2006 INTERNATIONAL COALBED METHANE SYMPOSIUM

0639

CO_2-ECBM DEVELOPMENTS IN EXPERIMENTS
A SUMMARY OF A WORKSHOP HELD AT DELFT UNIVERSITY OF TECHNOLOGY, DECEMBER 2005

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ABSTRACT

In order to understand CO_2-ECBM, sorption, diffusion, wettability and swelling results from experiments on the coal-CO_2-CH_2-H_2O systems are compared and explained. Variation in sorption methods and procedures make comparison of results complex to compare. To improve experimental precision, for CO_2 sorption in particular, accurate pressure and temperature measurements under super critical conditions are essential. Additionally, swelling behavior of coal can change volumes. Ash content, maceral type, degree of coalification and pressure variations change the wettability of coal. Hence, wettability experiments at scales varying from nanometer- to centimeter-range, and three different methods of swelling measurements, are discussed. The swelling experiments are also used to determine swelling induced cleat permeability and associated stress built-up. Since the experiments take months and are very expensive, institutes must find agreement how to regulate measurements and results. The results are valuable input parameters for modeling.

INTRODUCTION

During a three day workshop on laboratory and theoretical work, held at the Faculty of Geotechnology, Delft University of Technology, laboratory researchers presented results of sorption, diffusion on and wettability of powdered coal, core flooding experiments, and field scale behavior in a CO_2-CH_4-H_2O-coal environment. In view of the fact that coal research is complex, time-consuming and expensive and results obtained by different groups are often ambiguous and inconsistent, this workshop aimed at bringing together experimentalists and modelers from different institutions to discuss ways of co-ordinating research efforts in this field. The presentations outlined technical procedures, progress and limitations in ECBM-related research with supercritical CO_2. The scope ranged from the assessment of

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fundamental thermodynamic and sorption-kinetic properties on coal powders and cuttings over coal plugs to whole core experiments and the aspects involved with upscaling to seam- and field-size. At the Dietz-laboratory in Delft, experimental activities are divided in micro-, meso- and macro-scale (figure 1). In this way of acting, intensive co-operation between the fields of geology, petroleum engineering, chemistry and geophysics/petrophysics is essential. Communication with other institutes and groups is essential, for example, in the distribution of workload, constructing of equipment, etc.
The three-day workshop program was dedicated to three topics; “Size and sorption”, “The seam and its environment”, and “Combining Methods and New Thoughts”. The authors of this paper present work from their institutions. Procedures, methods and equipment and the use of related theory, were discussed and conclusions were validated for homogenization and up-scaling. In this paper, presentations of the participants and discussions during the workshop are merged with special focus on coal powder and whole core experiments related to sorption, swelling, the relevance of CO_2-wettability and permeability. References are made to the abstracts and papers of this workshop, which are placed on the web-site:
http://www.citg.tudelft.nl/live/pagina.jsp?id=1f6bf92a-cae3-4f01-8a5b-03e97a3e706b&lang=en

SORPTION AND DIFFUSION EXPERIMENTS

Experiments on Powdered Coal

In the work of Busch, Siemons and van Hemert, the method of sorption determination is comparable (Figure 2). The set-up consists of a sample cell and reference cell with a pressure transducer. The whole system is placed in an oven or bath to keep it at constant temperature. Gas is inserted or removed via the reference cell. The essential differences between the set-ups are the volumes of the reference cells and sample cells. Busch, Siemons and van Hemert showed many corresponding results in sorption experiments, such as:

- Roughly two times the amount of CO_2 can be adsorbed to powdered coal, compared to CH4. In addition, the equilibration of sorption proceeds more rapidly for CO_2 than for CH_4.
- Diffusion, or sorption rate, decreases with an increase in grain size fraction for CO_2 and CH_4. But also, a preference of macerals concentration is observed with grain size distributions. As a result, sorption behavior changes for different experiments with the same coal sample.
- (Partly) Saturation of coal with water causes a serious increase in equilibration times for both measurements with CO_2 and CH_4.
- Equilibration times decrease with temperature for both gases and pressure (surface coverage) has a strong negative impact on half-life sorption times of CH_4 and CO_2.

Busch and Siemons used dual models to describe effective diffusion in powdered coal. Busch developed a model with two effective diffusion coefficients for transport and successive sorption in macro- and micro-pores, which occur at different time scales. A linear combination of two 1st order rate functions with different rate constants or half-life times ($\tau_{1/2}$) as characteristic parameters of the combined adsorption- and diffusion processes provide the characteristics for specific grain sizes, temperature and gas pressure (Figure 3.A). In a comparable way Siemons considers the coal as a combination of amorphous particles (fraction φ_A) and crystalline particles (fraction φ_B) with different characteristic diffusion times τ_1,τ_2 (Figure 3.B). In order to calculate diffusion he used the Stehfest algorithm for inverse Laplace calculation and the EXCEL© optimizer tool. For a given fraction φ_A, the characteristic times τ_1, τ_2, and the initial and final pressure, respectively P(t=0) and P(t$\rightarrow\infty$) are calculated.

Accuracy of the Experiments

Busch presented results from a Round Robin on Argonne Premium Coals. Five institutes performed experiments on three coal samples under comparable conditions, i.e. experimental temperature, 55°C; pressure, up to 130 bars; moisture-equilibration at 55°C, but no rules for equilibration time, experimental setup, etc. Comparison of the results showed that moisture-equilibration between

different labs was not acceptable and could vary more than order of magnitude (variation for Pocahontas: 0.7 to 14 %). Sorption data of the different laboratories are comparable up to circa 50 bar working pressure. At higher pressures variations may increase to 100%.

Variations as mentioned above are discussed by Siemons and van Hemert, who analyzed experimental results on accuracy and precision. Especially, the behavior of CO_2 sorption on coal is investigated. Inaccuracies, or inconsistencies in sorption measurements usually starts when CO_2 approaches the super-critical stat, e.g. ~74 bar. Several options were mentioned as pitfalls for inaccuracies. They can be divided in two groups; measurement errors and phenomena affecting the gases and the sample. In the first category, systematic errors of the thermocouples and pressure transducers are known. Off-set, digital accuracy, drift and environmental influences (i.e. changing room temperature) are well know, but often underestimated.

In the presentation of Siemons, the calibration of the equipment with helium showed for an empty sample cell and a sample cell with a steel core a standard deviation of 0.53% and 0.70% respectively for the normalized volume ($V_{Sample}/V_{Referemce}$), for pressures ranging from 3 to 37 bar. Now the first error is introduced when the helium void volume is considered the same as the carbon dioxide void volume. Thereafter, he showed with a thermocouple calibration in a CO_2 blind run the vulnerability of calculated normalized volumes. Using for temperature and pressure single offsets of -1.08°C and 0.576 bar respectively, and applying EOS for CO_2 (Span & Wagner) on 30 pressure steps, he calculated for a normalized volume a standard deviation of 14.9% (Figure 4.A). In the next parameter study, by using a fixed pressure, a fixed temperature or no constraints on the same dataset, the standard deviations on normalized volume were 10%, 3.9% and 3% respectively (Figure 4.B,C,D).

Van Hemert approached in his presentation the accuracy problem from a theoretical point of view. He applies a model to compute the influence of experimental and physical uncertainties on sorption measurements. Using the physical dimensions of his duplex sorption apparatus and inserting theoretical uncertainties as input parameters, i.e. systematic errors for T and P (0.1 K, 0.51% respectively) and random errors T and P (0.5 K, 0.05 bar respectively), where random errors were assumed as normally distributed, he calculated deviations in adsorbed CO_2 of at most 25 % (Figure 5). He concluded that very accurate measurements are essential for CO_2 sorption measurement. Systematic uncertainties are not negligible and miscalculations of curves are without difficulty attained by pressure and temperature inaccuracies.

Figures 4 and 5 show that deviations start when CO_2 approaches super critical state and beyond. Van Hemert suggested improvements, e.g., increasing the amount of adsorbed CO_2 compared to the free CO_2, or improvement of the EOS for CO_2 at higher pressures. Siemons suggested, as an alterative, to compensate for the void volume in the sample cell. Depending on the gas pressure, the void volume reduces by coal swelling and the formation of a layer of adsorbed molecules. The design of our experimental set-ups makes it not feasible to recognize and to distinguish the effects mentioned. Moreover, it is not possible to estimate their contribution to an overall volume change, which is also unknown. For this reason, he used bulk volume corrections that were limited to a constantly increasing adsorption behavior. The application of the corrected void volume to all pressure steps can be interpreted as an average volume correction over the whole experiment (Figure 6).

Effects of Ash and Moisture

The variation in moisture values on the Round Robin, as presented by Busch, could be the result of different preparation techniques, methods of analysis, but also heterogeneity in samples. Bossie-Codreanu demonstrated with different techniques how macro- meso-/micro- and nano-size pore distribution is defined. Figure 7.A shows the nano-scale distribution (Angstrom scale) of coal pores, obtained with small angle neutron scattering (SANS). For micro-/meso- scale measurements, NMR provides good results with high resolutions. Even macro scale (up to cm) was measured (Figure 7.B), but better characterized by using CT-scans (Figure 7.C,D). CT-images give the best prospect to measure cleat density, -orientation and cementation. Prinz confirmed this pore distribution in the sub-micro scales, showing that the coal structure consist of two phases, i.e., the crystalline phase inaccessible to water,

and the amorphous phase that can be penetrated with water to a certain degree. He divided the system in macro-pores, or, a macro-molecular network of crystallites (aromatic carbon structures) and Molecular Orientation Domains (MOD´s).

The micro-pore system consists of two groups:
1. The meso- and macro-porous structure (2-200nm) (Figure 8.A)
2. The ultramicro- and micro-porous structure (0-2nm)

His adsorption isotherms on moisture-equilibrated coals suggest that the presence of water in coals reduces the adsorption space to the ultramicro-pores of the crystalline phase, i.e. the sorption places for CO_2 and CH_4. Furthermore, only the low rank coals are characterized by a wide pore size distribution, whereas the high rank coals do not show any significant meso- or macro-porosity(Figure 8.B).

A clear example by Siemons shows the variation in moisture with grain size and ash content (Figure 9.A). In the Tupton coal, the ash content decreases with increase of grain size. In the Selar Cornish coal, this relation is not observed and the ash content might affect sorption characteristics.

Plug used a newly developed set-up that measures capillary pressures as a function of the system pressure. From the capillary pressure curves the wettability of grounded coal can be obtained. For medium and high rank coal the primary drainage capillary pressure curves show a water-wet behavior (Figure 10.A). Secondary imbibition experiments show that the medium rank coal becomes more CO_2-wet as the CO_2 pressure increases. High rank coal is CO_2-wet during primary imbibition (Figure 10.B). The imbibition behavior is in agreement with contact angle measurements of Siemons. Hence, imbibition tests provide the most practically relevant data to evaluate the wetting properties of coal. The results illustrate that the effects of CO_2 (and probably also CH_4) on water saturated coal can be measured to obtain input parameters for modeling.

In addition, Busch showed that shales are able to adsorb CO_2 at 25% to 50% of the coal capacity (Figure 9.B). In addition, it is known from (partly) dried shales and clay minerals, that they are able to adsorb 10 to 30 vol.% of water, especially when smectites or kaolinite are involved. Hence, ash content of samples should be considered very carefully, before using of “homogeneous samples” in experiments.

SWELLING OF COAL

Methods of Measurements

Three different ways to measure swelling were introduced, all different in method and kind of coal samples used.
1. The method presented by Harpalani and Kumar, uses a coal cube that alternately is filled with He, CH_4, CH_4+CO_2 and CO_2 at different gas pressures. During this procedure, displacement transducers measure the strain in the three orthogonal directions. The coal cubes consist of solid coal, including a cleat system (Figure 11.A). The coal samples are thus free standing in a completely unconfined environment.
2. The method of Wolf-Mazumder, uses cylindrical cores with a differential stress over the sample sleeve, between the pore pressure and the supporting confining annular stress. Measured is the axial displacement over the length of the sample and the strain in the parallel and radial direction of the core with the use of four displacement transducers. Experiments could be conducted to measure both volumetric strain and permeability with multiple gas species(Figure 11.B).
3. The method of van Bergen and Spiers, uses powdered coal, which is compacted to a tight grain framework. The sample is fixed between plates in two directions, while swelling is constrained by a load in the third direction (Figure 11.C). A measure of the extra stress required to retain the piston in position is translated as a parameter to calculate the volumetric strain under confined conditions.

The three methods provide different swelling results. In the first set-up, solid coal or matrix is, independent of gas pressure, able to shrink or swell freely in all directions. Kumar presented results on He, CO_2 and CH_4 injection and resulting swelling in all cases (Figure 12.A). As for sorption experiments on powdered coal, the effects are the same for the gases, i.e. little effects when helium is used and much

effect for He+CO_2. The cylindrical cores of Mazumder's experiments are partly confined by a hydraulic stress, which is kept constant with the increase in pore pressure, and always is circa 3 MPa (Figure 12.B). In this way, a confining pressure and the increasing stiffness of the rubber sleeve around the core, partly limits volumetric strain. Under sub-surface conditions, injection pressures near or equal to the overburden stress will also play a role in the stress behavior of the seam. Mazumder and Bruining proposed a theory to explain the diffusion process of CO_2 in coal and its relation to matrix swelling. The theory introduced accounts for the phenomenon of anomalous diffusion which is observed when bituminous coal swells in CO_2. The theory explains the process in terms of the contrast in the diffusion coefficients (D_{rubber} and D_{glass}) and the viscosity of the "unswollen" coal. The swelling of coal matrix by the sorption of CO_2 is characterized by an anomalous diffusion process. They suggest the application of theories of sorption behavior of polymers for coals. Anomalous and Case II diffusion are indicative of the coupling of diffusional and relaxational mechanisms. Relaxation is related to the transition of coal from glassy to a rubbery state. Major relaxational mechanisms are indicative of swelling related stresses in coal. A mathematical model was presented at the symposium, which can be used to describe the anomalous transport of CO_2 in thin coal slabs. Parameters specific to a CO_2 - coal system were determined and simulation results presented. The sharp diffusion front which is a characteristic of Case II diffusion is observed and results from a discontinuity in the diffusivity - concentration relationship. This model will be useful in defining anomalous transport behavior of CO_2 in the macromolecular network structure of coal. Both methods, however, prove that swelling takes place, but are not able to measure the stress built-up under zero strain conditions. Considering the coal to be a glassy polymer, where CO_2 imbibition causes relaxation and swelling, is also followed by van Bergen. He discriminates between physisorption, for which CO_2 effects are largely reversible and pressure dependent, and chemisorption, for which CO_2 effects are largely irreversible. The concentration as well as the reaction is time dependent. With their swelling experiments on packed grains, both swelling and excess stress can be measured (Figure 13).

Despite differences in methods, preliminary results of all experiments are similar, suggesting that plastic behavior starts when CO_2 reacts with coal due to chemisorption. Physisorption cause elastic behavior. Effects of gases different to CO_2 are not well investigated up to now. Van Bergen stated that "preliminary experiments under constant load show shrinkage and swelling, depending on stress". Additionally, Plug observed in his capillary pressure experiments that for imbibition experiments, displacement of CO_2 by water injection, a fast water breakthrough occurs. This phenomena can be explained by the CO_2-wet behavior of the coal and swelling of the grains. However, the latter is hard to prove, because no in-situ porosity measurement can be performed.

Swelling Induced Permeability

Permeability in coal is only possible through the fracture system of face cleats, butt cleats and maceral dependent micro-fractures in the matrix. Bossie-Codreanu proposed to use various methods to determine the flow potential of a system by using drilling cores and petrophysics in the drilling holes. The first method mentioned uses fracture determination from CT-scans (Figure 7.C,D) by determining cleats by pixel class and a percolation threshold. This procedure contains recording of all cleats length distribution and selecting the percolating cleats. A method for cleat density determination is described by Mazumder et al. during this symposium. Finally porosity/permeability relation can be determined. Further, a capillary pressure curve is used to find the threshold pressure of the percolating cleats. The results of this method, i.e. absolute (macro cleat) permeability, macro-/micro-porosity, an effective diffusion coefficient, relative permeability and Pc-curves, are used as input parameters for up-scaling. However, a problem is the validity of CT-scan images for the determined fracture width calculations after relaxation of coal samples. Moreover, the maximum X,Y resolution of CT-images is about 0.25 mm. Therefore, a CT-image is not suited for heterogeneous rocks because of the product of data-merging with algorithms. Effects, such as beam hardening and scattering diffuse the image and also troubles the definition of exact locations, or features can be imaged at the wrong location. Nevertheless, the method is applicable when core analysis provides swelling and permeability information. In this way, core flow can be connected to cleat spacing, size distribution and width.

The groups of Durucan & Shi, Wolf & Mazumder and Harpalani and Kumar investigated the core permeability of coal. All results show that at increasing confining stresses (up to about 3 MPa) cleat permeability reduces from Darcy-range to milli-Darcy range. Shi mentioned that, based on laboratory experiments and field observation, lab values are usually one order of magnitude higher, due to irreversible relaxation.

Mazumder shows that under laboratory conditions unconstrained swelling gives an increase of cleat aperture (Figure 14.A). When free CH_4 and water are replaced by CO_2 (Figure 14.B) swelling increases permeability. It starts when CO_2 breakthrough occurs in the product gas, at about 1.2 displaced volume. The increase in permeability stops when approximately 90% of the produced gas volume consists of CO_2, i.e. after circa 2 displaced volumes. Thereafter the permeability remains constantly high, in the order of 30 mD (Figure 14.A). An alternative experiment, where swelling is constrained, shows drastic reduction of permeability to zero (Figure 14.D).

These findings are also observed in the experiments introduced by Kumar and Harpalani. By using a set-up, where both radial confining stress and axial load are imposed on the sample, the coal was stressed vertically and horizontally. Then the sample was saturated with gas (CH_4/CO_2) via an inlet. After equilibrium, a pressure gradient of 2.72 – 4.08 bar was applied across the sample using relief valve and flow rate measurements were made for permeability calculation. The experiment was conducted in two phases: First the sample was subjected to constant loads (constant axial and confining stress) and varying mean gas pressure (Primary Depletion Scenario). Subsequently, the sample was subjected to constant effective stress by changing the mean gas pressure as well as applied stress (Enhanced Coalbed Scenario). The results show that no permeability rebound occurs with desorption of methane, i.e. matrix shrinkage had no negative impact. CO_2 permeability was always significantly lower than CH_4 permeability, but there was no extraordinary perm loss with adsorption of CO_2. This is in contrast with the work of Mazumder, previously describe. Reasons for this difference might be the use of low stresses on shallow coal samples or maybe due to lack of good lateral confinement, the sample could physically shrink or swell.

CONCLUSIONS

The variety in experiments and experimental equipment makes clear that characterization of coal for unconventional applications in a chemical and physical way is still under development, even after 25 years of CBM. It also reveals that uniformity in experimental procedures does not provide consistent results, even when different groups were using the same samples. It is clear that with powdered coal experiments the variety in mineral/maceral composition increases when different grain sizes are used. Moreover, the ash content, i.e. clay minerals or shales, affects both gas sorption behavior and moisture capacity. The duration of the experiments is also a bottleneck in obtaining results on sorption and diffusion. Novel methods, which use less amount of sample and smaller grain sizes, reduce time. However, in what way can laboratory results be used for up scaling purposes? Agreement between research institutes to regulate experimental procedures will improve comparison of outcomes. When considering the accuracy measurements of Siemons, van Hemert and Busch, it also improves the accuracy of the outcomes.

The cleat system provides conduits for transport of fluids and gases through the coal. Hence, core experiments at a scale where cleat systems are present in the sample can give an indication of bulk capacities and physical and chemical reactions during exchange of gases. Compared to CH_4 and H_2O, CO_2 has the highest impact on coal matrix and volumes, i.e. permeability, porosity, wettability and free surface (diffusion). Mechanical measurements under constraint conditions are essential to correlate gas effects to flow, sorption/diffusion and sweep efficiencies. Since those experiments take months (if they succeed in one time), institutes must find agreement how to regulate measurements and results.

The use of image analysis on CT-scans to characterize cleat systems, i.e. cleat spacing, orientation and distributions is the fastest and, for the time being, the best option. One should be careful when distances are measured. The images are often distorted during processing.

Al results, especially those obtained under simulated in-situ conditions, are useful parameters for up scaling and modeling. This topic is not discussed in this paper due to its complexity and the variety in presentations. For the presentations of Shi, Bruining, Busch and Bossie-Codreanu we refer to the symposium website.

ACKNOWLEDGEMENTS

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REFERENCES

Presentations of the ECBM-WORKSHOP, held at Monday 28th of November – Wednesday the 30th of November at the Geotechnology Department, Delft University of Technology, Mijnbouwstraat 120, 2628 RX Delft - The Netherlands

Monday: The seam and its environment
- Karl-Heinz Wolf : Introduction
- Shi Quan : Phenomenon around a borehole
- Hans Bruining : Homogenization by
- Dan Bossie-Codreanu : Up scaling

Tuesday: Size and sorption
- Dirk Prinz and Andreas Busch: coal structures and sorption behavior
- Patrick van Hemert and Nikolai Siemons: Pitfalls in sorption experiments and theory

Wednesday: Combining methods, new thoughts
- Willem-Jan Plug: Wettabiltiy and Capillary Pressure Behavior for the Coal-Water -CO_2 System in Unconsolidated Coal Samples
- Satya Harpalani and Ajayendra Kumar: An American Story
- Saikat Mazumder, Frank van Bergen: Case II diffusion & swelling

All presentations and abstract are on the web-site:
http://www.citg.tudelft.nl/live/pagina.jsp?id=1f6bf92a-cae3-4f01-8a5b-03e97a3e706b&lang=en

GRAPHS

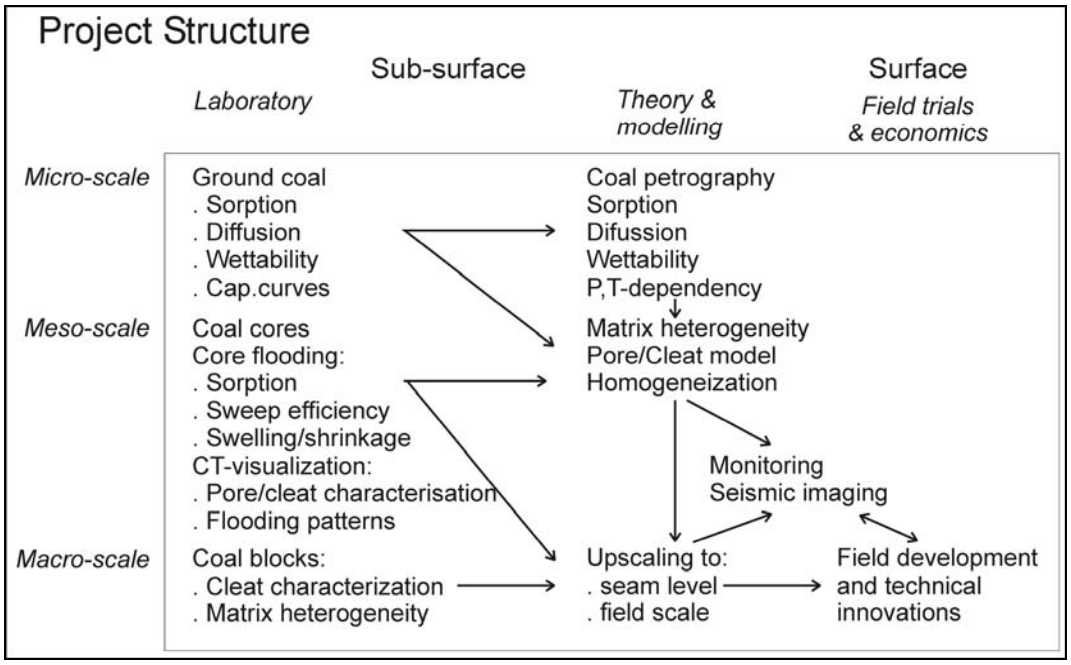

Figure 1. Scales, sample sizes and results of experimental work, and its coherence with theory and up-scaling. (From the presentation of K-H. Wolf)

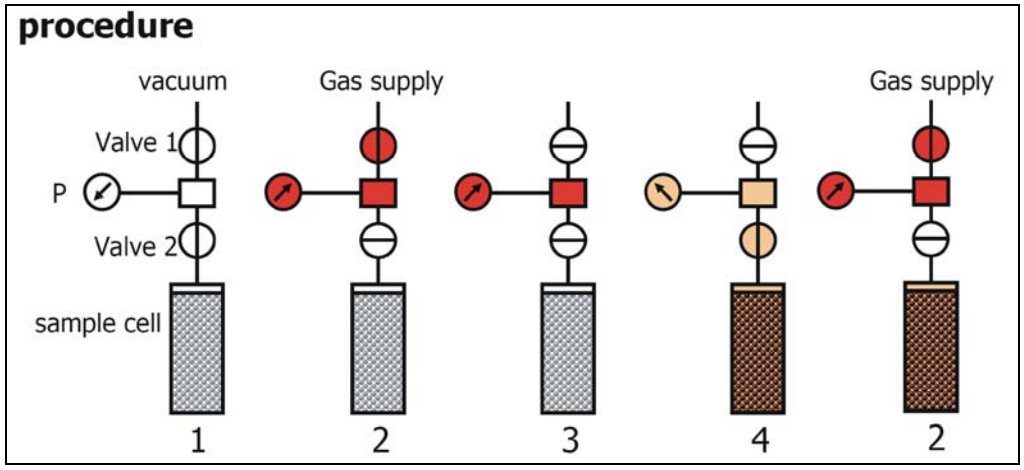

Figure 2. Experimental set-up and the four stages (1 – 4) during a pressure step in a sorption experiment. (From the presentation of N. Siemons)

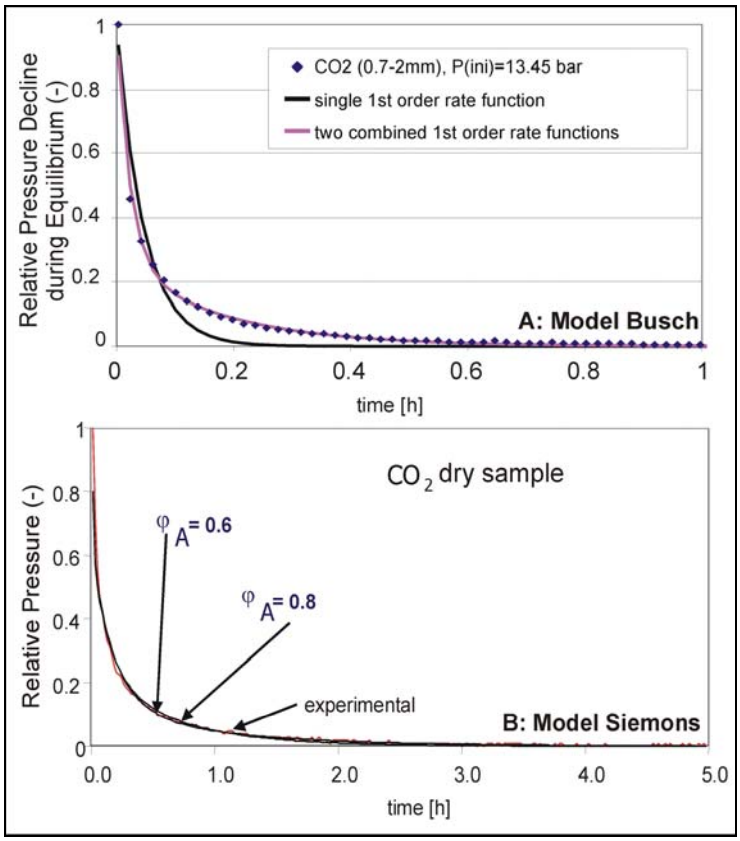

Figure 3. Comparison of modeling results on equilibrium sorption by Busch (A) and Siemons (B) on ground coal. Sorption time versus relative pressure. (From presentations of Busch and Siemons)

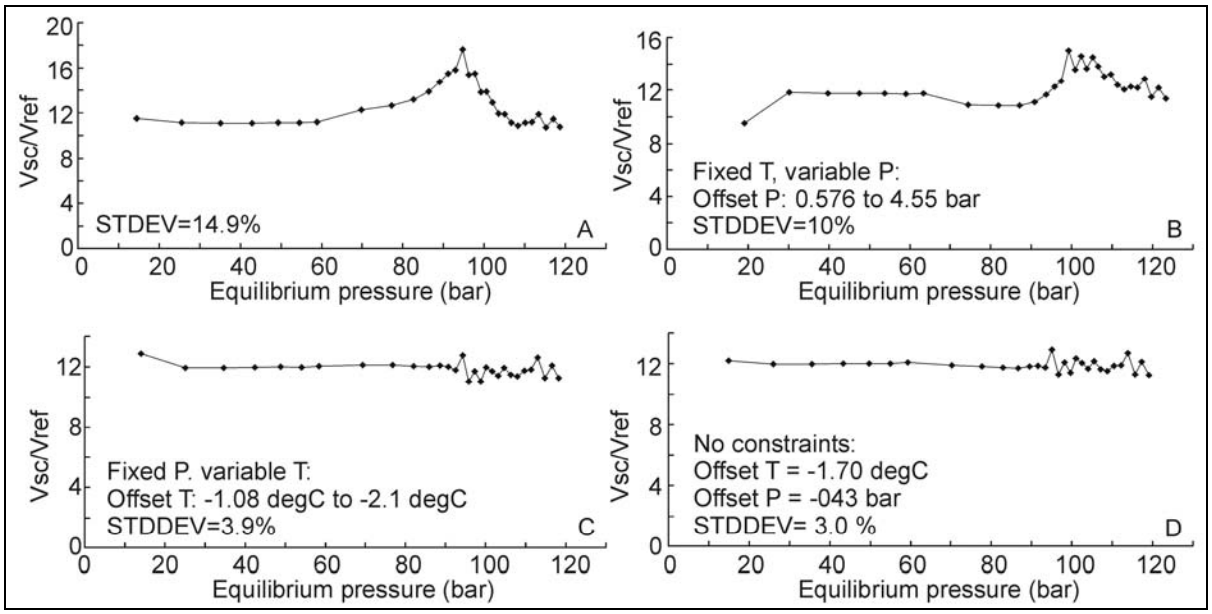

Figure 4. Standard deviations for normalized volumes versus cell pressure of a blind CO_2 sorption test, 30 pressure steps up to 125 bar. A: No offsets. B. Fixed T, variable P, C: Fixed P, variable T, D: No constraints, just offsets. (From the presentation of Siemons)

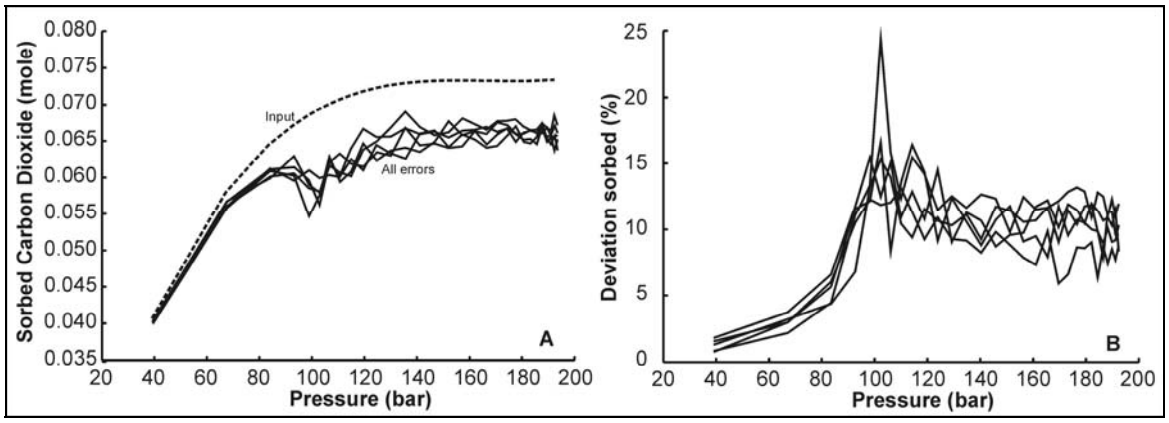

Figure 5. Sensitivities of sorption calculations. Accuracies of adsorbed CO_2 with beforehand determined random and systematic errors in P and T. A: Sorption versus pressure, B: Deviation in sorption versus pressure. (From the presentation of van Hemert)

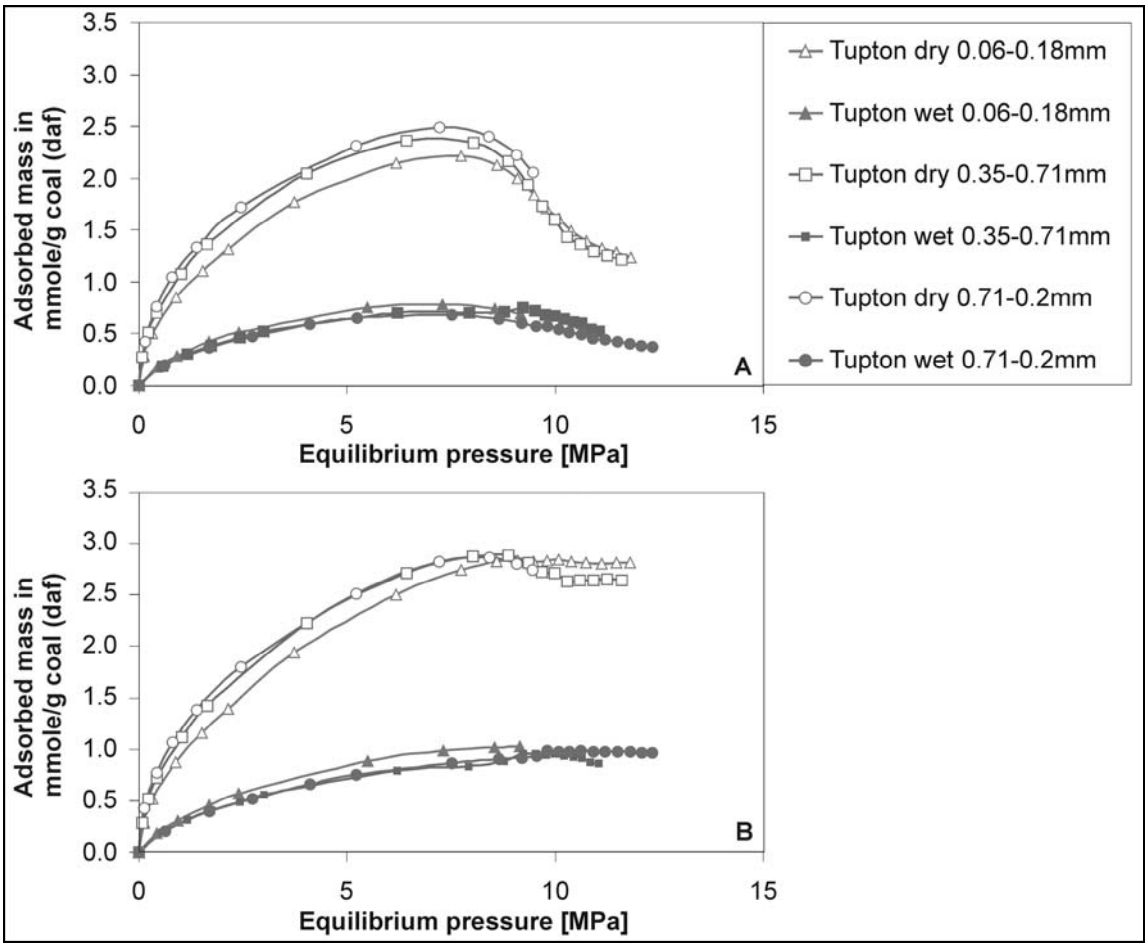

Figure 6. A: Adsorption experiments on Tupton H coal for dry and wet grains at different grain sizes. B: Same experiments, corrected for volume with a void volume reduction of ca. 15%. (From the presentation of Siemons)

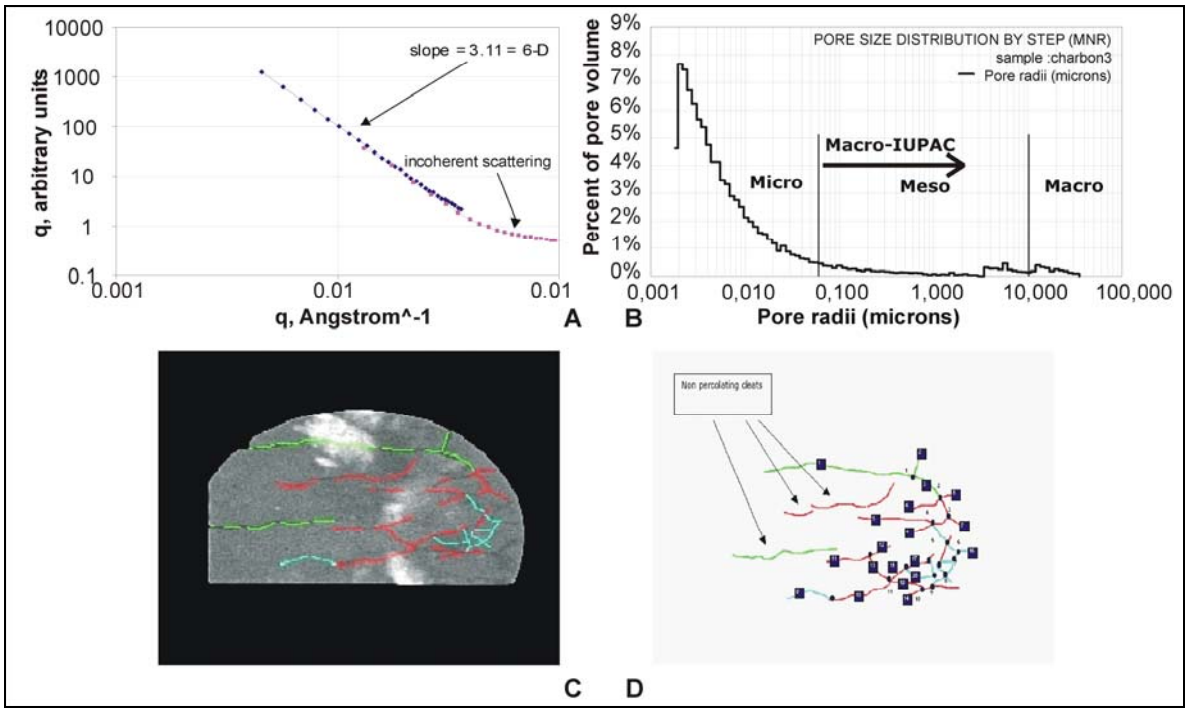

Figure 7. Various scales of pore size distribution measurements. A: Nano-scale by using SANS. Micro-/meso-scale by using NMR, and C,D: Macro scale cleats by using CT-images. (From the presentation of Bossie-Codreanu)

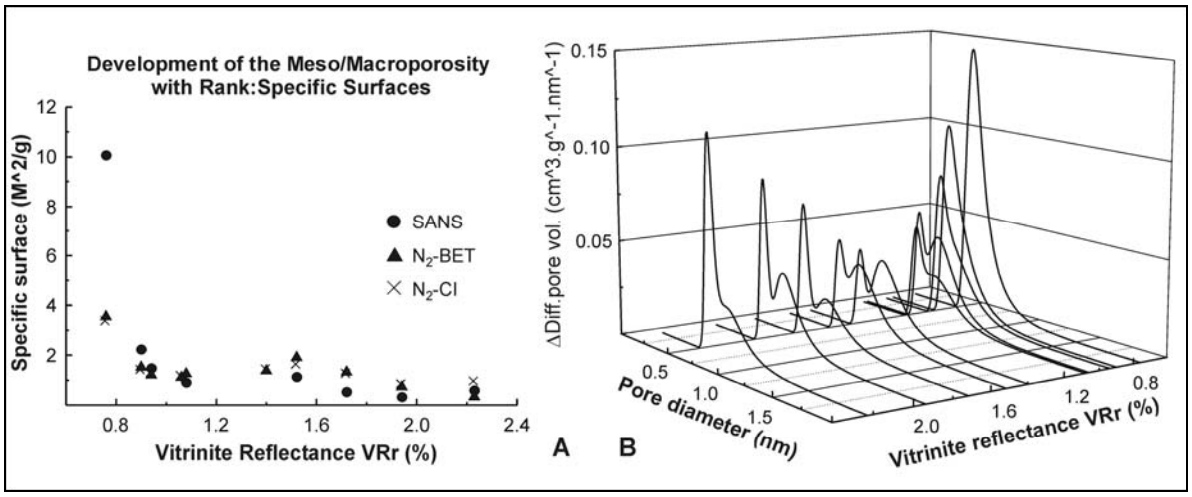

Figure 8. Development of the meso- and macro-porosity with rank, derived with Small Angle Neutron Scattering, N_2-BET analysis and N_2-CL analysis. (From the presentation of Prinz).

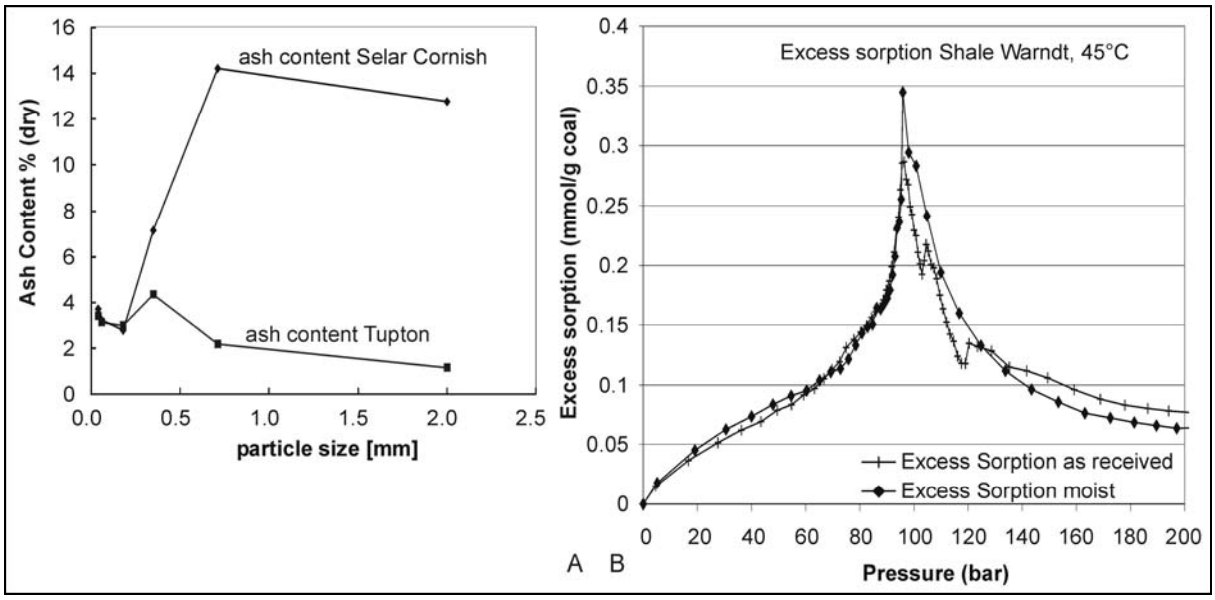

Figure 9. A: Distribution of ash content with grain size. (From the presentation of Siemons). B: Excess CO_2 sorption of shale Warndt-Luisenthal with pressure. T=45°C, 0.66% H_2O as received, moisted to 9.33% H_2O. (From the presentation of Busch).

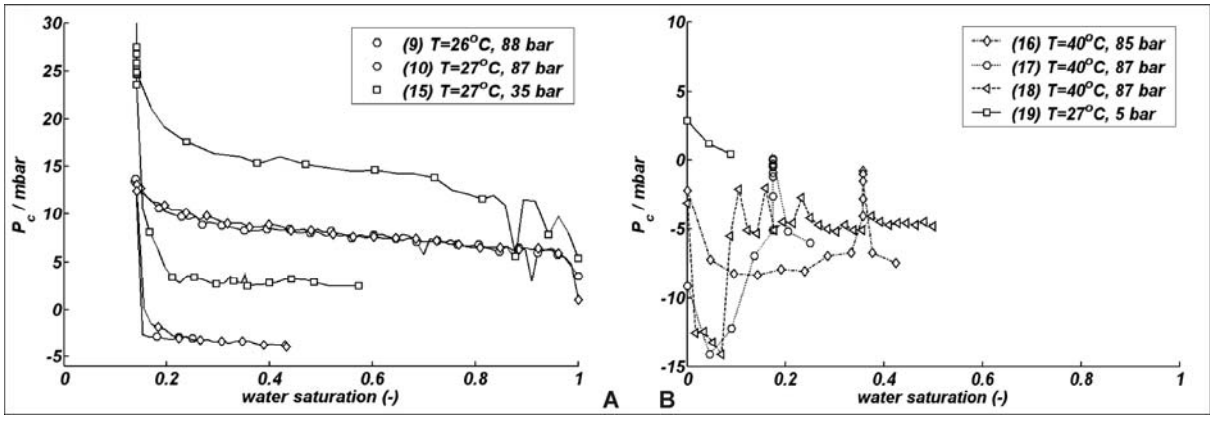

Figure 10. Example of wettability experiments for the replacement of water by CO_2 in a water saturated ground coal. A: Drainage and secondary imbibition, wetting change with increasing pressure for medium rank coal Warndt-Luisenthal. B: Primary imbibition curves for super-critical and gaseous CO_2 high rank coal Selar Cornish. (From the presentation of Plug)

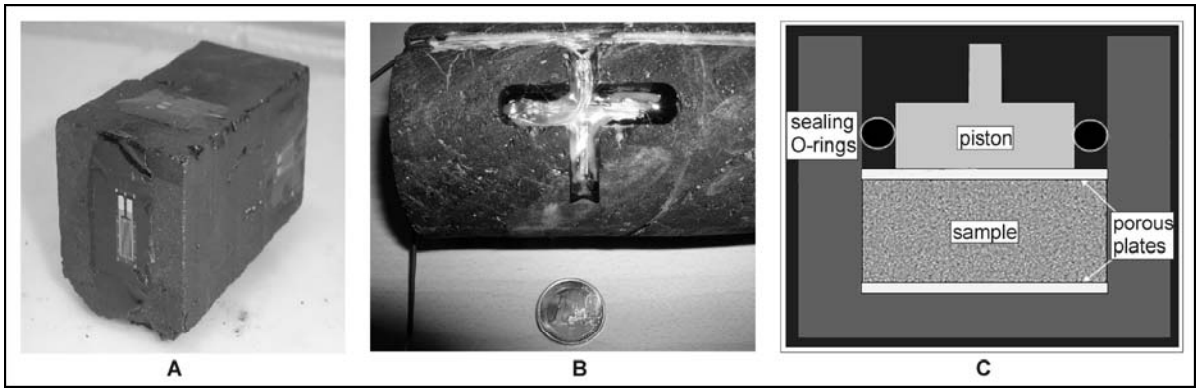

Figure 11. A: Coal blocks with displacement transducers on each face. (From the presentation of Busch) B: Placement of two radial displacement transducers in a cylindrical coal core. (From the presentation of Mazumder). C: An drawing of a device to measure swelling of coal grain aggregates. (From the presentation of van Bergen.)

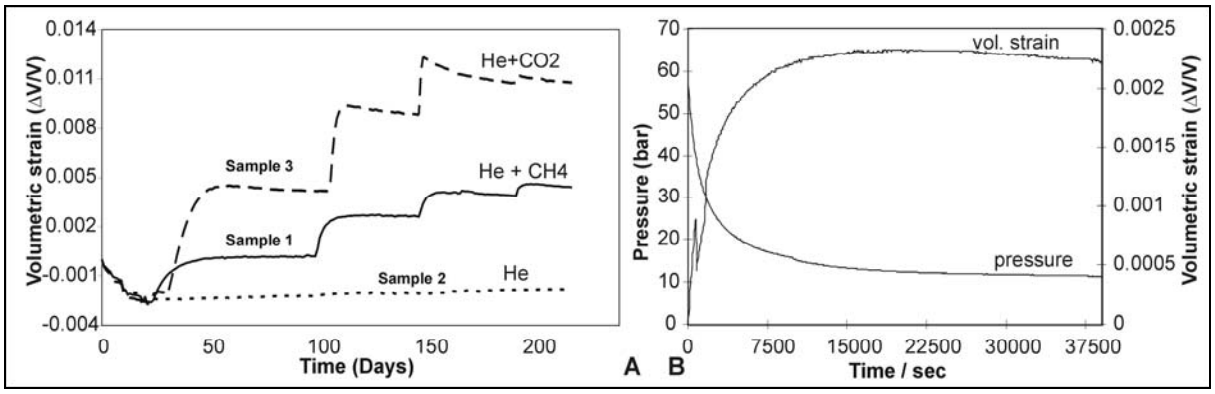

Figure 12. A: Stepwise increase of gas pressure with resulting volumetric strain of free swelling coal in He, He+CH_4 and He+CO_2 (From the presentation of Harpalani/Kumar). B: One pressure step and resulting volumetric strain of partially constrained (3 MPa) swelling coal in CO_2. (From the presentation of Mazumder)

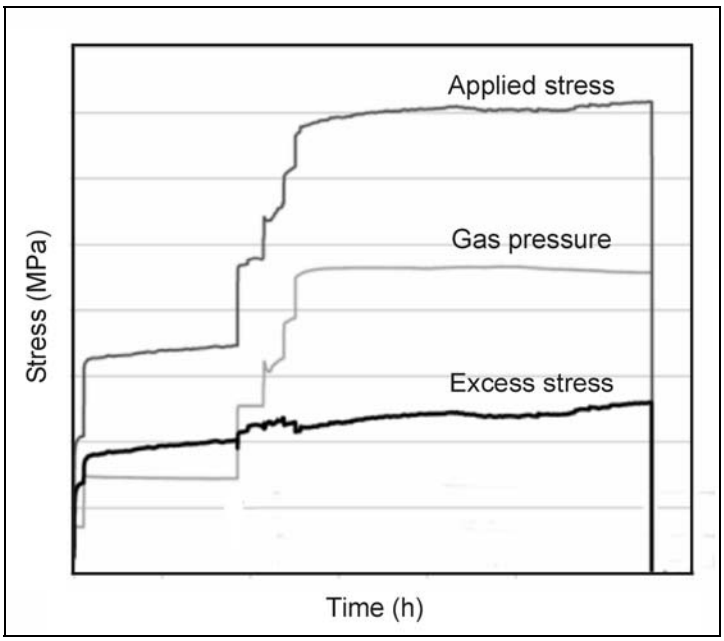

Figure 13. Example of measurement of swelling induced stress of CO_2 on a coal grain aggregate. Based on the original applied stress and gas pressure, the excess stress or counter pressure is calculated. (From the presentation of van Bergen)

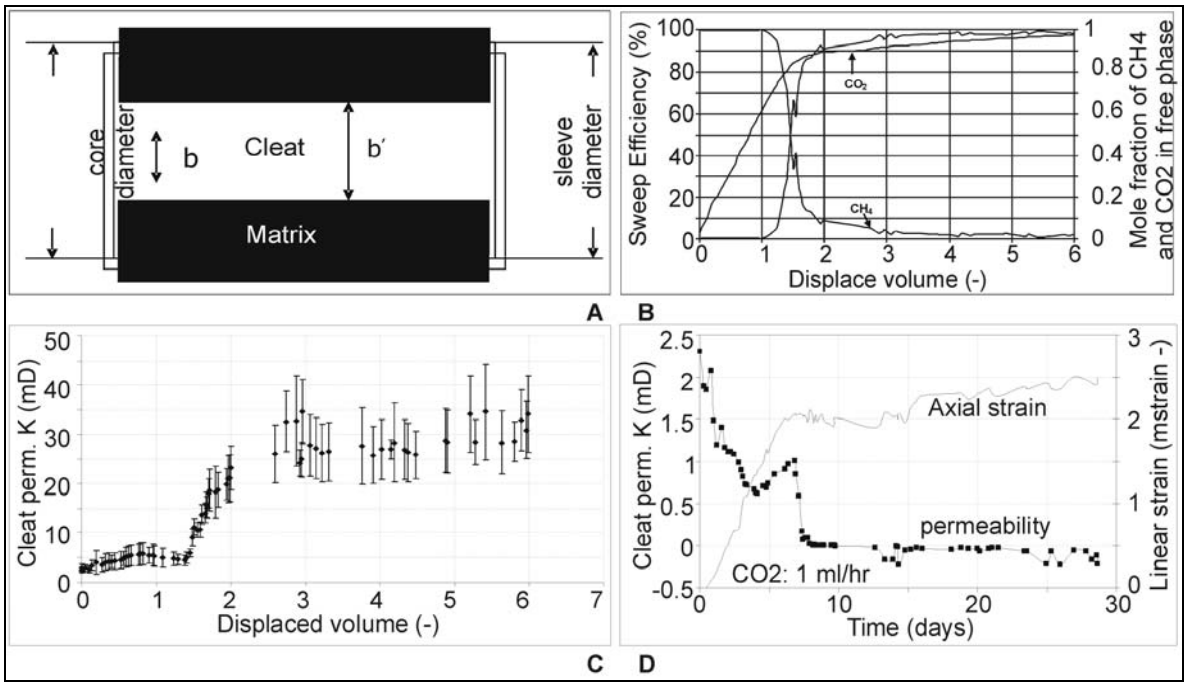

Figure 14. A: Unconstrained swelling under laboratory conditions. B: Sweep efficiency and produced mole fractions of CH_4 and CO_2 versus displaced volume. C: Increasing cleat permeability with increasing CO_2 charge related to figure B. D: Swelling and permeability versus time under constrained conditions. (From the presentation of Mazumder)