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Energy and Green House Gas Mitigation Technologies

Japan Society for the Promotion of Science-Imperial College London-University of Tokyo Symposium on Climate Change

Thursday 28th and Friday 29th September 2006

energy futures lab

Imperial College London, South Kensington Campus, London SW7 2AZ

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CO_2 Storage in Coal Seam Reservoirs:
Permeability, Injectivity, Well Configuration and the Choice of Injectant

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Imperial College London

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MINING AND ENVIRONMENTAL ENGINEERING RESEARCH GROUP MERG

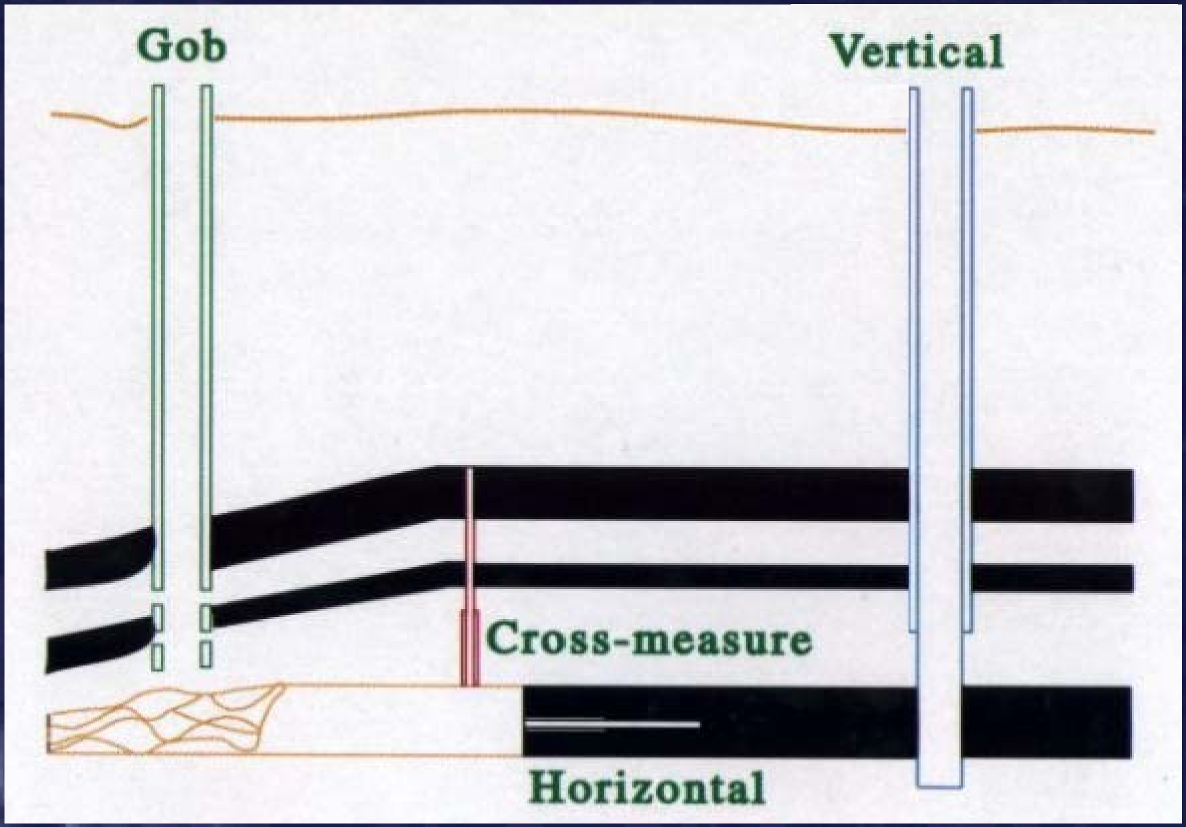
Outline

- Background, coal structure
- Coal permeability, well injectivity
- Imperial College permeability and CO_2-ECBM model
- Field Examples
- Conclusions

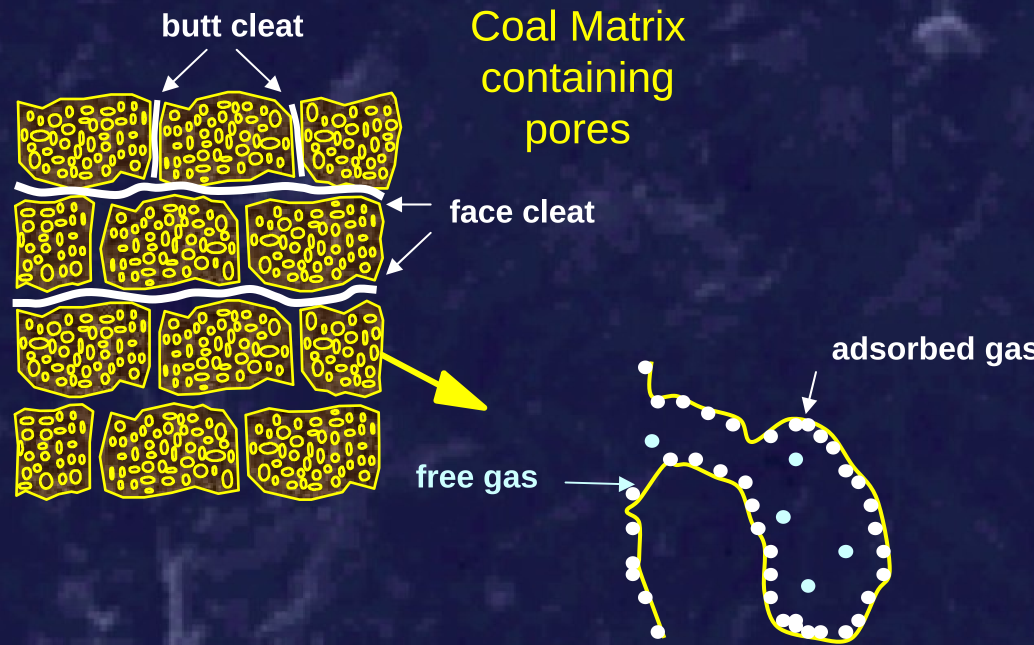
Methane Extraction from Coal Seams: Well Technology

Underground Methane Drainage Practice

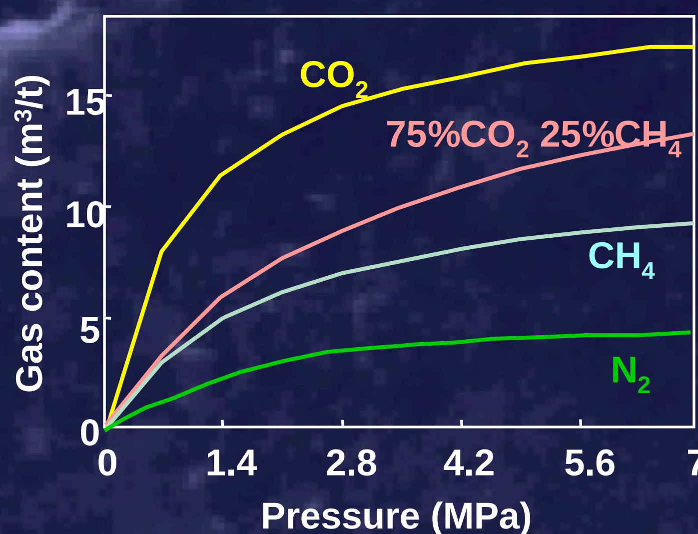
Coalbed Methane Technology



Coal as a Reservoir Rock

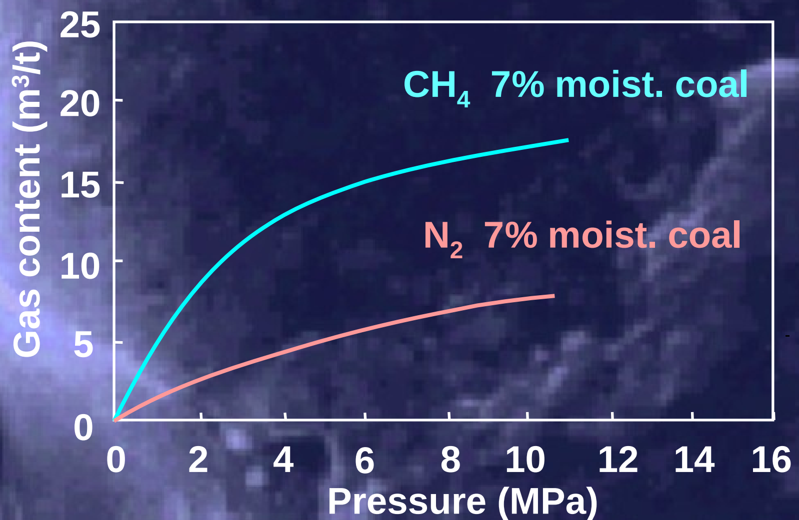


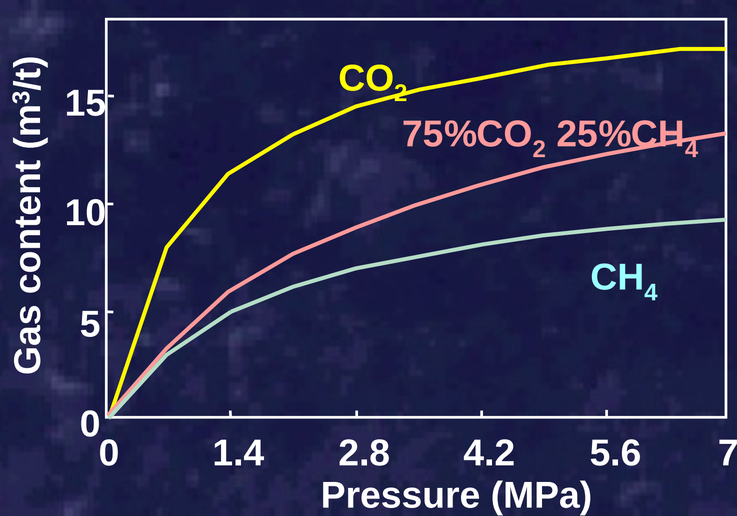
- Cleat system (2mm - 25 mm)
- Pore surface area 20 – 200 m^2



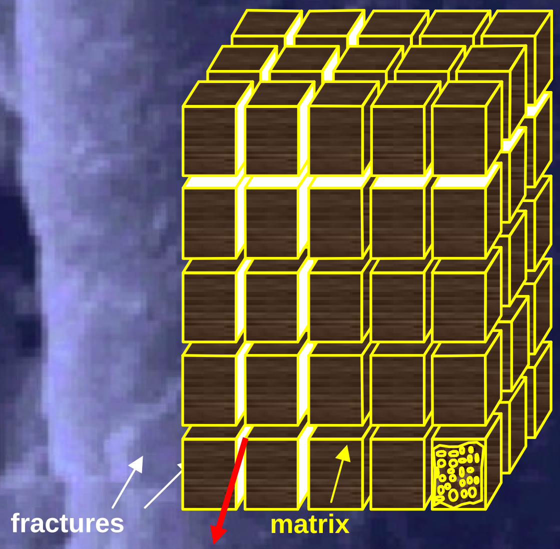
Enhanced Coalbed Methane Recovery (ECBM)

- two principal methods of ECBM, namely N_2 and CO_2 injection (inert gas stripping and displacement sorption respectively)
- injection of nitrogen reduces the partial pressure of methane in the reservoir, thus promotes methane desorption without lowering the total reservoir pressure
- coal can adsorb approximately twice as much CO_2 by volume as methane, therefore, the assumption has been that the CO_2 injection stores 2 moles of CO_2 for every mole of CH_4 desorbed.





Strength, Elastic and Flow Properties of Coal



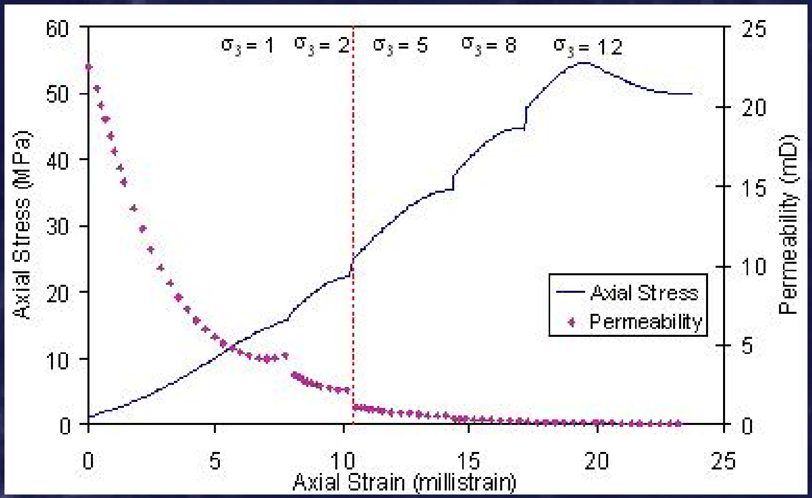
Coal structure is highly elastic

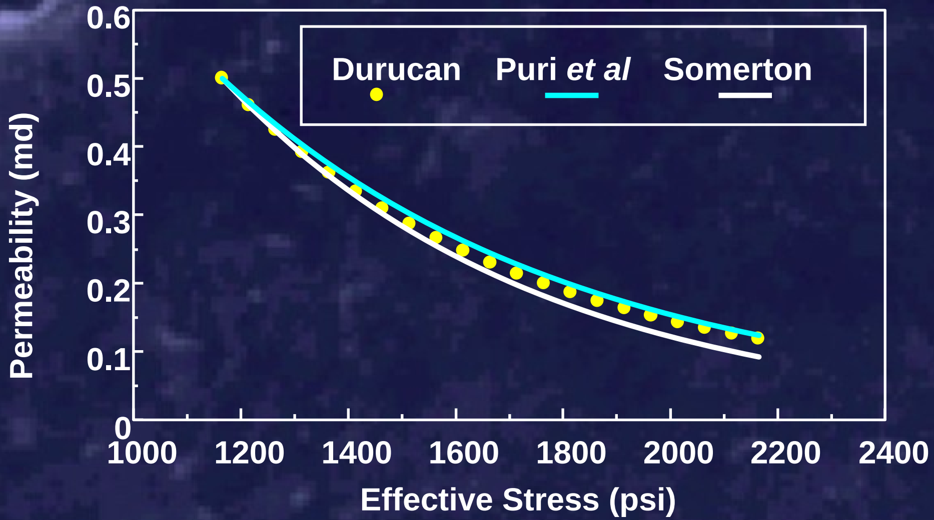
	Coal (Various)	Weak Reservoir Sandstone	Sandstone	Limestone	Shale
Young's Modulus, *E* (GPa)	0.86 - 3.9	0.4 – 1.8	10- 20	35 - 55	5 - 70

Coal permeability is

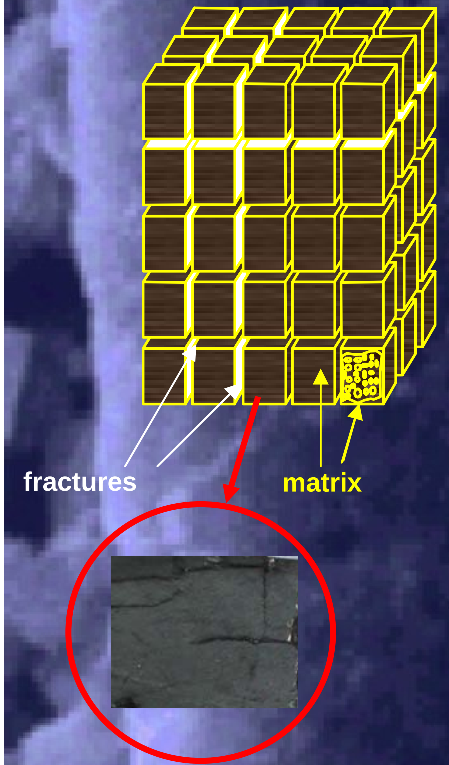
- Anisotropic
- Highly stress dependent

Stress Effects and Permeability

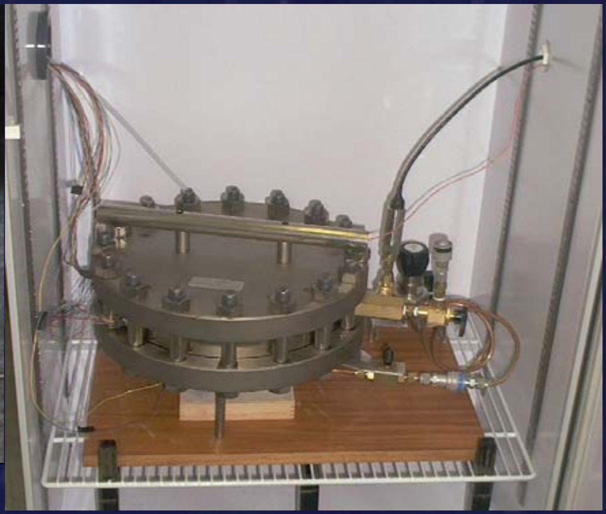


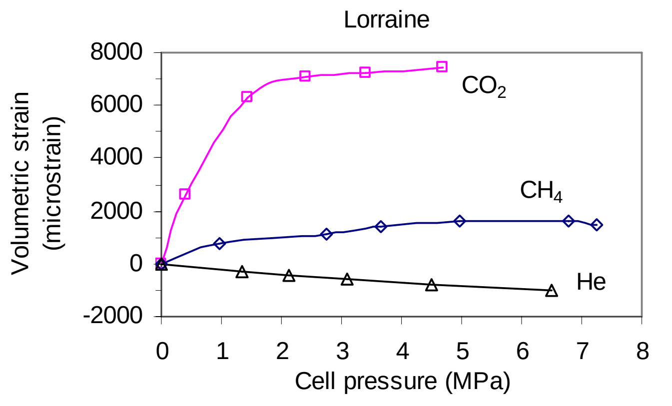


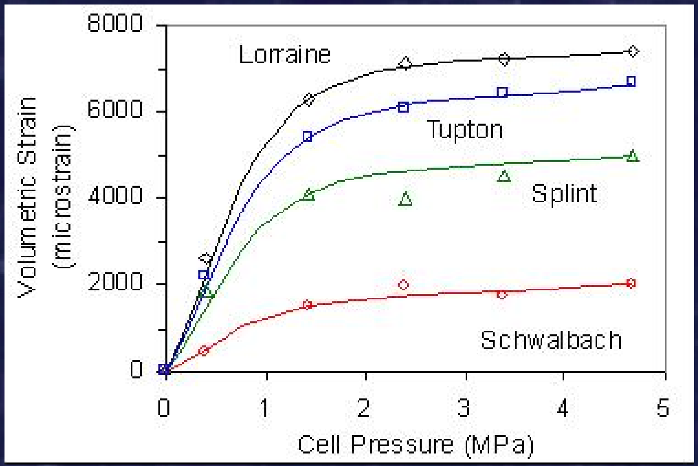
Pore Pressure Effects, Matrix Deformation and Permeability



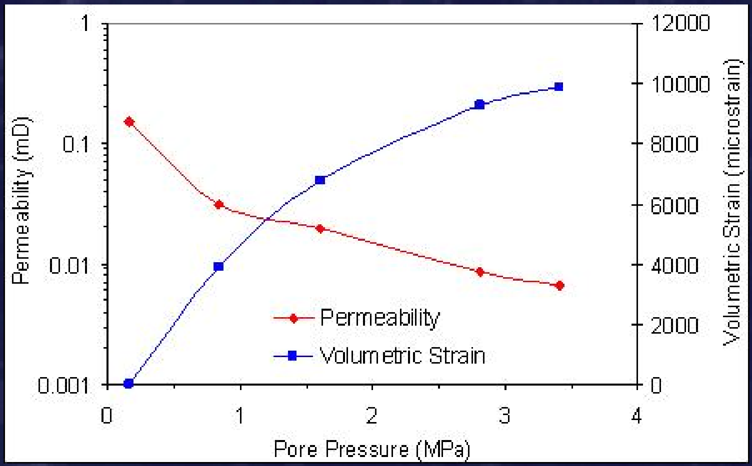
Matrix Shrinkage or Swelling

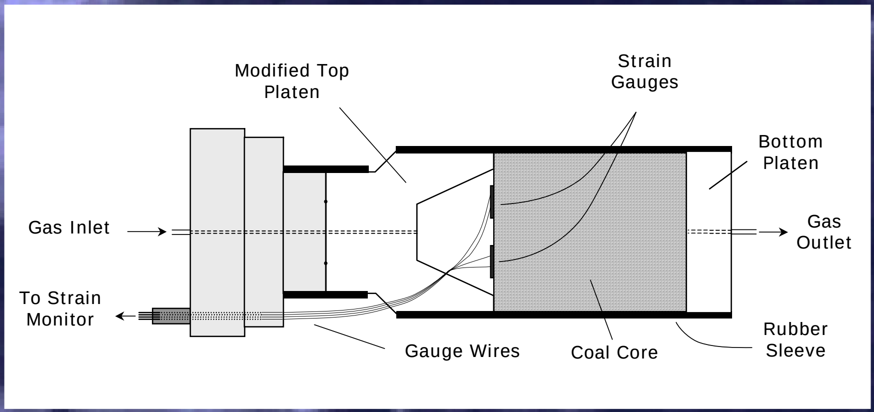


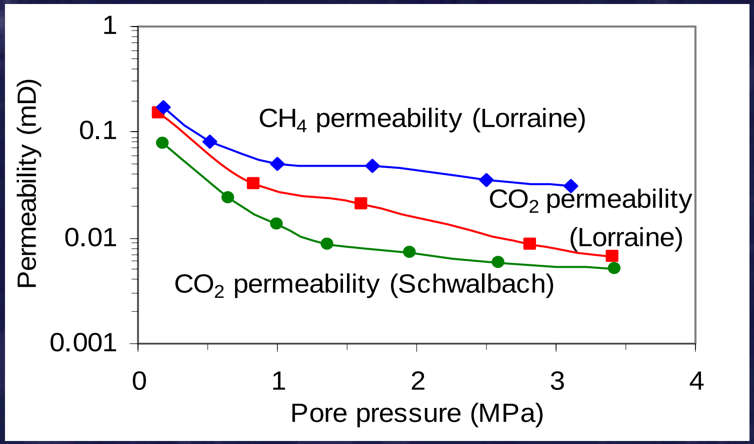




Stress and Pore Pressure Effects, Permeability

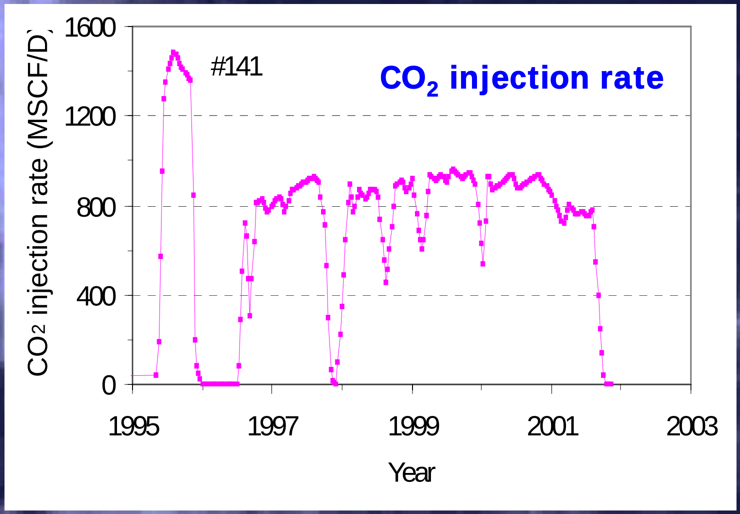




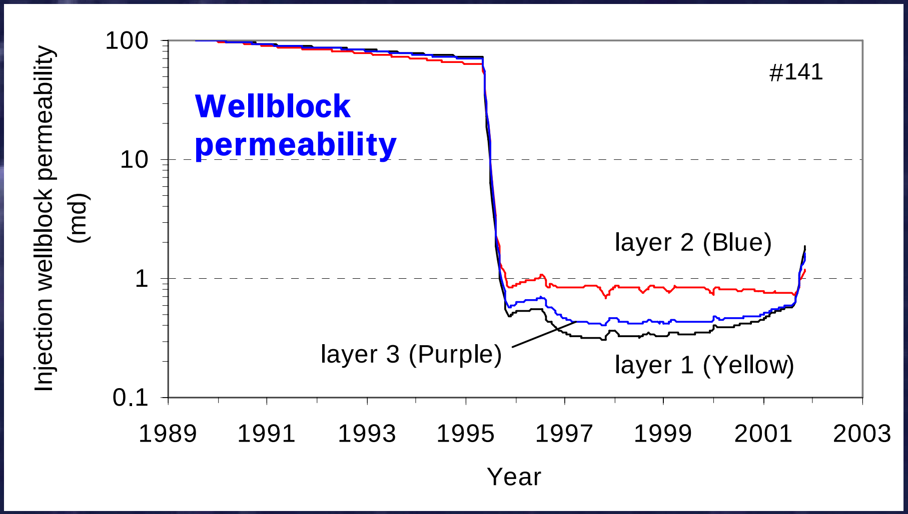


Field CO_2 Injection Pilots

- CO_2 induced matrix swelling can have a severe impact on injection well permeability and injectivity
- A reduction of over two orders of magnitude in injection well permeability was reported in the Allison CO_2-ECBM pilot in the San Juan Basin

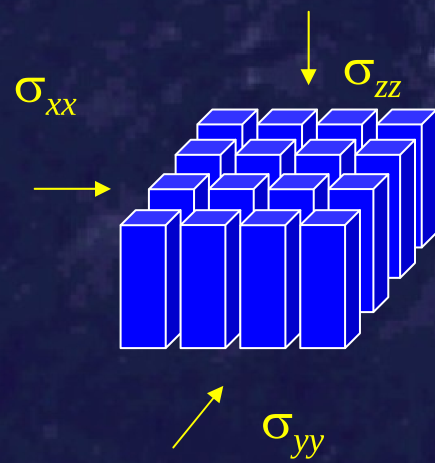


(Reeves et al., 2003)



(Shi and Durucan, 2004)

Permeability Model for CO_2 Enhanced Methane Recovery and CO_2 Storage



$$k = k_0 e^{-3c_f(\sigma - \sigma_0)}$$

Primary recovery

$$\sigma - \sigma_0 = -\frac{\nu}{1-\nu}(p - p_0) + \frac{E\alpha_S(V - V_0)}{3(1-\nu)}$$

Enhanced recovery and CO_2 storage

Shrinkage/swelling term

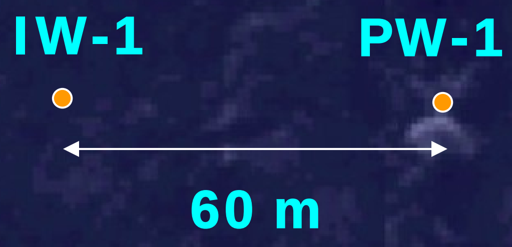
$$\sigma - \sigma_0 = -\frac{\nu}{1-\nu}(p - p_0) + \frac{E}{3(1-\nu)}\sum_{j=1}^{n}\alpha_{Sj}(V_j - V_{j0})$$

α_{Sj} **– shrinkage/swelling coefficient for gas component j**

METSIM2 – Imperial College CO_2 ECBM Simulator

- A dedicated ECBM simulator: 3D, two-phase, multi-component (CH_4, CO_2 and N_2)
- Mixed gas diffusion
- Mixed gas sorption - Extended Langmuir equation
- Accounts for the effects of matrix shrinkage/swelling on cleat permeability

JCOAL Yubari Field Pilot, Japan



- **Micro-pilot CO_2 huff-puff test (well IW-1 only)**
  - Pre-injection production (~ 60 days)
  - CO_2 injection (7.5 hours) – 7.4 tones injected
  - Shut-in (21 days)
  - Post-injection flow back (30 days)

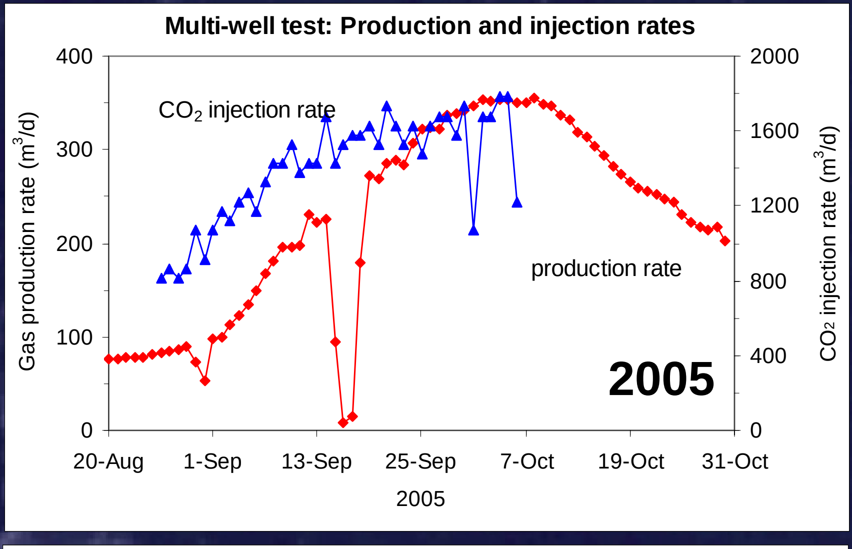
- **CO_2 injection tests (wells IW-1 & PW-1)**
  - 1 October – 20 December 2004
  - 20 August – 30 October 2005
- **N_2 flooding (wells IW-1 & PW-1)**
  - Pre-N_2 flooding CO_2 injection (11 April – 10 May 2006)
  - N_2-flooding (11 – 19 May 2006)
  - Post-N_2 flooding CO_2 injection (July - August 2006)

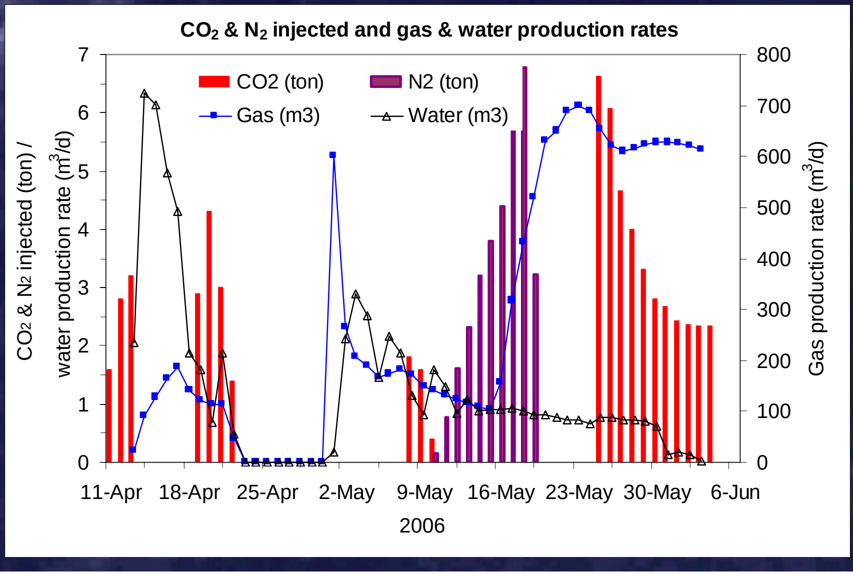
CO_2 Injection and N_2 Flooding Test
Field Injection and Gas Production Rates

- **2004:**
  - **15 days injection**
  - **1.8 – 2.9 tones CO_2/day (1 ton = 506 std. m^3)**

- **2005:**
  - **40 days injection**
  - **1.7 – 3.5 tones/day**

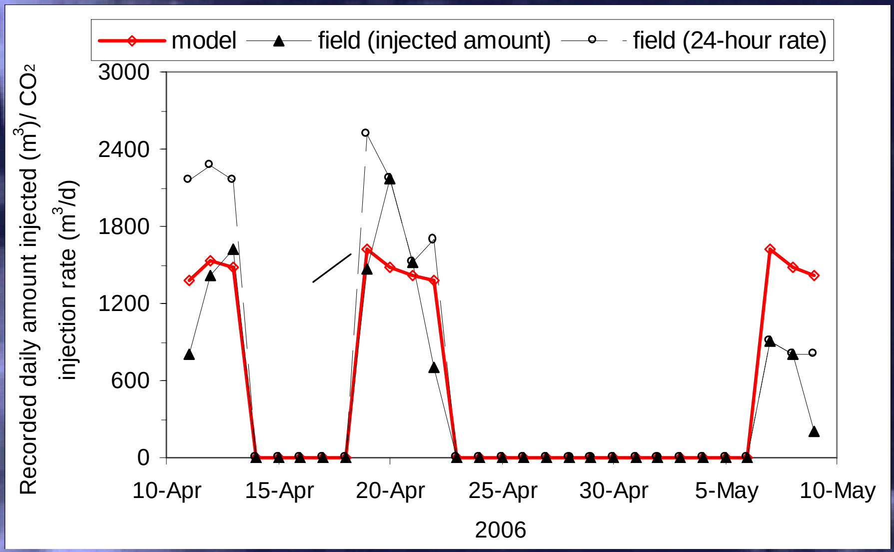
Low production rates: < 400 m^3/day

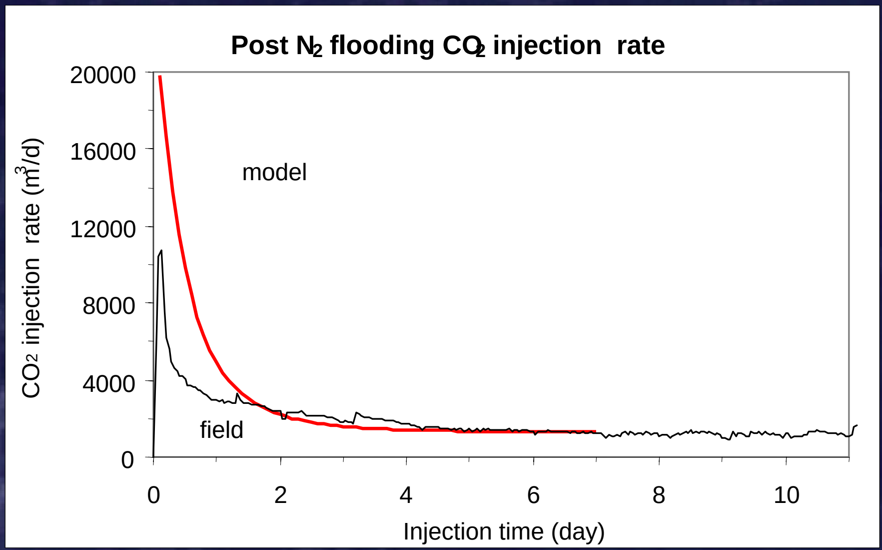




Model Prediction vs Field Data: Pre- and Post- N_2 Flooding CO_2 Injection Rates

Pre-N_2 flooding

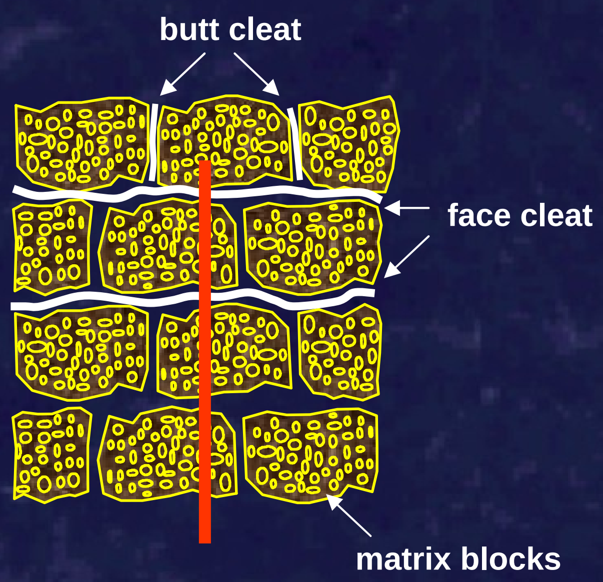




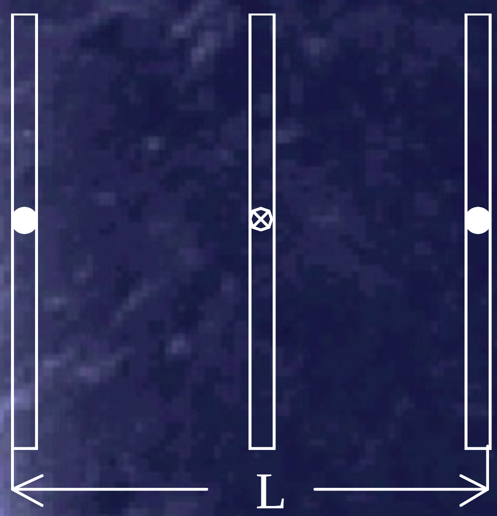
- N_2 flooding temporarily improved CO_2 injectivity, which declined quickly back to the pre-flooding level (~ 3 tones/ day) after two days.

Horizontal Well to Improve Well Injectivity

- Able to access a larger reservoir area than vertical wells
- Horizontal wells may be used to help alleviate permeability reduction and injectivity loss in a CO_2-ECBM and/or CO_2 storage project
- Horizontal wells in coal seams have the added advantage that they could potentially tap into the inherent permeability anisotropy of coalbeds by cutting across the more permeable face cleats



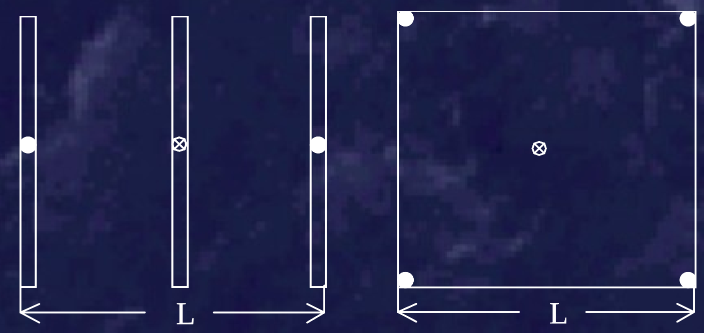
A Three-Well Pattern



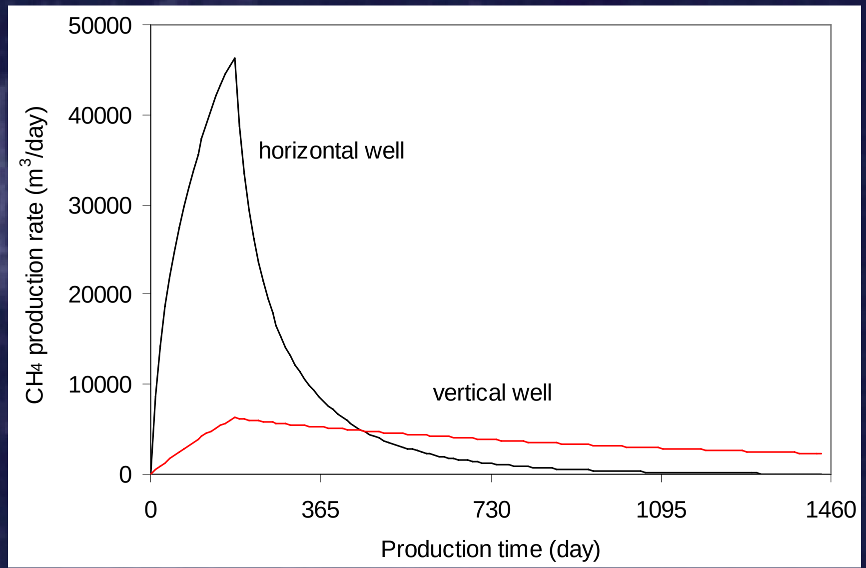
3-well pattern
(914 m x 914 m)

- Linear flow between parallel boreholes – a reasonable approximation for thin seams

Horizontal vs 5-spot pattern

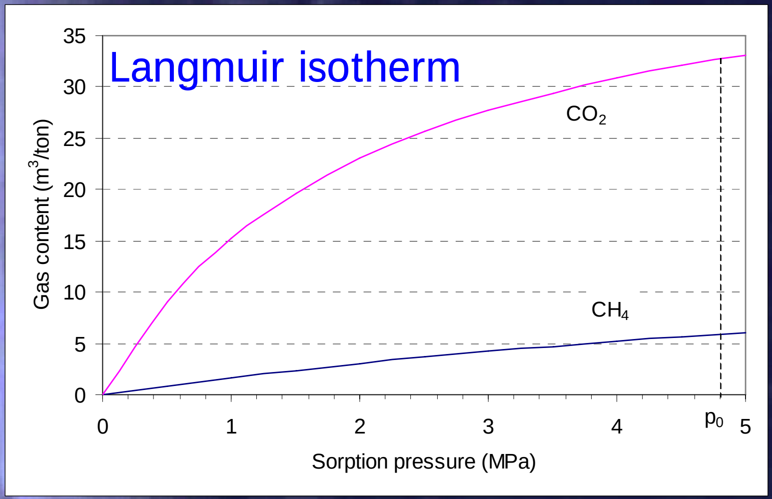


Primary Production

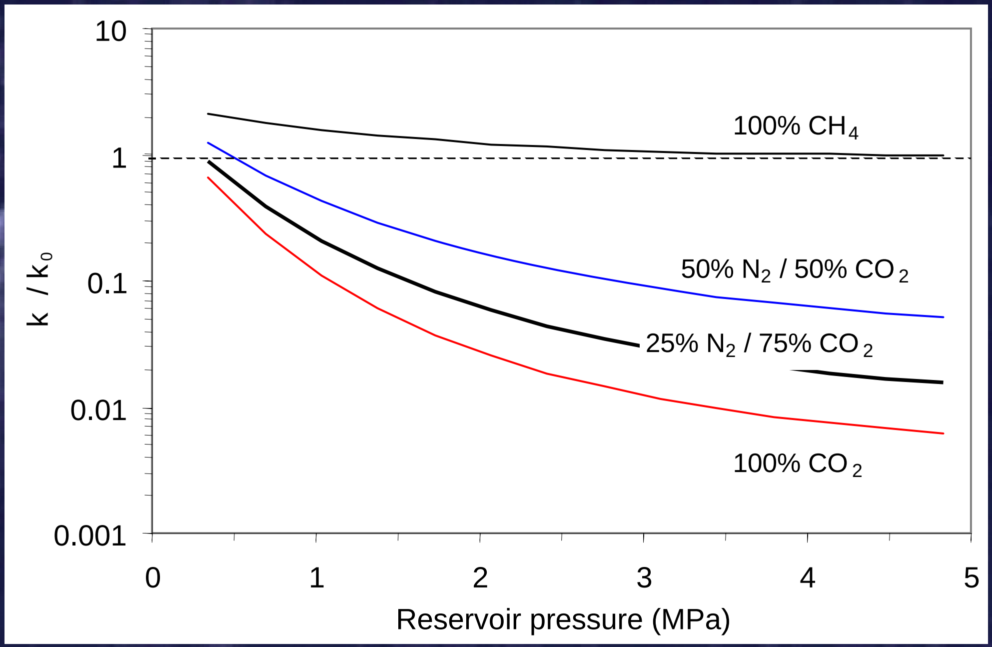


- Outperforms 5-spot by a factor of 5 in the first year

Estimating Changes in Permeability During Enhanced Recovery using CO_2 Enriched Flue Gas



(Sams et al., 2004)



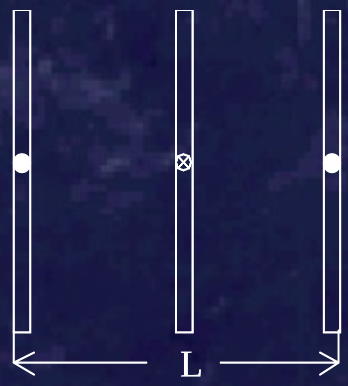
E = 2,900 MPa

ν = 0.35

c_f = 0.139 MPa^{-1}

α_s = 2.5 x10^{-4} m^3/sm^3

Simulation of CO_2 Storage and ECBM Recovery Using Horizontal Wells



3-well pattern

Three ECBM Schemes:

- Pure CO_2
- 75% CO_2/25% N_2
- 50% CO_2/50% N_2
- Primary production from all the wells in the first year
- Injection starts at year 2, with the central borehole converted into an injection well

Cumulative CH_4 Production/Recovery Factor

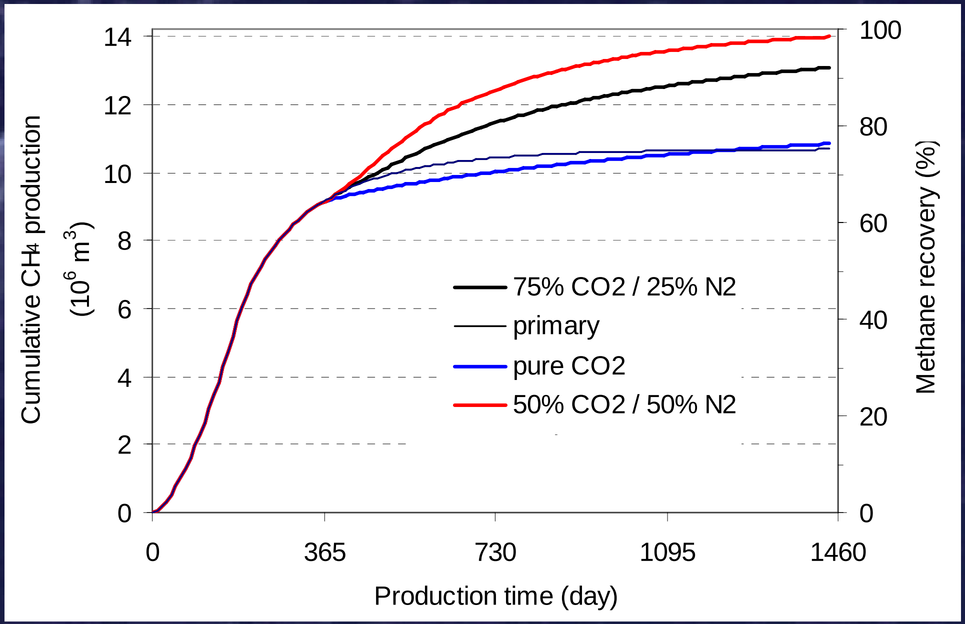
- **Primary production from all the wells in the first year ~65% recovery**
- **Incremental recovery for the next three years:**

Primary recovery

Pure CO_2 : 10%, no improvement over primary

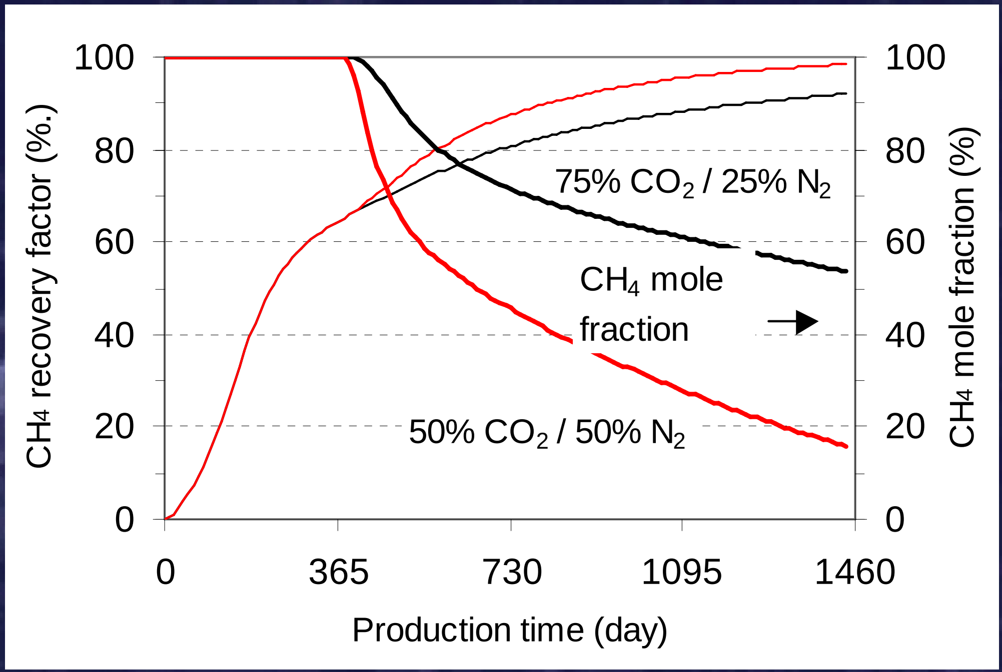
75% CO_2/25% N_2: 27%

50% CO_2/50% N_2: 33%



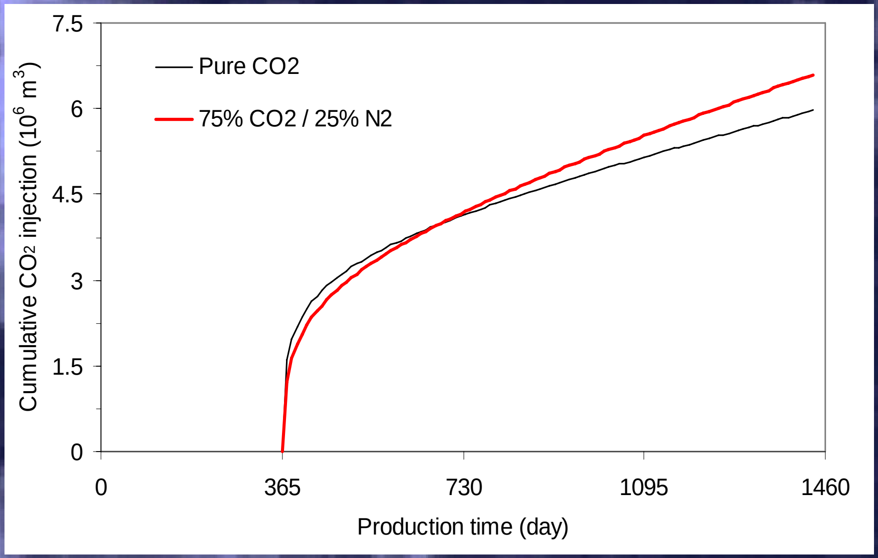
Trade-Off Between CH_4 Recovery Factor and Gas Quality

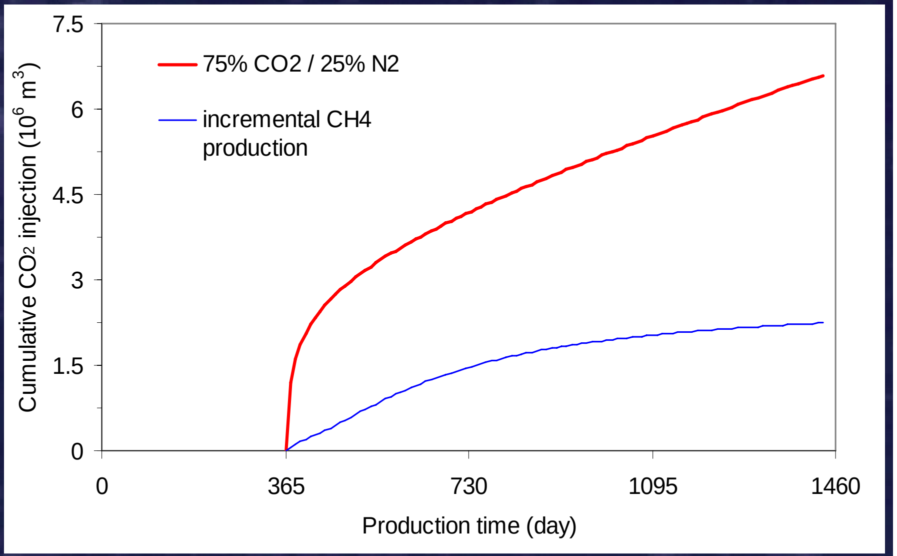
- Gas quality deteriorates with increasing N_2 content in the gas injectant
- For the 75% CO_2 / 25% N_2 mixture, CH_4 mole fraction stays above 50% level throughout the production period
- Further enrichment in N_2 results in a steep decline in gas quality



Cumulative CO_2 Injection

- **5.91 million m³ CO_2 injected over the 3-year period for CO_2-ECBM**
- **Interestingly, ~10% more net CO_2 could be injected/stored if the CO_2 were mixed with N_2 at a ratio 3:1.**
- **The incremental CH_4 production over primary stands at 2.4 million m³, yielding an overall CO_2/CH_4 ratio of about 2.75:1**





Concluding Remarks

- The 3-well horizontal well configuration was up to five times more productive than the 5-spot vertical well pattern for the coal seam reservoir used in the study.
- Injection of pure CO_2 into the central horizontal well, is likely to result in only limited incremental methane recovery over primary recovery
- The presence of the nitrogen component in the injected gas stream is capable of significantly improving the efficiency of enhanced methane recovery and CO_2 storage without compromising the CO_2 injection rates.
- There is, however, a trade off between incremental methane recovery and produced gas purity due to early nitrogen breakthrough.