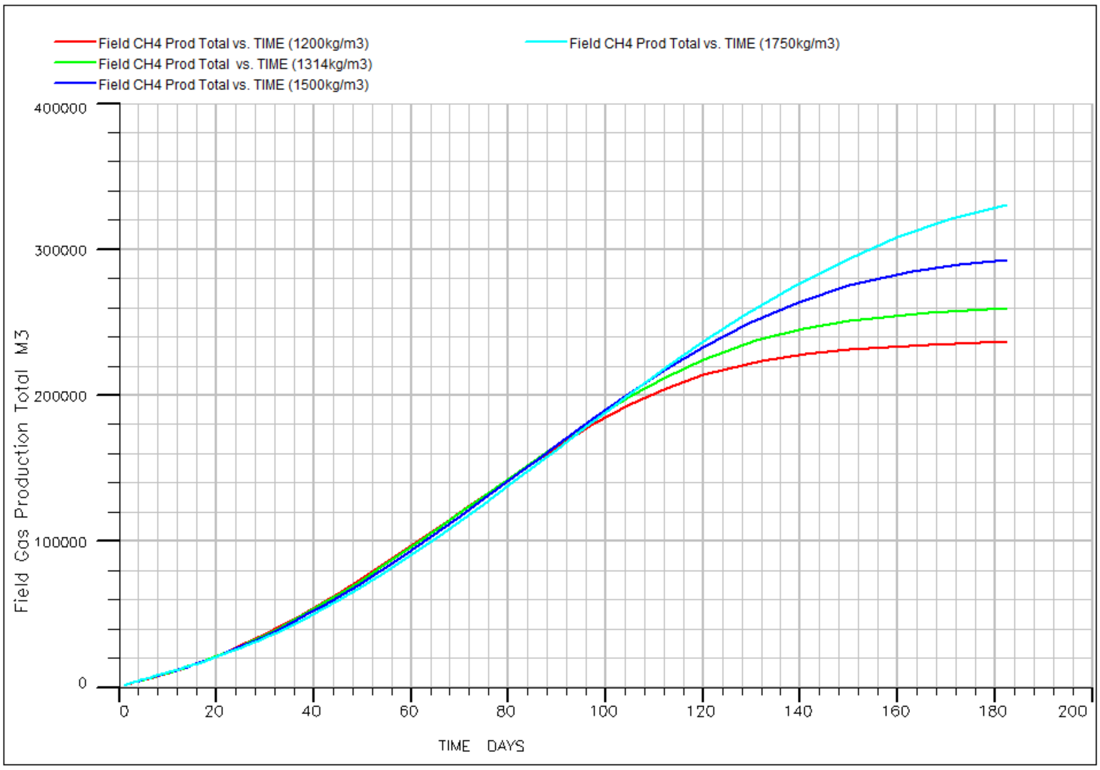


Figure 41 : Field Gas Production Total, Coal Density All Cases, Western Canada Basin

The figure for gas in place indicates that more coal density affect gas in place volume and when gas in place increases it will affect gas production.

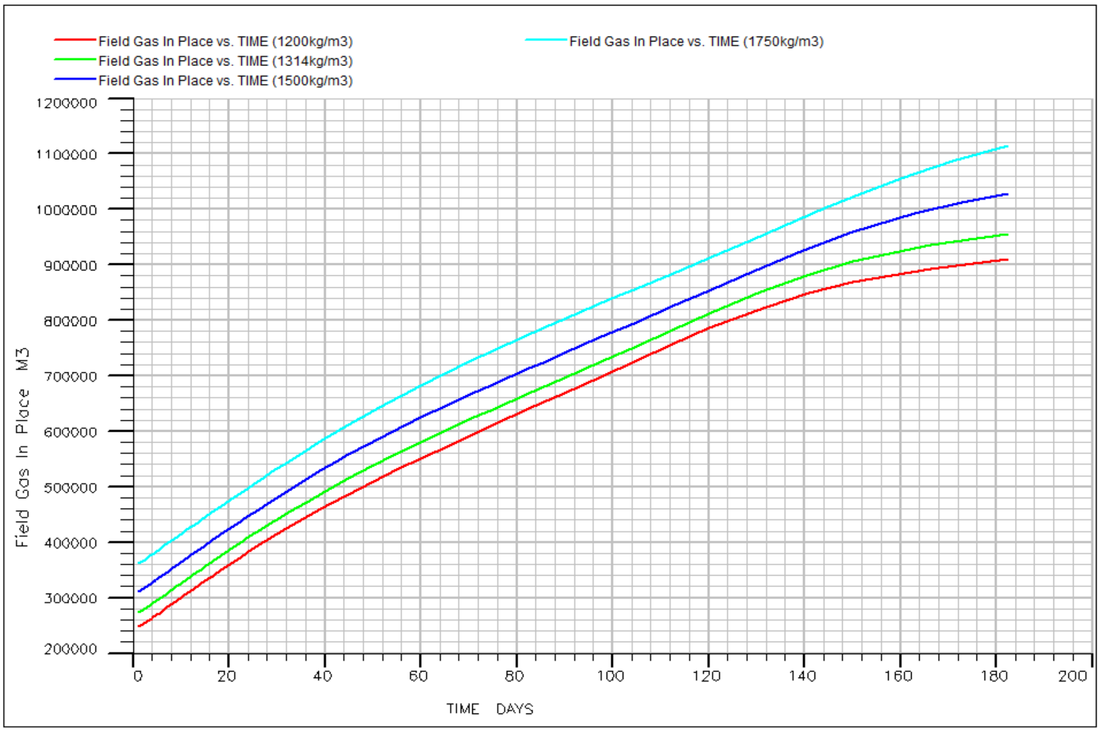


Figure 42 : Field Gas In Place, Coal Density, Western Canada Basin

Every basin shows different value of gas in place volume production rate and total methane production. This is due to different coal rank that have been already discussed which are different in data such as reservoir pressure, reservoir temperature, gas content and other reservoir properties. Theoretically, we understand the concept that higher the coal density, the higher the gas in place. But due to different coal ranks, there are many factors we need to consider. The density of a coal is a function of its composition. Since the mineral matter component of coal has a significantly higher density than the bulk organic matter, in general, all compositional factors being equal, coal density will be directly correlated with the mineral matter content.

Moisture content affects the coal density. The moisture content varies inversely as a function of coal rank. Anthracite coal has lowest in situ moisture contents whereas subbituminous coals have very high in situ moisture contents. This density value difference indicates how crucial an accurate moisture content value is for reliable gas in place analysis of coal bed reservoirs. The hydrogeology of these fields is also important because the water strongly influences reservoir pressure, the gas saturation, and the ability to de-water the coals. This shows that many parameters we need to consider in order obtaining optimum total methane production.

Table 6 below shows the value of methane produced at coal density, 1500kg/m3.

Coal density can affect the value of gas production in CBM reservoir. As we can see from the table below, for Qinshui basin, this study indicated that the coal density can influence the value of methane produced as high the coal density the faster the desorption rate. So from day 100 until day 180, this basin has constant production limit 270000M3. We need to consider the characteristics of coal rank.

Table 6 : Methane Produced in Qinshui Basin, San Juan Basin, Western Canada Basin, Coal Density 15000kg/m3

Coal density 1500kg/m3	Qinshui	San Juan	Western Canada
	Methane produced (M3)		
Day 20	110000	70000	20000
Day 40	170000	135000	50000
Day 60	221000	190000	90000
Day 80	260000	230000	140000
Day 100	270000	275000	190000
Day 120	270000	280000	230000
Day 140	270000	290000	268000
Day 160	270000	290000	280000
Day 180	270000	290000	290000

Qinshui start with highest initial production due to high initial reservoir pressure and high gas content Therefore, it shows high production at initial development stage. Qinshui basin reached the peak production at day 100 (270000M3) which shows that even though they have high value in gas content and have been subjected to a larger effective stress (high rock compressibility). This will reduce the permeability and limits the production.

San Juan basin show great jump in gas production during day 40 whereas Western Canada at day 80. This shows that at this point they have high gas ratio and the phenomenon happen due to the reduction in water production. They have faster dewatering period at this stage. As the gas ratio increase, the gas production also increases.

Conclusively it can be said that San Juan is the best basin to explore due to its coal rank, Bituminous. Graph itself shows that this basin produce maximum methane at day 140 (290000M3). Whereas Western Canada Basin produce maximum cumulative production at day 180(290000M3) and Qinshui Basin only reached 270000M3 at day 100.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

The research on coal density and its effect towards the gas in place, production rates and cumulative production of gas in CBM wells have given great insight into the properties of coal and how they relate to other properties such as moisture content, gas content and permeability. The following conclusions were inferred from this research:

i. Coal density is undeveloped parameter that has an enhanced effect on methane gas production rate.

ii. An increase in coal density leads to higher production rate and a prolonged production period at the maximum production rate regarding to each coal rank.

iii. San Juan Basin are the best coal basin that must be developed as they have high potential in produce CBM, however further research into the other coal rank formation must be conducted.

iv. Coal density related to gas content as high value in coal density will give high value in gas content as well as give high value in gas in place.

Among the recommendations that can be made as a follow-up to this project are:

i. Simulation should also be run for higher coal density and how they affect production of CBM

ii. Further research need to be conducted in other parameter that interrelate with coal density especially gas content (gas saturation). High gas saturation inevitably leads to a short dewatering period and good productivity, especially the initial productivity.

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