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Project Title: **IMPACT OF GAS RELEASE CHARACTERISTICS ON CBM DELIVERABILITY IN ILLINOIS**

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ABSTRACT

Movement of gas in a coalbed methane (CBM) reservoir starts in the coal matrix with *diffusion* towards the naturally occurring *cleats* surrounding the matrix blocks. This study was aimed at predicting the gas deliverability of CBM reservoirs by evaluating these two properties, diffusion behavior and cleat characteristics, of Illinois coals.

Diffusion experiments were conducted using coals from two Illinois seams, Herrin and Seelyville, with ongoing as well as upcoming commercial CBM production. The experiments were conducted at *in situ* conditions of temperature and pressure. The diffusion coefficient, D, was first determined for coal and methane, followed by establishing the variation trend in its value with continued production.

The results of the work indicated that there was a negative correlation between D and pressure, that is, there was a significant increase in its value with decrease in pressure. This translates to enhanced gas movement in the coal matrix as production continues from a reservoir. Also, the trend showed a bi-modal value of D, where its value remained constant at high pressures, and started increasing once the pressure decreased and significant gas desorption was initiated. The behavior is explained by drawing an analogy with the Klinkenberg effect, where the permeability of porous media increases at low pressure due to gas "slippage" along the walls. A mathematical relationship, similar to the slippage effect, was established for this pressure range since the *in situ* gas pressure in Illinois coals falls within the range. The experimental data fitted the model well.

Simultaneously, effort was made to establish coal cleat characteristics using Computer Aided Tomography X-ray (CT Scan) imaging. This became problematic due to the resolution of the equipment as well as the fact that most of the cleats present in the cores were filled with minerals. A complete three-dimensional fracture map of coal cores was also obtained although it did not provide any significant, or meaningful, information. Hence, application of the technique to see "inside coal is somewhat limited at this time.

Using the experimental results, along with other relevant parameters for Illinois coals, a simulation exercise was carried out to predict the long-term deliverability of CBM in Illinois, its dependence on the value of D and its variation. The results showed that, for large values of D, the overall production can be significantly higher. Also, for high permeability coals, gas production during early stages of a reservoir is significantly higher. Since Illinois coals have a well defined cleat network, the permeability is medium to high, and the results favor CBM production in the State.

EXECUTIVE SUMMARY

To date, most of the effort towards evaluating the potential of commercial coalbed methane (CBM) production in Illinois has concentrated on estimating the gas-in-place (GIP). Given the early stage of CBM production in the State, this is only reasonable. However, in the last two years, commercial production of CBM in Illinois has increased significantly, with 77 wells currently producing gas and additional 52 nearing production. In order to promote the growth of this resource in the State, there is a need to study the basic flow characteristics of coal and make the information available to the current CBM operators, as well as those considering commercial CBM production, in the State. The overall objective of the proposed research study was to determine the CBM deliverability, that is, the ease with which gas can be produced from gas bearing coals in Illinois.

Migration of methane in a CBM reservoir starts in the matrix of coal (micropores) by diffusion, controlled by the diffusion coefficient and gas concentration gradient. After diffusing through the matrix, gas reaches the naturally occurring fractures (cleats) present in coal, where the flow becomes viscous in nature, and is controlled by the permeability of coal. The permeability, in turn, is characterized by the cleats present in coal. Production of gas from CBM reservoirs is, therefore, determined by the two properties, diffusion and permeability, of coal. This study was aimed at predicting the gas deliverability of CBM reservoirs by evaluating the diffusion behavior and cleat characteristics of Illinois coals, and evaluating their impact on gas production.

The rate of gas diffusion in coal depends on the physical properties of coal matrix structure and cleat spacing. The coal matrix properties include composition of coal, ash and moisture content, and its physical properties, such as, grain size and compactness. Cleat spacing, on the other hand, determines the distance through which the gas molecule must diffuse prior to entering the cleats, thus determining the "sorption time" required for the release of methane from the coal matrix. For Illinois coals tested, this parameter is critical since sorption time has been found to be rather long, compared to San Juan and Black Warrior Basins.

The first step of this study was to obtain cores of coal from two Illinois coal seams, namely Herrin and Seelyville, with ongoing as well as future commercial CBM production. To start with, basic characterization of coal samples was conducted. This included carrying out laboratory tests to obtain information about the relevant parameters, such as, coal density, moisture and ash content, and grain size analysis. After physical characterization of coal samples was completed, experiments were carried out to determine the gas diffusion characteristics of coal.

Diffusion experimental work was conducted using samples of coal obtained from the two seams. The experiments were conducted at *in situ* conditions of temperature and pressure. The diffusion coefficient, D, for coal and methane was determined for the coal types using the "Particle Method", where a sample of coal is first saturated with methane at high pressure. The pressure is then reduced, monitoring the gas content of coal

continuously for the entire pressure step. The change in gas content over elapsed time, which is an indication of the rate of methane release, is used to calculate the diffusion coefficient using the unipore diffusion model, which assumes a single pore size within coal. Sorption isotherms are a natural by-product of these experiments.

Following the measurement of D at *in situ* pressure, variation in the value of D was established for gradual step-wise reduction in gas pressure, thus replicating continuous production. The results showed a negative correlation between the measured value of D and pressure for most part of the pressure range relevant to Illinois coals, that is, there was a significant increase in its value with decrease in pressure. This translates to an increase in the pace of gas movement in the coal matrix as production continues from a reservoir. The overall trend showed a bi-modal distribution for D, where the value of D remained constant at high pressures, and started to increase almost exponentially once the pressure fell below the value where significant desorption takes place. This was corroborated by the finding that the desorption isotherm and variation trend in the value of D were almost mirror images of each other.

The traditional experimental technique typically used to estimate the value of D is slightly different, inducing sudden and large pressure jumps as opposed to gradual reduction in pressure. Hence, the "pressure jump" technique was used for one experiment. The results using the two techniques exhibited identical trends. Since the pressure in an actual reservoir decreases gradually, the technique used in this study, where pressure was brought down gradually, is believed to better replicate the actual conditions *in situ*.

The established variation trend was compared with the ones obtained for Canadian coals using the bi-disperse diffusion model, which assumes a bi-modal pore size distribution. To facilitate comparison, the results of the Canadian study were re-constructed. The trend established in this study matched well with the results obtained using the bi-disperse model.

The variation trend established in this study was explained by drawing an analogy with the well accepted Klinkenberg phenomenon in permeability, where the permeability of rocks is known to increase at low and very low pressures, and is attributed to a gas "slippage" effect. When there is crowding of gas molecules in rock fractures, typically at high pressures, the gas molecules along the fracture surface are immobile, the permeability approaching liquid permeability at very high pressures. On the other hand, at low pressures, the gas molecules slip along the surface of the fractures, thus adding to the natural permeability of the medium. A similar relationship appears to be occurring for diffusion of methane in coal as well. When the gas pressure is high, there is a crowding of gas molecules trying to diffuse out of the matrix, resulting in increased inter-molecular resistance and low diffusivity. With continued desorption, there is a reduction in the number of molecules diffusing out, resulting in lower resistance to its movement and increased diffusivity. A mathematical relationship similar to slippage effect was established for this pressure range, which fitted the experimental data very well.

The second probable explanation for the negative correlation between the D and pressure is the shrinkage of coal matrix with continued desorption. Matrix shrinkage has been measured in the laboratory for all Illinois coals tested to date. As methane pressure decreases, shrinkage of coal matrix results in decreased space between the micropores, that is, an increase in pore size. As this occurs, movement of methane towards the cleat structure is eased, resulting in an increase in diffusivity. The relationship between pore size distribution and diffusion has been reported in the past, where an increase in pore diameter results in increased diffusion of gas.

The second task in this study was aimed at establishing the cleat characteristics of coal using Computer Aided Tomography X-ray (CT Scan) imaging of whole cores. The major imaging work was carried out at the TerraTek facility using cores from the two Illinois seams. Images were obtained every 2 mm along the length of the core. For one of the cores, CO_2 was injected at 300 psi, while the core was still in the CT equipment, with the expectation that the sorption-induced swelling of the matrix would result in a measurable change in the cleat aperture. The core was then scanned a second time.

The overall results were disappointing due to the resolution of the equipment as well as the fact that most of the cleats were filled with minerals. The images obtained prior to CO_2 injection did not provide the desired information. Only major cleats were visible in the images, and the ones that were visible, were filled with minerals. Hence, the cleats truly contributing to the movement of gas could not be identified. After CO_2 injection, there was no measurable difference in the cleat aperture, probably because the only cleats apparent in the images were the filled ones, and these did not open up as a result of matrix swelling. Using the images obtained, a three-dimensional fracture map of cores of coal was obtained although it did not reveal any significant or meaningful information. The expectation was to determine the continuity of the cleats along the length of the sample. Since only the major cleats were visible in the images obtained, majority of the cleats was probably left out during construction of the 3-D model. The application of the technique, therefore, appears somewhat limited at this time.

Using the measured D, along with other relevant parameters for Illinois coal, a simulation exercise was carried out to predict the long-term deliverability of CBM in Illinois, and its dependence on the value of D. Using three different values of D for different pressures as input parameters, gas production was simulated over a period of 3000 days. The simulation results showed that the overall production with the largest value of D, measured at low pressures, was more than 200% higher compared to D measured at high pressures. This was followed by a second set of simulation, where methane production rate for two different values of D, for low and high permeability reservoirs, was simulated. For low permeability reservoir, the results showed insignificant difference, suggesting that diffusion has little role in determining the gas deliverability. On the other hand, for high permeability reservoir, diffusion can have a significant impact on production during the initial period of three to four months, with the production rate being almost twice that for small values of D. Typically, Illinois coals have a well defined cleat system and the permeability has been measured to be medium to high, suggesting that diffusion can have a significant role in CBM production during the initial production phase.

The simulation results also suggest that, in situations where permeability is not the production bottleneck, diffusion can have a significant impact on gas production. A good example of this is Coal Mine Methane (CMM) operations from gob degasification systems, where permeability of coal typically increases by orders of magnitude due to breakage of coal in the gob area, thus corresponding well with a very high permeability reservoir. The field production data from coal mines practicing gob degasification, where gas production continues for long periods of time after commencement of the degasification operation, corroborates this finding.

Based on the results of this study, it was concluded that, as the reservoir pressure declines with continued production, the ease with which methane molecules move in the matrix would increase. The deliverability of CBM reservoirs would, therefore, improve with time. Since the gas pressure in Illinois coals is low, the value of D would increase continuously throughout the life of producing reservoirs. Also, gas production during the initial stage of a reservoir can be expected to be good for the permeability values encountered/anticipated in Illinois coals. Both findings are extremely favorable for CBM production in the State.

Finally, the proposed study was carried out working closely with the ISGS and TerraTek. Excellent working relationship was established with the two CBM producers in the State, Peabody Natural Gas (PNG), currently operating two CBM pilots in Illinois, and BPI, currently the only major CBM producer in the State.

OBJECTIVES

Overall Objective: The overall objective of this research study was to determine the CBM deliverability of Illinois coals. Since gas deliverability depends on the diffusion and cleat characteristics of coal, the effort was aimed at studying these two properties in detail and assessing their impact on short- and long- term production of CBM in the Illinois Basin.

Specific Objectives of the Study: In order to achieve the primary objective, the following specific objectives were pursued during the project period:

I. Estimate the diffusion coefficient for coals in the Illinois Basin, and establish its variation with desorption, that is, with continued production;
II. Assess the cleat characteristics of cores obtained from the Basin using imaging and filtering techniques; and
III. Conduct a simulation exercise to determine the effect of diffusion on short- and long-term CBM production from typical gas bearing reservoirs in Illinois.

The work was divided into the following different tasks/sub-tasks:

Task I: Basic Coal Characterization Tests: This task included the following sub tasks:

a) <u>Procurement/Preparation of Coal Samples</u>: This sub-task included collecting coal cores from the ongoing drilling program of Illinois State Geological Survey (ISGS), and preserving these in their native state. The objective was to test coal samples representative of *in situ* coal reservoir conditions. Sample preparation included cutting/grinding and pulverizing appropriate test specimens for imaging and sorption/diffusion experiments.
b) <u>Coal Characterization Tests</u>: This sub-task included conducting some basic coal characterization tests like ash, moisture and density analysis for the samples using standard testing procedure and equipment available at SIU.
c) <u>Sorption Characteristics</u>: This sub-task included establishing methane sorption isotherms for the coal samples to determine the ability of coal to retain/release methane.

TASK II: Methane Diffusion Characteristics of Illinois Coal: This task included estimation of the diffusion coefficient, D, for movement of methane in Illinois coals using the Particle Method and unipore model of diffusion. The variation in the value of diffusion coefficient, D, with adsorption and desorption was also established as a part of this task. Two different techniques were used to measure D.

Task III: Cleat Characterization of Illinois Coal: This task included use of computer-aided tomography (CT-Scan) to assess the cleat characteristics of Illinois coals and produce 3-D models using various imaging and filtering techniques.

Task IV: Evaluation of CBM Deliverability of Illinois Coal: This task was aimed at carrying out simulation exercises to assess the short- and long- term CBM production from Herrin and Seelyville seams using the COMET3 simulator. Assessment of the effect of variation in the value of diffusion coefficient on the overall CBM production from these two seams was also included in the task. Finally, the impact of different values of the coefficient for both, low and high permeability reservoirs, was evaluated.

Task V: Reporting and Communication: This task included maintaining close contact with the ISGS personnel throughout the project duration, reporting project progress on a regular basis, obtaining information about the field and analytical work, providing pertinent information to ISGS, and most importantly, obtaining cores from their drilling program. This task also included dissemination of the results to potential CBM developers and researchers at various forums and conferences. A good relationship with the two major CBM producers in the state was established.

INTRODUCTION AND BACKGROUND

Coal is typically characterized as having a dual porosity, micropore and macropore system. The micropores in coal occur as part of the coal matrix and serve as the storehouse for over 95% of the gas in adsorbed form [1]. The macropore system consists of a naturally occurring network of closely spaced fractures surrounding blocks of matrix, called the *cleat* system. Most coals have two distinct sets of cleats, the continuous ‘face’ cleats, and another set of orthogonal ‘butt’ cleats intersecting the face cleats. The porosity of the coal cleat system is small, and if free gas is present in these fractures, it accounts for an insignificant portion of the total gas stored in coal. However, the cleat system provides the flow paths for gas and water in the reservoir. There is a third set of fractures present in coal, the horizontal bedding planes, although these have are typically believed to play little role in movement of gas due to their inability to transmit fluids as a result of the weight of the overlying rock.

Mass transfer of gas through the coal matrix is dominated by diffusion. The general solution for the CBM reservoir behavior assumes that gas is transported through the primary porosity of coal (micropores) by diffusion towards the cleat network. Upon reaching the secondary porosity, gas enters the cleat system in free gas state. For transport of methane in coal, cleats have two major impacts. First, they provide the pathways for water and gas molecules to flow towards producing wells, which is governed by Darcy’s Law and controlled by the permeability of coal. Permeability of coal, in turn, is determined by the cleat aperture and spacing. There is another significant impact of cleat spacing on CBM production, which is often overlooked. It determines the distance that the gas must diffuse through, prior to entering the cleat network, and thus determines the “sorption time” required for the gas to reach the cleat system.

When the pore pressure in coal is reduced, the gas molecules at the matrix-cleat interface desorb to enter the fracture media as free gas. This results in a concentration gradient across the coal matrix resulting in diffusion of gas. Diffusion, in turn, determines the rate of gas release from the coal matrix. The concentration gradient controlling the diffusion of gas is the difference between the average gas concentration within a matrix element, and that at the matrix-cleat interface. Fick's Law is used to relate the diffusional mass transfer to concentration gradient by assuming that the mass flowrate across a surface is proportional to the concentration gradient across the surface, area of the surface, and diffusion coefficient of the medium. Fick's Law for mass transport in the direction of decreasing concentration is given as:

$$\mathbf{J = -D * \Delta c/\Delta x}$$

where, J is the mass flux in moles per unit area over time, D is the diffusion coefficient of the flow medium, and $\Delta c/\Delta x$ is the concentration gradient.

In general, flow of gas through coal, and hence the gas deliverability, is assumed to be controlled by the permeability of coal. However, production data has shown that many gas bearing coal seams, in spite of having sufficient gas content and well developed cleat network, are not suitable for CBM production. This has been attributed to the extremely slow rate of methane diffusion through the coal matrix, resulting in high sorption times, thus making diffusion the controlling mechanism in CBM production. Typical sorption time for the San Juan and Black Warrior Basins is short, in the range of seven to ten days. This favors CBM production to such a significant extent that CBM production in these basins is considered to be purely permeability-controlled. The diffusion of gas, in turn, is assumed to be instantaneous. These being the most prolific basins in the past, evaluation of the diffusion property has not received the attention it merits. For Illinois coals, the sorption time is extremely long, in the range of 60 to 100 days, and sometimes even longer. This has led to low production rates observed at several pilots in the State. The coal in the basin has a well defined cleat pattern, which suggests that permeability is not the bottleneck to gas production. It is the sorption time or, in other words, the production is diffusion-controlled, at least to a significant extent. A study of the diffusion characteristics is, therefore, imperative for Illinois coals in order to project the CBM deliverability of coal.

The importance of diffusion is also significant when considering Coal Mine Methane (CMM) operations from gob wells. In a typical gob degasification system, shown in Figure 1, permeability of coal increases by orders of magnitude due to breakage of coal in the gob area of a longwall mine. Due to formation of this large cavity, permeability is no longer the flow controlling mechanism. The gas production rate and the overall production are both determined by the ease with which methane molecules can move through the coal matrix blocks into the void space in the gob, and gas production is diffusion-controlled.

In CBM industry, the diffusion coefficient, D, is typically not measured directly, nor used in the simulation of long-term production. The effect of diffusion is included in modeling by using the *cleat spacing* and *sorption time*. Sorption time is the time taken by drill cuttings to desorb 63 % of the original gas-in-place. It is directly related to the diffusion properties since permeability has no role in flow of methane in small pieces of unstressed coal. For coal-gas reservoirs, sorption time is related to the diffusion coefficient and cleat spacing by the following relationship:

$$\boldsymbol{\tau = s^2 / 8 \pi D}$$

where, τ is the sorption time, s is the cleat spacing, and D is the diffusion coefficient.

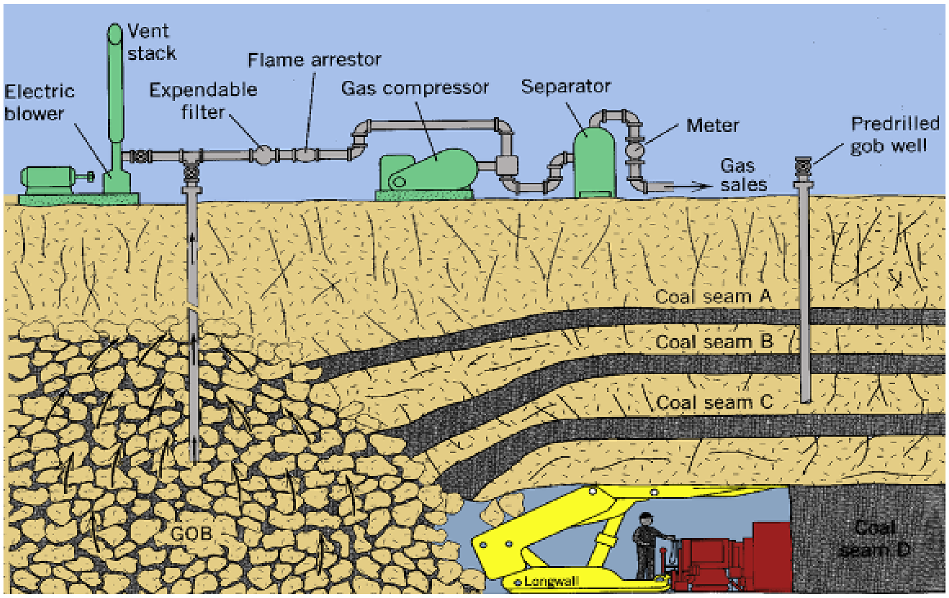


Figure 1: A typical gob degasification operation [2].

Cleat characteristics of coal, which include cleat spacing, orientation, aperture and continuity, affect the overall production of CBM in two ways. First, as discussed above, cleat spacing is directly related to the sorption time. Second, orientation, aperture and continuity affect the secondary porosity of the coal, that is, permeability of coal. Therefore, an understanding of the cleat structure is equally important for evaluating the overall deliverability of CBM.

From the above discussion, it is clear that, prior to any full-scale commercial CBM production, it is critical to carry out elaborate testing of coal to evaluate its diffusion behavior and cleat characteristics. Hence, this research study was aimed at developing a good understanding of these two parameters. Specifically, the study was initiated in order to: 1) determine the diffusion coefficient of coal samples taken from Illinois coals with current, or future potential for, commercial CBM production, 2) better understand the diffusion behavior of coals by studying the variation in the value of D over the life of typical CBM reservoirs, 3) determine the cleat spacing, orientation, aperture, and continuity by developing three-dimensional model of whole cores, and 4) carry out long-term gas production simulation to estimate the CBM deliverability of Illinois coals.

EXPERIMENTAL PROCEDURE

Sample Procurement and Preparation: Cores of coal were obtained from the ongoing exploratory drilling program of the Illinois State Geological Survey (ISGS) in Illinois. The cores, taken from Seelyville and Herrin seams, were preserved in their native state in an environmental chamber at controlled temperature and humidity conditions with no source of light to prevent any damage or weathering.

Diffusion/Sorption Experiments

The broken pieces of cores were ground and separated using sieve analysis. For a close representation of *in situ* conditions, the size of the test specimens was kept between 40 and 120 mesh, providing an average radius of 0.0125 cm. Approximately 90 g of sample was used for each experiment. The sample size was governed by the size of the sample container in order to minimize the dead space. Prior to use, the samples were kept in an environmental chamber at respective reservoir temperature and 97% humidity for 24 to 36 hours. One g of sample was used to measure the ash and moisture content.

Experimental Setup and Procedure: The experimental setup consisted of a sample container, made of stainless steel to withstand high pressures, connected to a fixed volume cylinder via a filter. The filter was provided to prevent movement of coal particles between the sample container and fixed volume cylinder due to sudden pressure changes. A set of two- and three- way valves was used in the setup to achieve the desired flow and storage of gas. The entire setup was placed in a high precision constant temperature bath, set at *in situ* reservoir temperature. The experimental setup is shown schematically in Figure 2 and pictorially in Figure 3. In addition to replicating the *in situ* conditions of temperature, pressure and gas content, precise monitoring of pressure variation in the sample container is critical in order to calculate the amount of gas diffusing from the matrix. Hence, a highly sensitive data acquisition system (DAS), capable of recording data at very short time intervals, and a pressure transducer were used.

Prior to diffusion tests, calibration of the setup included determining the volume of the dead space in the sample container using helium since it does not sorb on coal. Diffusion tests were performed for increasing and decreasing pressure steps, also designated as adsorption/desorption steps. Initially, the fixed volume cylinder was subjected to a pressure of 150 psi and allowed to equilibrate. The pressure in the sample container was atmospheric. The valve between sample container and the fixed volume cylinder was then opened as quickly as possible. The DAS was programmed to take readings at 0.5 second intervals at this stage since methane adsorption rate is extremely fast during the initial period. Acquiring data at this pace continued until the pressure variation became insignificant, in this case, 0.1 psi per hour. After this, readings were taken at 50 second intervals and continued for approximately 20 hours, at which time, there was almost no further change in the pressure and the sample was believed to have attained equilibrium. At this condition, the coal sample was fully saturated with methane at equilibrium pressure. This procedure was repeated for a step-wise pressure increment of 150 psi, including one step beyond the *in situ* pressure, estimated to be ~800 psi. Finally, the entire procedure was followed in reverse for decreasing pressure steps of 150 psi.

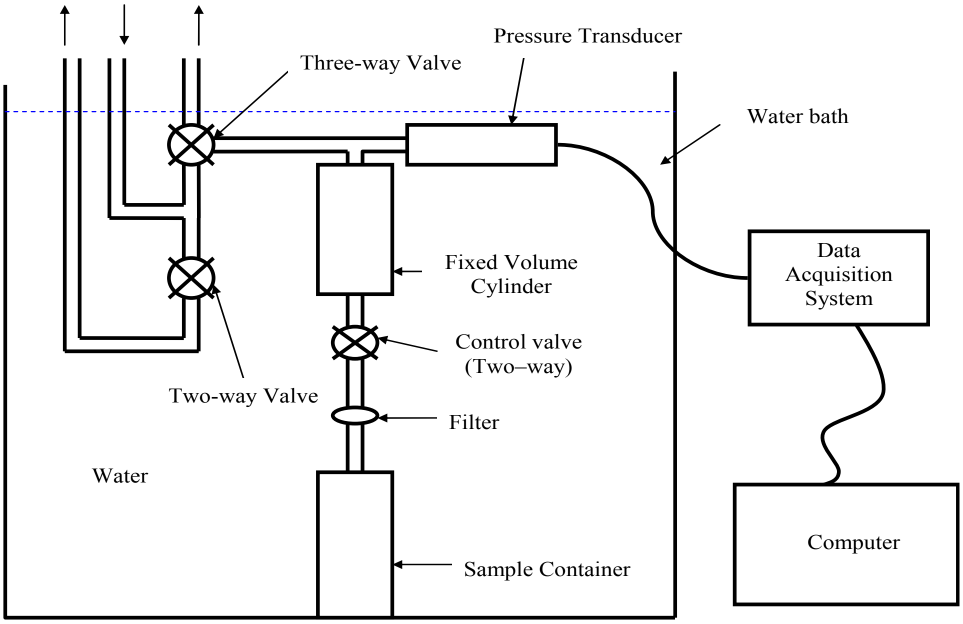


Figure 2: Schematic of the diffusion experimental setup.

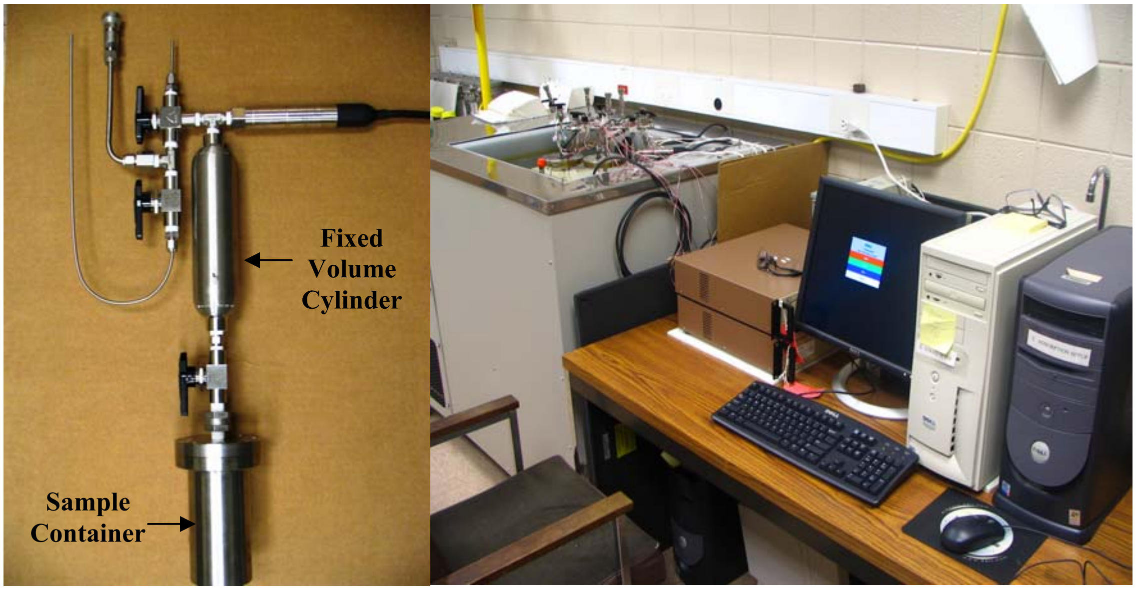


Figure 3: Left: Sample container and reference volume. Right: Entire setup including the constant temperature bath and DAS.

Experimental Conditions: The samples for these experiments were taken from drilling/coring operations performed at a depth of 1496 feet for Seelyville seam and 1232 feet for Herrin seam. The estimated reservoir temperature was 83.5^0F and 78^0F respectively. The tests were, therefore, carried out at these temperatures, at varying gas pressures, thus simulating conditions of methane desorption in the actual CBM reservoirs with pressure decline in the primary recovery method.

Sorption Isotherms: Adsorption and desorption isotherms are a natural by-product of this experiment. Hence, isotherms were established for every sample as a part of the diffusion experiment. Since the Langmuir Constants, Langmuir Pressure (P_L) and Langmuir Volume (V_L), are required for calculating the gas content of coal for every step, these were obtained from the isotherms.

Cleat Characterization Tests

Computer aided tomography (CT-Scan) was used to obtain the cleat characteristics of cores obtained. However, since cleat characteristics change when coal is exposed to a sorbing gas, it was decided to use a container to enable scanning the core before exposing it to methane, and again, while the container was still in the CT equipment, by injecting a sorbing gas, CO_2 in this study. Since aluminum does not cause interference when transmitting X-rays, an aluminum container capable of withstanding pressures up to 300 psi, was fabricated. The internal diameter of the container was just over three inches to ensure that the 3-inch diameter core fitted snugly inside. The cylinder was equipped with a valve assembly to allow injection/bleeding of gas, and care was taken to ensure that this was leak-proof. The container was significantly longer than the core to provide space on either side to ensure that the stainless steel valve did not cause any deviation of the X-rays. The entire assembly is shown in Figure 4.

The initial testing was carried out using a core from the Herrin seam, wrapped in plastic and scanned at a local medical facility. Subsequently, the high pressure container was used to seal the core prior to imaging. Two sets of images, one without gas pressure and another with CO_2 at 250 psi were analyzed. Due to low resolution of the CT equipment, primarily used for medical applications, and absence of filtering capabilities, cleats were not clearly visible. However, the larger fractures, filled with minerals/silica, were easily identified.

The entire specimen jacket was then taken to the TerraTek's CT facility in Salt Lake City, Utah, since TerraTek is a pioneer in developing the use of CT X-ray systems for geotechnical applications. The intent was to carry out imaging of cores and develop a three-dimensional fracture model of the entire core. Using different imaging procedures to determine the best technique for detection of fractures using cone-scan and/or slice image method, assisted by injecting a 'tag' compound into the fractures, several images were obtained.

The images produced were analyzed to obtain information on cleat spacing and cleat orientation as well as for construction of a 3-D model of the core.

Figure 4: Setup for CT-Scan of coal cores.

RESULTS AND DISCUSSION

Task I: Basic Coal Characterization Tests

To ascertain proper functioning of the entire system, rigorous testing of the DAS was first carried out to ensure accurate results during the actual experiments. A trial experiment was then conducted using a sample from Davis seam in the Illinois Basin. The results were in agreement with other studies, thus increasing the confidence in the testing procedure and the experimental setup.

The data recorded during the experiment was pressure and time, which formed the basis for all calculations. In the process of calculating D, Langmuir Constants, P_L and V_L, were also determined. The Langmuir model, given by the following equation, was used to establish the isotherms:

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

where, V is the volume of gas sorbed and P is equilibrium gas pressure. Although a by-product of the diffusion experiment, sorption isotherms are critical in the analysis of methane deliverability from CBM reservoirs as well as calculation of D.

The *ad/de-* sorption isotherms established for Seelyville and Herrin seams are shown in Figures 5 and 6 respectively. It is evident that the two isotherms are very close to each

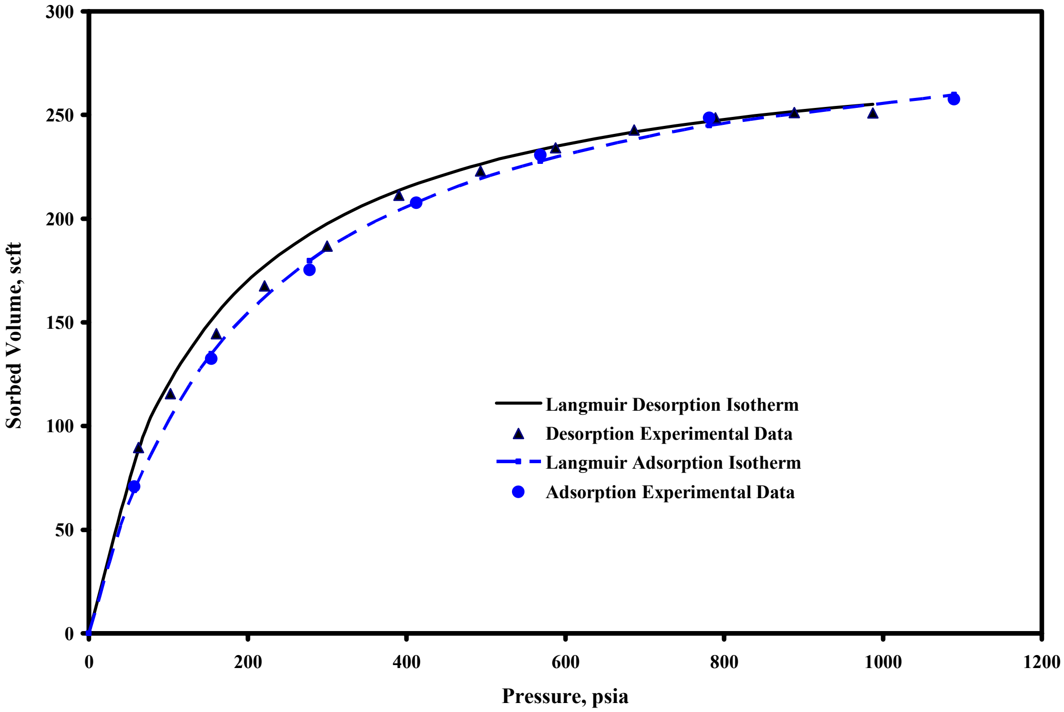


Figure 5: *Ad/de*- sorption isotherms for Seelyville sample.

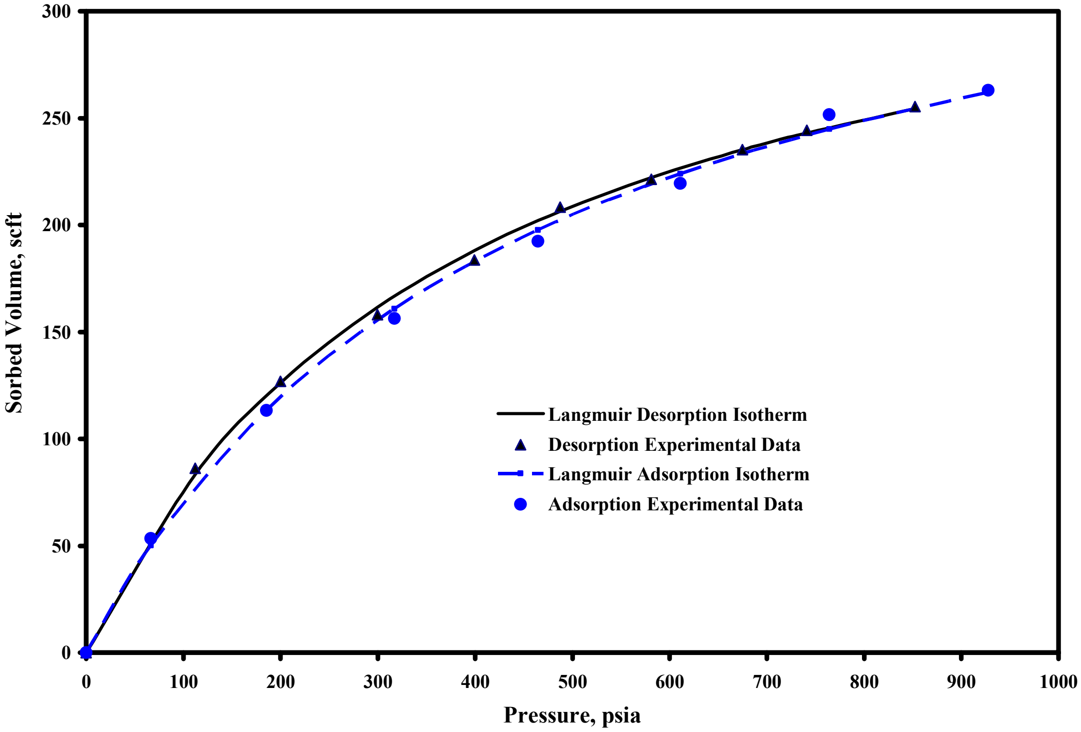


Figure 6: *Ad/de*- sorption plots for Herrin sample.

other, indicating small hysteresis between the two and attainment of reasonable equilibrium at each pressure step during the experiment.

Additional basic testing included determining the natural moisture and ash content of the coal samples tested. The results are shown in Table 1.

Table 1: Results of basic coal characteristics.

Sample	**Moisture Content (%)**	**Ash Content (%)**	**Adsorption**		**Desorption**	
			V_L(scft)	**P_L(psi)**	**V_L(scft)**	**P_L(psi)**
Herrin	7.7	8.39	389	451	385	369
Seelyville	6.0	8.36	307	197	293	144

TASK II: Methane Diffusion Characteristics of Illinois Coal

Compared to sorption experiments, where only the final equilibrium pressure is required, measurement of diffusion coefficient requires precise and continuous monitoring of the change in pressure in the sample container over time. This was repeated for every pressure step, that is, every time pressure in the sample container was changed to *ad/de*-sorb the gas. The frequency of data collection was decreased as equilibrium approached. Also, for calculation of the diffusion coefficient, only the initial sorption period is considered when the gas sorbs at an extremely fast pace. Gas content, and hence, the change in gas content was calculated for each time interval during one pressure step. A model, derived from Fick's Law during the half-slope period, is given as [3]:

$$g - g_{I-1} = 3.3851(g_I - g_{I-1})\left[\frac{D}{r_s^2}\Delta t\right]^{0.5}$$

where, g is the gas storage capacity in scf/ton, g_I is the gas content at the end of step I in scf/ton, g_{I-1} is the gas content at the end of step I-1 in scf/ton, D is the diffusion coefficient in cm^2/sec, r_s is the spherical particle radius in cm, and t is the time in seconds.

The calculated change in gas content and the square root of elapsed time for each step was plotted for each step. An example of a typical plot is shown in Figure 7. The diffusion coefficient was then estimated from the slope of the initial linear part of the plot, b, radius of the spherical particles, and gas content change using the equation:

$$D = \left\{\frac{b r_s}{3.3851(g_I - g_{I-1})}\right\}^2$$

Since the slope of the plot for the initial period is somewhat subjective, a sensitivity analysis was carried out to evaluate the impact of selecting different slopes by expanding the plot in three steps and considering three different slopes. The results were almost insensitive to the exact location on the plot where the slope is considered.

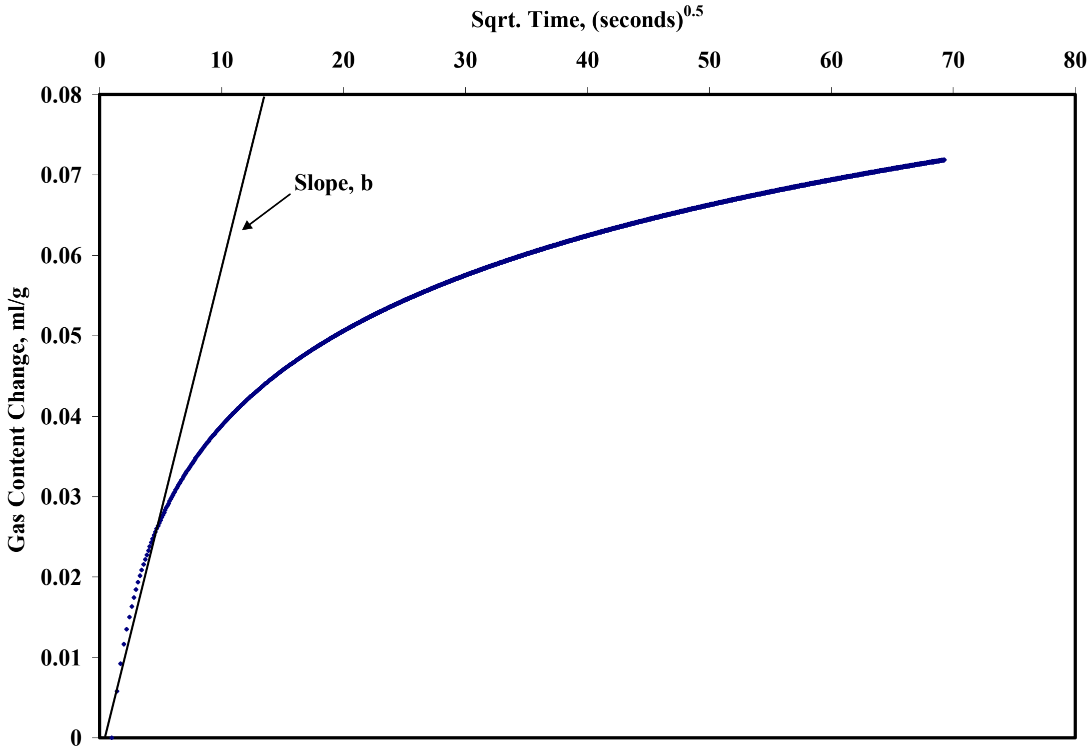


Figure 7: A typical gas content change vs. square root time plot.

After initial tests, samples obtained from the Seelyville and Herrin seams in Illinois Basin, provided by the ISGS from the Ameren well in Effingham County, were tested. The temperature throughout the tests was kept at 83.5^0F for the Seelyville and 78^0F for Herrin samples.

Starting at the first equilibrium pressure of ~70 psi in the sample container, pressure was increased in steps to ~1000 psi for both samples. For adsorption, or increasing pressure steps, the maximum pressure was achieved in seven steps. For desorption, or decreasing pressures, additional pressure steps were utilized since decreasing pressure values are more relevant to CBM production and the results required more precision.

The calculated values of D for Herrin sample are shown in Figure 8. It is apparent from the results that there is a negative correlation between D and pressure, both for increasing as well as decreasing pressure steps. Also, the established trend was the same for both samples under identical experimental conditions, except for the experimental temperature, since *in situ* temperature of the two seams is different. The variation in the value of diffusion coefficient with decreasing pressure for the two samples is shown in Figure 9. It is evident from the results that the diffusivity increases with pressure decline.

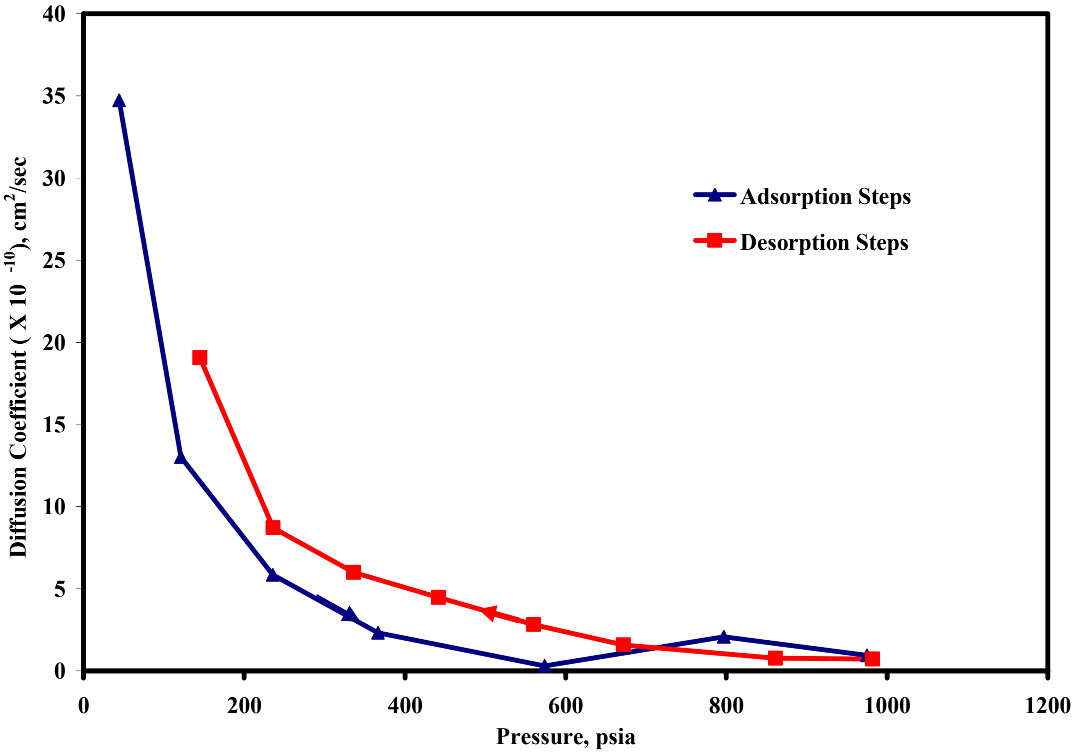


Figure 8: Variation in D for adsorption and desorption steps for Herrin sample.

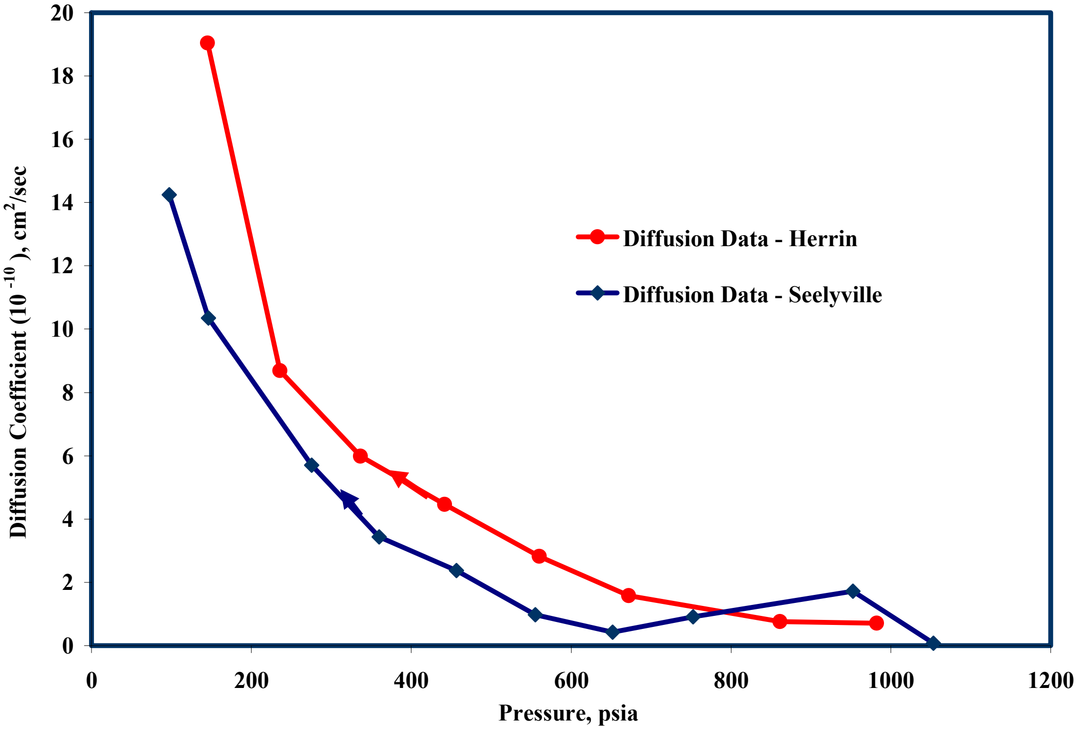


Figure 9: Variation in D with decreasing reservoir pressure (desorption).

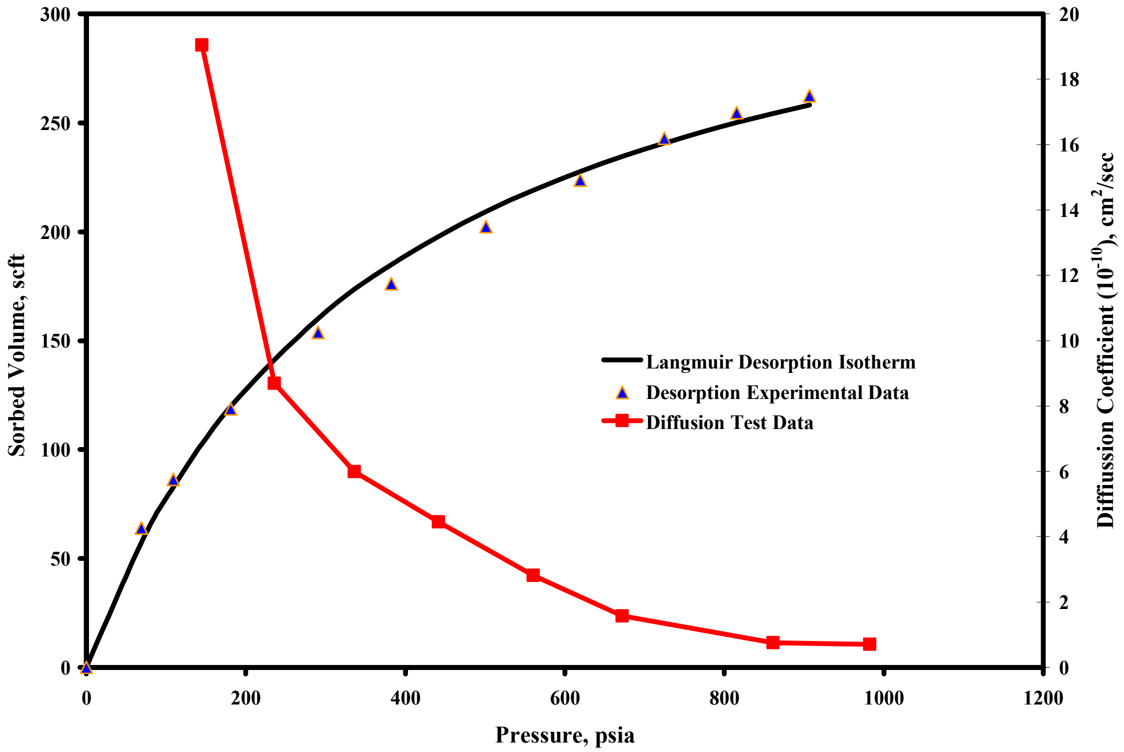


Figure 10: Desorption isotherm and variation in D with pressure – Herrin sample.

The gas pressure in the seam at this location is estimated to be ~800 psi. Hence, the ease of gas movement is expected to improve with continued production in a reservoir in this region. Once again, from a CBM operation point of view, only desorption part of the cycle is meaningful. This is further shown in Figure 10, where desorption isotherm is plotted along with the variation in the value of D, indicating that the two are almost mirror images of each other. The observed trend was same for both samples tested.

The nature of the overall D vs P trend established suggests that the variation in the value of D with pressure is dual-natured. At high pressures, its value remains almost constant. However, after a certain pressure, the value of D starts to increase, the rate of increase being almost exponential, suggesting that substantial desorption is responsible for the increase in the value of D.

The entire work discussed above is based on physical representation of coal using the unipore model. The model assumes that all pores in the coal matrix are of similar size and shape. The model is simple and calculations are less cumbersome. However, bi-disperse model of diffusion is believed to better represent coal's physical structure. The bi-disperse model assumes that coals have bi-modal pore size distribution, making the analyses and mathematics more involved. Hence, a comparative analysis was carried out with the results obtained using the bi-disperse model for Canadian coals. The study, reported by Cui *et al* [4], used the bi-disperse model of diffusion. The results reported similar trends as the ones established in the current study. The results reported by Cui and Bustin were, therefore, used to re-construct the trend. The results, shown in Figure 11, indicate an increase in the diffusivity with decrease in pressure, very similar to the one established in the current study.

The technique typically used to measure D is slightly different. The difference between the traditional technique and the one used in this research study is the way pressure steps are carried out. In the traditional technique, the pressure is dropped from different values to atmospheric for each step, thus providing a value of D for each step, like 200-0, 400-0, 600-0, psi. In the current study, pressure was brought down gradually from 1000 psi since this was believed to better replicate the conditions *in situ*. Hence, one experiment was carried out at SIU using the traditional technique. The results are shown in Figure 12, clearly indicating that the trend is the same, that is, a negative correlation between D and pressure.

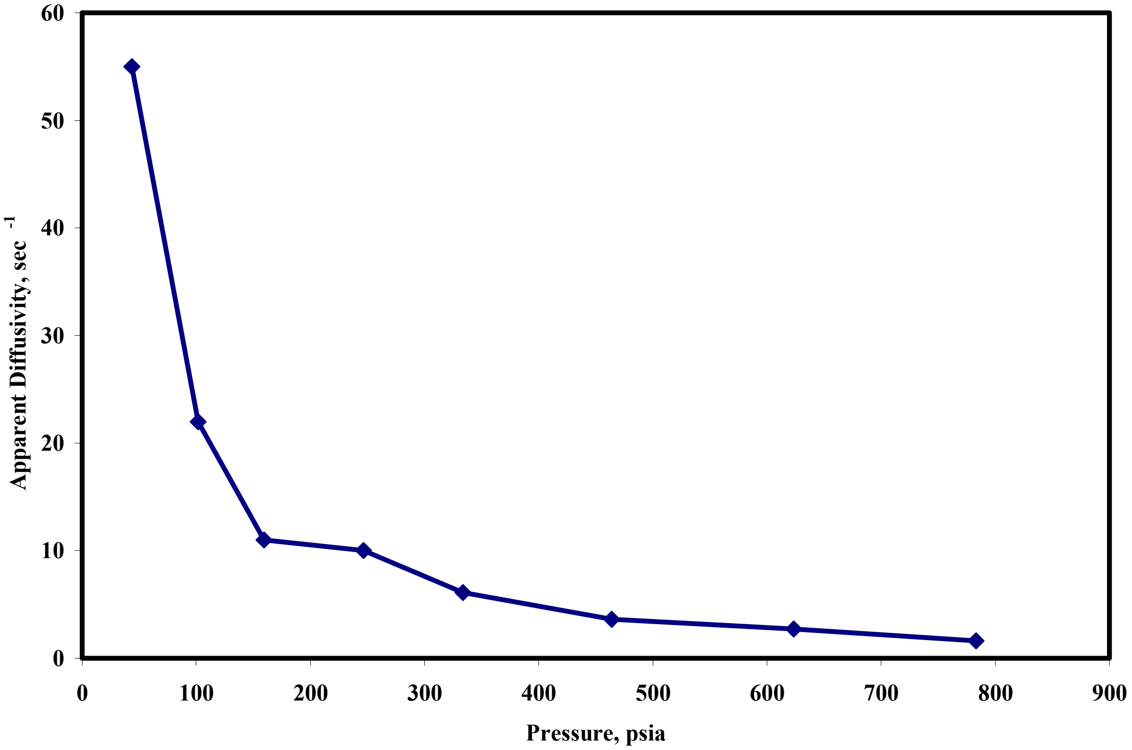


Figure 11: Reconstructed plot showing results using bi-disperse model [4].

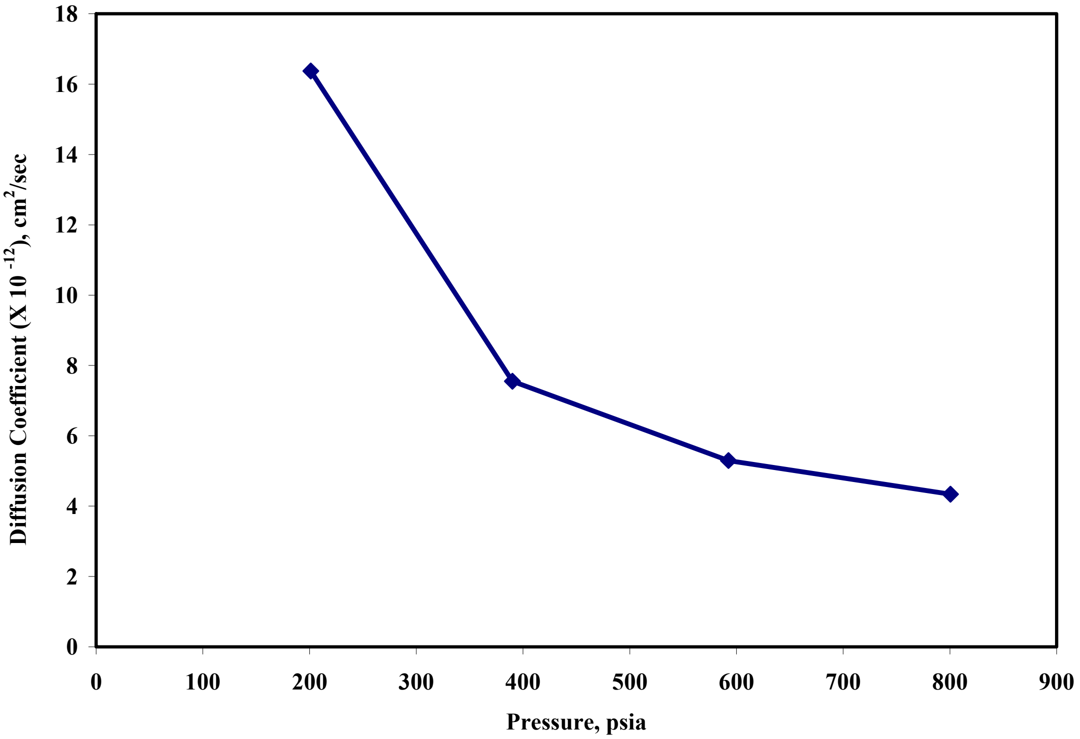


Figure 12: Variation in the value of D with pressure using the pressure-jump method.

Finally, effort was made to explain the results obtained in this study by drawing an analogy with the well accepted Klinkenberg phenomenon observed in permeability. At low and very low pressures, the permeability of a porous media is known to increase, and this is attributed to a gas "slippage" effect [5]. When there is crowding of gas molecules in rock fractures, typically at high pressures, the gas molecules along the fracture surface are immobile, the permeability approaching liquid permeability at very high pressures. On the other hand, at low pressures, the gas molecules slip along the surface of the fractures, thus adding to the natural permeability of the medium. Hence, with decrease in pressure, there is an apparent increase in permeability at low pressures. The phenomenon, shown in Figure 13, is given in the Klinkenberg equation as:

$$K_g = K_L + b/P_m$$

where, k_g is the gas permeability, k_L is the liquid permeability, P_m is the gas mean gas pressure, and b is the Klinkenberg constant depending on the solid-gas system. The Klinkenberg plot shows that the rock permeability to every gas decreases with reciprocal of mean gas pressure. At infinite pressure ($1/P_m = 0$), the permeability to every gas converges to a single value, considered to be equal to the liquid permeability of the rock.

A similar relationship appears to be occurring for diffusion of methane in coal. An explanation can thus be given for the diffusive movement of gas in the coal matrix as well. When the gas pressure is high, there are a large number of gas molecules trying to

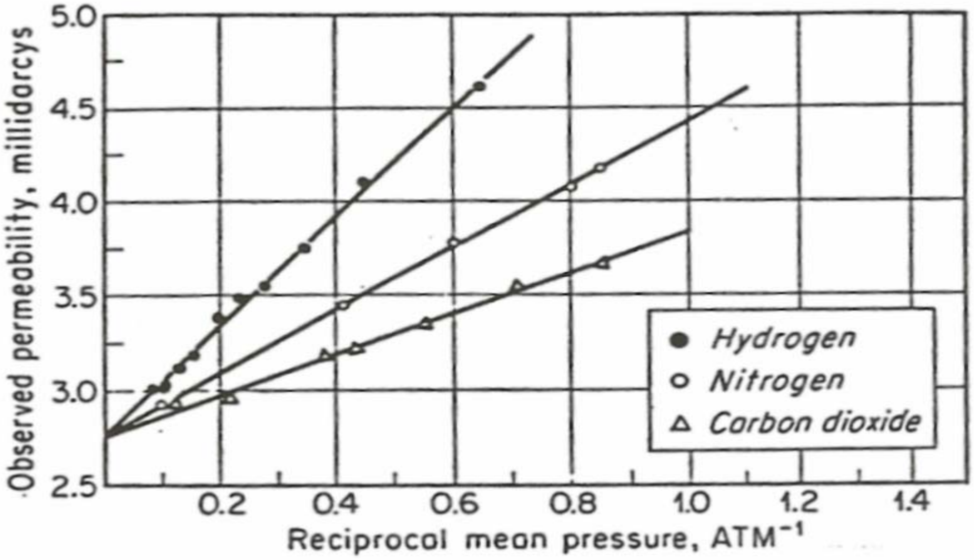


Figure 13: Relationship of gas permeability with reciprocal of mean gas pressure [5].

diffuse out of the matrix, resulting in increased inter-molecular resistance and low diffusivity. As the gas continues to desorb from the matrix, there is a reduction in the pressure and thus the number of molecules diffusing out, resulting in lower resistance to its movement and increased diffusivity. Based on this, the measured values of D were plotted as a function of reciprocal of gas pressure. This is shown on Figure 14. One apparent difference is that the value of D approaches a negative value at high/infinite pressure, which is impossible. For practical and applicability reasons, the experiments in this study were performed only up to 1000 psi, making the extrapolation of diffusivity for very high pressures difficult. However, during analysis of the experimental results, the experimental data appeared to be flattening out for the two higher pressure values. Hence, the variation in D may very well be dual in nature, where its value remains constant at high pressures, still retaining a positive value, although it may be extremely low. However, once the gas pressure is reduced, the value of D starts to increase with continued desorption of gas. This hypothetical explanation can be represented mathematically as:

$D = D_D$ for $P > P_D$

where, the gas pressure (P) is above the pressure when gas desorption is significant (P_D), and

$D = D_D + b/P_m$ for $P < P_D$

when gas desorption becomes significant. The value of "b" is expected to be constant for a particular coal type and methane.

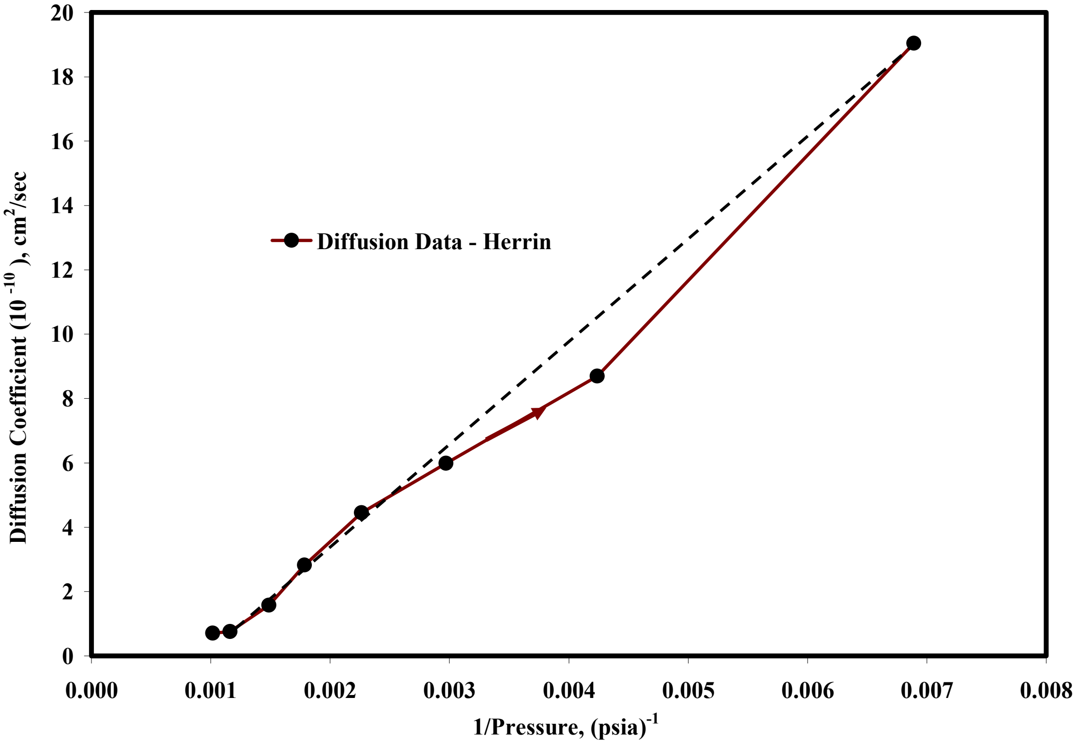


Figure 14: Klinkenberg plot showing D as a function of pressure.

There is yet another explanation for the negative correlation between the diffusion coefficient and pressure, once again, based on drawing an analogy with the permeability-pressure variation. Typically, there is shrinkage of coal matrix with continued desorption. This has been found to be universally true and reported for all coal types [6, 7, 8, 9, 10, 11]. Its impact, on the other hand, has been found not to be universal. In the deeper coal basins, this results in increased permeability [12, 13, 14]. In shallower coal, like in the Illinois Basin, this positive effect has not been measured in the laboratory, and given the stage of CBM activity in the basin, it is too early to observe the effect in the field. However, matrix swelling with adsorption of a gas, and shrinkage with desorption, have been measured in the laboratory for Herrin and Seelyville coals [15, 16]. The phenomenon would explain the variation in diffusion properties of the coal as well. At the macropore level, when coal matrix shrinks as a result of desorption, solid coal contracts, resulting in opening up of cleats and fractures, and hence, an increase in permeability. Extending this argument, a similar mechanism may be playing a role at the micropore level as well. As methane pressure decreases, shrinkage of coal matrix results in decreased space between the micropores, that is, an increase in pore size. As this occurs, movement of methane in the matrix is eased, resulting in an increase in the diffusivity. The relationship between pore size distribution and diffusion, reported by researchers in the past [17], supports this argument since an increase in pore size results in an increase in the value of D.

Task III: Cleat Characterization of Illinois Coal

The major imaging work was carried out at the TerraTek facility using cores of coal. The core was first placed in the core container, as shown in Figure 15, and images were obtained every 2 mm along the length of the core. For the core from Herrin seam, CO_2 was injected while the core was still in the CT equipment. CO_2 was used since it is more sorptive than methane, and it was expected that the higher swelling of the matrix would result in measurable change in the cleat aperture and matrix blocks. After 24 hours, the core was scanned a second time. The overall results were disappointing.

Figure 16(a) shows an image for the core taken from Herrin seam. The images prior to CO_2 injection did not provide the desired information. Only major cleats were visible in the images, and that too, the ones filled with minerals. Hence, the cleats truly contributing to the movement of gas could not be identified. Figure 16(b) shows the same image after CO_2 injection at 300 psi. The injected CO_2 did not result in measurable difference in the cleat aperture. This could be because the only cleats apparent in the images are the filled ones, and these probably did not open up as a result of matrix swelling. It could also be due to the fact that the core was unconfined and the matrix simply expanded outwards although matrix blocks did not exhibit any measurable difference either. Finally, it may be due to the resolution of the CT equipment used.

As a second exercise, the images were used to construct a three-dimensional model of the core using a 3-D software available at TerraTek. The expectation was that this would enable determining the continuity of the cleats along the length of the sample. The software used had the ability to discern between empty and filled space. The model developed is shown in Figure 17. Since the software looks only for filled versus empty space, it can not be said with any confidence that all cleats were mapped successfully. Furthermore, only the major cleats were visible in the images obtained, suggesting that majority of the cleats were probably left out during construction of the 3-D model.

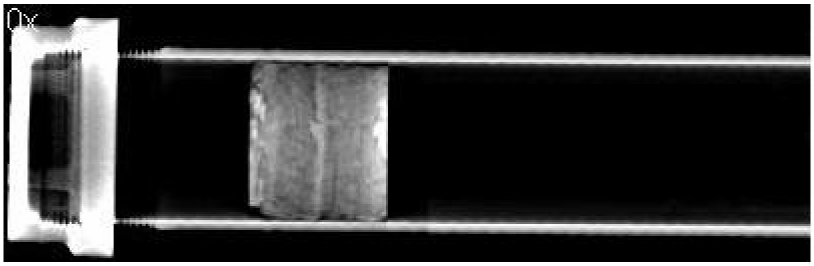


Figure 15: An image of a part of the container and the core.

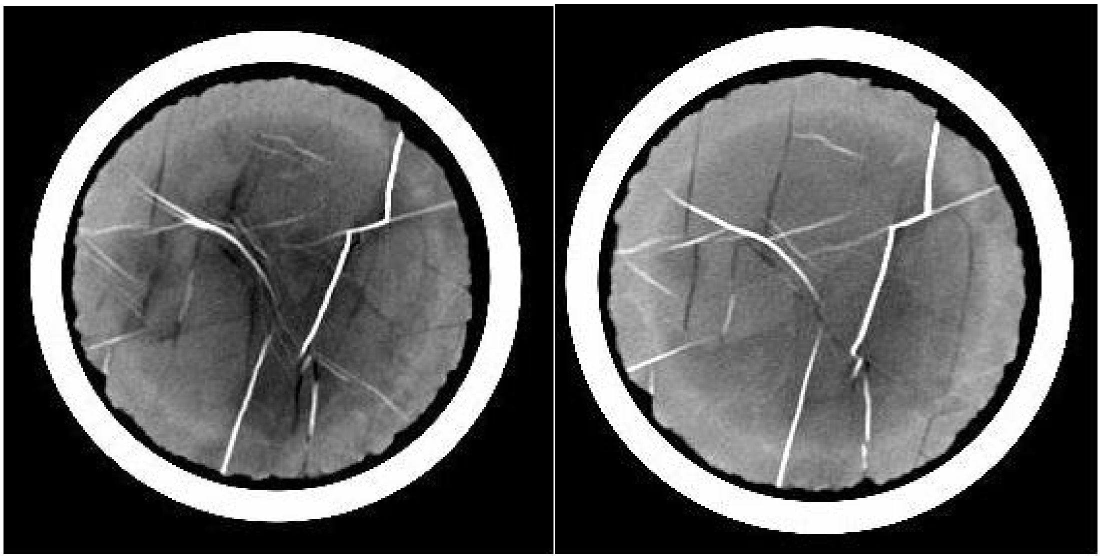
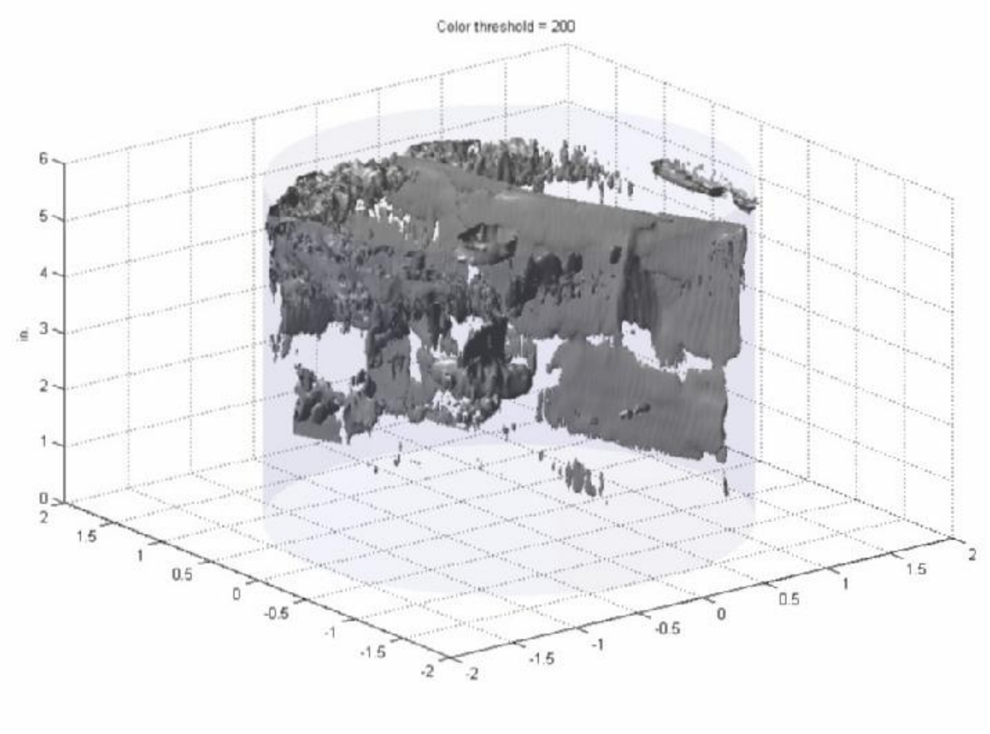


Figure 16: (a) Image of the core showing the filled cleats – pre-injection. (b) Post-injection image.



Figures 17: A 3-D model constructed from CT scanned image - Herrin sample.

Task IV: Evaluation of CBM Deliverability of Illinois Coal

Typically, CBM simulators used in the CBM industry are oil reservoir based, and the simulator used for this study, COMET3, is one of them. The permeability is considered to be the controlling factor in methane deliverability and, therefore, the effect of diffusion on the overall production is not considered significant. In spite of this shortcoming, effort was made in this study to evaluate the effect of diffusion on the overall gas producibility of Illinois reservoirs using COMET3.

Sorption time, which is inversely proportional to the diffusion coefficient, was calculated for different values of D. This was used as one of the input parameters in the simulation runs. Three different values of D for different pressures were used and gas production over a period of 3000 days was simulated. The simulation results showed that the production with the highest diffusion coefficient, that is, 1.42 X 10^{-9} cm^2/sec, was the highest, 34 MMscf (Million standard cubic feet), compared to ~15 and 12 for values of D measured at higher pressures. The simulation results are shown in Figure 18.

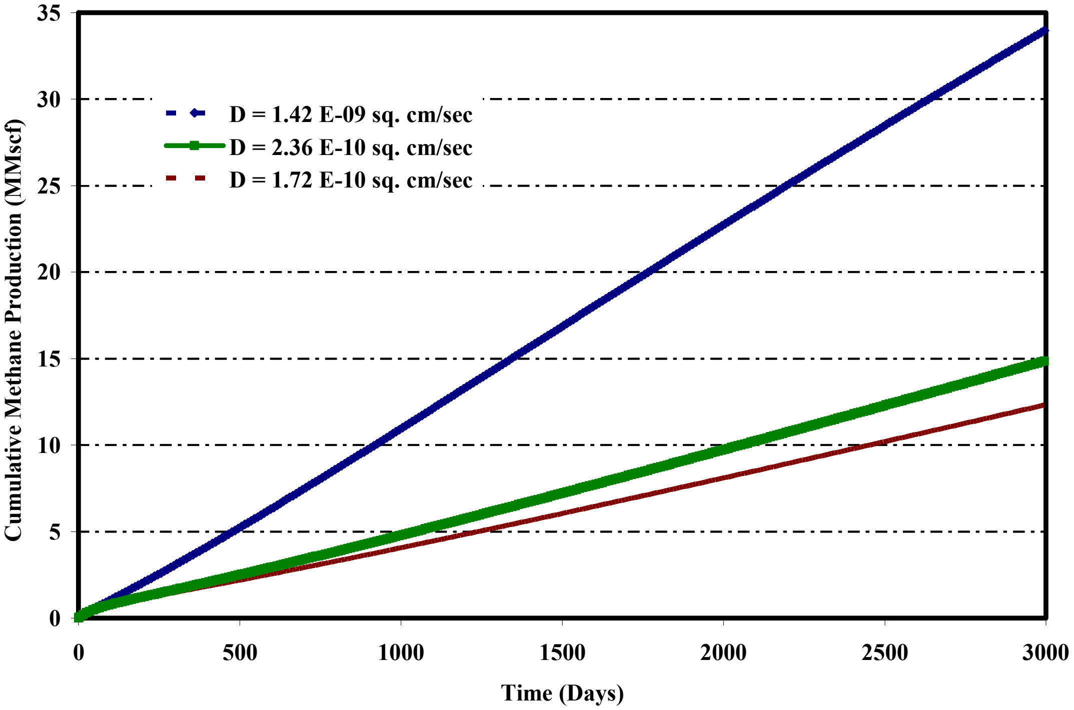


Figure 18: Impact of different values of D on overall production.

This was followed by a second set of simulation, where methane production rate for two different sorption times, that is, two different values of D, was simulated for low and high permeability reservoirs, and the simulation results were compared. For the first simulation, a low permeability reservoir, 10 md, was considered. The results, shown in Figure 19, showed insignificant difference between methane production rate for sorption times of 20 days and 100 days. Hence, for a low permeability reservoir, diffusion is not the controlling mechanism in determining the gas deliverability although this could be due to the fact that the simulator is not very sensitive to sorption time. The second simulation was carried out for a high permeability reservoir, 100 md, all other input parameters remaining unchanged. The results of the simulation are shown in Figure 20. It is evident from the production trend that, for a high permeability reservoir, diffusion can have a significant impact on production rate. For shorter sorption time, the production rate is almost twice that for the longer sorption time during the initial period of three to four months. These results are significant for Illinois coals since the permeability of coals has been measured to be medium to high with a well defined cleat system. In a recent well-test, *in situ* permeability of a potential CBM reservoir was measured by the Illinois State Geological Survey using the drill stem test (DST) to be 60 md, which is considered to be good.

The simulation results also suggest that in situations where permeability is not the production bottleneck, like methane recovery from gob wells, diffusion can have a significant impact on gas production. This corresponds well with the field production data from coal mines practicing gob degasification, where gas production continues for long periods of time after commencement of the degasification operation. The simulation results for a high permeability reservoir would correlate well with the mine degasification scenario.

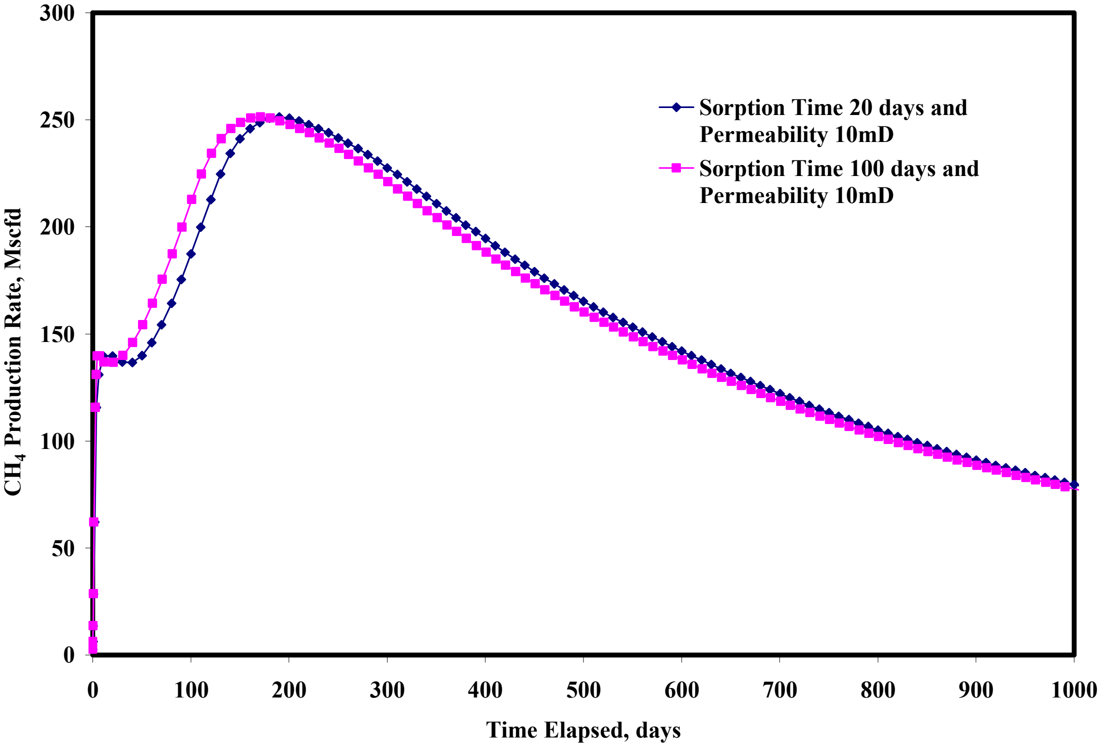


Figure 19: Effect of different sorption times for a low permeability reservoir.

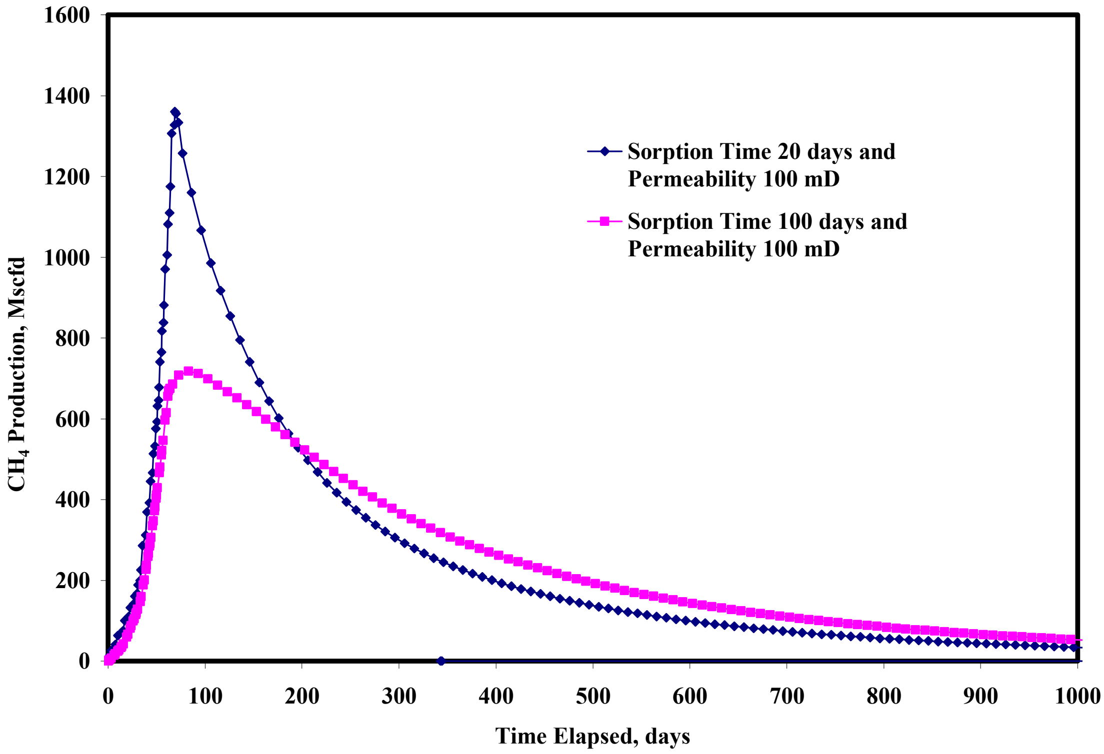


Figure 20: Effect of different sorption times for a high permeability reservoir.

Task V: Reporting and Communication

This task included the following activities:

- Fifteen monthly reports were prepared and submitted to ICCI.
- Close contact was maintained with the ISGS personnel throughout the project duration. This included six meetings with them during the period.
- Close contact was also maintained with the Indiana Geological Survey personnel since they work closely with the CBM operators in the Indiana portion of the Illinois Basin. Two meetings were held with them during the period.
- Good working relationship was established with Peabody Natural Gas (PNG), currently operating two CBM pilots in Illinois. Two meetings were held with the Director of PNG, one in Denver and one at SIU.
- Contact was established with the only major CBM producer in Illinois, BPI, currently producing CBM from 77 wells.
- The results of the work completed were presented formally at the 2006 International Coalbed Methane Symposium. A manuscript is currently being prepared for submission to a journal.

CONCLUSIONS AND RECOMMENDATIONS

Based on the work completed, the following conclusions are made:

- The value of diffusion coefficient, D, is not a constant over the life of a CBM reservoir. There is a negative correlation between D and pressure for the pressure range encountered in Illinois. The value of D can be represented by a dual model, its value remaining constant at high pressures, and increasing continuously when accompanied by substantial desorption of gas. The variation in the value of D, after desorption is initiated, can be explanation adequately using the Klinkenberg theory as well as the matrix shrinkage theory. The mathematical model developed for this regime, based on the Klinkenberg theory, fits the results very well.
- The two techniques typically used to measure the diffusion coefficient, D, show exactly the same trends in the variation in its value with pressure. The use of unipore model, as opposed to bi-disperse model, is appropriate for studies aimed at establishing trends of variation.
- For CBM deliverability, as the reservoir pressure declines with continued production, the ease with which methane molecules can move in the matrix would improve. Since the gas pressure in Illinois coals is low, compared to other basins in the US, the value of D would increase continuously throughout the life of producing reservoirs. This is, therefore, a favorable finding for CBM production in the State.
- Based on the simulation studies, gas production from low permeability reservoirs is not controlled by diffusion although this may be due to the design of the simulator, which underplays the importance of diffusion. However, for high permeability reservoirs, diffusion becomes a deciding factor in methane production, at least during the initial production period. Once again, this favors CBM production in Illinois since coal permeability has been measured to be good. The initial high production would be beneficial for the operators due to an early return on the capital investment.
- Simulation results also show that the overall production improves significantly with increase in the value of D. Hence, the overall recovery from CBM reservoirs in Illinois can be expected to increase substantially as the value of D increases with production.
- CT imaging as a technique to establish cleat characteristics would probably not provide any significant results at this time. The level of resolution required to obtain meaningful images of cores and availability of software to develop three-dimensional models using sectional images are the bottlenecks to use of this technology in order to see “inside” coal. The images did reveal that cleats in Illinois coals can be filled with minerals thus limiting their ability to transmit fluids.

Based on the findings of this study, the following topics of research should be pursued further:

- A simulation model, where the gas production controlling mechanism is not assumed to be permeability should be developed, or the current simulators should be modified to incorporate the impact of diffusion. In these models, the value of D should be treated as a variable, bi-modal in nature.

- Effort should be made to develop a database that would enable determining the value of the constant “b” in the mathematical model developed.
- For cleat characterization, injection of wood’s metal/fluorescent dye should be considered, followed by mapping of the cleats using imaging.
- Finally, based on the measured values of D for coal-methane system, the value of D should be measured for coal-CO_2 system as well. In a scenario, where CO_2 is injected in coalbeds to enhance CBM production as well as CO_2sequestration, there is counter-diffusion in the matrix, with CO_2 diffusing in to the matrix, and methane diffusing out.
- For ECBM using nitrogen injection, diffusion characteristics for transport of nitrogen should be evaluated.
- Since Illinois coals contain a fairly high concentration of nitrogen, diffusion of methane/nitrogen mixture should be evaluated.

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