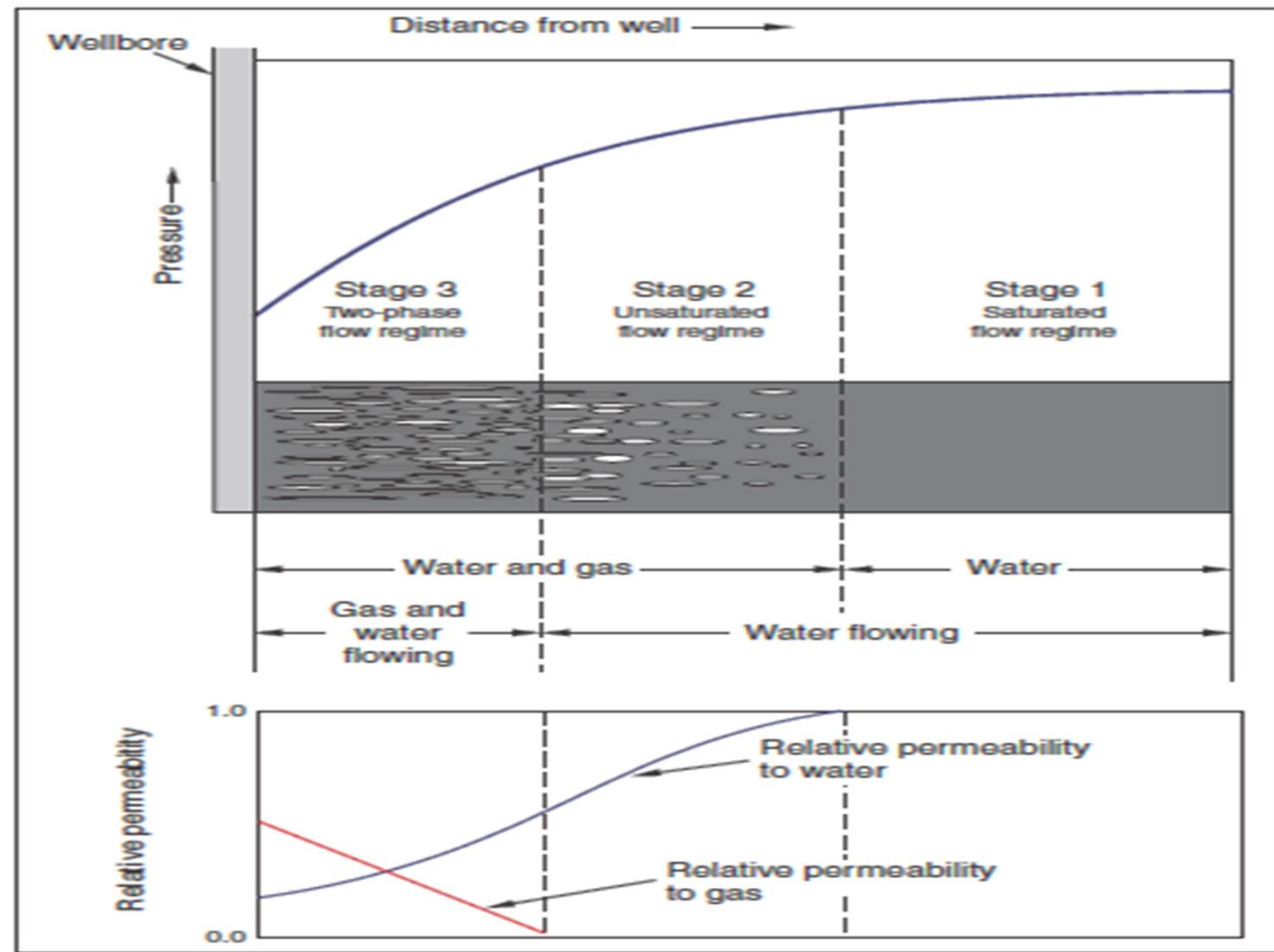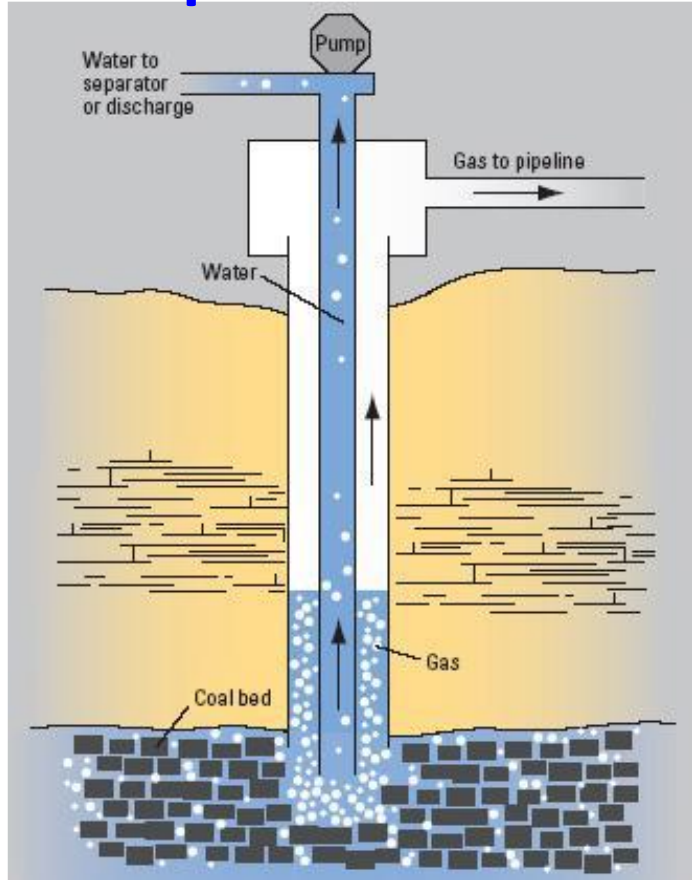# CBM production process

DR PATITAPABAN SAHU
ASSOCIATE PROFESSOR
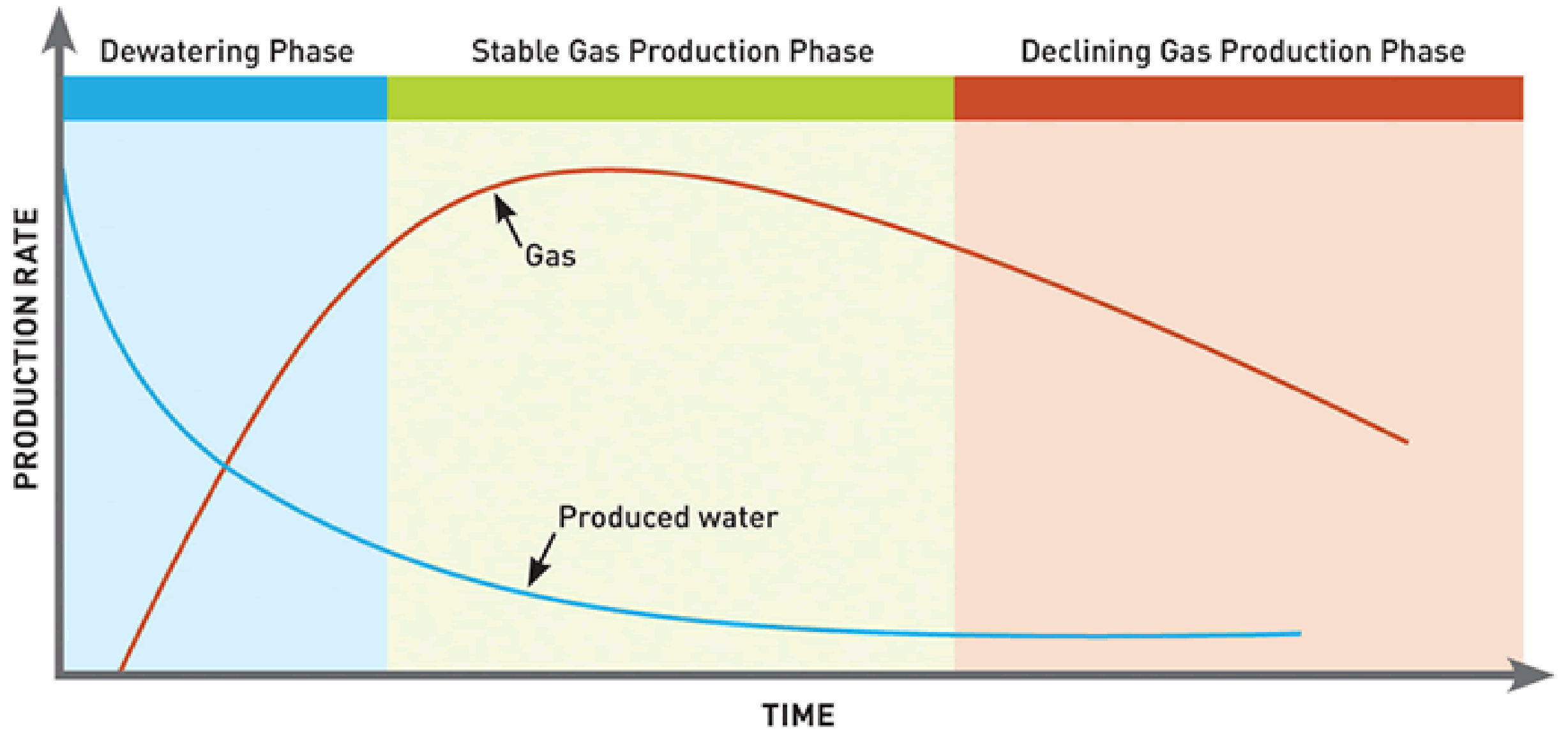**DEPARTMENT OF MINING ENGINEERING**

CBM production phase

- CBM wells are completed in several ways, depending upon the type of coal in the basin and fluid content. Each type of coal (sub-bituminous to bituminous) offers production options that are different due to the inherent natural fracturing and competency of the coal seams.
- The sub-bituminous coals are softer and less competent than the higher rank low-volatile bituminous coals, and therefore are typically completed and produced using more conventional vertical well bores.
- The more competent higher rank coals lend themselves to completions using horizontal as well as vertical well bores.
- Coalbed methane production passes through three phases during the life-time of the reservoir.

✓ Phase I: Dewatering phase
✓ Phase II: Stable production phase
✓ Phase III: Declining phase

Gas production well

The flow of fluids through the cleats is by Darcy's law. When the well is first drilled, water may fully occupy the cleat space. In terms of the Langmuir isotherm, the seams may be undersaturated with respect to gas, and some water must be removed to lower the pressure and initiate desorption. As water is produced with time, a two-phase flow regime near the wellbore is established as shown in Figure. It is an important occurrence that gas relative permeability improves greatly and rapidly as the water saturation decreases. Finally, a flow regime is reached where the gas moves through the cleats accompanied by only small amounts of water

Gas production phases

Dewatering phase

During this phase CBM wells experiment a constant water production with a very low or negligible gas production. Initially, most CBM wells are naturally water saturated because water liberation occurs during the coalification process. The water is occupying the principal cleat network and there is the need of removing the water from the major fractures system in order to produce gas. The number of days of this dewatering process and the amount of produced water can vary widely. Their impact deals with the economics of gas production. In this sense, they are very difficult to estimate and their influence in the economics is very hard to predict. However, it seems that they are controlled by the physical properties of the coal. The major physical properties that affect the efficiency of the dewatering process are:

✓ Permeability,
✓ Adsorbed gas content
✓ Relative permeability

Stable production phase

Phase II is described by a dramatically decrease in the water production and increase of the gas production rate. The water relative permeability decrease and the gas relative permeability increase. The gas production has stabilized and starts to experiment a typical decline trend. The gas production behavior in this stage is dominated by diffusion.

Declining phase

During phase III, the well is considered to be dewatered, so the water production is low-level or negligible. The water and gas relative permeability do not change extensively. The steady-state exists for the rest of producing life. The limit between phase II and III is determined by the peak gas rate is reached.

CBM production control

It depends on the following factors:-
- **Total gas-in-place in coal reservoir**
- **Methane sorption capacity of coal**
- **Diffusion in coal**
- **Permeability of coal**

Total gas in place

- The vast majority of the gas in CBM reservoirs is stored in the coal matrix by sorption. The following equation is generally used to estimate the total initial adsorbed gas in a CBM reservoir:

$$G = 1359.7\ Ah\ \rho_c\ G_c$$

Where:

G = Gas-in-Place, scf

A= Reservoir Area, acres

h= Thickness, feet

ρ_c= Average In-Situ Coal Density, g/cm3

G_c = Average In-Situ Gas Content, scf/ton

So Gas-in-place depends on following factors:

As it can be seen from above formula, average in-situ gas content, coal thickness, reservoir or well drainage area, and average in-situ coal density are the parameters that are needed for estimating gas-in-place in a CBM reservoir. These parameters are discussed below:

Reservoir Area

- The reservoir area is usually estimated based on the well spacing if the coal seam can be assumed to be laterally continuous. Structural and stratigraphic variations throughout the reservoir determine the three dimensional distribution of the coal. Therefore, geological evaluations can provide clues about coal seam continuity and its other pertinent characteristics. However, it may be difficult to identify localized stratigraphic variations. Three dimensional seismic data can be also used to determine coalbed methane reservoir geometry.

In-Situ Density

- The correct in-situ density should be estimated from open-hole density log data. A common practice of using a value of 1.32 to 1.36 g/cm3 for the average in-situ density can lead to erroneous results. In the absence of well log data, in-situ density can be estimated based on the density of the ash, moisture, and organic (pure coal) fractions.

Reservoir Thickness

- Gross coal thickness usually can be determined accurately with wireline logs. Open-hole density logs generally provide the most reliable and cost-effective estimates of gross thickness in newly drilled wells. The gross reservoir thickness is commonly computed by summing the thicknesses of the intervals having densities less than a cut-off value generally equal to the coal ash density. However, using a too low value for density cut off can lead to erroneous estimates. Determining net thickness is more complicated because it requires evaluating how much of the gross coal thickness actually contributes to production. Resistivity logs, well tests, production logs, or zonal isolation tests can be used to estimate the net thickness.

WIRELINE LOG

- Wireline logs are defined as measurements of one or more physical properties of rocks as a function of depths.

- A wireline is a metal cable that holds electrical conductors, which power downhole instruments or tools and transmit signals from the tools to the surface to be recorded by logs as a function of lithology and depth.

- The basic or traditional tools required to measure properties of coal reservoirs and associated rocks as well as best suited for coalbed gas evaluation include the following: 1) resistivity log, 2) gamma ray log, 3) density log, 4) acoustic (sonic) log, and 5) neutron log.

- Fundamentally, wireline logs are used to identify the thickness, continuity, and stratigraphic correlations of coal beds for coal resource assessment.

- Coal logs can be run in both open and cased holes filled with either liquid or air. More than a dozen wireline tools show response in coals, with the most useful logs for coal gas reservoir engineering being bulk density, gamma ray, and caliper logs.

- Identification of coal reservoirs with wireline logs is somewhat dependent on local coal properties, but for reservoir engineering purposes, coals generally exhibit densities less than 2.0 g/cm^3, and a gamma ray response of less than 70 API units measured in an in-gauge hole.

- Additional logs sometimes run in coals include compensated neutron porosity, spectral density (photoelectric), sonic, spontaneous potential (SP), desorption pressure, resistivity, microlog, laterolog, formation imaging logs, carbon/oxygen, cement, and production logs.

API- American Petroleum Institute

Typical log responses in a coal, along with reservoir engineering information derived from a particular log, are listed in the Table

<div align="center">**Table** - Wireline log responses in coals</div>

Log	Purpose	Open/cased hole	Mud/air	Response	Units
Bulk density	Coal identification Net thickness Coal density Proximate analysis Mechanical properties	o	m/a	0.70-1.80	g/cm^3
Gamma ray	Coal identification Proximate analysis Mineralogy	o/c	m/a	20-25	API
Caliper	Hole size washouts	o	m/a	varies	Inches, cm
Compensated neutron	Coal identification Proximate analysis Gas content	o/c	m	>50	---
Spectral density (photoelectric)	Lithology Same as bulk density	o	m/a	0.18	---

API- American Petroleum Institute

Log	Purpose	Open/cased hole	Mud/air	Response	Units
Sonic	Coal identification Coal rank	o	m	95-135	μsec/ft
Spontaneous potential (SP)	none	o	m	varies	mv
Desorption pressure	Desorption pressure	o	water	varies	psi, MPa
Resistivity	Coal identification	o	m	50-2,000	ohm-m
Microlog	Permeability Cleating	o	m	Varies Varies	ohm-m ohm-m
Laterolog	Permeability Cleating	o	m	Varies Varies	ohm-m ohm-m
FMS (Formation Micro Scanner)	Cleat development	o	m	Varies	---
FMI (Fullbore formation Micro Imager)	Cleat development Cleat orientation	o	m	Varies Varies	---

Log	Purpose	Open/cased hole	Mud/air	Response	Units
Carbon/oxygen	Coal identification Coal density	o/c	m/a	varies	---
Cement	Cement integrity	c	m	varies	---

API- American Petroleum Institute

Logs to determine specific reservoir properties are shown in following Table.

Table - Wireline logs for measuring specific reservoir properties

Property	Wireline log
Coal identification	Bulk density Spectral density Gamma ray Caliper Carbon/oxygen Sonic Compensated neutron Resistivity
Net thickness	Bulk density Spectral density Compensated neutron
Coal density	Bulk density Spectral density Carbon/oxygen
Proximate analysis	Bulk density Spectral density Gamma ray Compensated neutron

Property	Wireline log
Coal rank	Sonic Compensated neutron
Mechanical properties	Bulk density Spectral density
Permeability	Microlog FMS (Formation Micro Scanner) FMI (Fullbore formation Micro Imager)
Gas content	Density Gamma ray Compensated neutron

Coal Identification

- The gross thickness of a particular coal seam is determined by following these general wireline log measurement cut offs:

1. Bulk-density measurements less than 2 g/cc.

2. Gamma ray measurements less than 60 API.

3. Neutron porosity measurements greater than 50%.

4. Sonic transit time greater than 80 μs/ft.

5. Shear transit time greater than 180 μs/ft.

6. Resistivity greater than 50 $\Omega m^2/m$.

All of the preceding cut offs must to be determined locally. The condition of the borehole in which the wireline log was recorded must be considered when using wireline logs for the identification of coal.

Coal Tonnage

- A convenient measure to assess analog CBM projects compares coal tonnage per acre. Since no two CBM fields are identical, there is no reason for two CBM fields with similar coal tonnage per acre to be identical. However, coal tonnage per acre gives a starting place with stimulation treatment design. Determining coal tonnage in the project area is the first step to quantify the available resource. Coal tonnage is calculated using

$$CTpA = 1359.7 * h * RHOB$$

where

CTpA = coal tonnage per acre

h = coal thickness, feet

RHOB = minimum bulk density in the coal, g/cc

Resistivity log

- The resistivity log is acquired by measurements of the resistance of the coal and associated rocks to flow of electrical currents and by inducing currents into the reservoir rock.

- Consequently, various combinations of electric and induction resistivity logs are deployed depending on the borehole diameter, drilling fluid, and salinity of the fluid. Thus, resistivity logs involve fluids to measure the resistance of the rocks surrounding the borehole. The resistivity is expressed in a 'resistivity profile' or variation into the coal reservoir from the borehole.

- The high moisture of coal beds (e.g. lignites and subbituminous coal) account for the high-resistivity deflections on the resistivity profiles.

- Limestones and sandstones such as in the Powder River Basin show high-resistance deflections and could be mistaken for coals.

Gamma Ray Log

- The gamma ray log measures the natural gamma radiation emitted by the coal and associated rocks.

- Gamma ray logs mainly differentiate the reservoir rock for shales, which have high natural gamma ray radiation.

- Characteristically, gamma ray logs are adaptable for use in coal-bearing rocks for the following reasons:

1) They do not require fluids such that shales with relatively low or no permeability with no or minor fluids are amenable for gamma ray measurements,

2) They are not sensitive to variations of borehole diameter,

3) They can be used to measure through casing,

4) They can be the least expensive logs to run.

- This is in contrast to resistivity logs, which require the presence of fluid for determining the resistivity of the rocks.

Density log

- The density log measures the bulk density of the coal reservoir and associated rocks.

- The density tool or gamma density tool utilizes a gamma ray source placed a distance from the gamma ray detector, which measures gamma ray count that is an inverse function of the density of the coal or associated rocks.

- The more gamma rays that are absorbed in denser rocks, the lesser is the ray count transmitted to the detector.

- The majority of coal ranks have low density (e.g. 0.7 – 1.8 g/cc) compared to adjoining lithologies, which make it a valuable tool to identify coal beds.

- The traditional use of density log is to measure the porosity of the reservoir. That is, if the matrix density is constant, the density of the coal and associated rocks is an inverse function of the porosity.

- In addition, the density log may provide information on the rank of the coal, that is, high-rank coal is denser than low-rank coal.

- The advantage of a density log is that it can detect coal partings much like the gamma ray log and thin coal beds.

- Unlike the gamma ray log, a density log must be run without the casing and varies with the borehole diameter.

Acoustic (Sonic) Log

- Acoustic (sonic) logs can be used to measure travel time (amplitude of the wave) of a sound wave emitted from a logging tool and transmitted to a receiver tool.

- The velocity of the acoustic or sonic wave is controlled by the lithology and porosity of the coal and associated rocks.

- The main purpose of the acoustic or sonic log is to measure the porosity of the reservoir and associated rocks, which is calculated based on the linear relationship between effective (e.g. non-fracture) porosity and travel time in clay-free reservoir.

- The decrease in velocity or increase in transit time is interpreted to be an increase in porosity.

- The short travel time of sonic waves in coal indicates high-rank coal. However, this technology is of less value than in oil and gas reservoir because in coal reservoir the gas is stored in the pore systems (e.g. micro-, meso-, and macro-pores).

- Acoustic or sonic logs are of better value in detecting coals in deeper- than – unconsolidated shallower coal-bearing rocks. A few acoustic or sonic tools measure the diameter, condition, stability of the borehole.

Neutron Log

- Neutron logs measure the hydrogen ion concentration of the reservoir and associated rocks. As with the acoustic tool, the neutron tool uses a source and a detector.

- Neutron log is of value in identifying coals because the tool measures high porosity due to the high hydrogen composition of the coal.

Caliper Logs

- The caliper log is a mechanical device that measures the diameter of a borehole along its depth using acoustic or sonic devices.

Gas Content

- The volume of gas contained in coal at standard temperature and pressure (STP) is termed the gas content of the coal and is expressed in Standard Cubic Feet per ton (SCF/ton).
- Gas content is the standard volume of gas per unit weight of coal or rock and usually is reported in units of standard cubic feet per ton (scf/ton). The desorbed gas is estimated by the "Direct Method" or canister desorption test.
- Gas content measurement methods are classified as (1) conventional and (2) pressurized desorption techniques. In the conventional technique, coal cores or drill cuttings are retrieved from the core holes and immediately put in a sealed container to measure the desorbed gas. This method suffers from uncertainty in the estimate of gas lost during sample retrieval and handling. To eliminate this problem, the pressurized core desorption technique has been developed. In this technique, gas loss is minimized by sealing the coal samples while they are in the core hole.

The direct method of gas content measurement: This technique was originally Bertard et al. (1970) and Kissell (1973). It was further improved by Diamond and Schatzel (1998) and it became the "ASTM standard practice for determination of gas content of coal". In this technique, the desorbed gas from the coal sample is measured first. Next, the cumulative gas production is plotted against the square root of time to determine the lost gas. Finally, a small, weighted portion of coal sample is crushed in a hermetically sealed mill to get the residual gas.

Desorbed Gas: After coal cores or drill cuttings are put in a hermetically sealed container, called a desorption canister, the desorbed gas is measured periodically. In the first few days, readings may be taken every hour, but later a measurement once a day is sufficient.

Lost gas: The fraction of the total gas content is the gas that escapes from the sample during its collection and retrieval, prior to being sealed in an airtight canister. It is estimated indirectly.

Residual gas: Even when the coal sample in the desorption container has stopped producing gas, a significant volume of gas is still left in the sample. It can only be retrieved and measured by crushing the sample to very fine sizes.
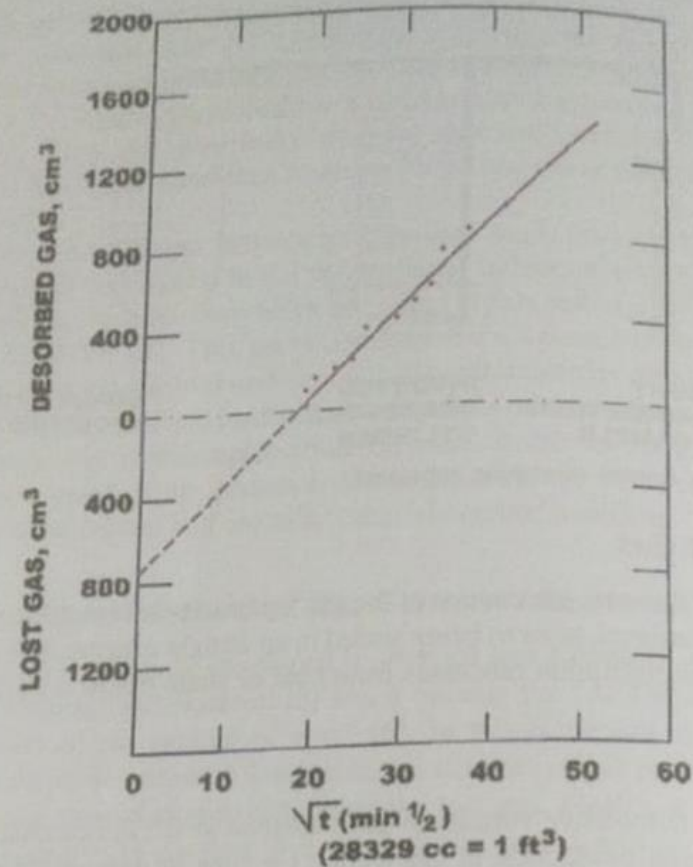
14.1.3 Lost Gas

This portion of the total gas content is the gas that escapes from the sample during its collection and retrieval, prior to being sealed in an airtight canister. It is estimated indirectly. Most gas desorption processes from coal or shale follow a power law [8,9].

$$Q = At^n \qquad (14.1)$$

where Q is the cumulative volume of gas desorbed in ft^3; A is a characteristic of the coal (equals initial production in gas wells); t is time in days or minutes; and n is a characteristic of the coal or shale.

Eq. (14.1) can be expressed in its logarithmic form as

$$\ln Q = \ln A + n \ln t \qquad (14.2)$$

The value of "n" for most coal is 0.8–1.00. Hence, a plot of ln Q against ln t yields a straight line. The intercept on the "y" axis is equal to ln A.

In a simplified version of Eq. (14.1), (refer to Equation (14.16))

$$Q = B t^{\frac{1}{2}} \qquad (14.3)$$

Hence, a plot of cumulative desorbed gas, Q, against $(t)^{0.5}$ yields a straight line. Here, B is the intercept on the y axis and is a measure of the lost gas as shown in Fig. 14.2.

14.1.4 Residual Gas

Even when the coal sample in the desorption container has stopped producing gas, a significant volume of gas is still left in the sample. It can only be retrieved and measured by crushing the sample to very fine sizes.

Figure 14.2 Lost gas estimation graph.

A hermetically sealed modified ball mill (Bleuler Mill) [10] is used for this purpose. A measured quantity of the coal core or drill cutting is put in the mill and crushed. The released gas is measured by the same setup that was used for desorbed gas measurements.

The total gas content of the coal sample is obtained by adding the three components, i.e., desorbed gas, lost gas, and residual gas. The coal sample is next weighed and sent to a laboratory for a proximate analysis which yields the moisture, ash, volatile matter, and fixed carbon contents of coal. The weight of coal is calculated on a dry, ash-free basis. The total gas content of the coal sample is divided by the weight of the coal sample (dry, ash-free) to get the final gas content of coal in ft^3/t (1 cm^3/gm = 32 ft^3/t).

Table 14.1 shows the gas content and gas composition data for some typical US coal seams.

Gas Volume Measurements

- The time-tested method for measuring the volume of gas released from a coal sample in the field is a volumetric technique whereby core or drill cuttings are sealed in a canister and the amount of gas released is measured over time.

- The gas-volume measurement apparatus is often referred to as a "Balanced Burette" system or manometer system.

The general layout of the experimental setup is shown in the figure. The desorption canister **is equipped with a pressure gauge and a valve to let the desorbed gas out. The desorbed gas is measured by water displacement in a graduated glass cylinde**r. **During a measurement, the reservoir is adjusted vertically to maintain the water level in the reservoir at the same height as that in the burette being used. This procedure ensures that the pressure of the gas in the burette is equal to the barometric pressure of the laboratory.**

By using a balanced-burette system, in conjunction with measurements of barometric pressure and burette temperature, high accuracy measurements of desorbed gas are obtained.

The glass cylinder is connected to a levelling water reservoir, and the gas volume measurement is taken when the water levels in the cylinder and levelling reservoir are the same. The precision of the measurement is about ± 4%.

The desorption process typically extends to 4-6 weeks. It is stopped when gas desorption is less than 10 cm³/day. The cumulative gas production is plotted on a graph paper against (time)$^{0.5}$ to determine the lost gas component of the total gas content.
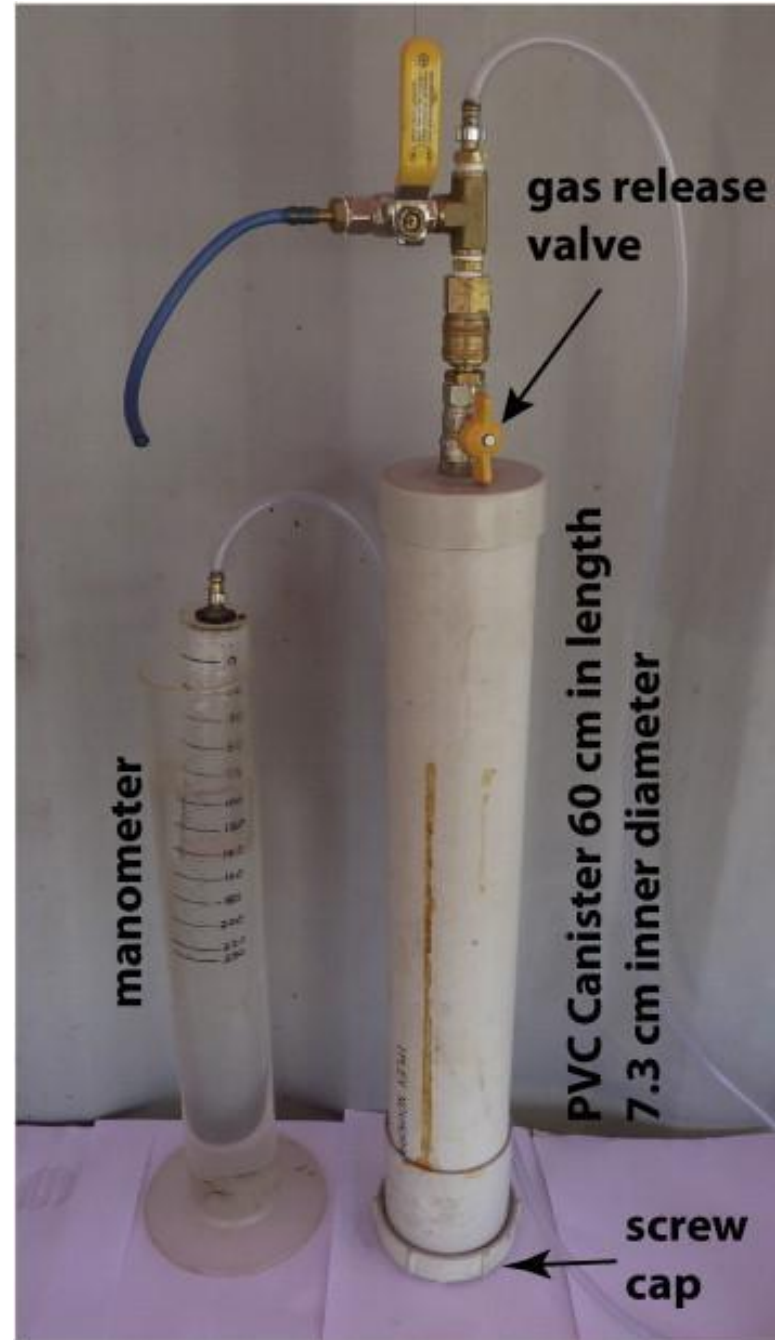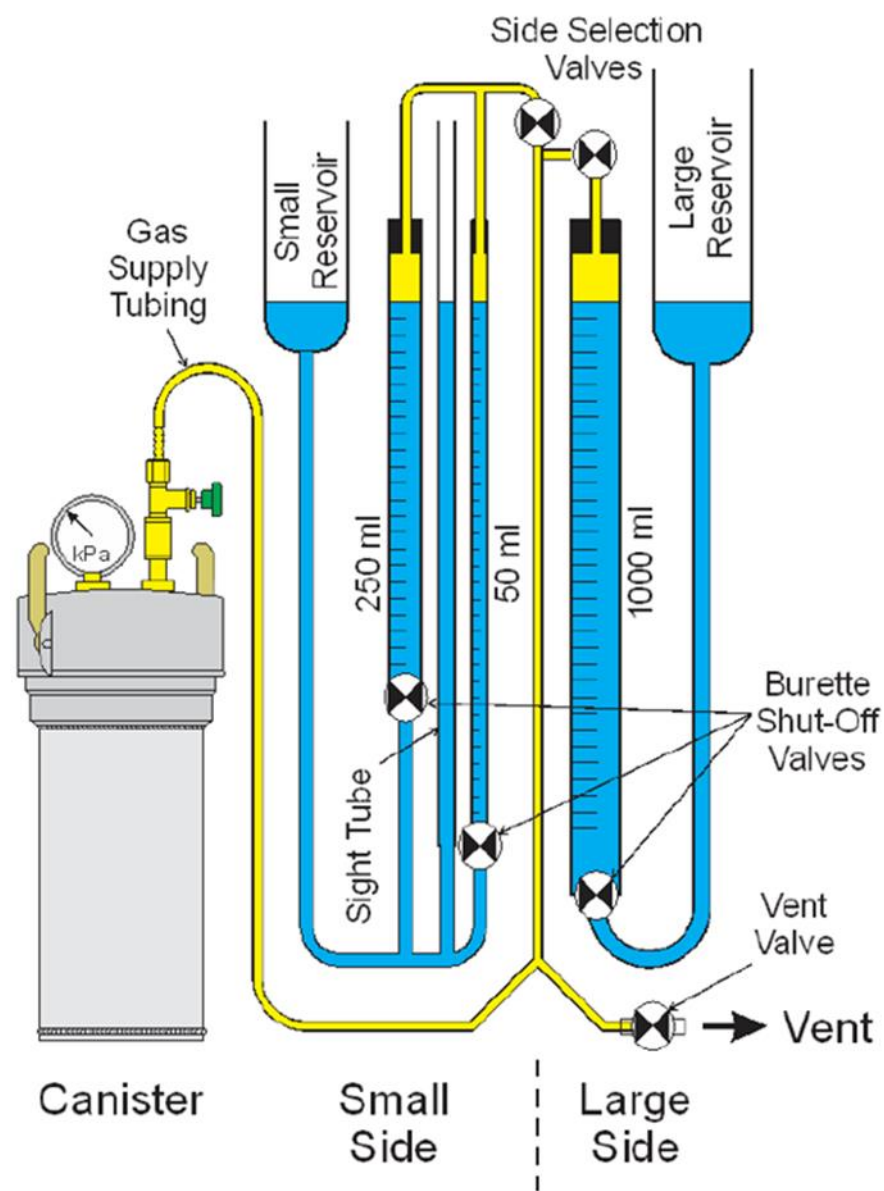
gas release valve

manometer

PVC Canister 60 cm in length
7.3 cm inner diameter

screw cap

Figure 9. Triple-Tube Layout Diagram

Figure 6

FRONT VIEW | SIDE VIEW

- Thermocouple
- Burette Clamp
- Reservoir
- 2-Arm Clamp
- 100 ml Burette
- Vent Valve
- Burette Clamp
- Burette Clamp
- Thermocouple Readout
- Barometer

Figure 5. Balanced-Burette Manometer Method

Gas Flow from Canister

Atmospheric Pressure Here when Fluid Level is Balanced

Atmospheric Pressure through Open Top of Reservoir

U-Tube Effect

Single Burette System:

A single burette system is the simplest setup to consider. The single burette is used for performing residual gas measurements or for long-term measurements when volumes are reduced. A photograph of the single burette system is shown as Figure 6
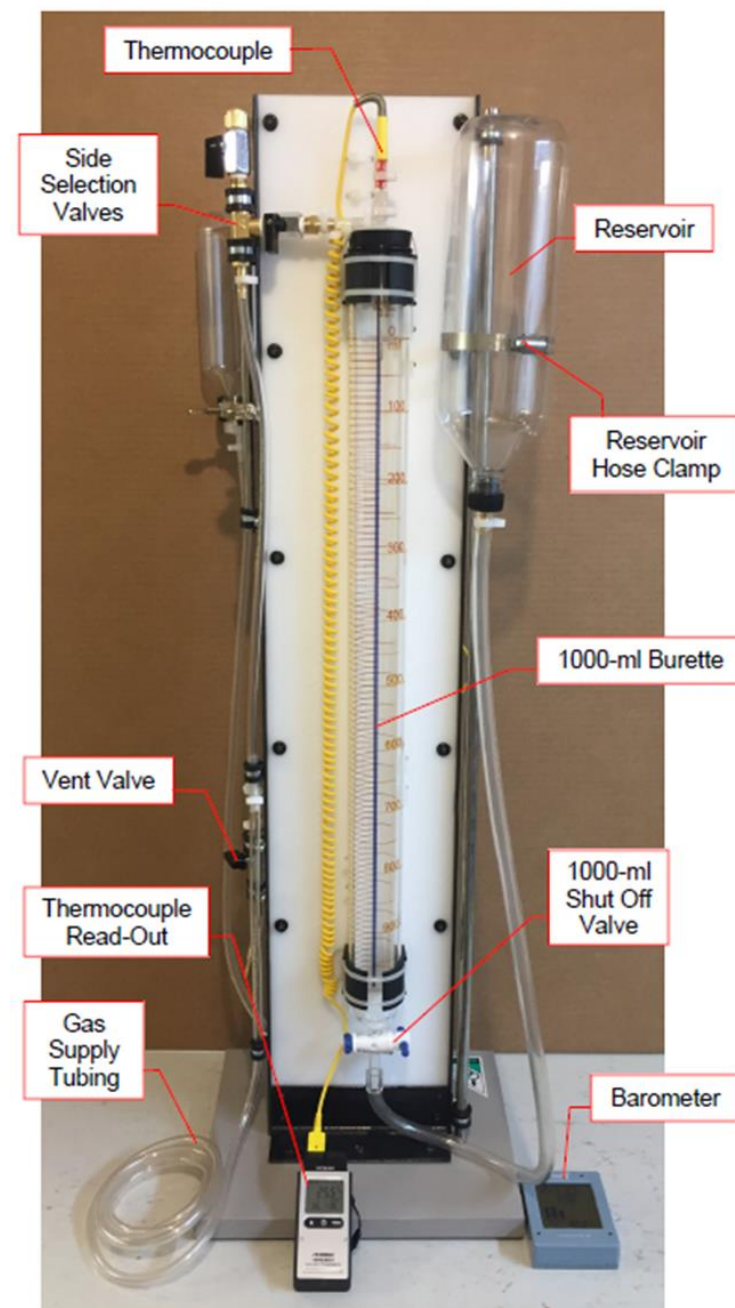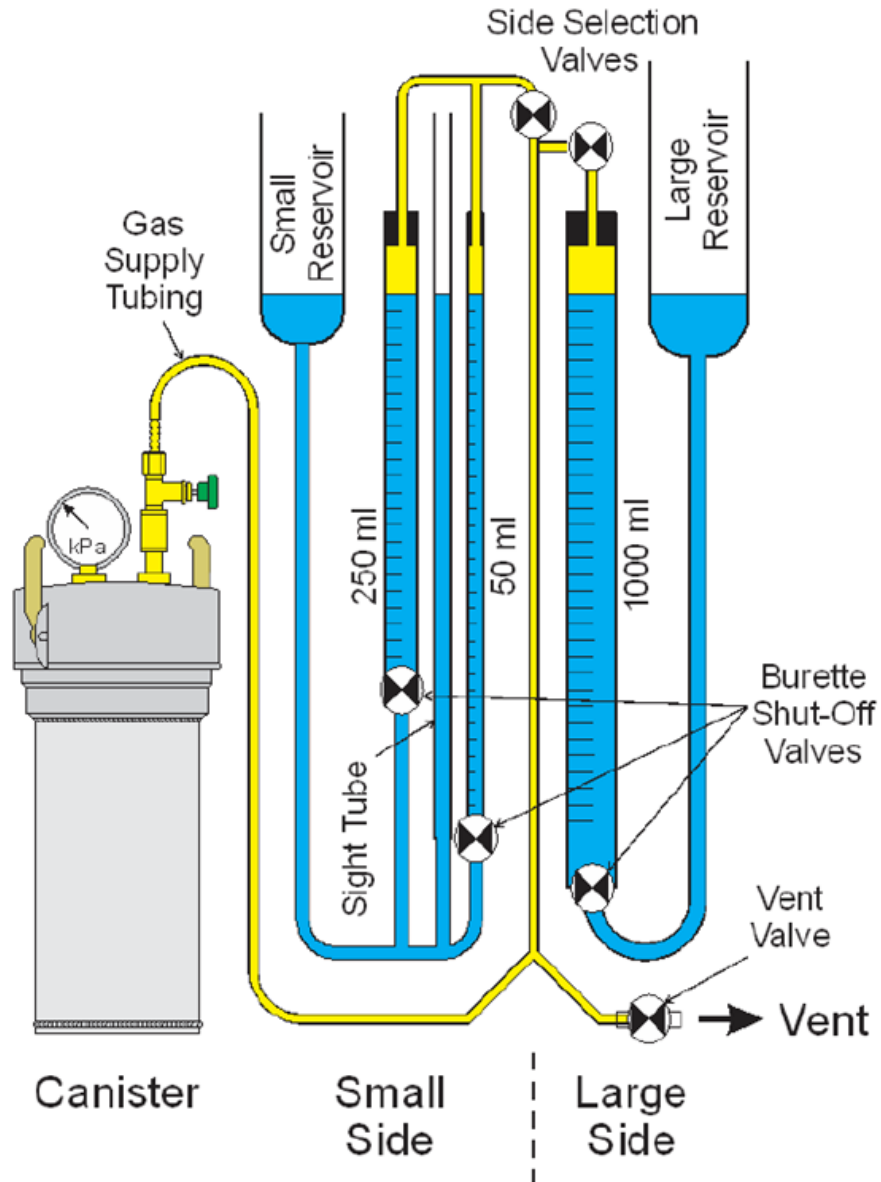
Triple-Tube Burette System:

- The Triple-Tube burette system combines three different burette sizes into one apparatus, and this allows the user to choose the optimal burette based on the anticipated volume to be measured. The Triple-Tube burette system is used for performing gas measurements in the field and laboratory for canister desorption. A photograph of the Triple-Tube burette system is shown as Figures 7 and 8 while Figure 9 shows a simplified diagram of the Triple-Tube layout.

Figure 7. Triple-Tube Burette System – Small Side

Thermocouple
Side Selection Valves
Reservoir
2-Arm Clamp
250-ml Burette
50-ml Burette
Sight Tube
250-ml Shut Off Valve
Vent Valve
Thermocouple Read-Out
50-ml Shut Off Valve
Gas Supply Tubing
Barometer

Figure 8. Triple-Tube Burette System – Large Side

Thermocouple
Side Selection Valves
Reservoir
Reservoir Hose Clamp
1000-ml Burette
Vent Valve
Thermocouple Read-Out
1000-ml Shut Off Valve
Gas Supply Tubing
Barometer

Figure 9. Triple-Tube Layout Diagram

Triple-Tube Burette System:

The Triple-Tube burette system combines three different burette sizes into one apparatus, and this allows the user to choose the optimal burette based on the anticipated volume to be measured. The Triple-Tube burette system is used for performing gas measurements in the field and laboratory for canister desorption. A photograph of the Triple-Tube burette system is shown as Figures 7 and 8 while Figure 9 shows a simplified diagram of the Triple-Tube layout.

Gas adsorption isotherm

- The adsorption isotherm expresses the relationship between the free phase gas pressure and the mass/volume of gas adsorbed into coal at a constant temperature (isothermal conditions).
- The quantity of gas adsorbed reduces with increase in temperature and increases with increase in pressure. The magnitude of adsorption depends upon the surface pore area of adsorbent (coal) and type of adsorbate (gas).
- Coal is porous and adsorbent rock has significant storage capacity for methane and carbon oxide gases. The gas adsorption storage capacity of coal is measured in terms of adsorption isotherm. The adsorption isotherm depends on coal rank, moisture content and isothermal temperature at which measurement is undertaken.
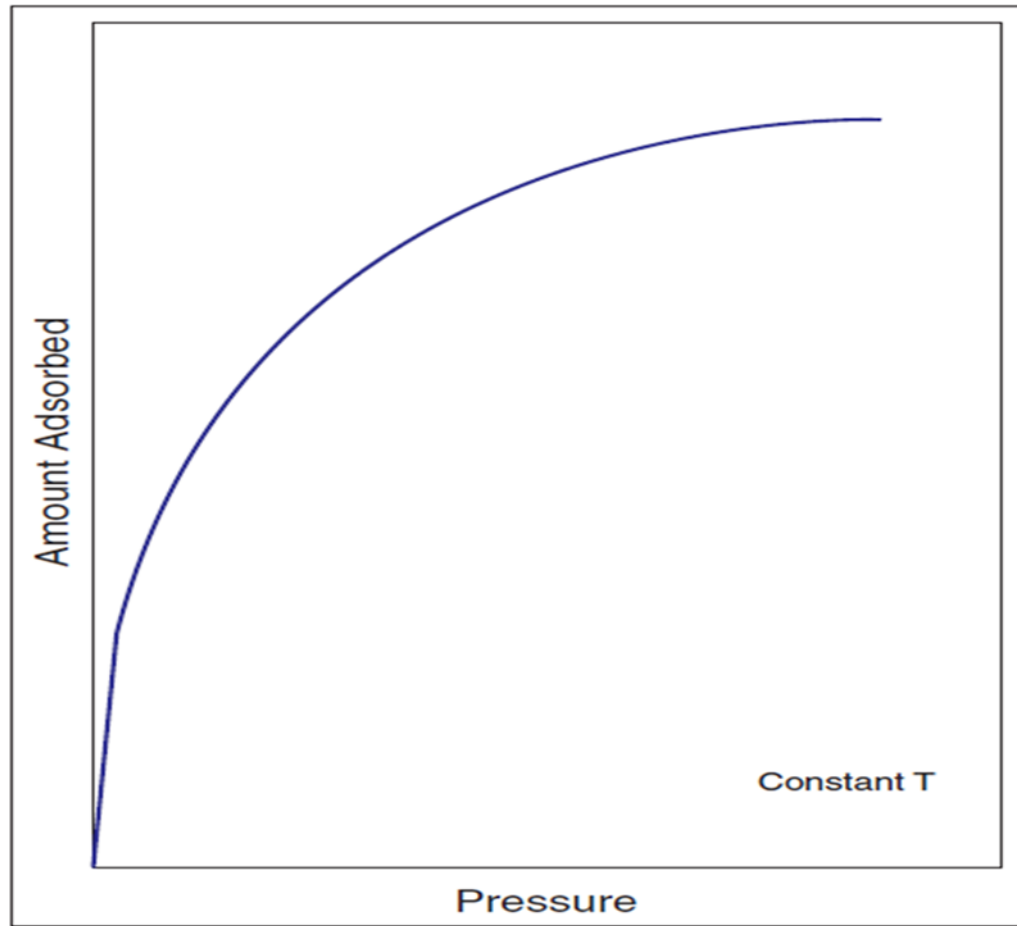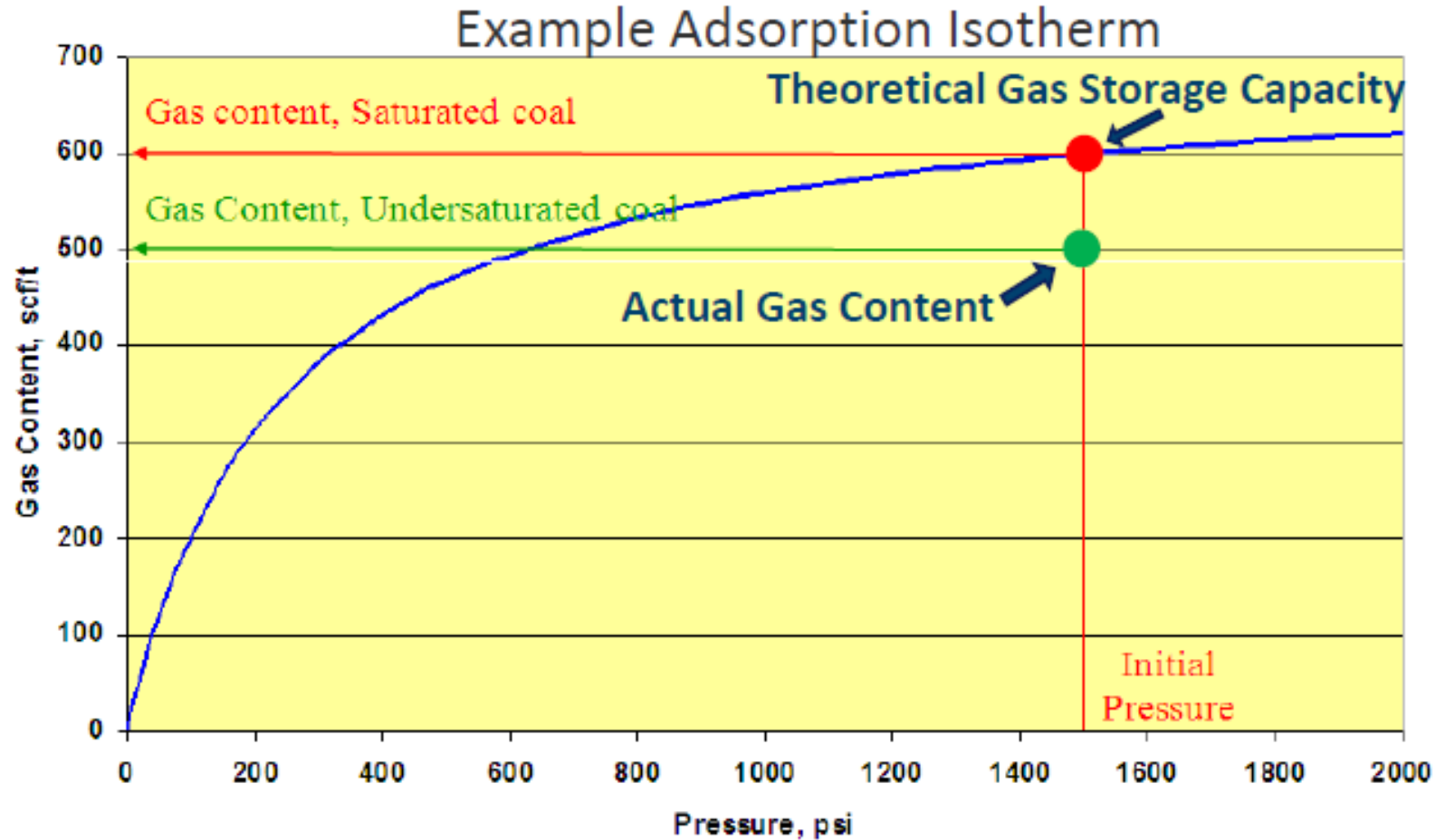
Figure: Type I isotherm of Brunauer

Gas **adsorption isotherms** describe the maximum amount of gas that can be stored in a coal at any pressure

According to Brunauer's classification, a Type I isotherm, as characterized by Figure, applies to the adsorption of gases in microporous solids.

At high pressures, the amount adsorbed becomes asymptotic with pressure. At higher temperatures, the amount adsorbed decreases.
Type I isotherms closely describe the adsorption/desorption behaviour of methane on coals.
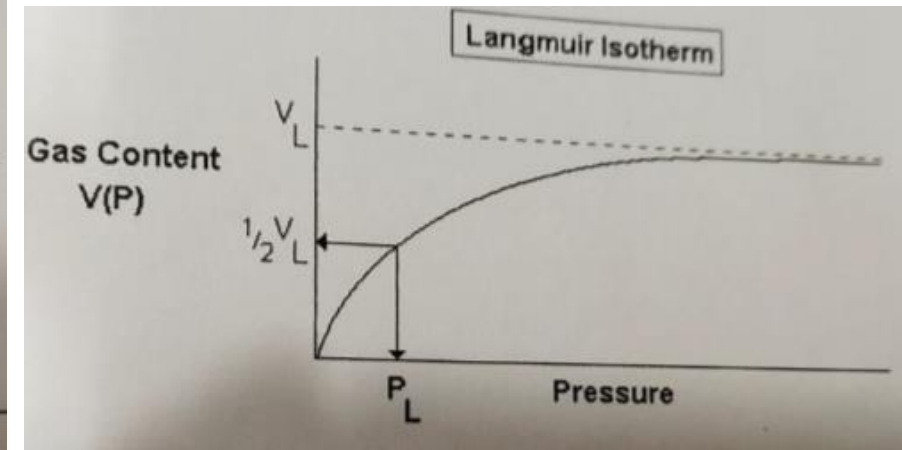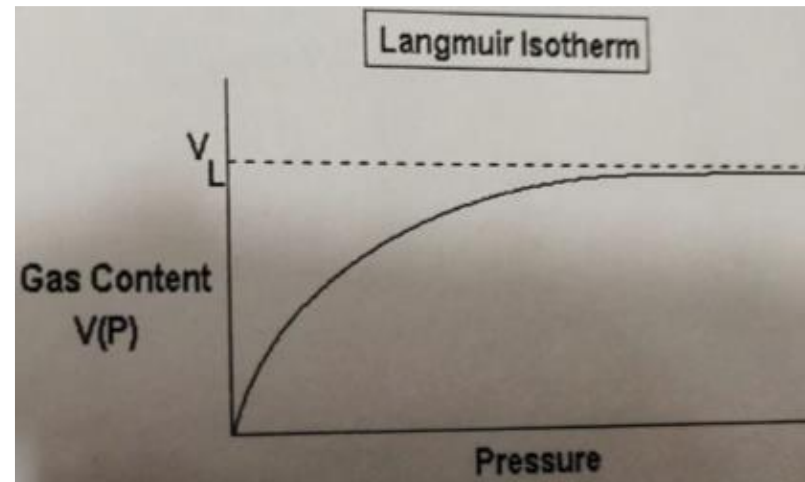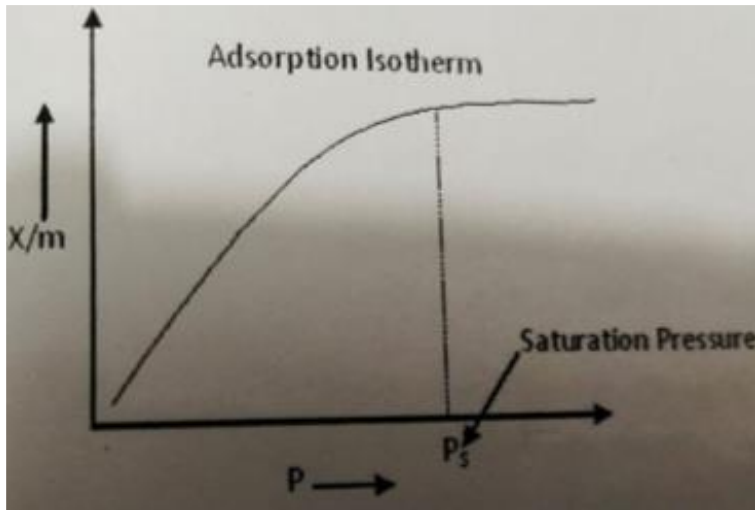
Gas Saturation

Example Adsorption Isotherm

- The ratio between the theoretical storage capacity and the actual gas content is termed the **gas saturation.**

- A coal is said to be **undersaturated** when the gas content is lower than the theoretical storage capacity

- Under-saturated coal may require significant depressurisation before gas is produced

Langmuir isotherm

- Whenever a gas is in contact with a solid, there will be an equilibrium established between the molecules in the gas phase and the corresponding adsorbed species (molecules or atoms) which are bound to the surface of the solid. The adsorption isotherm expresses the relationship between the mass/volume of gas adsorbed and free gas pressure.

- The Langmuir isotherm was developed by Irving Langmuir in 1916 to describe the dependence of the surface coverage of an adsorbed gas on the pressure of the gas above the surface at a fixed temperature. The Langmuir isotherm is one of the simplest, it still provides a useful insight into the pressure dependence of the extent of surface adsorption.

- The Langmuir equation fits the adsorption data of methane on coal and is used exclusively in the CBM process to describe the Type I curves.

Adsorption process is usually studied through graphs known as adsorption isotherm. Adsorption isotherm is the amount of adsorbate on the adsorbent as function of its pressure or concentration at constant temperature. The quantity adsorbed is always normalized by the mass of the adsorbent to allow comparison of different materials. The Langmuir adsorption model explains adsorption by assuming an adsorbate behaves as an ideal gas at isothermal conditions. The typical formulation of Langmuir isotherm is:
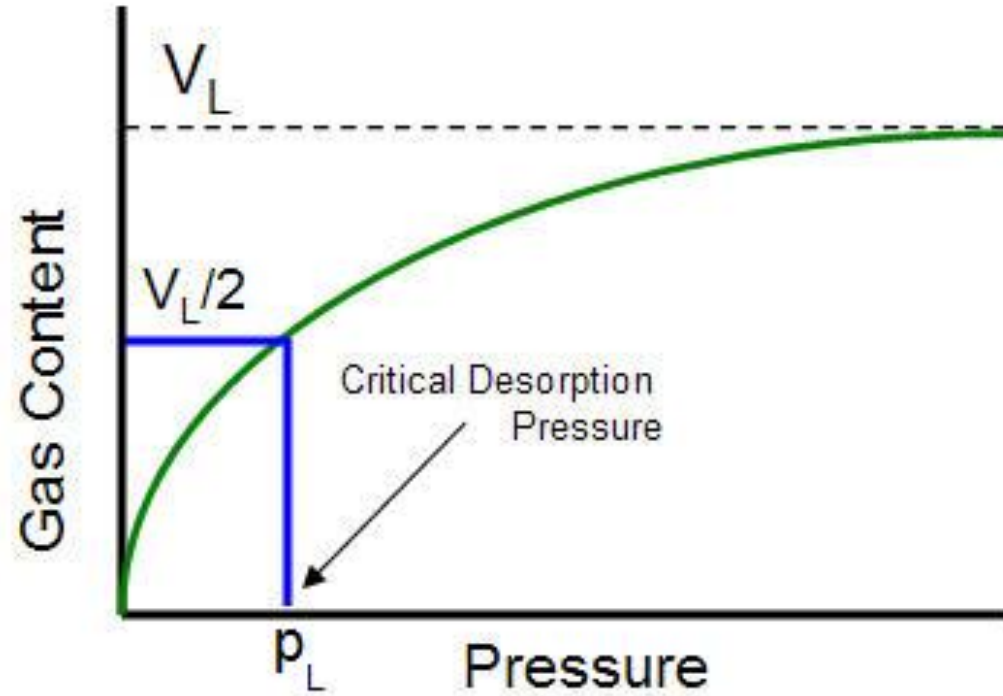
$$V(P) = \frac{V_L P}{P_L + P}$$

Where P is pressure (psia), V(P) is amount of gas at P, also known as gas content (scf/ton), V_L is Langmuir volume parameter (scf/ton) and P_L is Langmuir pressure parameter (psia).

The Langmuir isotherm equation has two parameters:

- Langmuir Volume (V_L): This is the maximum amount of gas that can be adsorbed on a piece of coal at infinite pressure. The following image is of a typical isotherm and shows its relationship with V_L:

  Typically, the units for the Langmuir volume parameter (V_L) are scf/ton (volume gas per mass of unit coal). The volume parameter can be converted to a scf/ft^3 (volume gas per volume unit coal) by multiplying it by the coal bulk density.

- Langmuir Pressure (P_L): This parameter affects the shape of the isotherm. The Langmuir pressure is the pressure at which half of the total gas is desorbed from the coal.

The Langmuir pressure is the pressure at which one half of the Langmuir volume can be adsorbed. As seen in the figure below, it changes the curvature of the line and thus affects the shape of the isotherm.

14.1.5 Gas Isotherms and Indirect Methods of Gas Content Determination

At constant temperature, each coal seam shows a measurable relationship between the total gas adsorbed (or desorbed) and the confining pressure. Fig. 14.3 shows typical gas isotherms for five US coal seams.
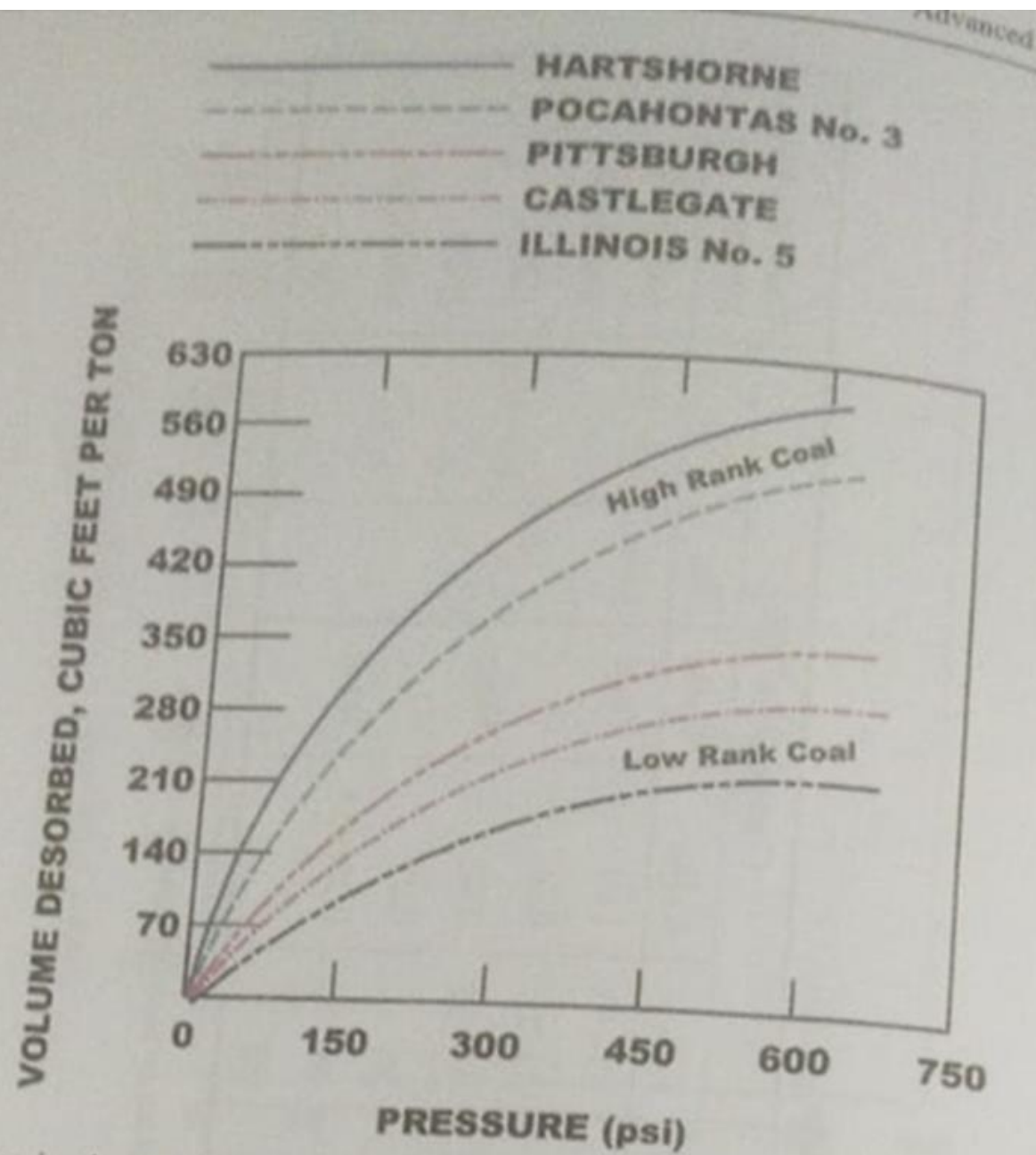
Figure 14.3 Gas isotherms for US coal seams.

Table 14.1 Coalbed Methane Content and Composition of US Coal Seams

Coal Seam	Rank	Gas Content (ft³/t)	Composition[a] (%)					Calorific Value BTU/ft³
			CH₄	C₂H₆	C₃H₈	H₂	CO₂	
Pocahontas #3 (VA)	LV	450–650	97–98	1–2	Trace	0.02	0.2–0.5	949–1058
Hartshorne (OK)	LV	200–500	99.20	0.01	—	—	—	900–1058
Kittanning (PA)	LV	200–300	95–98	0.02	Trace	—	0.1–0.2	1020
Mary Lee (AL)	LV	200–500	96	0.01	—	—	—	1024
Pittsburgh #8 (WV)	HVA	100–250	89–95	0.25–0.5	Trace	—	2–11	949–1000
Mesaverde Formation (NM)	Sub bituminous	100–300	88	—	—	—	12	938

The composition numbers are given on a volume percent basis. The balance is N₂ and minor amounts of other gases.

[a] N₂, LV - Low Volume, HVA - High Volume Anthracite, and argon contents are not listed but are needed to make the total 100%.

It is to be noted that high-rank (low-volatile bituminous) coals contain more gas than the low-rank (high-volatile bituminous) coals (HVA, HVB, HVC) at the same confining pressure. It is also clear that the sorption capacity of all coal increases with pressure, but the increase occurs at an ever-decreasing rate as the sorption capacity reaches an asymptotic limit—the saturation limit.

A mathematical representation for these isotherms was given by Langmuir [11] and is expressed as

$$V = V_m \frac{bP}{1 + bP}$$

(14.4)

where V is the volume of gas contained at pressure P, ft^3/t; V_m is the maximum sorption capacity of coal, ft^3/t; P is the pressure, psi; and b is the Langmuir constant, $psi.^{-1}$

For indirect determination of the gas content of coal at a given pressure, Eq. (14.4) can be rewritten as

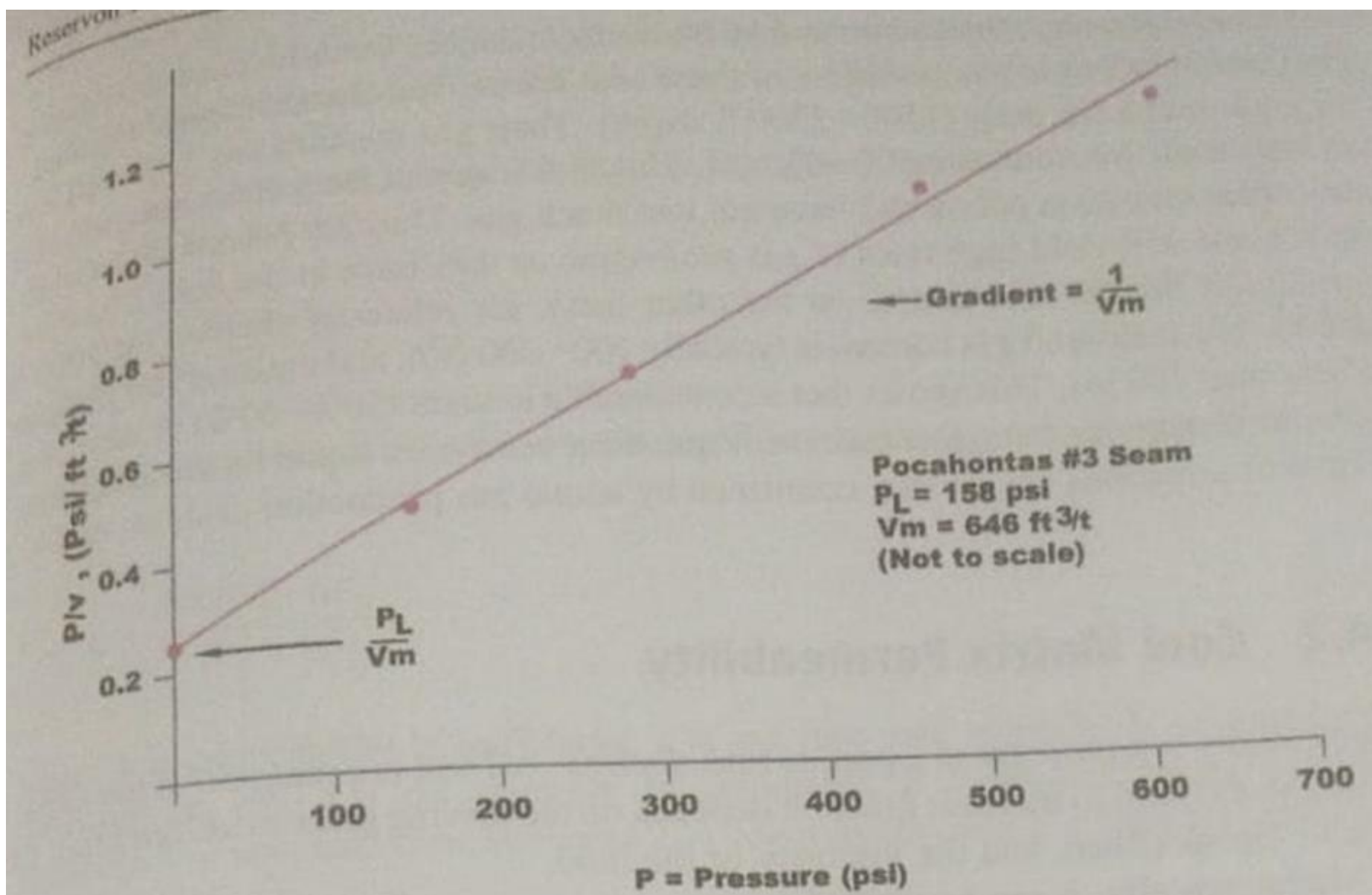$$\frac{P}{V} = \frac{P}{V_m} + \frac{1}{b V_m}$$

Figure 14.4 A plot of P/V against P.

The term "b" is experimentally found to be equal to $1/P_L$, where P_L is the charac-
teristic pressure that corresponds with $V_m/2$ on the gas isotherm.

Thus, Eq. (14.5) can be written as

$$\frac{P}{V} = \frac{P_L}{V_m} + \frac{P}{V_m} \qquad (14.6)$$

If the isotherms shown in Fig. 14.3 are replotted with P/V on the y axis and P on the
x axis, a straight line is obtained. The plot for the Pocahontas #3 seam is shown in
Fig. 14.4. The slope of the line is $1/V_m$, from which V_m can be determined. The inter-
cept on y axis is P_L/V_m, from which P_L can be determined.

Calculated values of P_L and V_L for all gas isotherms shown in Fig. 14.3 are shown
in Table 14.2.

Table 14.2 Calculated V_L and P_L Values for US Coal Seams

Coal Seam	V_L (ft³/t)	P_L (psi)
Hartshorne	788	205
Pocahontas #3	646	158
Pittsburgh	443	170
Castlegate	409	229
Illinois #6	353	273

Some interesting conclusions can be drawn from data in Table 14.2 and the existing gas content and reservoir pressures of these coal seams. The Hartshorne and Pocahontas coal seams are deep (1500–2500 ft depth). Their gas contents are 550–650 ft^3/t and reservoir pressures are 500–650 psi. This indicates that these coal seams are still near their saturation points and have not lost much gas. They are potentially good reserves and will yield high rates of gas production as they have in the field. The Pittsburgh and Illinois coal seams, on the other hand, are relatively shallow (at 1000 ft depth). The measured gas content is typically 100–200 ft^3/t, and the reservoir pressure is less than 200 psi. This shows that a considerable amount (50%–60%) of their original gas content has been lost and, therefore, these reservoirs would be low producers. These observations are, in fact, confirmed by actual gas production data.

3.3. Coalbed methane production prediction using adsorption isotherm

CBM reservoir contains less amount of gas than its maximum adsorbed amount, therefore designated as under saturated. In
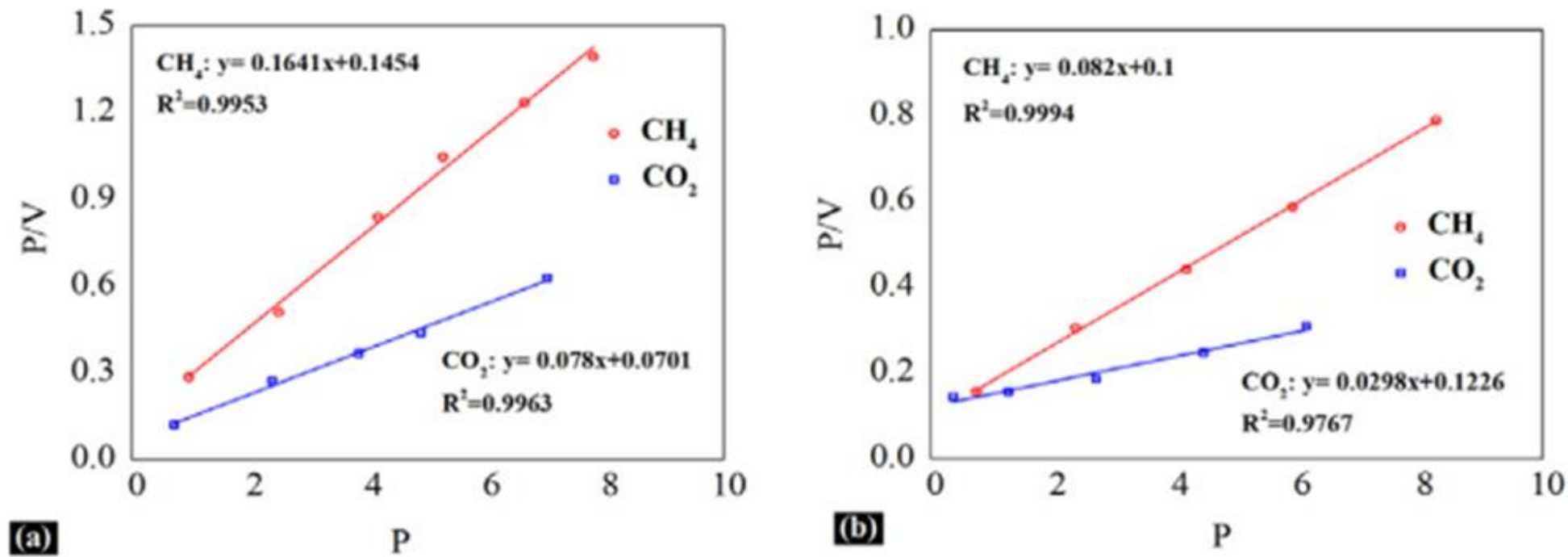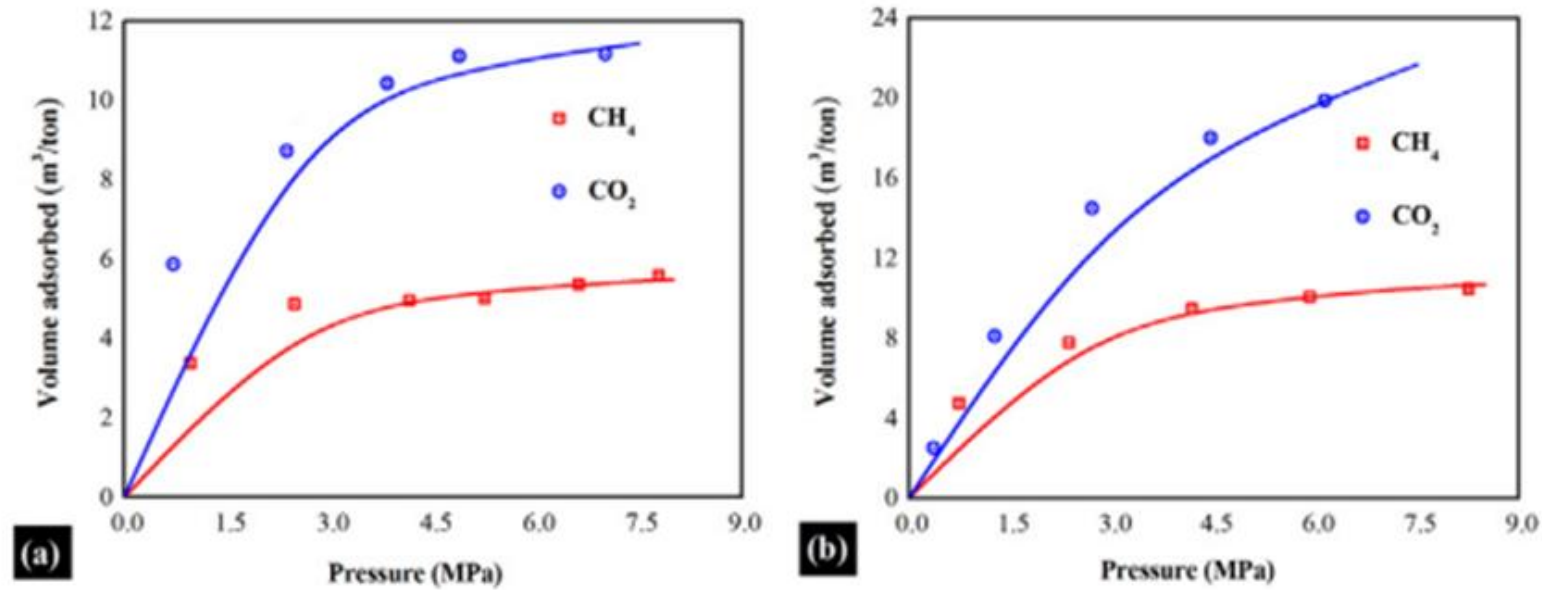

Fig. 4. Langmuir constants calculation: (a) J/01 (b) J/02.

Table 5
Langmuir constants for the samples.

Properties	J/01	J/02
CH_4-V_L (m^3/t)	6.09	12.19
CH_4-P_L (MPa)	0.89	1.22
CO_2-V_L (m^3/t)	12.80	33.52
CO_2-P_L (MPa)	0.90	4.11

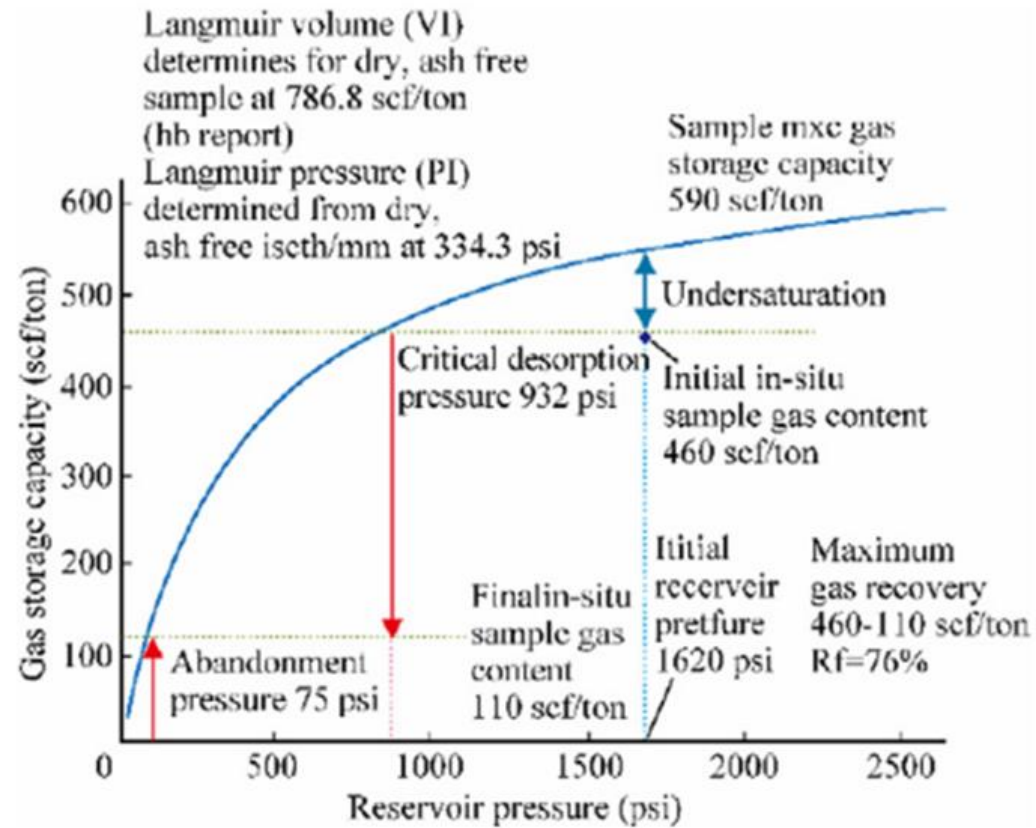**Fig. 5.** Adsorption isotherm of the samples (symbols) and their Langmuir fittings (line) (a) J/01 (b) J/02.

Fig. 6. Adsorption isotherm for the prediction of methane production recovery

- *Abandonment Pressure: The minimum pressure of the reservoir when the wells are abandonment*
- *Undersaturation = (1620 psi – 932 psi)/1620 psi = 0.43 or 43%*
- *Percentage recovery = (460 scf/ton -110 scf/ton)/460 scf/ton = 0.76 or 76%*

Fig. 6 describes the typical isotherm for the CH4 prediction. The measured gas content was 13.8 m3 /t (460 scf/t) at an initial reservoir pressure of 11.34 MPa (1620 psi). VL and PL values for this isotherm are 23.60 m3/t (786.8 scf/t) and 2.34 MPa (334.3 psi) respectively. Moving vertically upward it cuts the isotherm at 16.8 m3/t (590 scf/t), making this coal undersaturated by three m3 /t (16.8–13.8 = 3 m3/t). Subsequently, it cuts the isotherm at critical desorption pressure 6.52 MPa (932 psi) by moving horizontally to the left. Thus reservoir pressure would have to be reduced by 4.82 MPa (11.34–6.52 = 4.82 MPa) or (1620 psi – 932 psi = 688 psi). This coal is under saturated by 4.82 MPa or 3 m3 /t in gas. Relatively reservoir is undersaturated by 43% of initial reservoir pressure. It was found that percentage recovery was around 76% for this particular reservoir. The parameters of coalbed methane recovery were shown in Table 6.

Critical desorption pressure

It is two-phase flow during well testing in the exploitation period of coalbed methane wells. After water is drained from the coalbed methane wells and the pressure is reduced, methane begins to be desorbed and flow into the fissures.
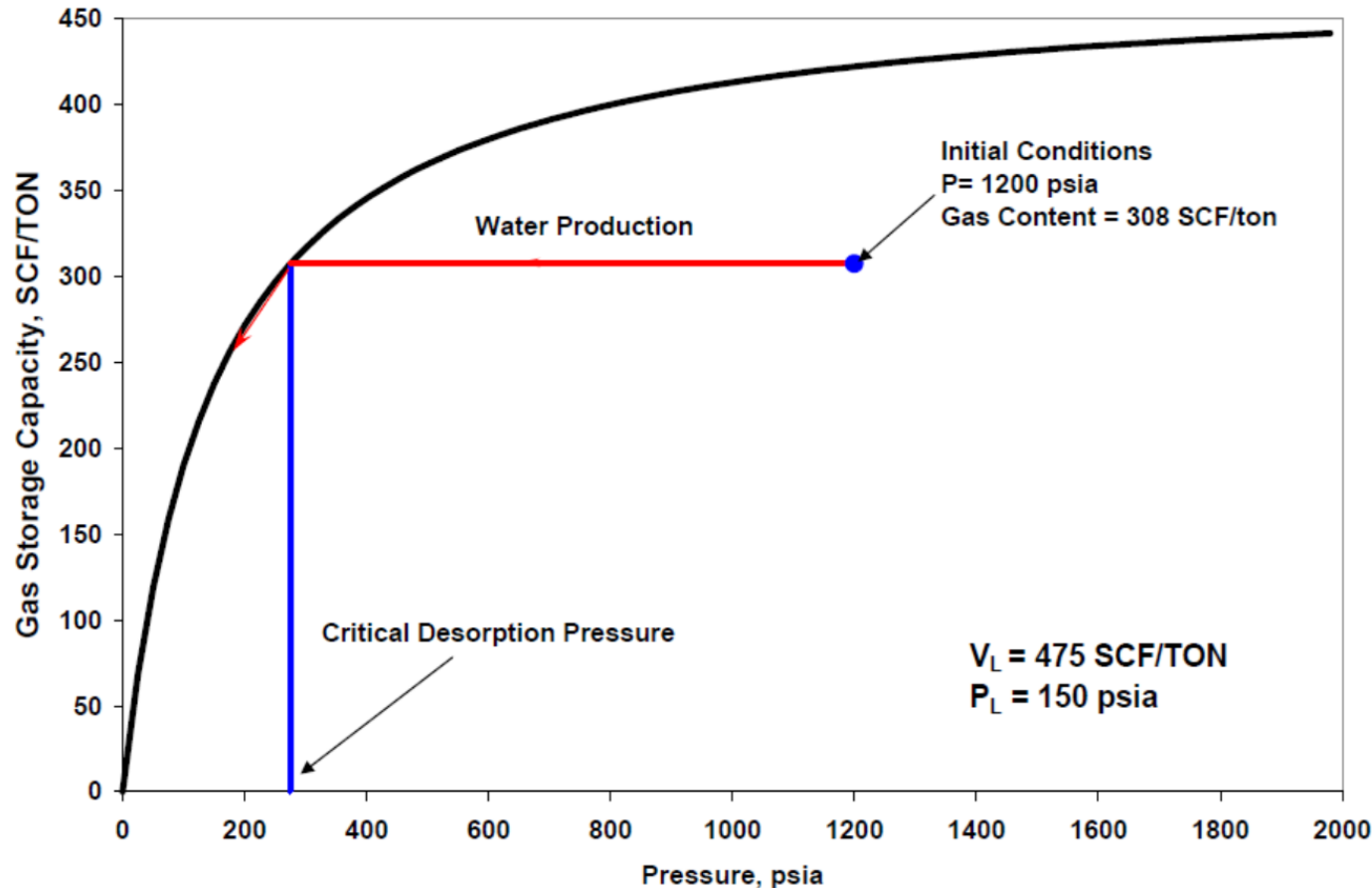

Figure 7: A typical adsorption isotherm

Table 6
Coalbed methane recovery parameters.

Sample	Gas content (m³/t)	P_r (MPa)	P_{cdp} (MPa)	P_{ab} (MPa)	Under saturation	V_{cdp} (m³/t)	V_{ab} (m³/t)	R_c (%)
J/01	2.29	3.85	0.95	0.53	75%	2.28	1.41	38
J/02	2.75	4.67	0.81	0.53	83%	2.76	2.34	15

- P_r = recovery pressure
- P_{cdp} = critical desorption pressure
- P_{ab} = abandonment pressure
- Under saturation = (3.85-0.95)/3.85 = 75%
- V_{cdp} = Gas content at critical desorption pressure = (2.28-1.41)/2.28 = 38%
- V_{ab} = Gas content at abandonment pressure

Methane Sorption Capacity Of Coal

- Adsorption capacity of coal is defined as the volume of gas adsorbed per unit mass of coal usually expressed in SCF (*standard cubic feet*, the volume at standard pressure temperature conditions) gas/ton of coal.

- Most of the gas in coal is adsorbed on the internal surface of micropores. The amount of gas that a coal can adsorb varies directly with pressure and inversely with temperature. The relationship between the volume of gas adsorbed by the coal, and pressure and temperature can be described by the equation:

$$V_0 = K_0 P^n_0 - bT$$

where V = volume of gas adsorbed, in cubic centimetres per gram of moisture and

ash-free coal;

P = pressure, in atmospheres;

T = temperature, in degrees Centigrade;

k, = a constant, in cubic centimetres per gram per atmosphere;

n_o = a constant; and

b = a constant, in cubic centimetres per gram per degree Centigrade

Important factors that affect methane sorption capacity of coal are:

- Pressure
- Temperature
- Rank
- Ash and moisture content

Pressure

- The volume of gas adsorbed increases with increasing pressure.

At a given depth, the pressure P is usually assumed to equal the hydrostatic head given by the equation:

$$P_{hyd}=0.096h$$

Where P is expressed in atmospheres and h is the depth, in meters. Since it is primarily dependent on pressure, the estimated adsorbed gas volume will be only as accurate as the pressure value. If the pressure at depth or pressure gradient for an area is known, this value should be used to estimate the adsorbed gas content of a coal. If hydrostatic head is used, it

should be realized that this represents limiting case and actual gas content gas content may
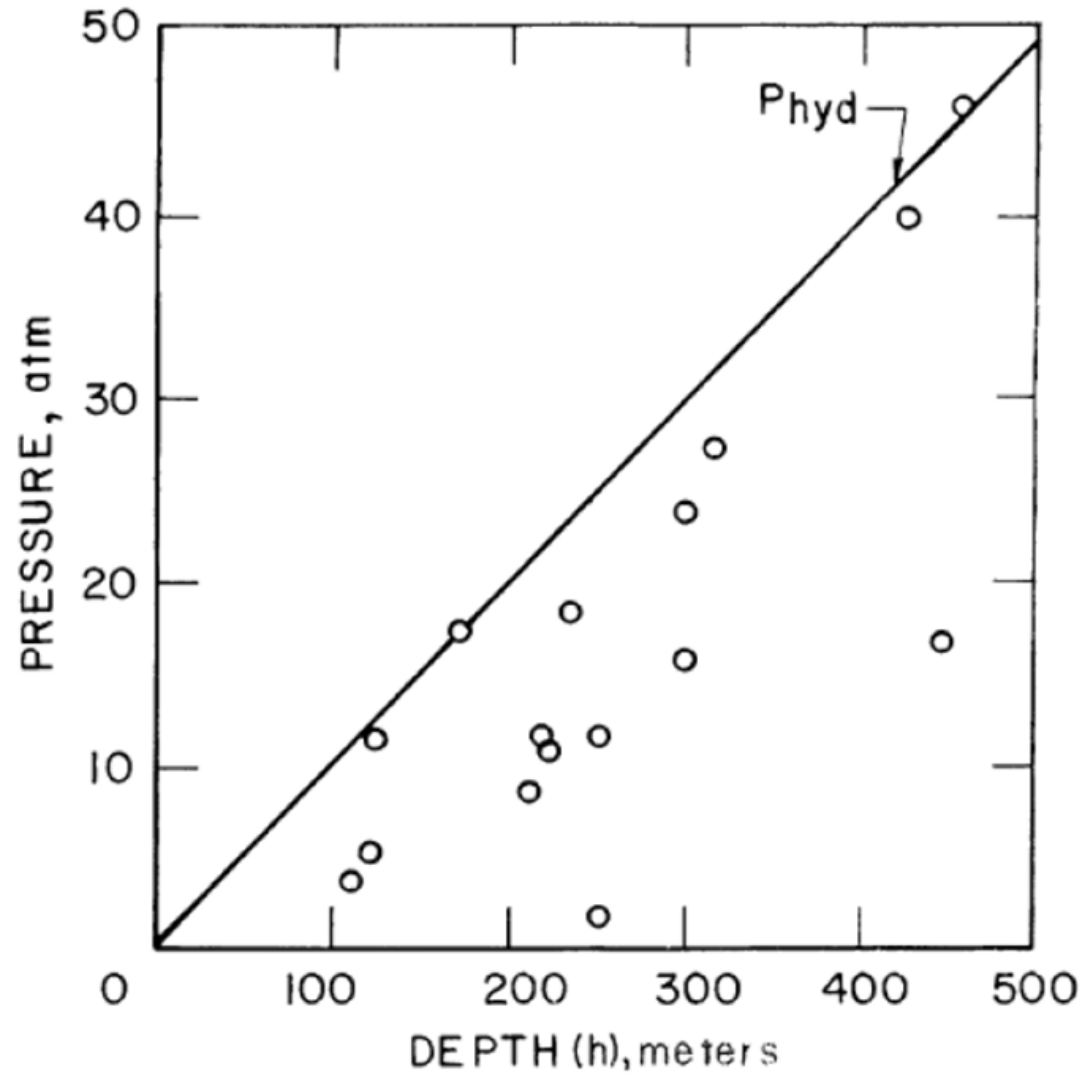
be lower than the estimated value.

Figure 8: A relationship of pressure to depth

Temperature

- At given pressure the volume of adsorbed methane decreases with increasing temperature. Furthermore, the curvature of sorption isotherm changes with temperature, becoming more concave downward as the coal warms. In practice an approximate relation for the effect of temperature on gas content can be developed from experimental work. It can be seen that from experiment for bituminous coal at a temperature of 23°C, sorption capacity drops 0.8%/°C. Thus experiment for different basins shows that for a temperature increase of 10°F, gas content drops 6%.

Temperature at a given depth h is estimated as the geothermal gradient multiplied by h and added to the ground temperature. Although the geothermal gradient varies in different areas, a commonly used value is 1.8°C/100 m.
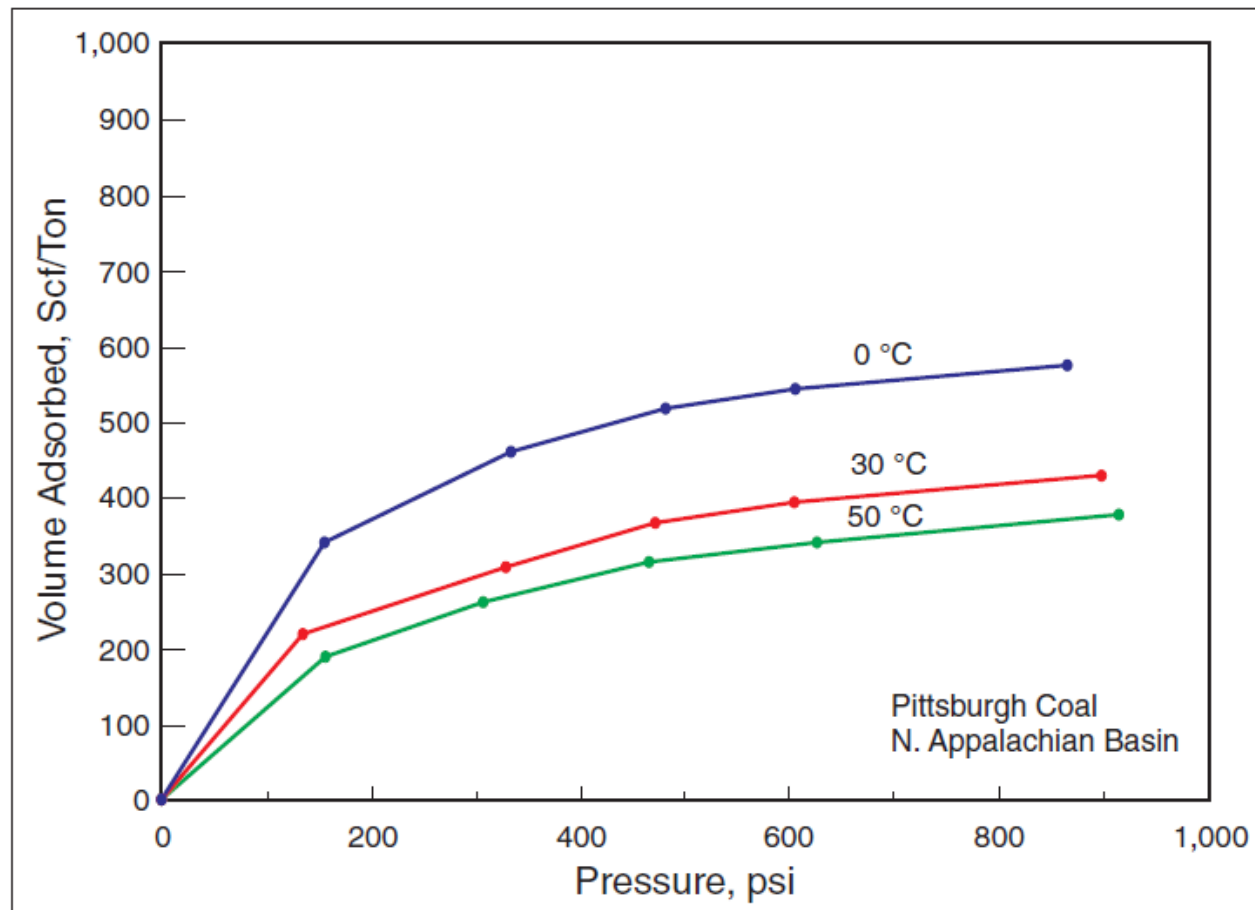

Figure 9: Effect of temperature on adsorption

Rank

- The amount of gas adsorbed by coal increases with increasing rank at a given temperature and pressure (figures 10-11). At a given temperature and pressure, higher rank coals contain larger volumes of methane than lower rank coals.
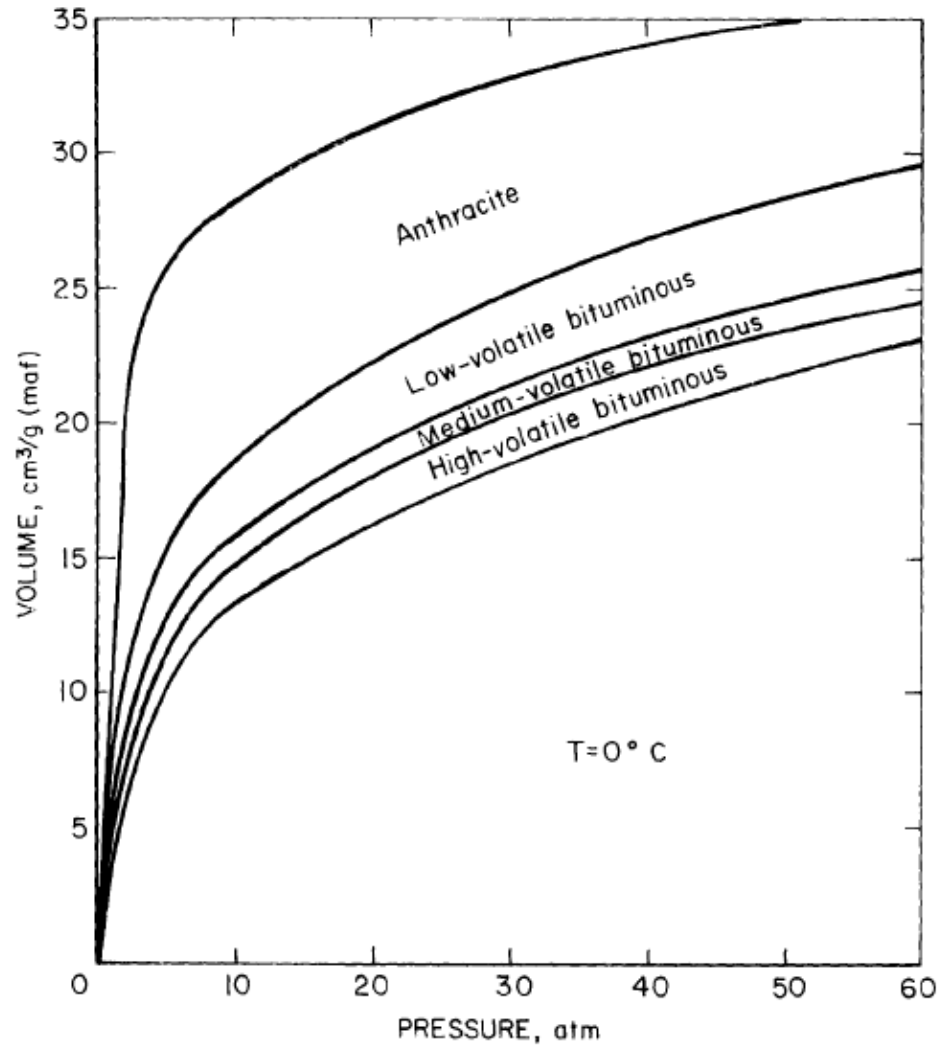

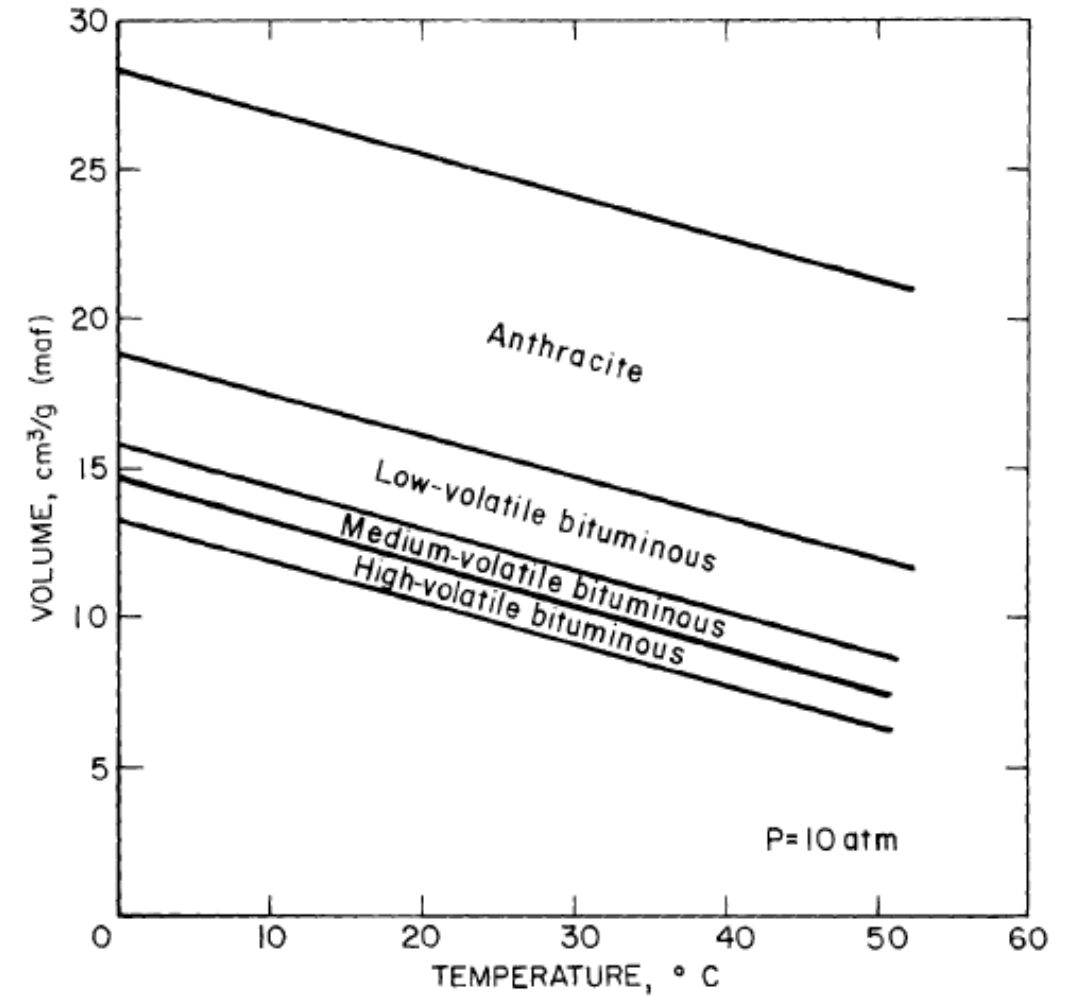**Figure 10**: Variation of adsorption isotherm with rank at 0°C

Figure 11: Variation of adsorption isotherm with temperature and rank at 10 atm

Moisture and ash content

- Gas content of a coal seam is affected by ash content and moisture in the coal matrix. The presence of either ash or moisture reduces the amount of methane that can be retained. The importance of bound water in the micropores is to reduce adsorption space for methane although bound water does not impede movement of methane through the micropores. However, the moisture is more strongly adsorbed to the micropore surface than the components of air or methane, and some swelling of the matrix can be expected upon moisture adsorption in a dry coal.

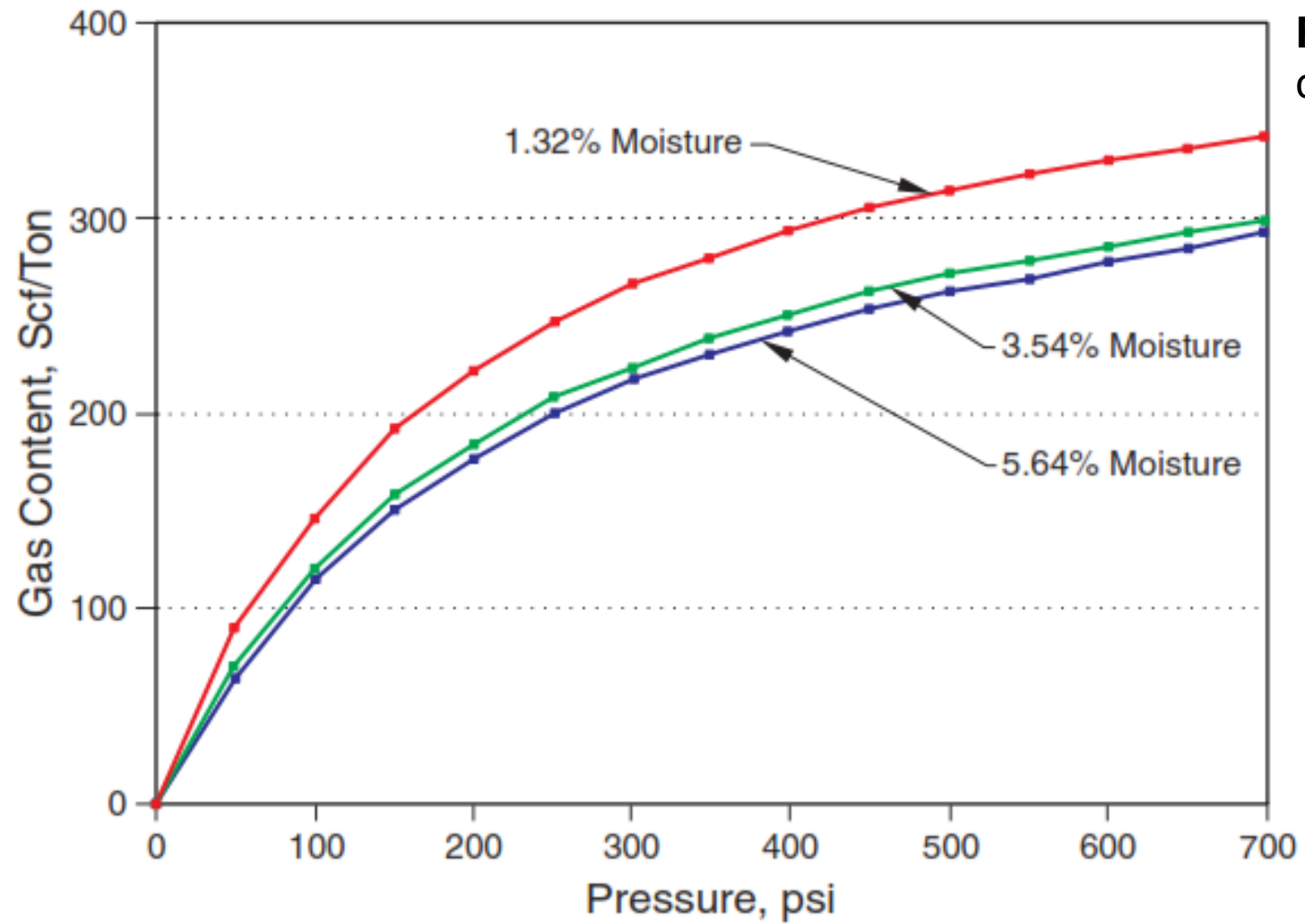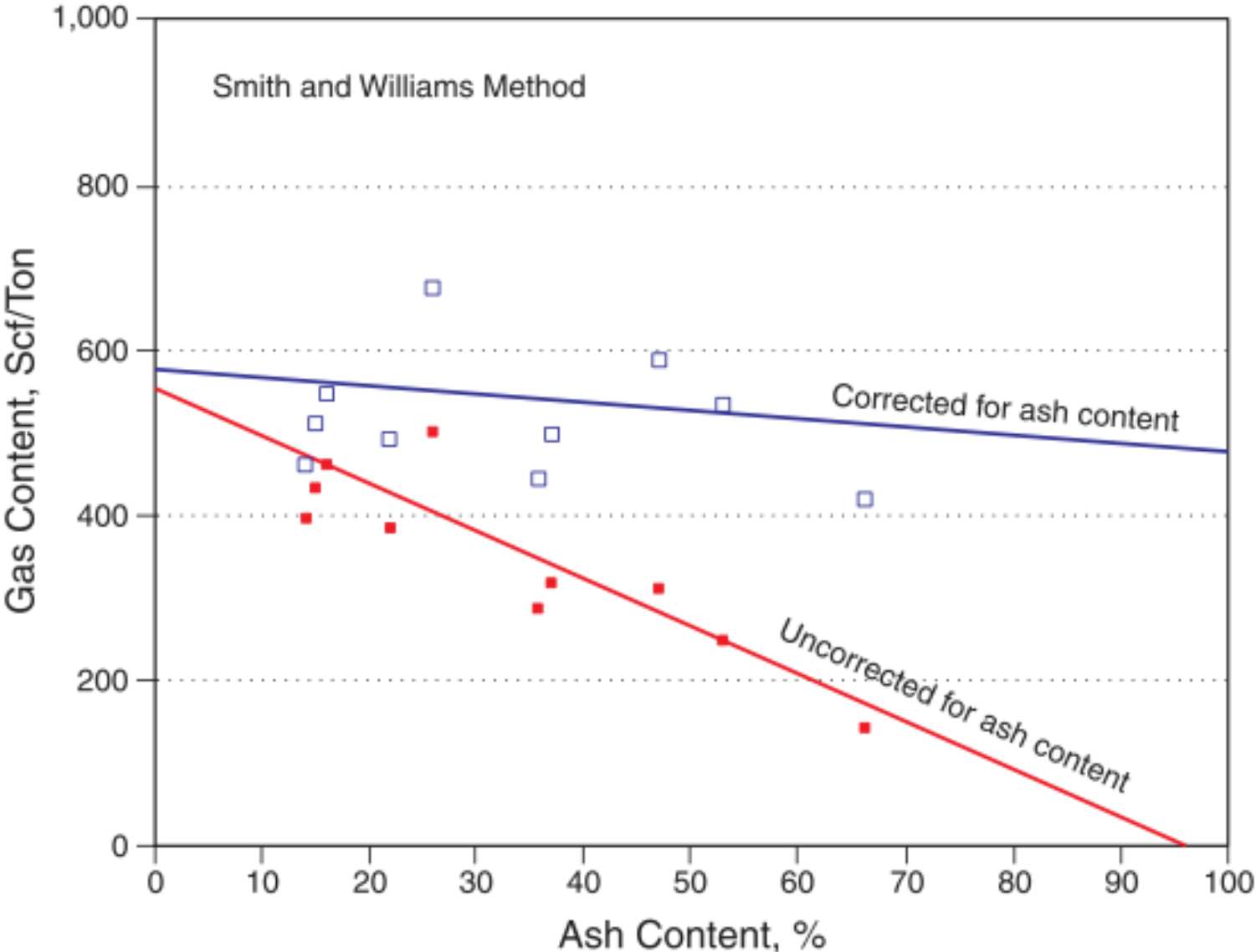**Figure 12:** Moisture reduces the adsorption capacity of coal

- The methane content of the coal decreases linearly with ash content. Figure 13 shows the importance of correcting the mass of the coal sample for ash content from the standpoint of potential gas capacity of the coal. This is in addition to the deleterious effect that ash has on the coal's fracturing capability.

Figure 13: Ash lowers the methane content

Diffusion in coal

Diffusion is a process where flow occurs as a result of random molecular motion from an area of high concentration to an area of lower concentration. Diffusion in coal is governed by Fick's 2nd Law which is concerned with concentration gradient changes with time.Sorption time is time taken by drill cuttings to desorb 63% of total gas in place. It is very important factor in determining the gas production rate in high permeability reservoir. The relationship between sorption time and diffusion coefficient is expressed as

$$\tau = \frac{S^2}{8\pi D}$$

Where:

S=Cleat spacing

D=Diffusion coefficient

τ=Sorption time

Three mechanisms have been identified for diffusion of an adsorbing gas in the matrix. They are molecular/bulk diffusion (molecule-molecule collisions dominate), Knudsen diffusion (molecule-wall collisions dominate) and surface diffusion (transport through physically adsorbed layer).

There are three mechanisms for defining diffusion in coal:

Molecular/Bulk diffusion

Molecular/bulk diffusion is significant for large pore sizes and high system pressures in which gas molecule-molecule collisions dominate over gas molecule-wall collisions. In this mode of transport, different species move relative to each other. The parameter characterizing this relative motion between species of different type is the binary diffusion coefficient.

Knudsen diffusion

- If the pores are very small, a particular gaseous molecule will collide more often with the pore walls and not very frequently with other molecules. This type of transport is called Knudsen diffusion. It is important when the mean free path (distance between molecular collisions) is greater than the pore diameter. This normally occurs at very low pressures and channels of small size, usually of order of 10nm to 100nm.

Surface diffusion

- Surface diffusion involves the transport of molecules through the physically adsorbed layer along the pore wall surface. This mechanism of transport becomes dominant for micropores and for strongly adsorbed species. The reason is that in very fine micropores (<1nm), the diffusing molecules never escape the potential field of the adsorbing surface and the transport involves the adsorbed molecules "hopping" across adsorption sites.

Permeability

- The ability of water and gas to flow through coal deposit is termed as permeability. Permeability may be the most common parameter to make or break a CBM play. It is the most important factor in determining the methane production rate from a coal seam. Any investigation of permeability in coal seams should therefore start with the description of the cleat properties. However, the measurement of width and length of cleat are not physically applicable, due to difficulty in protecting the original pattern of the cleat from damage during sampling. Permeability of coal seam is a function of the cleat spacing. For reservoir engineering purposes permeability is divided into two parts:

✓ Absolute permeability
✓ Relative permeability

Absolute permeability

Absolute permeability of a coal is function of the rock, not the fluids flowing through it. One of the primary reservoir properties that control the production of natural gas from coal seams is the absolute permeability of the natural fracture system. The purpose of obtaining the estimates of the absolute permeability, along with other reservoir properties, is to predict the dynamic behaviour of the coalbed methane reservoir under a variety of operating conditions.

Relative permeability

It is the ratio of effective permeability divided by absolute permeability. Relative permeability of gas or water is the ratio of permeability of that phase relative to permeability when only a single phase is present. Relative permeability of a phase depends on saturation that phase. Coal gas-water relative permeability's have been measured in laboratories, estimated from algebraic equations, and determined from history matching well performance with reservoir simulators.

Sorption time

- Sorption time is defined as the time required to release fraction of the total adsorbed methane from a coal sample initially saturated at reservoir temperature and pressure.

Example:

1. **If the desorbing samples of sub-bituminous Cretaceous-age coal from the San Juan Basin will have a coal diffusivity of 7.51 × 10-4 min-1. Calculate the time required to release 90% of the gas and 95% of the gas, respectively.**

Hint: **tDs = Dt/S2**, where tDs = dimensionless time (obtained from desorbed gas fraction time) , D= Coal diffusivity, t= time, S = spacing between cleats

2. **If sorption time (τ), which is defined as the time required to desrb 63% of the gas, for a sub-bituminous Paleocene sample from the Canyon coal in the Powder River Basin is 54.8 hr, calculate the time required to desorb 90% of the gas and 95% of the gas, respectively.**

Hint: *From the desorbed gas fraction table, 63% of the gas has been desorbed at a dimensionless time of 0.055265.*

Table:
Desorbed gas fraction

t_{Ds}	V/V_t	t_{Ds}	V/V_t	t_{Ds}	V/V_t
7.375E-06	0.01	0.012420	0.34	0.065540	0.67
3.521E-05	0.02	0.013258	0.35	0.068363	0.68
7.980E-05	0.03	0.014130	0.36	0.071300	0.69
1.426E-04	0.04	0.015038	0.37	0.074356	0.70
2.241E-04	0.05	0.015982	0.38	0.077538	0.71
3.244E-04	0.06	0.016963	0.39	0.080855	0.72
4.440E-04	0.07	0.017983	0.40	0.084315	0.73
5.832E-04	0.08	0.019042	0.41	0.087928	0.74
7.423E-04	0.09	0.020142	0.42	0.091704	0.75
9.216E-04	0.10	0.021283	0.43	0.095656	0.76
0.001122	0.11	0.022467	0.44	0.099797	0.77
0.001342	0.12	0.023696	0.45	0.104142	0.78
0.001585	0.13	0.024969	0.46	0.108710	0.79
0.001849	0.14	0.026290	0.47	0.113519	0.80
0.002135	0.15	0.027658	0.48	0.118594	0.81
0.002443	0.16	0.029077	0.49	0.123962	0.82
0.002775	0.17	0.030547	0.50	0.129653	0.83
0.003130	0.18	0.032069	0.51	0.135707	0.84
0.003509	0.19	0.033647	0.52	0.142167	0.85
0.003912	0.20	0.035282	0.53	0.149088	0.86
0.004341	0.21	0.036975	0.54	0.156536	0.87
0.004794	0.22	0.038730	0.55	0.164594	0.88
0.005273	0.23	0.040547	0.56	0.173366	0.89
0.005779	0.24	0.042430	0.57	0.182986	0.90
0.006312	0.25	0.044382	0.58	0.193631	0.91
0.006872	0.26	0.046404	0.59	0.205540	0.92
0.007460	0.27	0.048500	0.60	0.219051	0.93
0.008077	0.28	0.050674	0.61	0.234656	0.94
0.008723	0.29	0.052927	0.62	0.253118	0.95
0.009400	0.30	0.055265	0.63	0.275721	0.96
0.010107	0.31	0.057691	0.64	0.304867	0.97
0.010846	0.32	0.060209	0.65	0.345947	0.98
0.011617	0.33	0.062823	0.66	0.416180	0.99
				0.649538	0.999

V = desorbed gas volume

V_t = total desorbed gas volume.

$$\left[\begin{array}{l} t_{Ds} = \text{dimensionless time} \\ V/V_t = \text{desorbed gas fraction.} \end{array} \right]$$

If the Desorbing samples of sub-bituminous Cretaceous-age coal from the San Juan Basin will have a coal diffusivity of 7.51×10^{-4} min^{-1}, calculate the time required to release 90%, ~~95% and~~ 90% and 95% of the gas respectively. Refer the table, if necessary.

Ans:

We know $t_{DS} = \dfrac{Dt}{r_p^2}$

At 90% of the gas

$$0.182986 = 7.51 \times 10^{-4} \text{ min}^{-1} \, t_{90}$$

$$\Rightarrow t_{90} = 243.66 \text{ min} = 4.1 \text{ hr}$$

At 95% of the gas

$$0.253118 = 7.51 \times 10^{-4} \text{ min}^{-1} \, t_{95}$$

$$\Rightarrow t_{95} = 337.04 \text{ min}^{-1} = 5.6 \text{ hr}.$$

Sorption time (τ)

Q: If sorption time (τ), which is defined as the time required to desorb 63% of the gas, for a sub-bituminous Paleocene sample from the canyon coal in the powder River Basin is 54.8 hr, calculate the time required to desorb 90% of the gas and 95% of the gas respectively. Refer the table, if necessary.

Ans:-

From the table, 63% of the gas has been desorbed at a dimensionless time of ~~0.055743.0.55~~ 0.055265

At 90% of the gas

Time required to desorb 90% of the gas can be obtained from the ratio of the two times:

$$\frac{\left(Dt_{90}/r_p^2 \right)}{\left(\dfrac{D\tau}{r_p^2} \right)} = \frac{0.182986}{\substack{\sout{0.05574} \\ 0.055265}} = 3.31$$

or $\quad t_{90} = 3.312$

Thus, time to desorb 90% of the gas is

$$t_{90} = 3.31 \, (54.8 \, hr) = 179.7 \, hr = 7.5 \, days$$

At 95% of the gas

Similarly, time required to desorb 95% of the gas

$$t_{95} = \frac{0.253118}{0.055265} = ~~4.572$$

$$= 4.582$$

Therefore, Time required to release 95% of the gas from this sample is

$$t_{95} = 4.58 \, (54.8 \, hr) = 250.98 = 10.4 \, days.$$