Changes in Gas Storage and Transport Properties with Continued Bioconversion of Coal*

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Search and Discovery Article #41972 (2016)**
Posted December 26, 2016

*Adapted from oral presentation given at AAPG 2016 Annual Convention and Exhibition, Calgary, Alberta, Canada, June 19-22, 2016

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Abstract

This study was aimed at identifying the changes in coal properties affecting gas deliverability in coal-gas reservoirs, when treated with microbial consortia to generate/enhance production of methane. The work expanded on the technology of bioconversion, first proposed by Andrew Scott in order to imitate the natural/microbial process of biogenic gasification leading to recharging coal bed methane reservoirs or setting up natural gas reservoirs in non-producing coal beds, to coal waste, typically in the form of fines/ultra-fines. The pressure parameter was considered critical since, with continued production of methane, the produced gas would diffuse into the coal matrix and get adsorbed with increasing pressure. During production, the pressure would decrease and the process is reversed, gas diffusing out of the coal matrix and arriving at the cleat system. The experimental work tested the sorption and diffusion properties for the coal treated and, more importantly, the variation in the relevant parameters with continued bioconversion since these are the first two physical phenomena in CBM production. During the first phase, single component sorption-diffusion experiments were carried out using methane and CO_2 on virgin coals retrieved from the Illinois basin. Coals were then treated with nutrient amended microbial consortia for different periods. Gas production was monitored over thirty and sixty days of treatment after which, sorption-diffusion experiments were repeated on treated coals, thus establishing a trend over the sixty-day period. The sorption data was characterized using Langmuir pressure and volume constants, obtained by using the Langmuir model. The diffusion coefficient, D, work also established the variation trend as a function of pore pressure. The results indicated an increase in the sorption capacity of coal because of continued bioconversion. This was attributed to increased pore surface areas because of microbial actions due to change in the pore size or creation of new pores. It was further shown that the rate of diffusion increased, especially for methane, which exhibited rates higher than that for CO_2. These findings clearly support improved gas storage capacity with continued bio-version as well as significantly enhanced diffusion rates. As a continuation of this, change in permeability, the second gas transport phenomenon in coal-gas production, is being evaluated.

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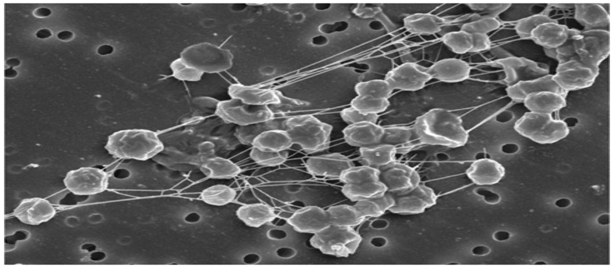
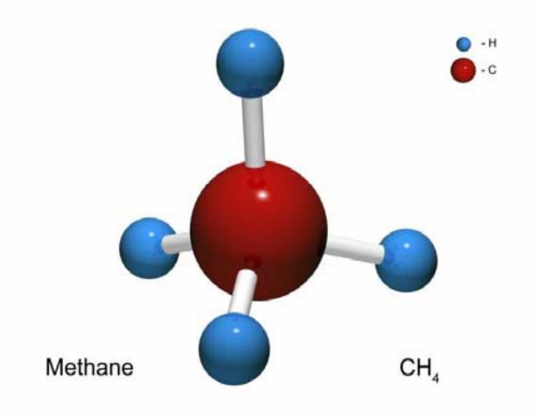
What is Bioconversion (of Coal)?

- Put simply, it is the process of interaction of the 'right' microbes in the 'right' environment with coal to produce methane.



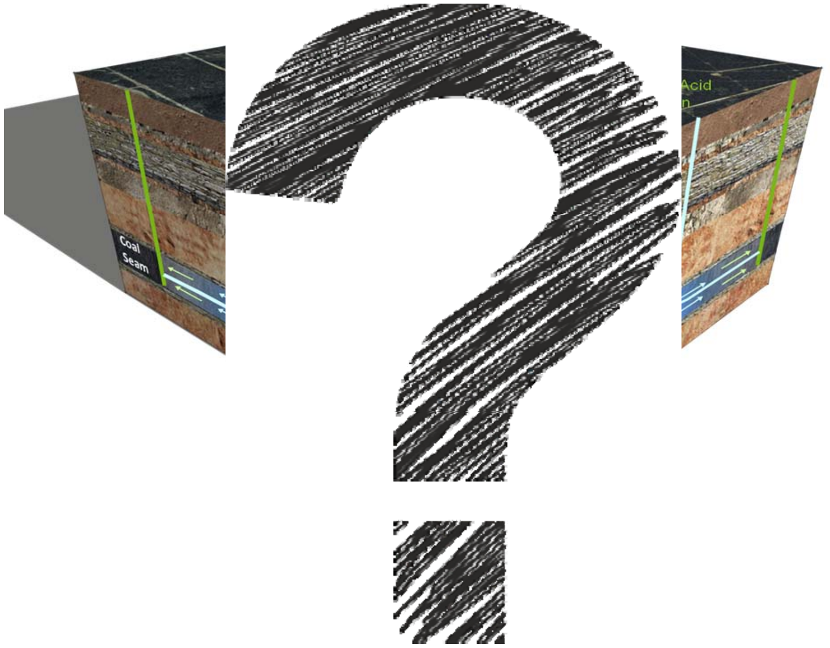
Microbes (methanogens)

Coal



Applications of Coal Bioconversion

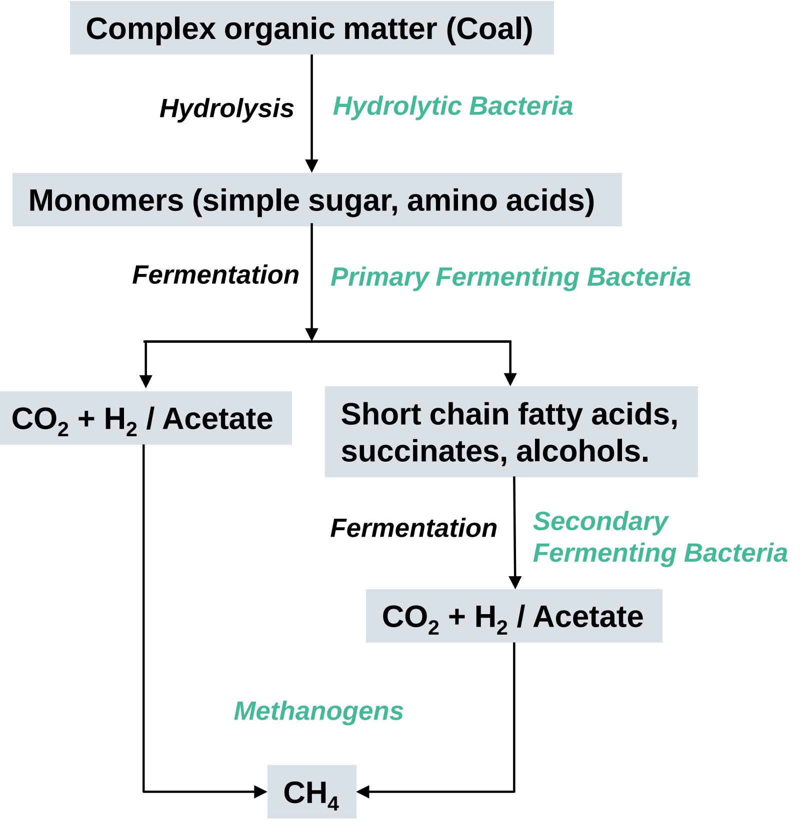
- This technology is suited for application in multiple situations:
  - Mined out coal seams,
  - Depleted coal bed methane reservoirs,
  - Waste/ undersize products of coal mines,
  - In-situ coal gasification,
  - Maybe more…



Microbes and Methane

The Concept of Consortium:

- The Driving Force: **Metabolism**
  - Limited by the lack of metabolic energy.
  - Overcome by mutually beneficial syntrophic relationships.
- The Action: **Microbial Transformations**
  - i. Hydrolytic/cellulolytic bacteria.
  - ii. Primary fermenting bacteria.
  - iii. Secondary fermenting bacteria.
  - iv. Acetoclastic and hydrogenotrophic archaea
- The Result: **Methane Formation**
  - Methane being dominant followed by carbon dioxide.



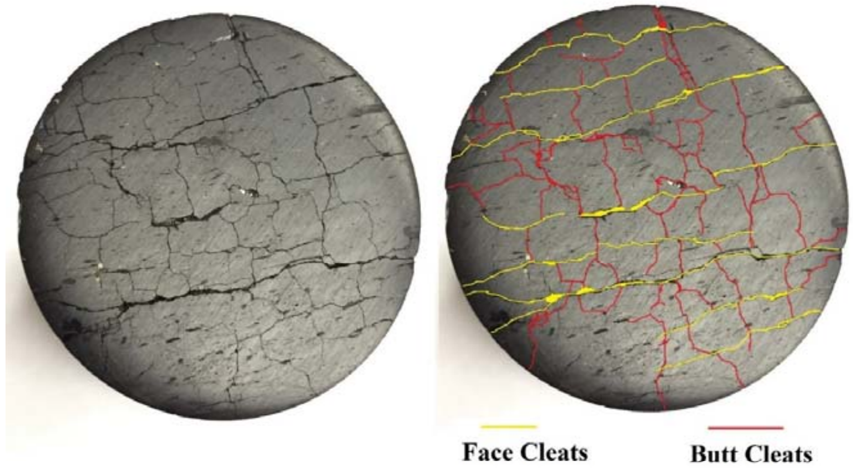
Coal Structure and Flow Characteristics

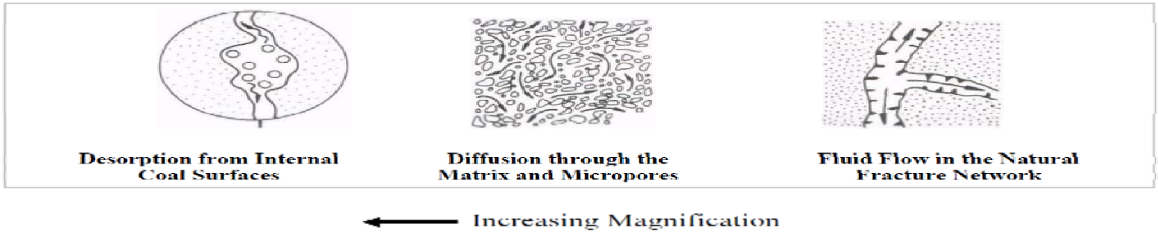
Structure of coal

- Coal has a distinct dual porosity structure:
  - Micro (<2 nm) and macro (>50 nm) pores
  - Micropores make up the matrix
  - Macropores make up the cleat network of face and butt cleats.

Gas transport in coal:

- Flow in CBM environments is three phased:
  - Desorption from the pore surface.
  - Diffusion from the pores to the cleats.
  - Darcian flow in the cleats leading to the wellbore.





Gas flow model through coal (King, 1985)

Past Work

Andrew Scott in 1994, learning the biogenic origin of coal bed gases, suggested the use of the process to enhance natural gas production from coal seams. Following which;

- Jones et al. in 2010 treated Zavala county coal to produce microbial methane.
- Papendick et al. in 2011 demonstrated potential for biogenic methane in Surat Basin, Australia .
- Opara et al. in 2012 screened ~150 different microbes, and successfully converting coal to methane

No documented studies characterize changes in coal properties as a result of bioconversion.

Objective of Study

The primary objective of the work presented was to evaluate the changes in coal properties brought about as a result of continued *in situ* bio-conversion.

Specifically, the properties to be evaluated are the sorption and diffusion characteristics.

Procedure

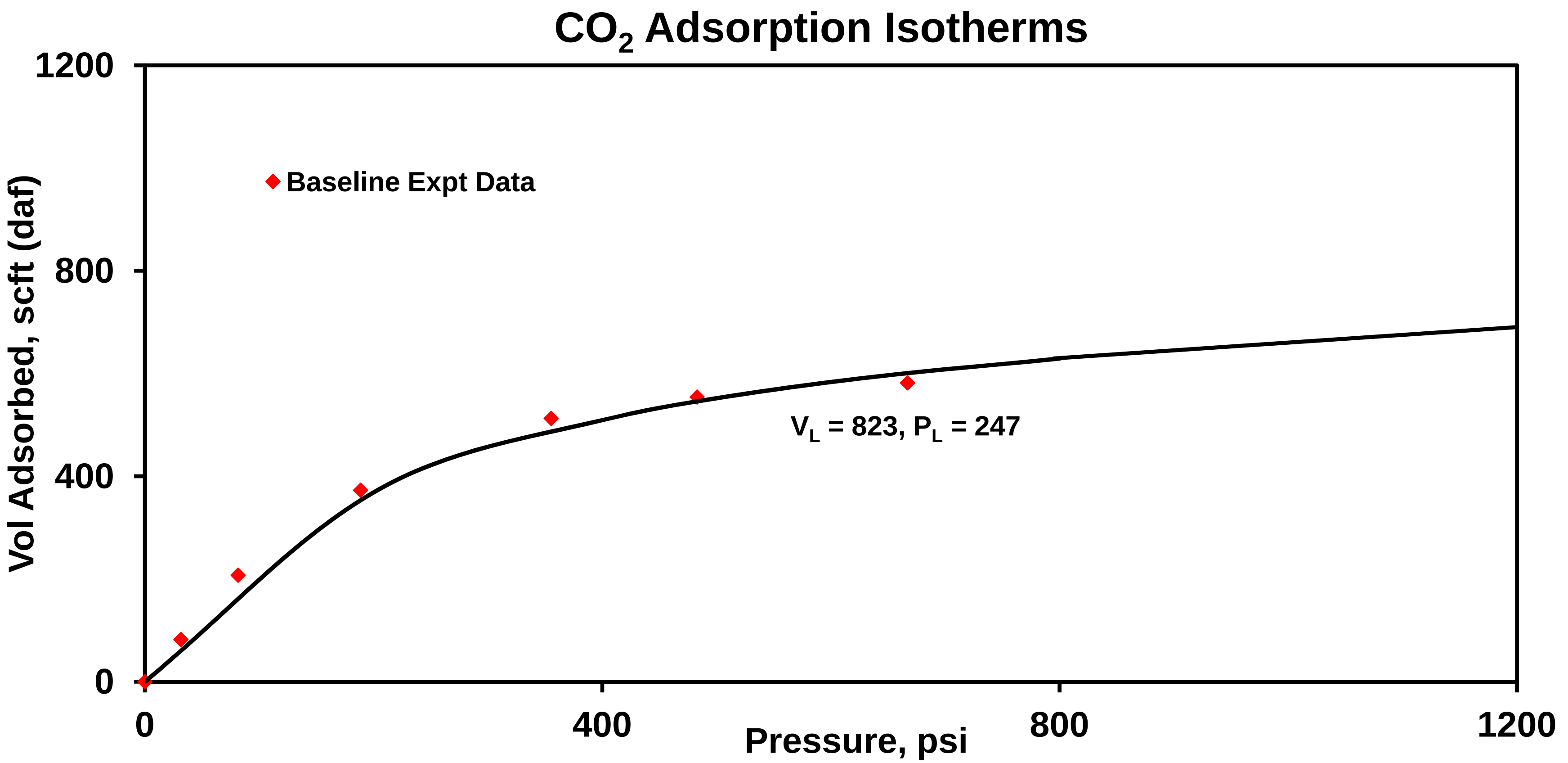
- A two step process has been followed:
  - Step 1: Estimation of baseline properties:
    - ❖Virgin/Untreated coal from Illinois 6 seam was tested.
    - ❖Sorption and Diffusion properties were obtained.
  - Step 2: Documenting changes due to bio-conversion:
    - ❖IL 6 coal was treated with methanogenic consortia over 30 and 60 days.
    - ❖Sorption and Diffusion properties were obtained at the end of treatment.

Production of Gases

Reactors were tested for methane and CO_2 content at the end of 30 and 60 days of methanogenesis.

Duration	CH_4 (scft)	CO_2 (scft)	Undetected (scft)
30 Days	92.7	65.4	60.9
60 Day	141.8	72.4	4.7

Experimental Results



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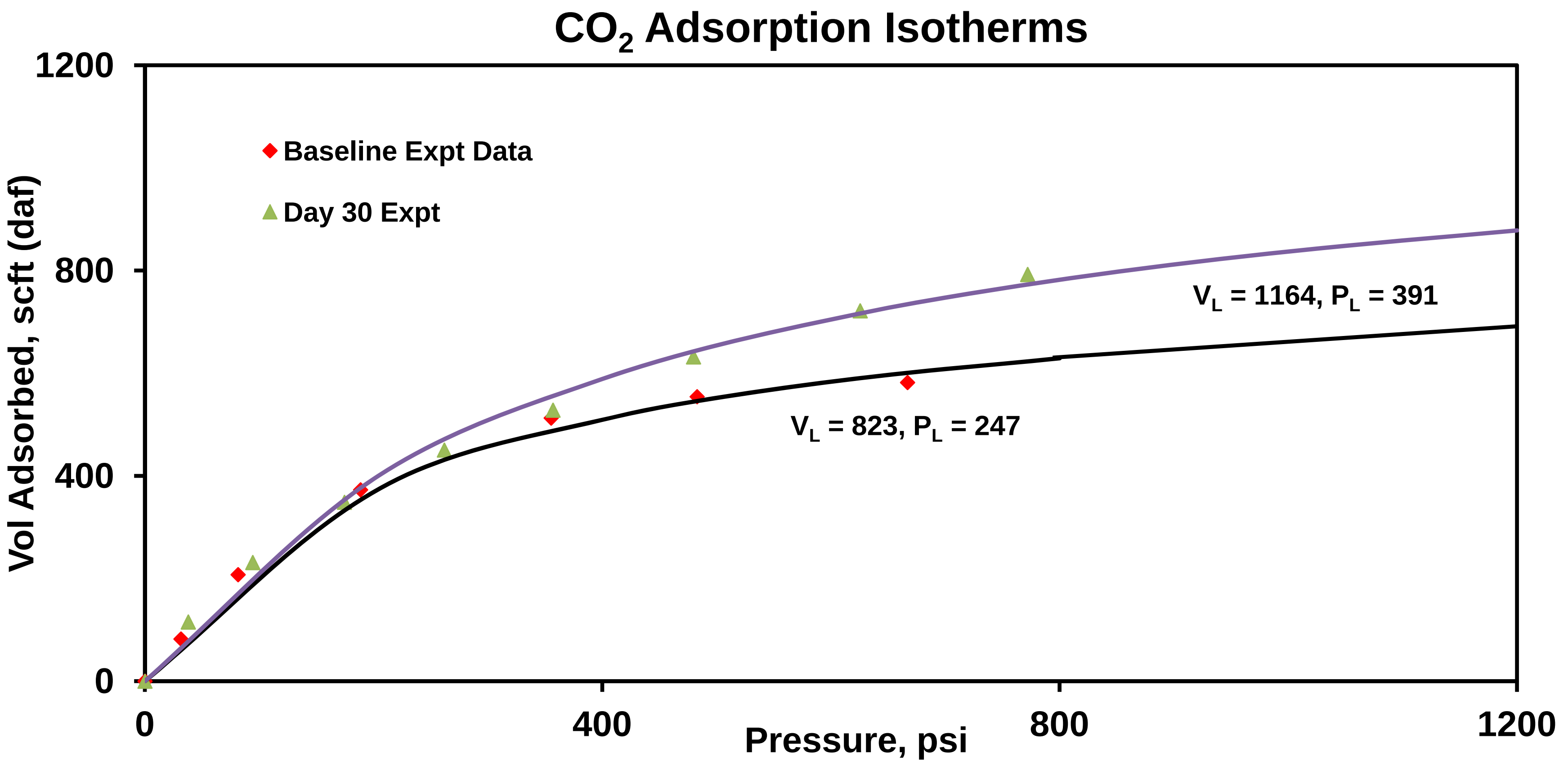

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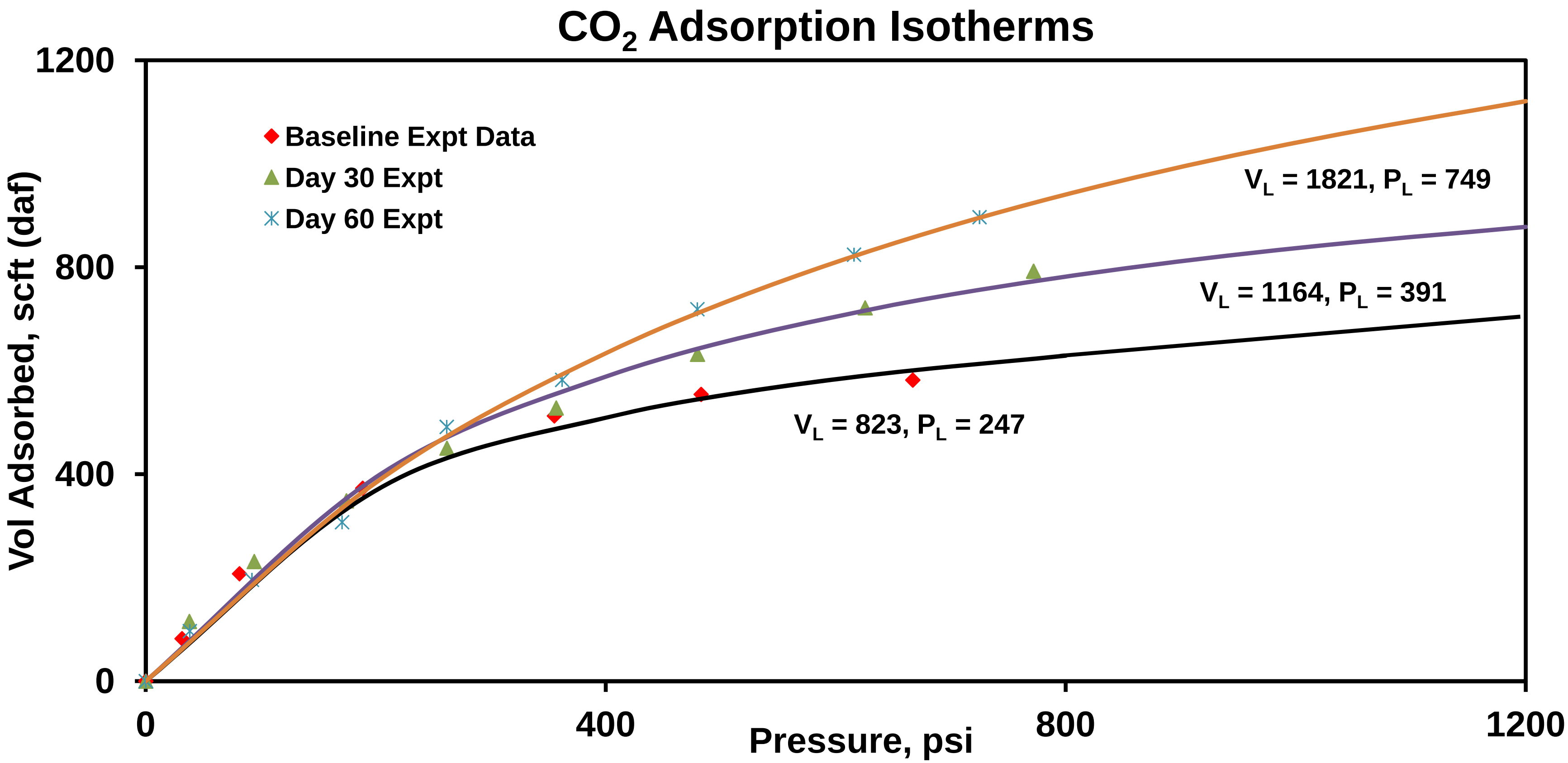

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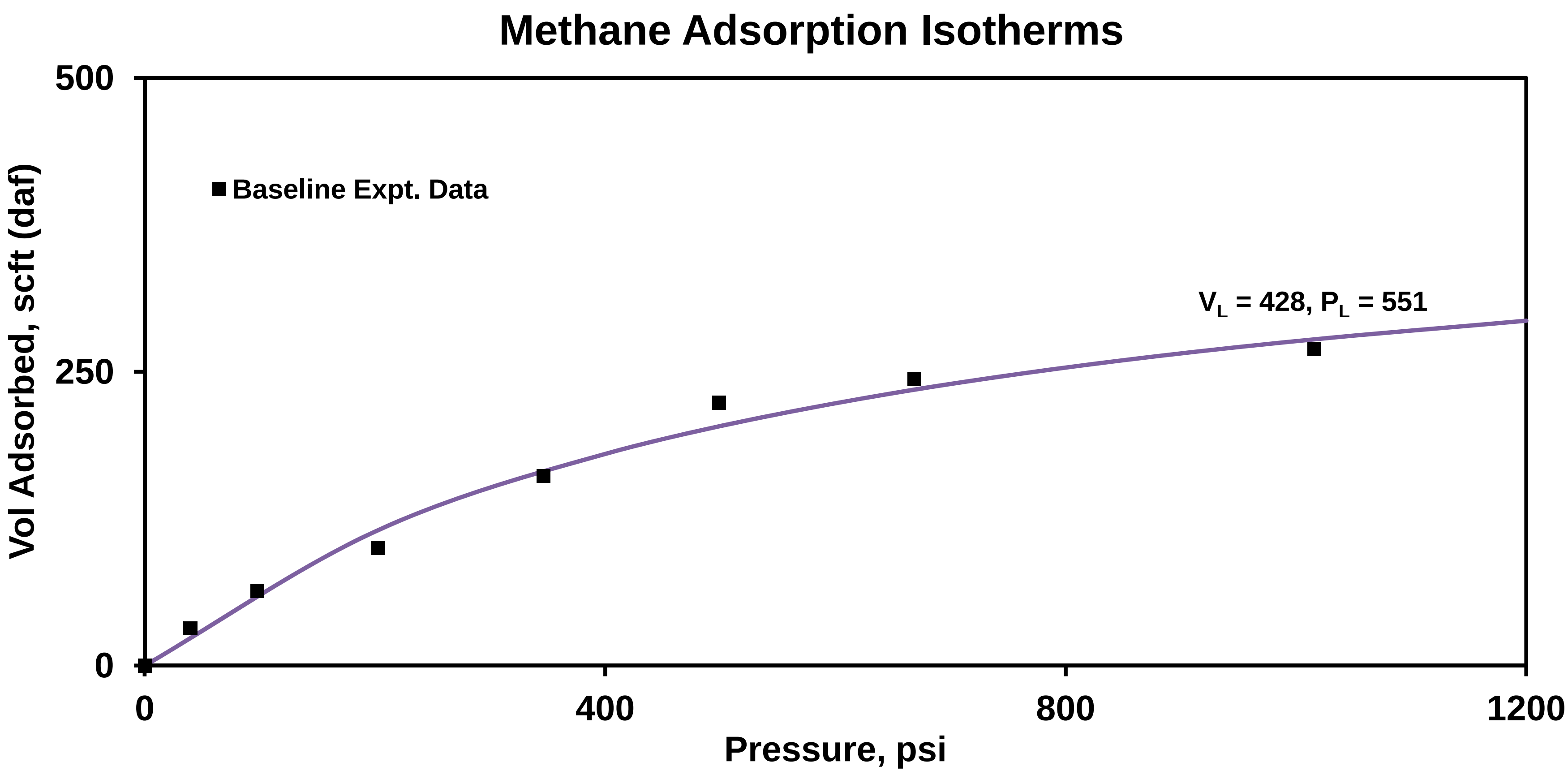

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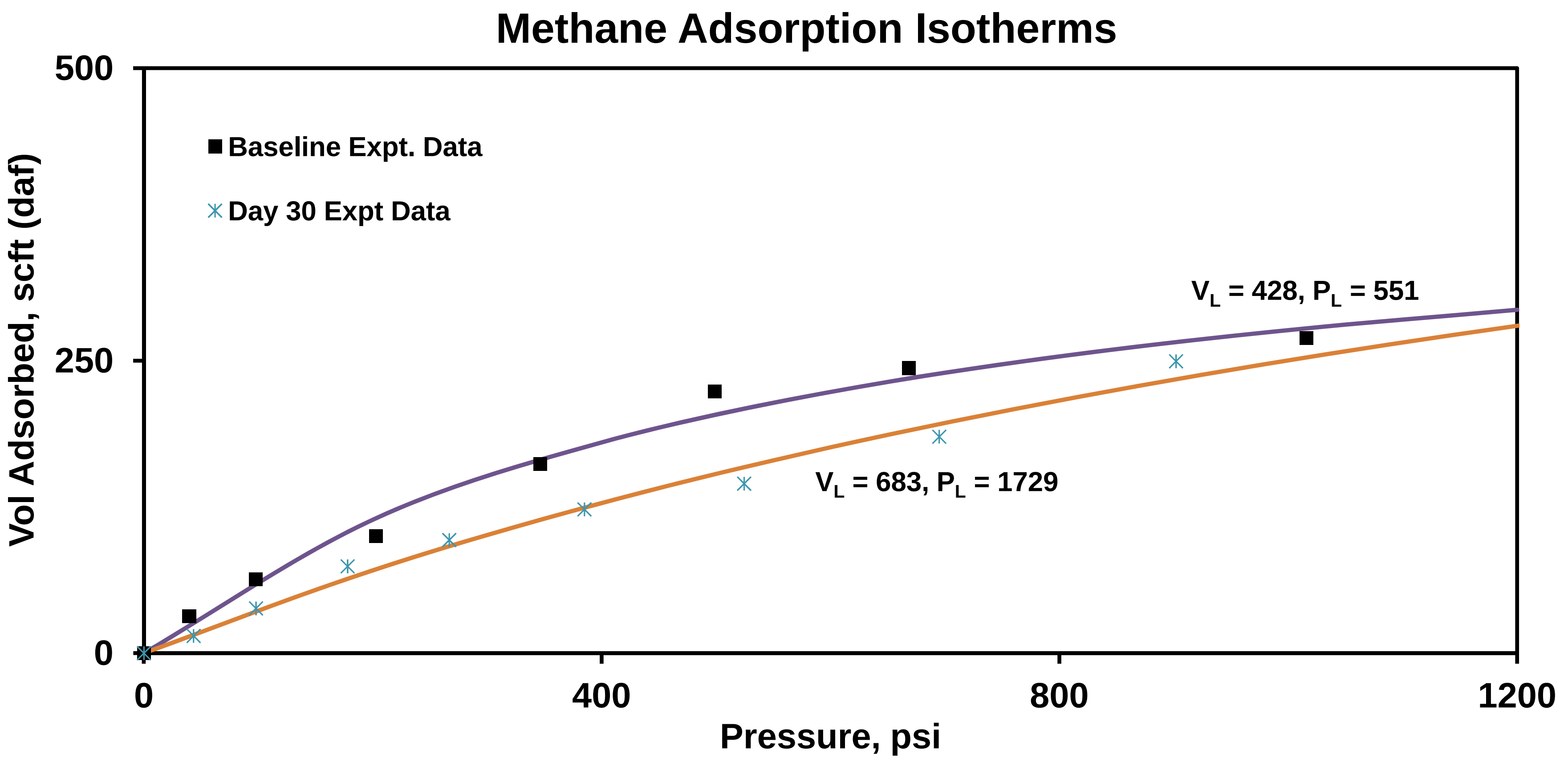

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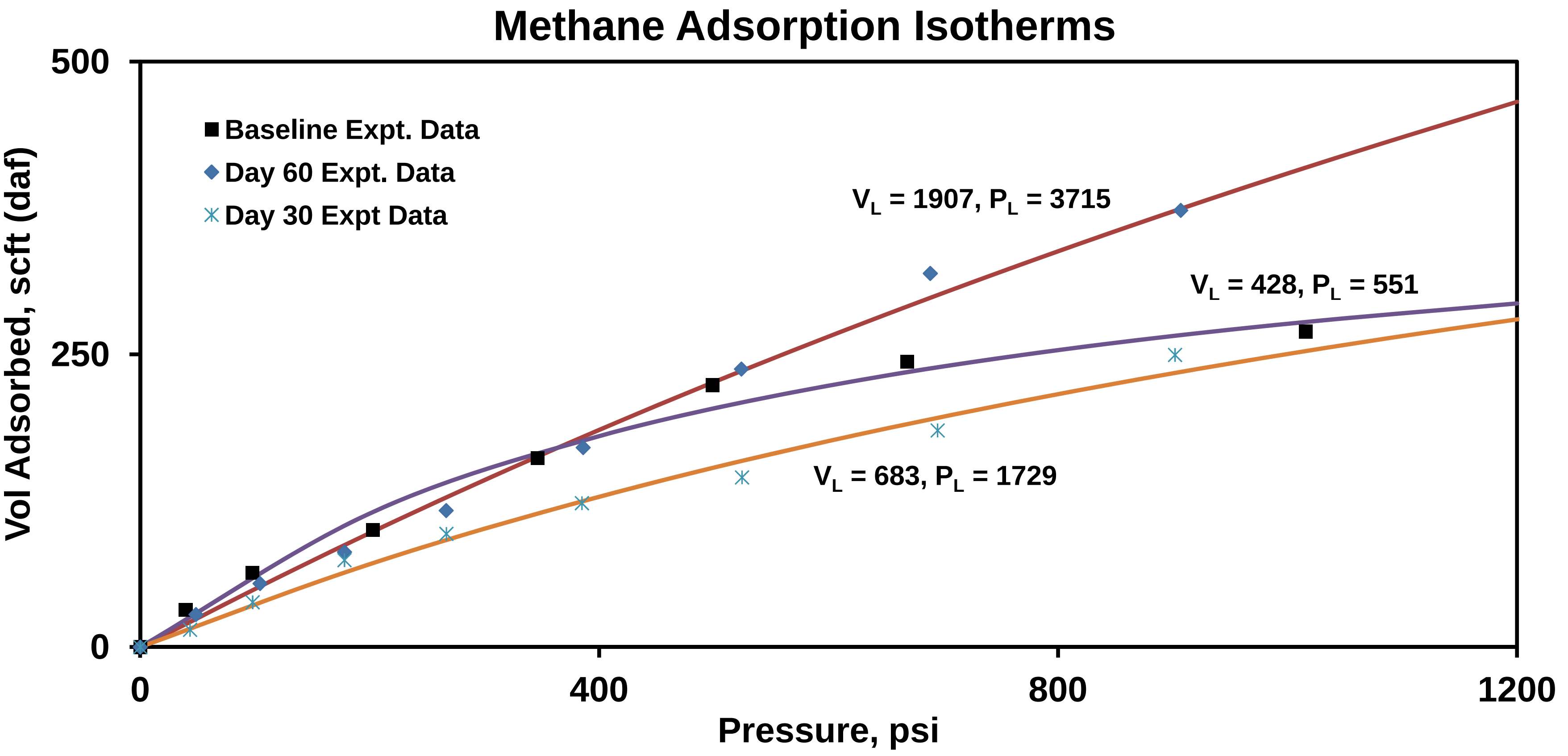

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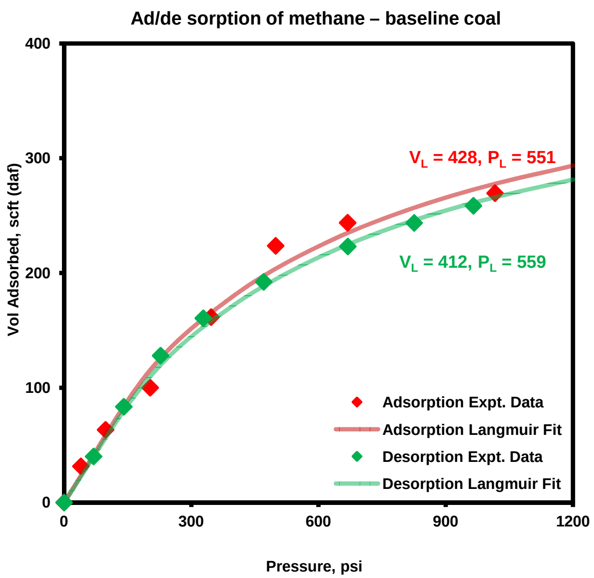

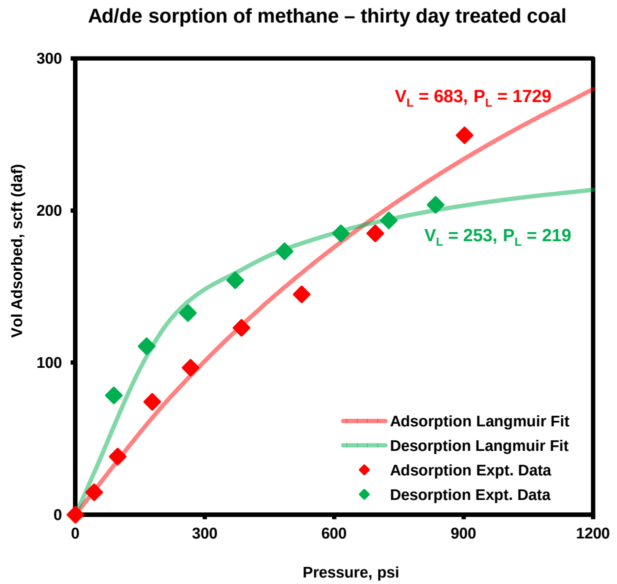

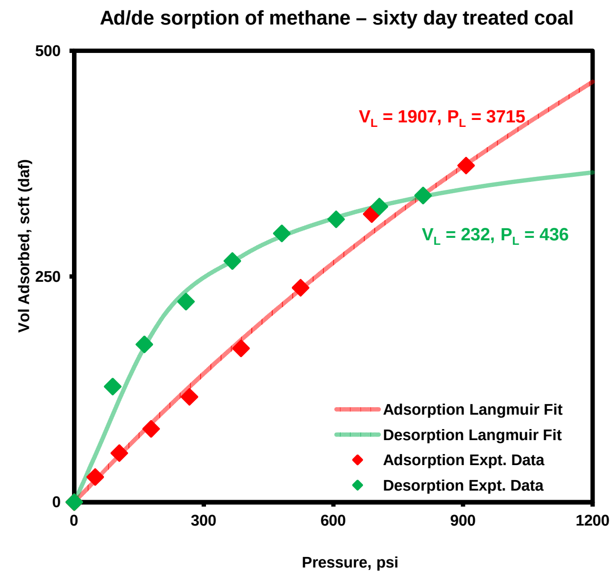

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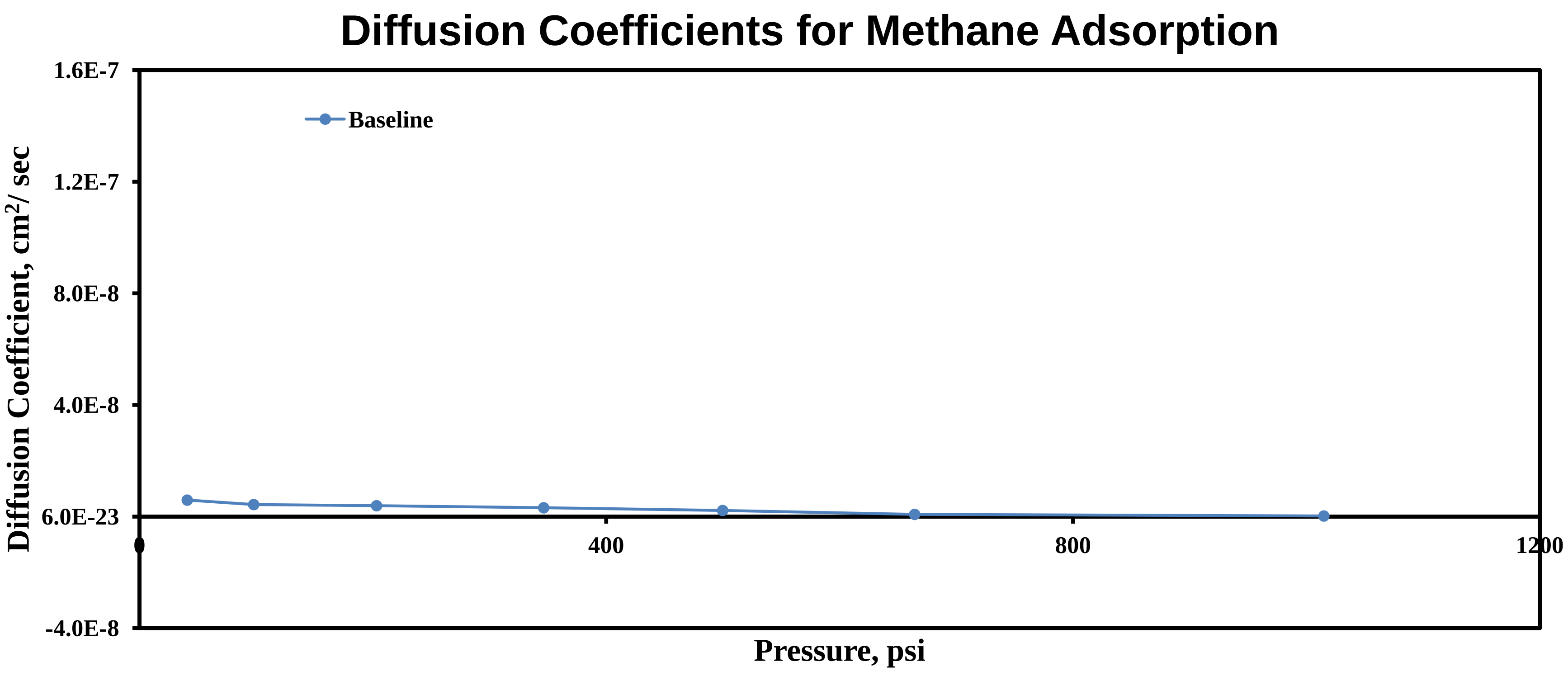

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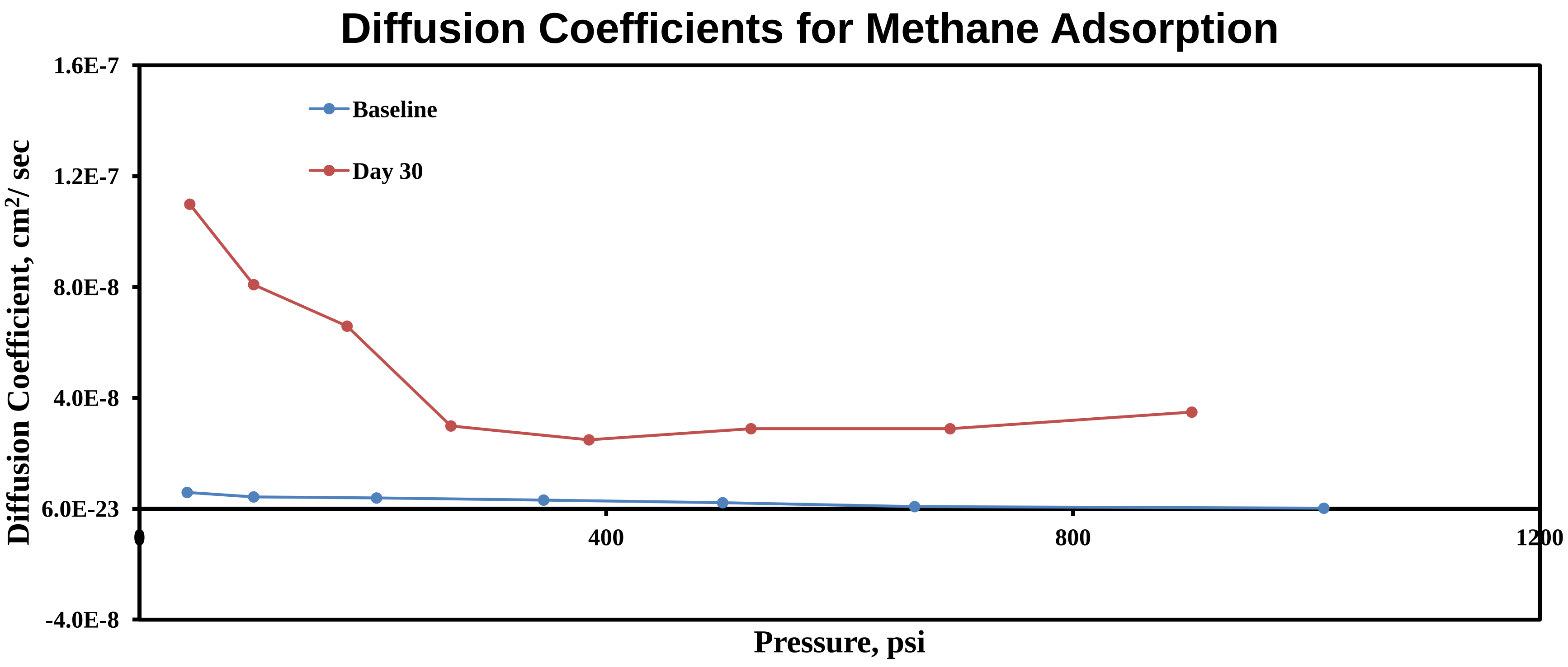

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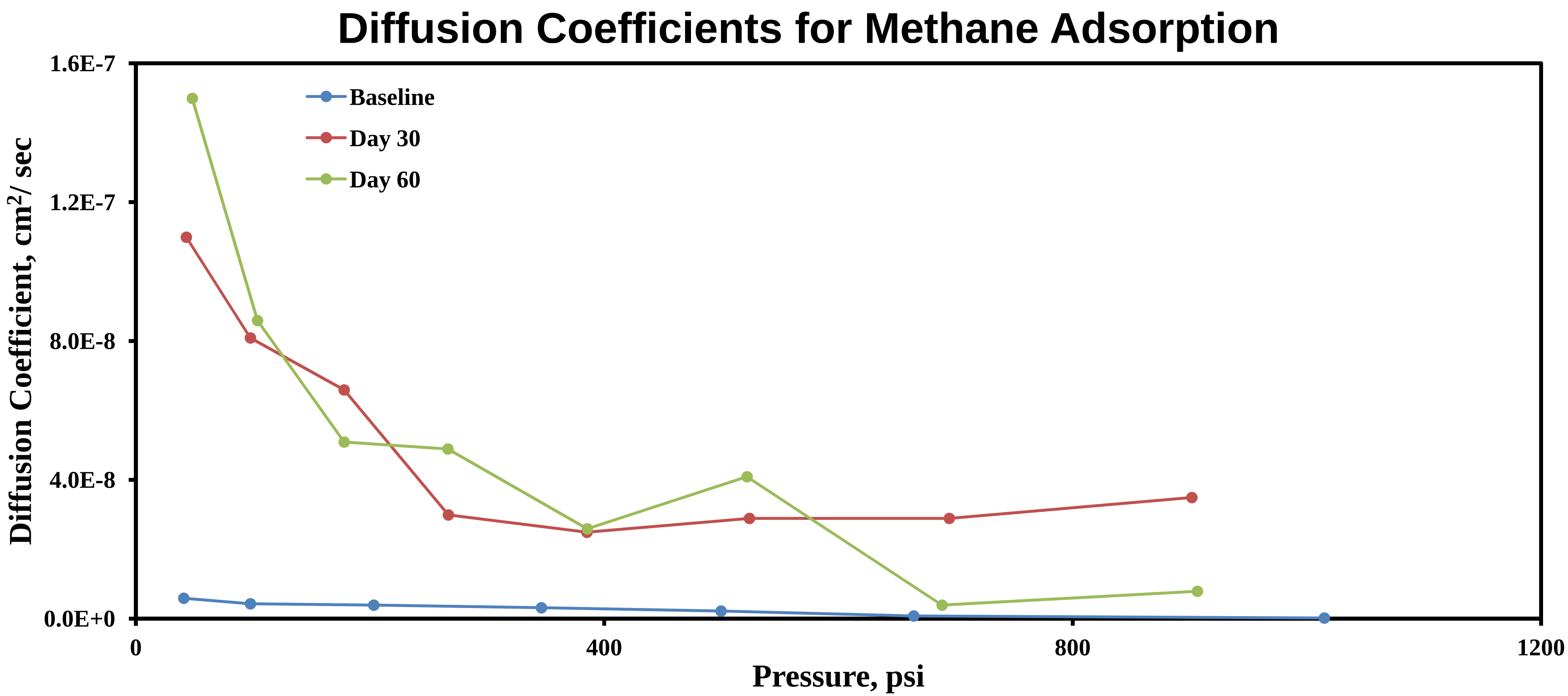

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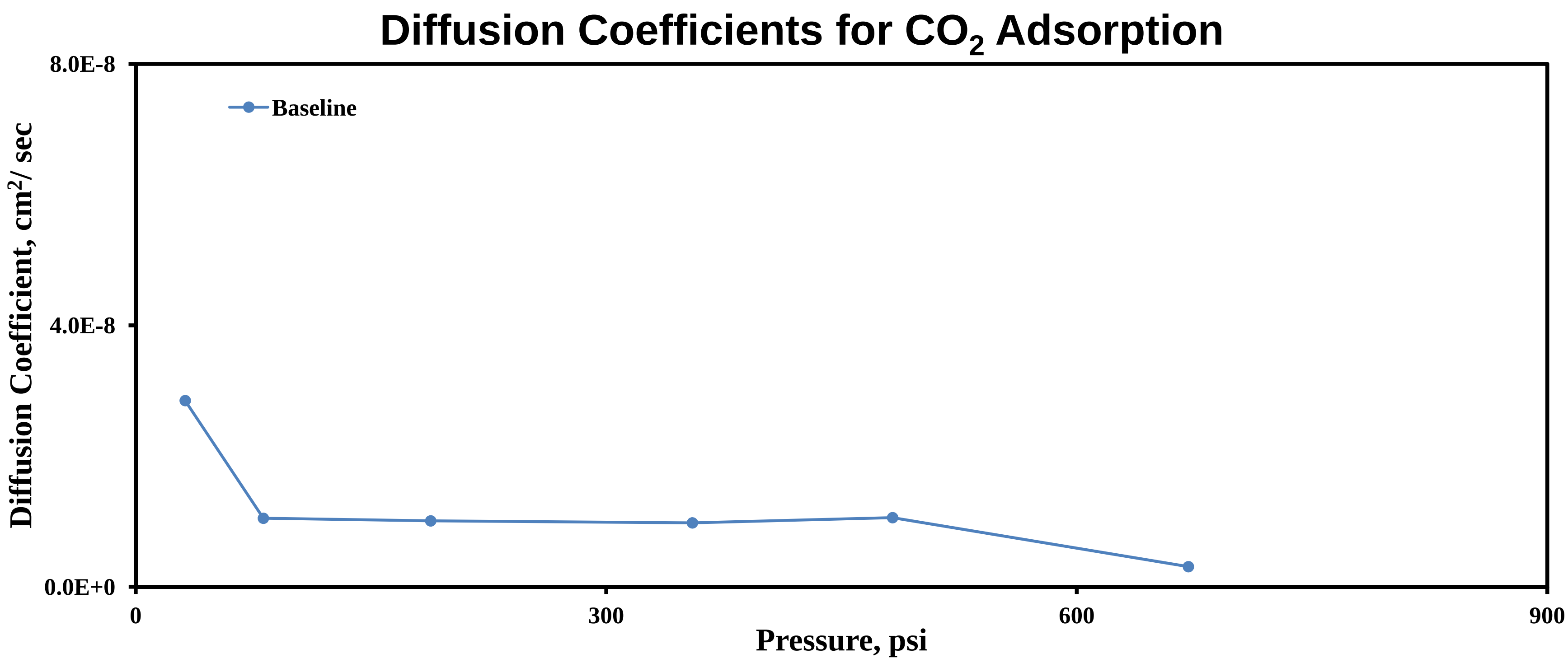

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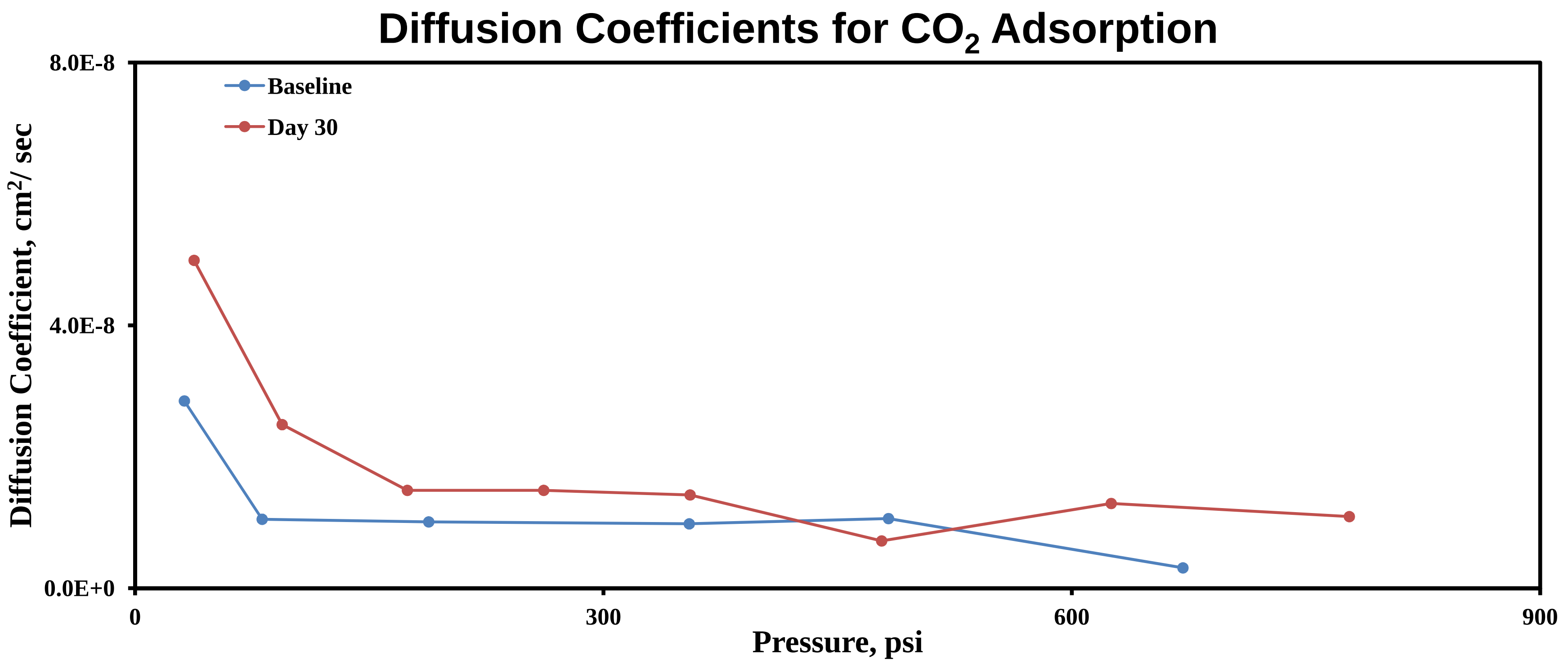

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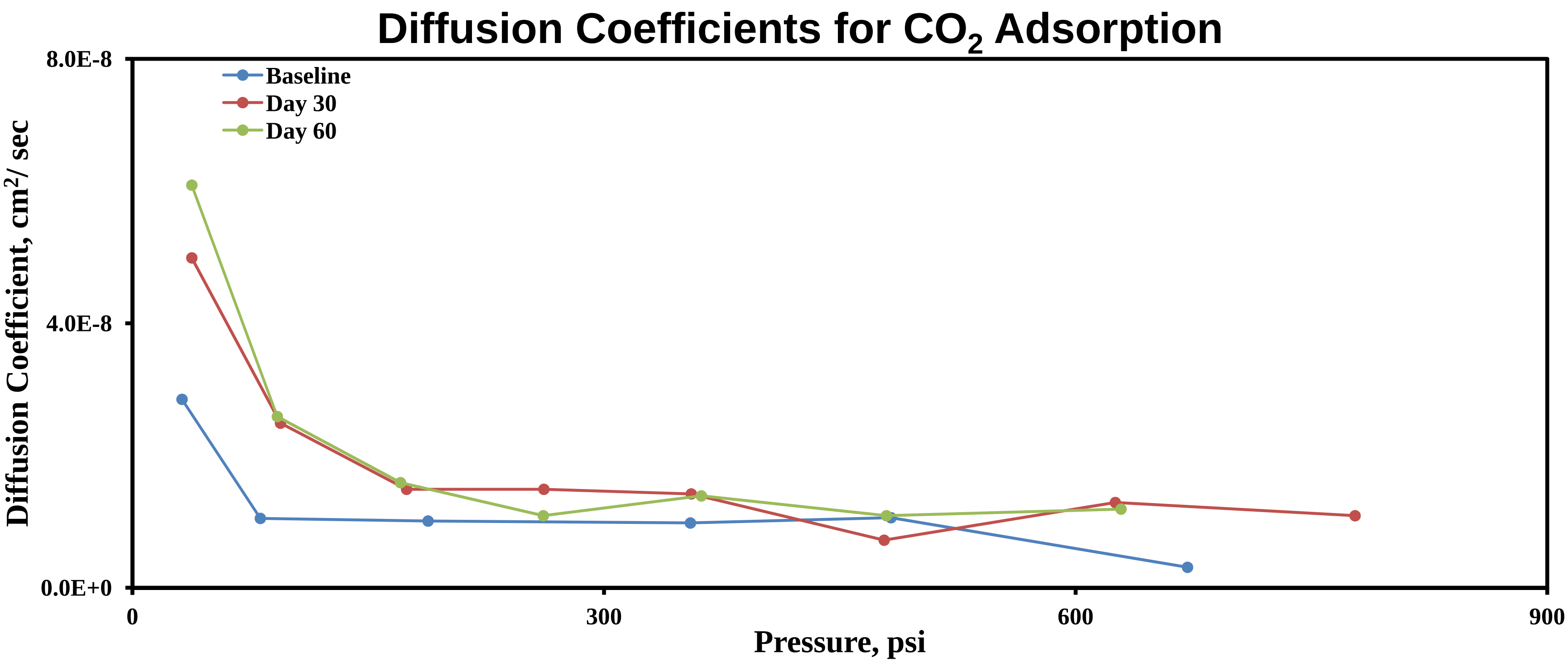

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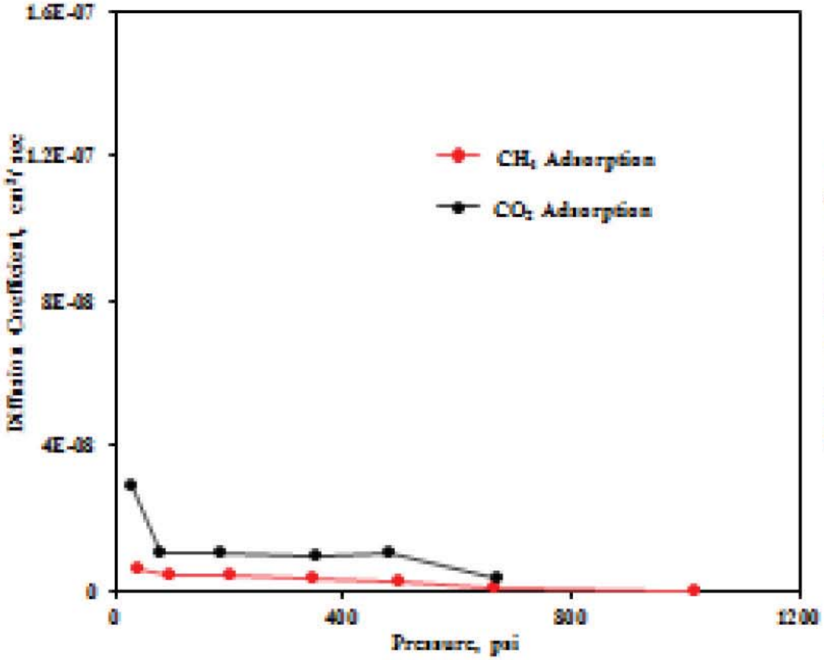

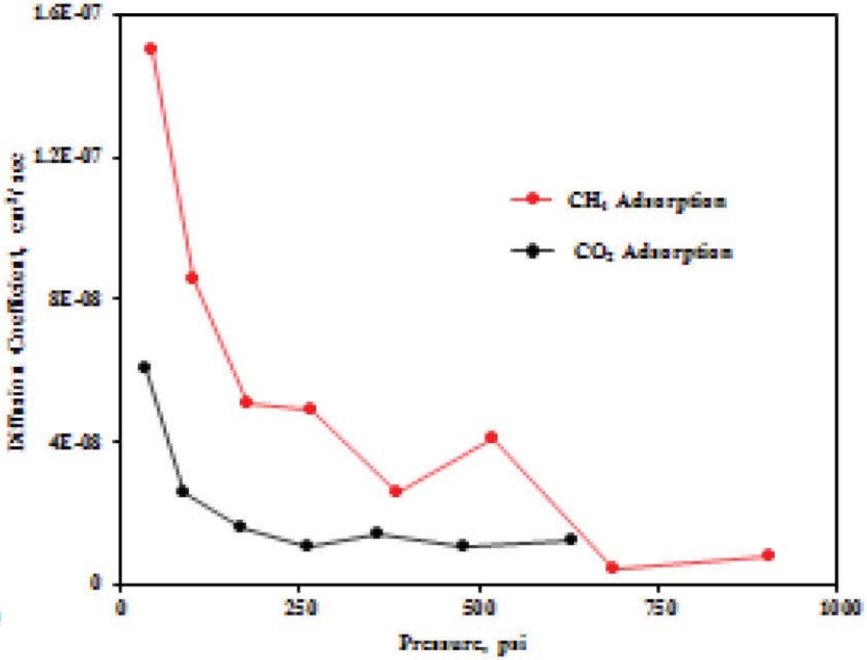

Non-monotonic Size Dependence of $D_e(r)$

Einstein-Stokes equation relates diffusion coefficient (D_e) to size of a diffusing molecule (r) as:

- $D_e \propto \frac{1}{r}$

Modal size of coal micropores is ~10 Å, with even smaller throats.

Dagdug et al. (2008) improved the equation for pore structure similar to coals to:

- $D_e \propto \frac{1}{r}$ for $r \ll a$ and $r > a$.
- D_e deviated non-monotonically for $r \approx a$.
- Variations in end-cavities resulted in a non-monotonic behavior of D_e.

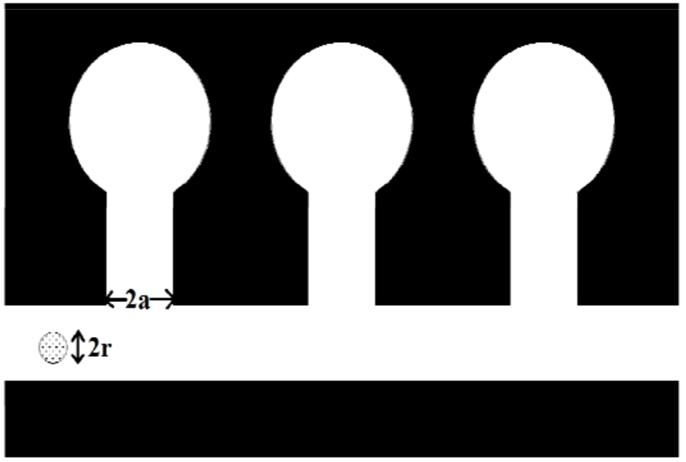

Fig: A tube with identical periodic dead ends with entry radius of ‘a’ and a diffusing particle of radius ‘r’.

Implications:

Larger particles can diffuse faster compared to smaller particles.

In CBM environments, 3.3 Å and 3.8 Å are the diameters of CO_2 and CH_4

Non-monotonic Size Dependence of $D_e(r)$

Diffusion Characteristics

- Baseline coal agreed with Einstein-Stokes equation, where D-CO_2 > D-CH_4.
- Treated coal followed Dagdug's observation, where larger CH_4 had higher diffusion rates.
- Thus it was concluded that, due to bio-conversion, the pore structure of coal changed to facilitate longer diffusion paths for CO_2.

Non-monotonic Size Dependence of $D_e(r)$

Adsorption Characteristics

- Methanogens consume coal along the pore entries, increasing pore area along entries, resulting in adsorption along the tube surfaces.

- Limiting the entry of the diffusing molecule results in preferential adsorption along tube walls at low pore pressures, and not the pore throat or cavity, explaining low volumes of gases adsorbed.

- Increased pore pressures increases Brownian collisions, eventually filling up sorption sites in the pore cavities at higher pressures.

Non-monotonic Size Dependence of $D_e(r)$

Desorption Characteristics

- Sorption along tube walls explain small volumes of methane being desorbed at higher pressure. The volume of gas desorbed at lower pressures increased significantly.
- At lower pressures, less Brownian collisions make it easier for the gas molecules to desorb from micropore cavity, thereby more volume.
- In addition to the assumptions in Langmuir's equation, preferential desorption from the tube walls at higher pressure results in the observed hysteresis.

Conclusions

- Sorption capacity of coal treated with microbial consortia was found to increase, which is indicative of the potential of long-term production of coalbed gas especially from depleting or depleted CBM wells/reservoirs.

- Results indicate preferential consumption of coal from the tube entries, thus accounting for small volumes of gases being adsorbed at lower pore pressures.

- Significant desorption hysteresis was observed, and is accounted by preferential desorption from sites in the tube entries leading to micropore cavities.

- Diffusion characteristics for baseline coal was in agreement with accepted data, whereas, treated coal exhibited a non-monotonic dependence of $D_e(r)$.

- Increased rates of diffusion for treated coal can have significant impact on basins such as the Illinois, where in spite of moderate permeability, extremely low diffusion rates have plagued CBM production.

Current Study

BIG QUESTION

In-Situ Feasibility

Generation Rates & Permeability

- **DOE #FE0024126** : Optimized Microbial Conversion of Bituminous Coal to Methane for In Situ and Ex Situ Applications; SIU Carbondale.

- **DOE #FE0026161:** A Scaling Study of Microbially-Enhanced Methane Production from Coal (MECBM): Optimizing Nutrient Delivery for Maximized Methane Production; Pennsylvania State University and SIU Carbondale.

THANK YOU