Programme Area: Carbon Capture and Storage

Project: Storage Appraisal

Title: Dynamic Modelling of Pressure Cells Using Representative Structures

Abstract:

This document is a supporting document to deliverable MS6.1 UK Storage Appraisal Final Report.

Context:

This £4m project produced the UK's first carbon dioxide storage appraisal database enabling more informed decisions on the economics of CO2 storage opportunities. It was delivered by a consortium of partners from across academia and industry - LR Senergy Limited, BGS, the Scottish Centre for Carbon Storage (University of Edinburgh, Heriot-Watt University), Durham University, GeoPressure Technology Ltd, Geospatial Research Ltd, Imperial College London, RPS Energy and Element Energy Ltd. The outputs were licensed to The Crown Estate and the British Geological Survey (BGS) who have hosted and further developed an online database of mapped UK offshore carbon dioxide storage capacity. This is publically available under the name CO2 Stored. It can be accessed via www.co2stored.co.uk.

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Appendix A5.7

Dynamic Modelling of Pressure Cells Using Representative Structures

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Executive Summary

The project identified three types of saline aquifer store relevant to UK CO_2 storage capacity, including the pressure cell. This is a bounded region with no flow and pressure communication across the boundaries either laterally or vertically. As injected CO_2 is assumed to be fully confined, the pressure behaviour, rather than CO_2 transport, is the main issue of interest. This report is concerned with dynamical modelling of such pressure cells, using numerical simulation of simplified generic models, 'Representative Structures', to check whether storage capacity estimates derived from an analytic solution were acceptable for the purposes of the project.

The analytic solution was programmed into a spreadsheet. Two simple box like numerical simulation models representing a medium sized, and a large pressure cell were constructed. Two sets of sensitivities were run reflecting both a simpler set of assumptions required by the analytic model and a more realistic set. The simple set assumed a vertical well with linear CO_2 relative permeability and the more realistic set, a horizontal well with a standard measured set of non-linear relative permeabilities. The sensitivities included such parameters as permeability, thickness, dip, porosity and aspect ratio. Although the analytic solution modelled both brine and rock compressibilities, it did not include dip, CO_2 compressibility, CO_2 dissolution into brine, brine vapourisation into CO_2, 'dryout', or non-linear relative permeabilities, all of which were modelled by simulation.

The pressure profiles and storage capacities calculated from numerical simulation were then compared to those from the analytic model. Very good agreement was found between the two modelling techniques for the simple set of data. Agreement was less good for the more realistic assumption set, diverging significantly for lower net thicknesses and permeabilities. However, it was found that very good agreement could be retained through an adjustment to the assumed relative permeability endpoint in the analytic solution. This effectively allowed for 'dryout' around the well. These conclusions were the same for each model size. It was therefore recommended that the analytic solution, with suitable input data, be used for direct calculation of dynamic capacities within CarbonStore for each pressure cell Unit.

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1 Introduction

The project identified three types of saline aquifer store relevant to UK CO_2 storage capacity, open, pressure cells and structural traps. All UKCS saline storage units were classified into these types, though, in practice, judgement was sometimes required in classifying particular units. The initial (static) storage capacity estimated for each of these storage types was significant and some dynamical modelling was performed for each. Typically this work involved numerical simulation of two types of model. These model types were simplified generic models, termed 'Representative Structures', and more detailed models of selected regions of actual UKCS aquifer units, termed 'Exemplars'. The Representative Structure models were primarily used for investigating typical behaviour and its range of variation and the Exemplar models for demonstrating storage capacity in a particular type of store, verifying preliminary conclusions and investigating mechanisms not included in the Representative Structure models.

This report is concerned with Representative Structure modelling of pressure cells which are the most numerous storage type in the CarbonStore database. A pressure cell is an aquifer that is completely sealed and bounded with no flow and pressure communication across the boundaries either laterally or vertically. The CO_2 is therefore fully confined, so pressure behaviour, rather than CO_2 transport, is the main issue of interest. This storage type is therefore the easiest to model dynamically and has proved amenable to an analytic solution which is reported in the literature (Mathias et al, 2009, 2012). Such analytic solutions inevitably require some simplifying assumptions so dynamical modelling of pressure cells focussed on Representative Structure modelling to check whether storage capacity estimates derived from the analytic solution were acceptable for the purposes of the project.

The Mathias et al analytic solution, (Mathias et al, 2009, 2012) was programmed into a spreadsheet. Two ECLIPSE 100™ simple box models representing a medium sized (232 Mt static capacity), and a large (1 Gt static capacity) pressure cell were constructed. These are described in sections 4 and 5 respectively. Two sets of sensitivities were run reflecting both a simpler set of assumptions required by the analytic model and a more realistic set. The simple set assumed a vertical well with linear CO_2 relative permeability and the more realistic set, a horizontal well with the standard set of non-linear relative permeabilities. The sensitivities included such parameters as permeability, thickness, dip, porosity and aspect ratio. Although the analytic solution modelled both brine and rock compressibilities and endpoint relative permeabilities, it did not include dip, CO_2 compressibility, CO_2 dissolution into brine, brine vapourization into CO_2, 'dryout', or non-linear relative permeabilities, all of which were modelled by simulation.

2 Simulation Modelling Approach

Preliminary scoping studies, (see Appendix A5.1), concluded that the bulk of the dynamic modelling could be performed isothermally sufficiently accurately using the industry standard finite difference 'black-oil' simulator ECLIPSE100™, with appropriate PVT data input. The extended black oil PVT data were generated using the TOUGH ECO2N module specifying salinity and temperature. It was recommended that the most comprehensive set of consistent CO_2/brine relative permeability and capillary pressure data available from a Canadian dataset (Bennion and Bachu, 2008). Here a particular set of relative permeability data, the 'Viking 2' set, has been used for modelling where measured relative permeability data are required.

An extended black oil ECLIPSE100™ formulation was used to approximate the phase behaviour of the injected CO_2. This is represented as the *gas* component and brine as the *oil* component such that the dissolution of CO_2 in brine and vaporisation of brine into CO_2 which are important physical processes for CO_2 storage can be modelled.

The modelling approach involved using a symmetry element simulation model to represent the pressure cell to minimise the computation time. The model is homogenous with constant permeability, porosity and initial brine saturation.

2.1 Simulation Modelling Assumptions

Some assumptions were made in the simulation model for both simplification and direct comparison with the analytical model (Mathias et al, 2009, 2012).

Consistent with CarbonStore capacity estimates, CO_2 injection was terminated if any model gridblock was predicted to exceed 90% of the estimated fracture pressure, referred to as the 'fracture pressure limit'. For dipping models this will usually be at the most updip injector. A linear fracture pressure gradient of 0.8 psi/ft was assumed. The calculations of the dynamic storage capacity use the shallowest depth as the reference depth for the maximum allowable fracture pressure in both analytic and simulation modelling. The shallowest depth is a likely point of maximum pressure loading which might cause fracturing during CO_2 injection.

2.1.1 Capillarity

Capillary pressure will contribute to the distribution of injected CO_2 in a saline aquifer which could ultimately determine the amount of CO_2 that can be stored. However, the effect of capillary pressure will only be significant if the permeability of the structure is very low or it has low permeability heterogeneities. The homogenous medium size pressure cell models considered have good permeability, so any effects of capillary pressure can be ignored with little or no consequence on the dynamic capacity.

2.1.2 Relative Permeability Hysteresis

Relative permeabilities can exhibit strong dependence on the saturation path and the saturation history during two-phase or three-phase flow in a porous media. The effect on the amount of CO_2 that can be rendered immobile can be very significant depending on the injection strategy. However, for this study the injection strategy is one of continuous injection of CO_2. As this study is not concerned beyond the injection period such history dependent saturations will have little or no impact on the dynamic storage capacity of the pressure cell model, so this has not been included in the model.

2.1.3 Salt Precipitation

The effect of salt precipitation during CO_2 injection can be represented as a reduction in the pore space available for fluid flow. The process depends on the salinity of the brine and temperature profile of the formation. The simulation modelling assumed that the pressure cell is isothermal with a constant salinity and the impact of brine precipitating out of solution is neglected. This assumption is not expected to have any significant impact on the dynamic storage capacity of the structures due to their large volumes and the distributions of the injected CO_2.

3 Application of Analytic Model

3.1 Model Description

The analytic model (Mathias et al, 2009, 2012) was programmed into a spreadsheet. As it is less computationally intensive to run than the numerical simulation model, it is quick to run multiple applications for dynamic capacity estimates. The analytic model accounts for relative permeability end points, brine and rock compressibility, near wellbore non-Darcy effects and explicit pressure distribution. However, it neglects some mechanisms including CO_2 compressibility, CO_2 dissolution in brine, brine vaporisation into CO_2 and non-linear relative permeability. It assumes a vertical well, a negligible vertical pressure gradient and an homogeneous reservoir.

The input parameters required by the analytic model are listed below:

- Relative permeability
    - residual brine saturation
    - CO_2 end point
- Total compressibility (brine and rock)
- Model dimension – thickness and area
- Initial conditions
    - pressure
    - temperature
    - brine viscosity
- Rock properties – porosity and permeability
- CO_2 properties at final storage conditions
    - density
    - viscosity
- Well radius
- Forchheimer parameter
- CO_2 injection rate and time steps.

The output is a solution for pressure varying over time.

3.2 Comparison of Well Pressure Profiles

Figure A3.1 presents an initial comparison of the analytic and simulation modelling results. The comparison is based on bottomhole pressure profiles of a vertical well injecting CO_2 using the input parameters listed in section 3.1. The reference depth for the comparison is at the centroid depth in both models. The plot shows that there is a good agreement between the two modelling techniques, albeit with some simplifying assumptions, most importantly assuming a relative permeability end point of 1 for CO_2. The analytic model requires CO_2 density and viscosity at final storage conditions in order to match the calculated injection well bottom hole pressure profile from simulation modelling. The simulation model uses linear relative permeability data and a fully completed vertical well. The analytic solution does not model relative permeabilities or a horizontal injection well.

There is a small difference between the two pressure profiles at the start of the injection. **Figure A3.2** shows that the simulation model exhibits a small pressure spike at the beginning of injection. This small pressure spike disappears very quickly and has no effect on the estimated dynamic capacity. There is no pressure spike in the analytic model.

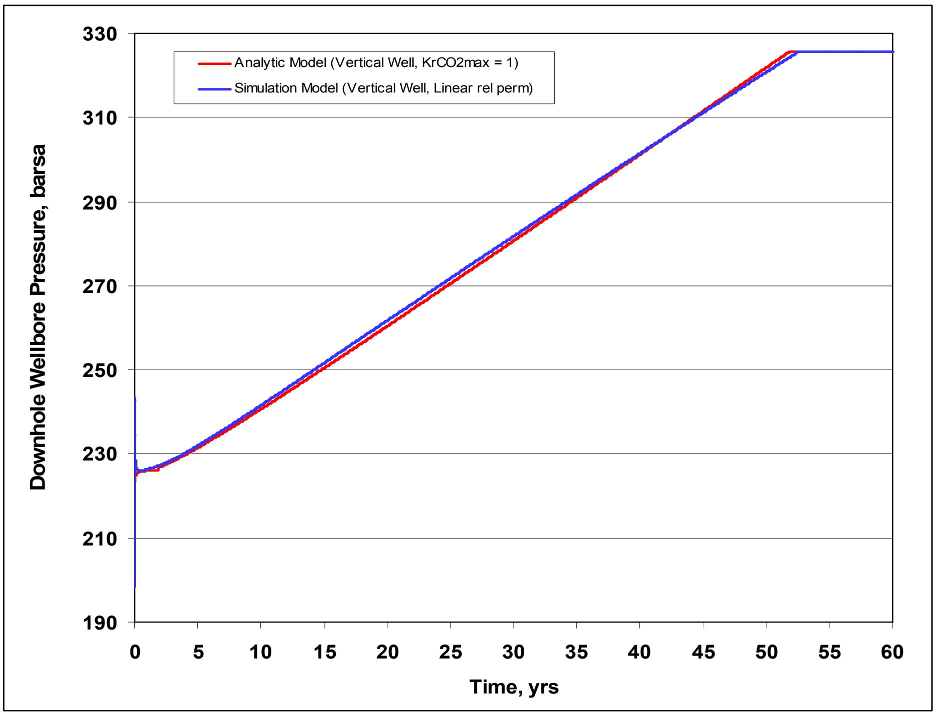

Figure A3.1: Comparing Well BHP Profiles of Analytic and Simulation Models

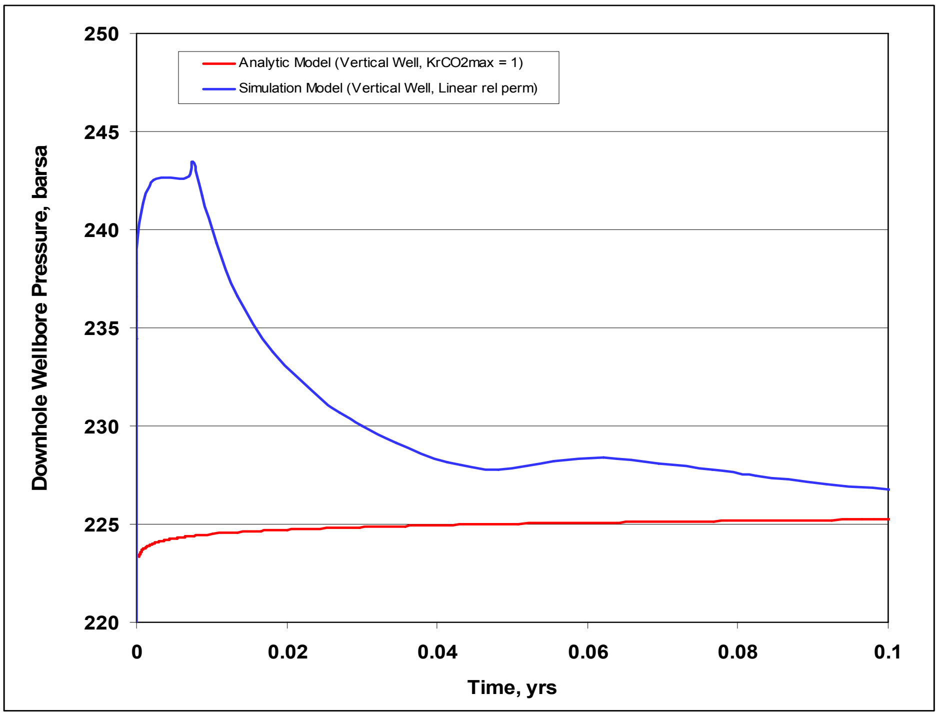

Figure A3.2: Bottomhole Pressure Spike at Start-up of Injection

4 Simulation of a Medium Sized Pressure Cell

This section describes the numerical simulation modelling of a medium size pressure cell. The model initialisation assumes hydrostatic equilibrium at the centroid depth.

4.1 Input Parameters

Table A4.1 summarises the simulation input parameters used for model development of the medium size pressure cell. The relative permeability data was initially made linear in order to compare results of simulation and analytic modelling. The two sets of relative permeability data are compared in **Figure A4.1**. For the Viking 2 data, the CO_2 relative permeability end point is 0.2638 at the residual brine saturation. The CO_2 relative permeability has been extended to 1 beyond the residual brine saturation, which may impact the region where CO_2 'dryout' occurs.

Model Parameters	Values
Depth at centroid, m	2,000
Fracture pressure gradient, psi/ft	0.8
Hydrostatic pressure gradient, psi/ft	0.433
Percentage fracture pressure limit, %	90
Model thickness, m	100
Temperature at centroid depth, ^oC	60
Brine salinity, ppm	100,000
Formation permeability, mD	300
Formation porosity, fraction	0.27
k_v/k_h	0.1
Rock compressibility, Mpa^{-1}	4E-05
Net-to-gross, fraction	1
CO_2 Surface ρ , kg/m^3	1.873
Residual brine saturation (S_{wr}), fraction	0.423
Maximum CO_2 relative permeability, fraction	1
CO_2 relative permeability @ (S_{wr}), fraction	0.2638
Target injection duration, years	58
Target injection rate, Mt/year/well	4

Table A4.1: Model Input Parameters

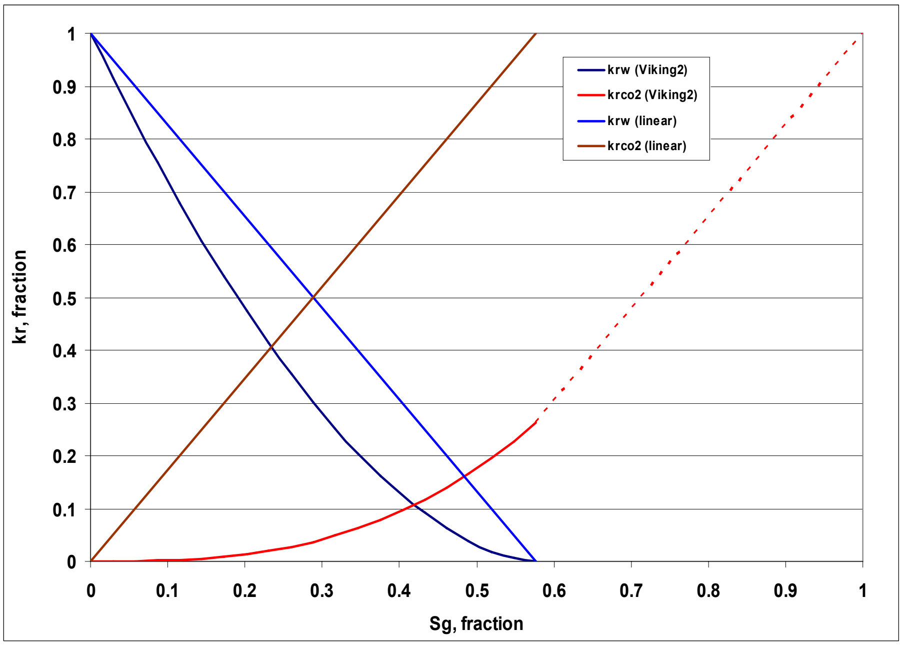

Figure A4.1: Relative Permeability Data

4.2 Calculation of Static Storage Capacity

The static storage capacity is calculated by the standard method used in CarbonStore.

The estimated area and pore volume of the medium size pressure cell structure are approximately 2,019 km^2 and 5,450 million m^3 respectively.

The calculated brine compressibility after correcting for final storage conditions, (pressure and temperature), at the centroid depth is 3.3×10^{-4} MPa^{-1}.

The calculated maximum allowable fracture pressure limit at the centroid depth is 36.2 Mpa. The initial reservoir pressure at the centroid depth is 20.4 MPa. The aquifer seal capacity is therefore 12.2 MPa.

The CO_2 density at the centroid depth and final storage pressure and temperature was computed by looking-up values of pressure and temperature in the American National Institute of Standards and Technology online database, (NIST, 2010), using two-dimensional linear interpolation.

The computed CO_2 density at the final storage conditions is approximately 848 kg/m^3 giving the static storage capacity of the medium size pressure cell model as approximately 232 Mt.

4.3 Grid Construction

A base case simulation model of the medium size pressure cell was built assuming the estimated static storage capacity of 232 Mt. The size of the pressure cell was 45 km by 45 km with 100 m thickness.

The base case simulation grid of the medium size pressure cell was constructed representing a quarter symmetry element of the medium size pressure cell. It is a single injection well model with the well positioned at the centre corner and assigned one quarter of the full injection rate. The model has the following dimensions:

- 151 grid blocks in (x-direction: 1 x 43.5 m, 149 x 150 m and 1 x 75 m);
- 151 grid blocks in (y-direction: 1 x 43.5 m, 149 x 150 m and 1 x 75 m);
- 50 grid blocks in (z-direction: 19 x 1 m, 17 x 2 m, 9 x 3 m, 5 x 4 m).

The total number of active gridblocks is 1,140,050. The well is located at the corner of the grid as shown in (**Figure A4.2**).

The injected CO_2 plume is expected to develop radially across the grids without any alignment to either X or Y-direction of the squared corner-point grids. To minimise any grid orientation effects in the horizontal plane, the 9-point finite difference scheme in ECLIPSE100™ was used.

Radial grid geometry was used to set up a simulation model similar in size with the same properties as the one described above for the purpose quality checking. The CO_2 plumes around the well at the end of injection for the two models are compared in **Figure A4.2**. The shapes of the CO_2 plumes using radial and Cartesian grid geometries are very similar, which suggests that grid orientation is expected to have a minimal effect on how the CO_2 plume will develop and pressure will dissipate in the model.

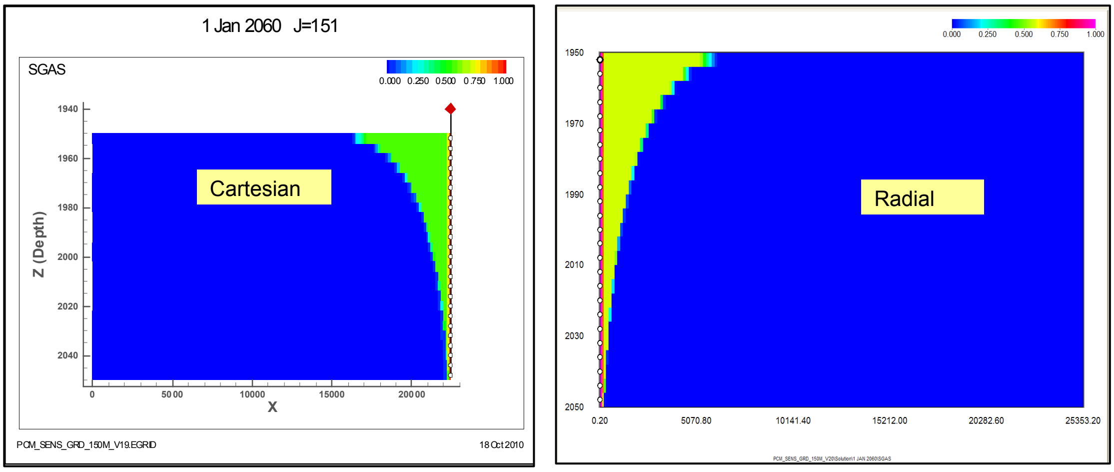

Figure A4.2: Quality Check of Grid Orientation Effect

A few simulation sensitivity cases based on grid size were also performed as part of the quality checks on the model grid construction. Three cases were run with grid sizes of 150x150 m (base case), 100x100m and 50x50m. The 50x50m grid size case increased the total number of grid cells to over 23 millions and required a very long run time. The other two cases are compared in **Figure A4.3** for pressure dissipation away from the injection well immediately at the end of 50 year CO_2 injection. The pressure distributions in both models are very similar, however using 100 x 100 m grid size instead of 150 x 150 m increased the run time significantly from about 1 hr to over 3 hrs. It was concluded that a Cartesian grid of 150 x 150 m could be used for the simulation of CO_2 storage of pressure cells without compromising the modelling accuracy.

The vertical grid resolution of the base case model is 1 – 4 m, see **Table A4.2**. This resolution is sufficient to model the pressure gradient around the injection well and movement of the CO_2 plume. The effect of the vertical grid refinement was investigated by running a sensitivity case with a uniform grid thickness of 4 m, see **Figure A4.4**. A more vertically refined grid captures the pressure and CO_2 distribution more accurately, but increases run times significantly.

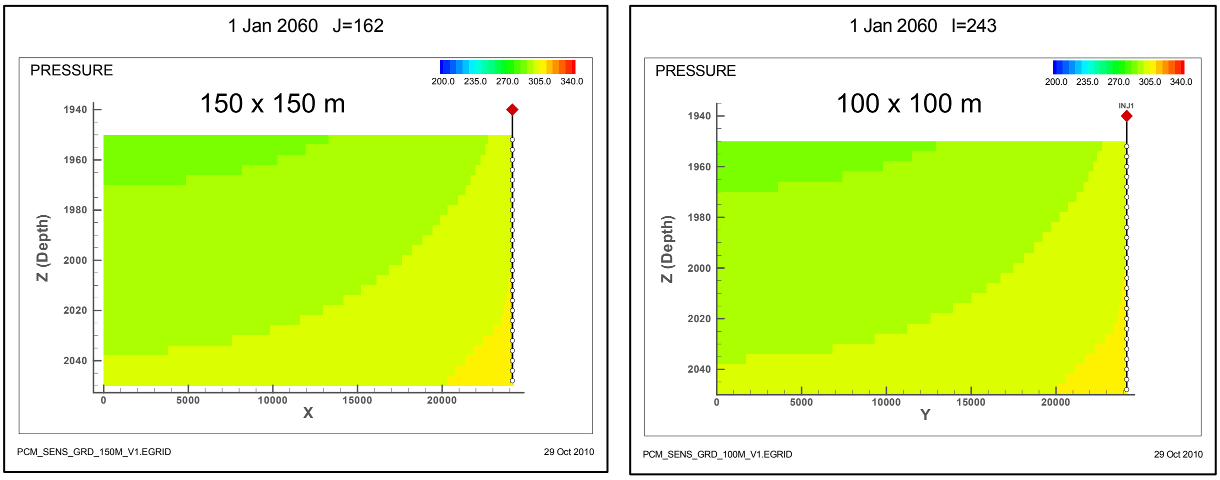

Figure A4.3: Quality Check of Grid Size Effect

Simulation Layers	Thickness, m
1 – 19	1
20 – 36	2
37 – 45	3
46 – 50	4

Table A4.2: Simulation Model Layering

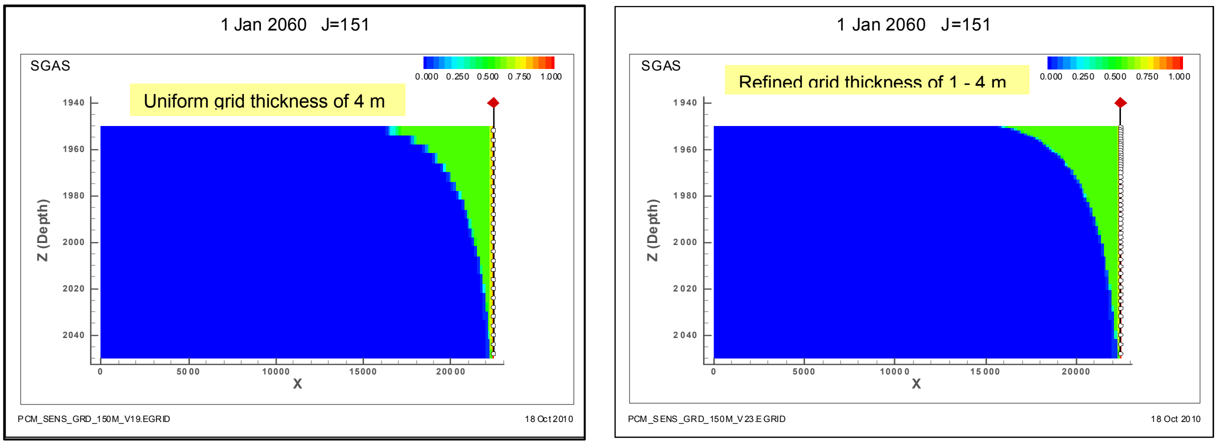

Figure A4.4: Quality Check of Vertical Grid Refinement Effect

4.4 Simulation Cases

Two sets of sensitivity cases were conducted using the base case simulation model as described in the introduction. The first set is based on the simple assumptions inherent in the analytic model while the second set considers some slightly more realistic assumptions. These involve changes to the relative permeability data, well type, dip and aspect ratio. Some multi-well simulation cases were also performed by using a lower permeability of 50 mD. The dynamic storage capacity was calculated for each scenario from the simulated injection pressure profiles at the shallowest depth.

4.4.1 Simple Assumptions

The sensitivity simulation cases under this category used a vertical well with full completion unless stated otherwise, linear relative permeability with CO_2 end point of 1, no dip and unit aspect ratio to ensure direct comparisons with the analytic model. All the cases were simulated by changing one variable at a time as indicated below:

- Permeability
  - Vertical Well Base Case – k = 300 mD
  - Case V24 – k = 30 mD
  - Case V42 – k = 50 mD
  - Case V48 – k = 75 mD
  - Case V43 – k = 100 mD
  - Case V44 – k = 150 mD
  - Case V25 – k = 3,000 mD
- Porosity
  - Vertical Well Base Case – phie = 0.27
  - Case V26 – phie = 0.1
- Relative Permeability
  - Vertical Well Base Case – Linear relative permeability
  - Case V27 – Viking 2 relative permeability
- Area Aspect ratio
  - Vertical Well Base Case – 1:1
  - Case V28 – 1:3
  - Case V38 – 1:10

- Net Thickness
  - Vertical Well Base Case – h =100 m
  - Case V29 – h = 50 m
  - Case V69 – h = 300 m
  - Case V30 – h = 400 m
- Well type
  - Base Case – Full completion vertical Well
  - Case V41 – 1 km long horizontal well

The sensitivity to net thickness adjusted the ratio of the net thickness to area but kept the volume the same. For Case V29 where the net thickness of the pressure cell was reduced from 100 m to 50 m, the area was increased proportionately to ensure no change in the volume.

- Well Completion
  - Vertical Well Base Case – Full completion
  - Case V35 – partial completion

The partial completion of the vertical well was defined as perforation of the middle half of the total model thickness. With a total model thickness of 100 m, the completed interval is between 26 – 75 m.

4.4.2 More Realistic Assumptions

A separate base case simulation model was set up for the more realistic assumptions by changing the well type from a vertical well to a 1 km long horizontal well. The linear relative permeability was changed to the Viking 2 dataset. This base case was used to perform sensitivity analysis by varying one parameter at a time. The sensitivity simulation cases for the more realistic assumptions are listed below.

- Permeability
  - Horizontal Well Base Case – k = 300 mD
  - Case V57 – k = 10 mD
  - Case V56 – k = 25 mD
  - Case V53 – k = 50 mD
  - Case V50 – k = 100 mD
  - Case V49 – k = 150 mD
- Dip
  - Horizontal Well Base Case – 0^0
  - Case V61 – 1^0
  - Case V58 – 3^0
- Net Thickness
  - Horizontal Well Base Case – h =100 m
  - Case V51 – h = 50 m
  - Case V70 – h = 300 m
- Area Aspect ratio
  - Horizontal Well Base Case – 1:1
  - Case V52 – 1:10

4.4.3 Multi-well Cases

Some multi-well simulation cases were set up to estimate the number of wells that may be required by lower permeability medium size pressure cells. These cases are based on the more realistic assumptions and a lower permeability of 50 mD as listed below:

- Horizontal Well Base Case – k=50 mD with 1 well
  - Case V62 – k=50mD with 2 wells
  - Case V63 – k=50mD with 3 wells
  - Case V59 – k=50mD with 4 wells
  - Case V66 – k=50mD with 8 wells

The additional well in Case V62 is located at the opposite corner to the existing well in the base case. The next two wells, (Cases V63 and V59), are located at the other corners of the model while the remaining four wells as in Case V66 are located equidistant from the centre of the model.

4.5 Simulation Results

The results are presented in this section expressed as a storage factor, which is the ratio of the dynamic storage capacity to the static storage capacity. There is good agreement between the analytic and simulation models for different values of permeability and net thickness based on the simple assumptions as shown in **Figures A4.5 and A4.6**. The differences between them are not significant and the trends of the sensitivities to permeability and net thickness are similar, both decreasing significantly at lower values.

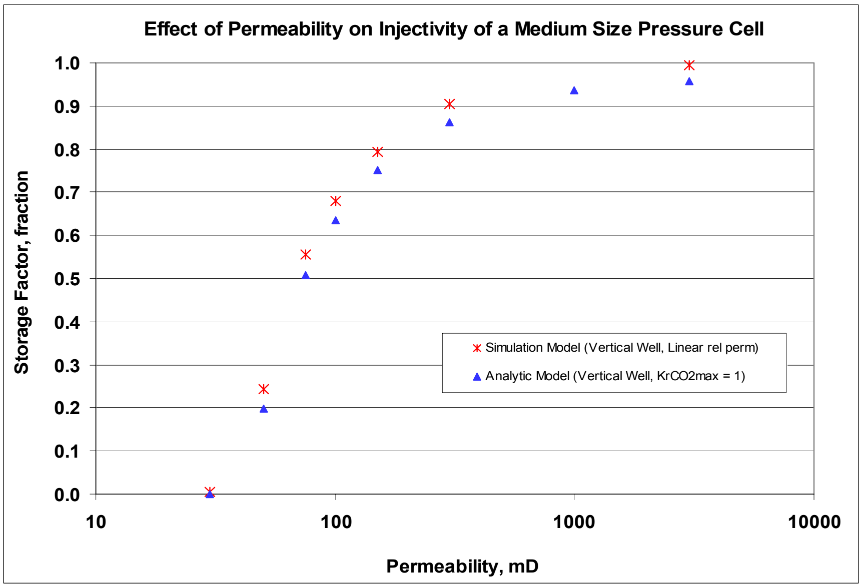

Figure A4.5: Model Comparison for Simple Assumptions with Different Permeability

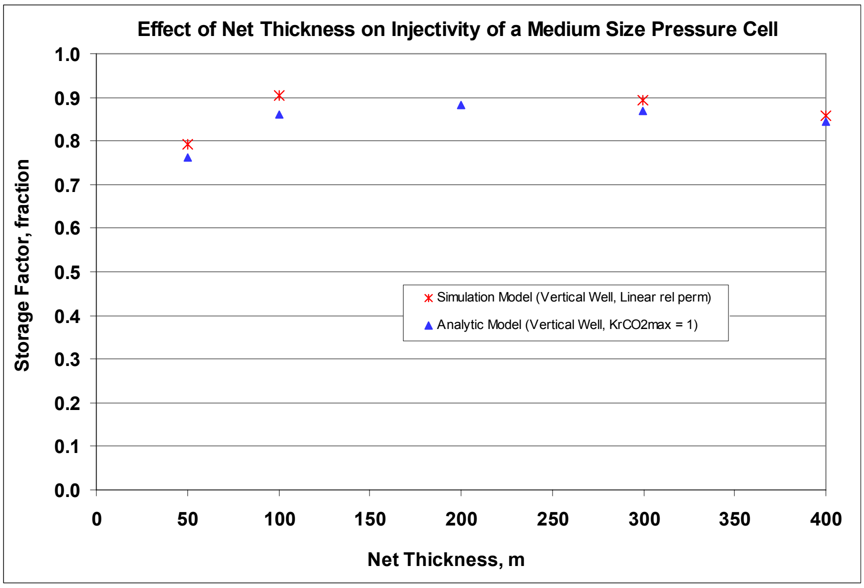

Figure A4.6: Model Comparison for Simple Assumptions with Different Net Thickness

Table A4.3 lists the results of all the simulation cases with the simple assumptions. These show that permeability, net thickness and aspect ratio are the key variables that will affect the dynamic storage capacity of the pressure cell. The full potential dynamic capacity of the structure could only be utilised if the permeability is high in the region of Darcies. A very high permeability means that the injected CO_2 plume will have a higher velocity and spread more uniformly and results in a lower rate of pressure build up near the wellbore, so more CO_2 can be injected and remain in free phase.

CO_2 injectivity is favoured by an area aspect ratio of 1:1. The injection pressure can be dissipated more radially and evenly away from the injection point as opposed to when the shape of the structure creates a linear flow regime when the area aspect ratio is significantly less than 1. For more realistic scenarios when the shape of the pressure cell is not square, any boundary effects would be accelerated, rate of pressure build up would be increased and the amount of CO_2 that can be injected would be limited.

Cases	SF, frac.	Time, yrs	Total CO_2 injected, (Mt)	Free CO_2, (Mt)	Dissolved CO_2, (Mte)	Dissolved CO_2, (%)
Case V23: Vertical Well Base Case	0.905	52.56	52.49	49.84	2.65	5.1
Case V24: k = 30 mD	0.005	0.29	0.29	0.16	0.13	45.7
Case V42: k = 50 mD	0.244	14.16	14.13	12.49	1.64	11.6
Case V48: k = 75 mD	0.557	32.33	32.28	30.19	2.09	6.5
Case V43: k = 100 mD	0.680	39.49	39.44	37.14	2.30	5.8
Case V44: k = 150 mD	0.795	46.16	46.10	43.60	2.50	5.4
Case V25: k = 3,000 mD	0.994	57.74	57.66	54.98	2.68	4.6
Case V26: phie = 0.1	0.897	52.08	52.01	49.67	2.35	4.5
Case V27: Viking 2 relative permeability	0.859	49.89	49.82	47.18	2.64	5.3
Case V28: Area aspect ratio = 1:3	0.884	51.33	51.26	48.65	2.61	5.1
Case V38: Area aspect ratio = 1:10	0.775	45.00	44.94	42.57	2.37	5.3
Case V29: Thickness = 50 m	0.793	46.08	46.02	43.59	2.43	5.3
Case V69: Thickness = 300 m	0.894	51.95	51.88	49.24	2.64	5.1
Case V30: Thickness = 400 m	0.858	49.82	49.75	47.08	2.68	5.4
Case V35: Partial completion well	0.868	50.41	50.34	47.79	2.56	5.1
Case V41: Horizontal well and linear relative permeability	0.963	56.14	55.86	53.09	2.77	5.0

Table A4.3: Medium Size Pressure Cell Sensitivity Cases with Vertical Well

The results of the sensitivity simulation cases with more realistic assumptions are presented in **Table A4.4**.

Cases	SF. Frac.	Time, yrs	Total CO_2 injected, (Mte)	Free CO_2, (Mte)	Dissolved CO_2, (Mte)	Dissolved CO_2, (%)
Case V47: Horizontal Well Base Case	0.915	53.18	53.11	50.29	2.82	5.3
Case V57: k = 10 mD	0.000	0.00	0.00	0.00	0.00	0.00
Case V56: k = 25 mD	0.003	0.17	0.17	0.14	0.03	19.8
Case V53: k = 50 mD	0.273	15.86	15.84	14.45	1.39	8.8
Case V50: k = 100 mD	0.680	39.48	39.43	36.97	2.46	6.2
Case V49: k = 150 mD	0.812	47.16	47.10	44.43	2.67	5.7
Case V52: Area aspect ratio = 1:10	0.782	45.43	45.37	42.90	2.47	5.5
Case V51: Thickness = 50 m	0.779	45.25	45.18	42.81	2.38	5.3
Case V69: Thickness = 300 m	0.917	53.24	53.17	50.03	3.14	5.9
Case V61: Dip = 1 deg	0.821	47.71	95.29	45.07	5.14	5.4
Case V58: Dip = 3 deg	0.425	24.67	49.27	23.10	3.06	6.2
Case V62: k= 50 mD, 2 wells	0.711	41.41	41.26	38.12	3.14	7.6
Case V63: k= 50 mD, 3 wells	0.827	48.16	47.97	44.22	3.75	7.8
Case V59: k= 50 mD, 4 wells	0.873	50.74	50.66	46.51	4.15	8.2
Case V66: k= 50 mD, 8 wells	0.873	50.74	50.67	45.15	5.52	10.9

Table A4.4: Medium Size Pressure Cell Sensitivity Cases with Horizontal Well

A comparison of the two sets of simulation results in **Table A4.3 and Table A4.4** shows that they are similar with only small differences between them even at lower permeability and net thickness. The estimated storage factor increases by only 6 percentage points when well type is the only different assumption i.e. cases V27 and V47 or cases V23 and V41.

The effect on the base case of using the more realistic Viking 2 relative permeability data instead of a linear relative permeability data is small, approximately 5% reduction in the storage factor, even though the CO_2 relative permeability end point is 0.2638 at the residual brine saturation, rather than 1. The amount of CO_2 dissolved in brine is typically about 5% of the total CO_2 injected.

4.5.1 Effect of Permeability

The simulation results show that reducing permeability to 50 mD significantly reduces CO_2 injectivity for the medium size pressure cell.

A comparison of the storage factors for different permeability cases with simulation model using one horizontal well and analytic model using one vertical but with the CO_2 end point of 0.2638 in both models is presented in **Figure A4.7**. The analytic model predicts dynamic capacities lower by more than 20% compared to the simulation model for lower permeability. For higher permeabilities over 1 D the differences are insignificant due to more uniform pressure dissipation and lower pressure gradients.

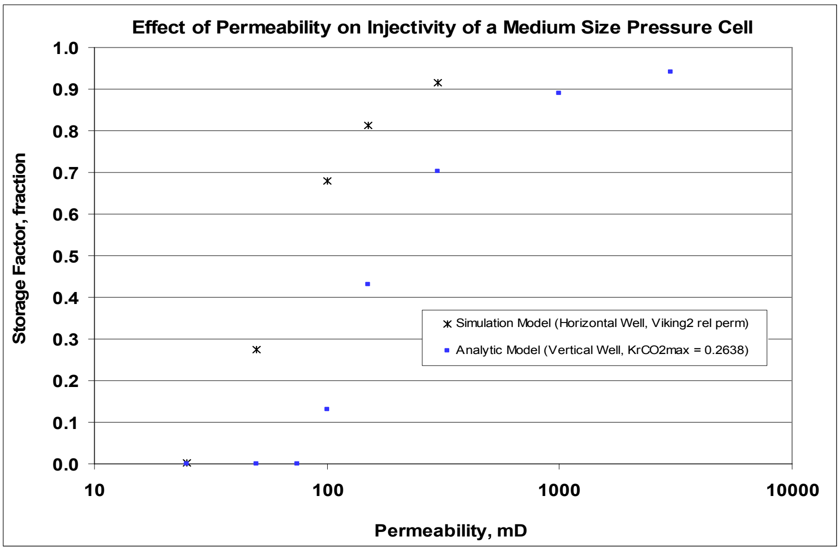

Figure A4.7: Model Comparison for Realistic Assumptions with Different Permeability

4.5.2 Effect of Net Thickness

The effect of net thickness on the dynamic capacity was also investigated by using different values of net thickness but adjusting the areas accordingly to keep the volumes the same. A comparison of the storage factors for the simulation and analytic models for different values of net thickness is shown in **Figure A4.8**. The analytic model predicts significantly lower dynamic capacities at lower net thicknesses, though the trends are similar. There is more than 20% reduction in the storage factor when the net thickness was reduced from 100 m to 50 m. With a lower net thickness, there is a significant increase in the local pressure build up around the well. This means that the fracture pressure limit which terminates injection will be reached sooner.

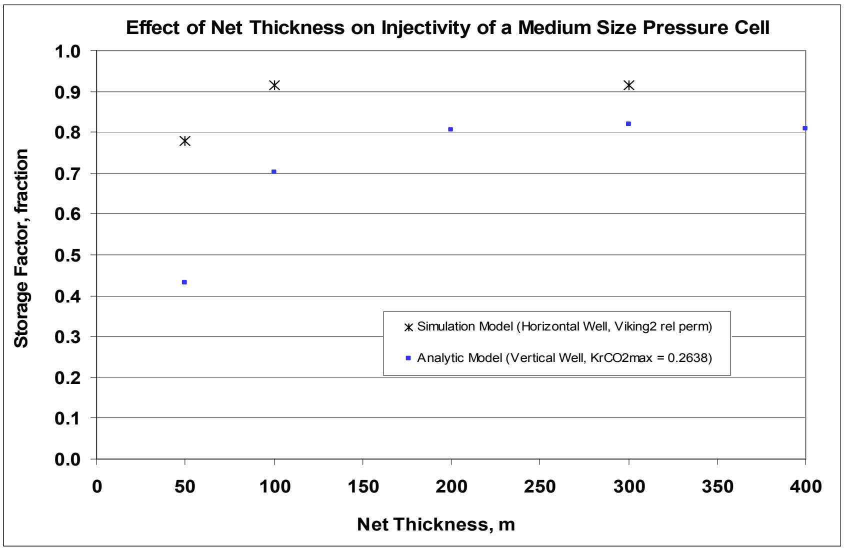

Figure A4.8: Model Comparison for Realistic Assumptions with Different Net Thicknesses

4.5.3 Effect of Aspect Ratio

Area aspect ratio may affect the dynamic storage capacity of the pressure cell. A comparison of the storage factors for some cases considered is shown in **Figure A4.9**. The analytic model assumes the area aspect ratio is 1:1. At a lower area aspect ratio of 1:10, the dynamic capacity reduces by more than 10%. Aspect ratio could have a significant effect on the CO_2 injectivity of pressurized cells where the length is significantly longer than the width.

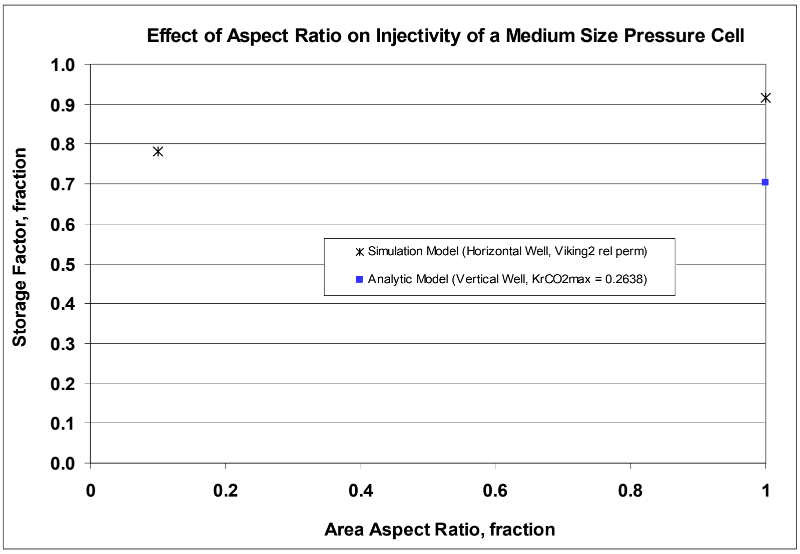

Figure A4.9: Model Comparison for Realistic Assumptions with Different Aspect Ratio

4.5.4 Effect of Dip

The highest pressure in the PVT data of the simulation model is 600 bars which means only up to about 3.5º dip could be investigated. Two sensitivity simulation cases were set up to investigate the effect of dip on the more realistic assumption base case. The analytic model does not account for dip but the shallowest depths from the simulation model for the two dip cases were used in the analytic model to compare between the two modeling techniques.

A comparison of the storage factors for the dip cases in both simulation and analytic models is shown in **Figure A4.10**. Storage factors tend to decrease with dip as there is less 'pressure space' available for storage at shallower depths. The analytic approach generally gives much lower storage factors, even when the CO_2 endpoint relative permeability is set to 1. From simulation, a small dip angle of 1^0 can limit the CO_2 injectivity of the medium size pressure cell by as much as 6%. However, this effect may be able to be engineered away in actual field operations by injecting downdip of the structure as much as possible.

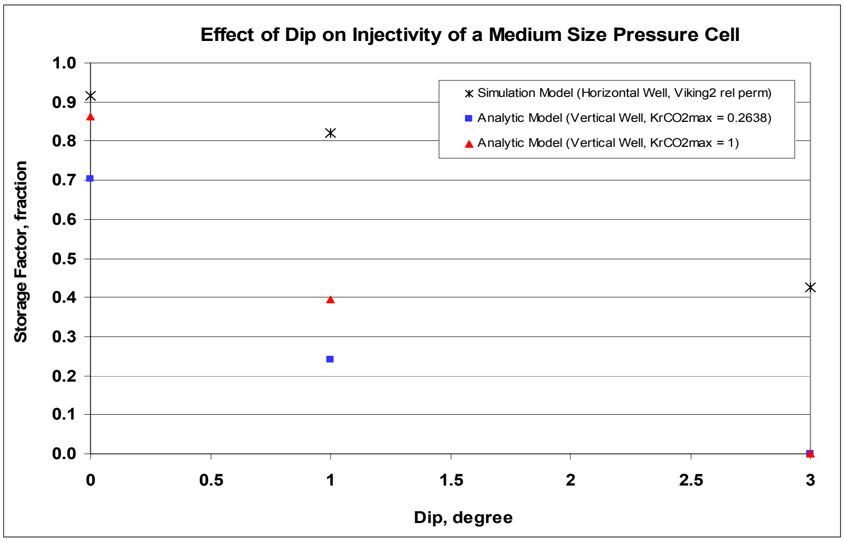

Figure A4.10: Model Comparison for Realistic Assumptions with Different Dip

4.5.5 Estimates of Well Count

For a permeability of 50 mD the dynamic storage capacity is only about a quarter of the estimated static storage capacity. Some additional simulation runs were conducted to estimate the number of wells that might be required to utilise more of the static capacity.

Some storage factor comparisons of the 50 mD medium size pressure cell with multiple injection wells are shown in **Figure A4.11**. According to the analytic model for a single injector, no CO_2 can be injected assuming a CO_2 relative permeability end point of 0.2638 at residual brine saturation. Using simulation modelling, a storage factor of about 27% can be achieved with one horizontal well.

The multi-well simulation cases show that two, three and four horizontal wells will increase the storage factor to 0.71, 0.83 and 0.87 respectively. The results further confirm the strong influence of permeability on CO_2 injectivity of the pressure cell. The well count was increased to eight horizontal wells to see if most of the capacity of the pressure cell could be utilised, but this only resulted in more dissolved CO_2. However, it might be possible to inject more CO_2 into the model with some optimisation of well locations.

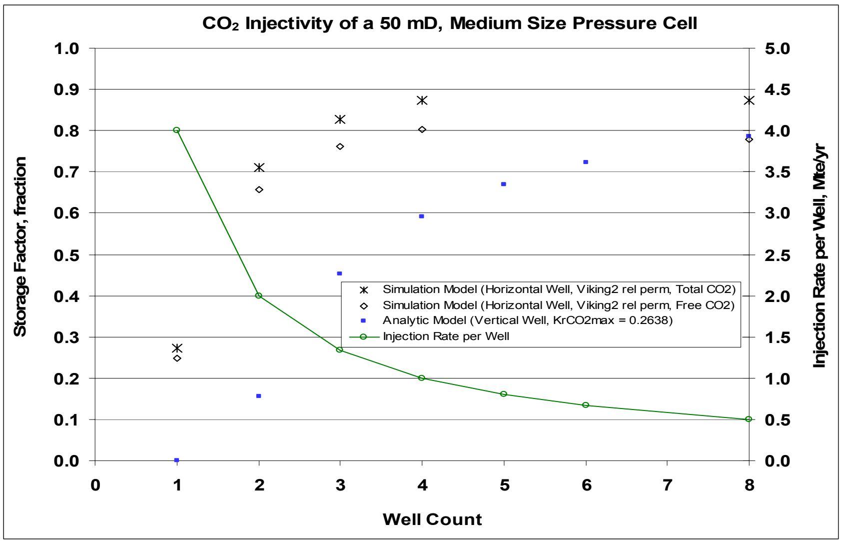

Figure A4.11: Model Comparison for Multi-well Scenarios

4.5.6 Adjustment to Analytic Solution

The pressure profiles and storage capacities calculated from numerical simulation were compared to those from the analytic model. Very good agreement was found between the two modelling techniques for the simple set of data. Agreement was less good, though still satisfactory, for the more realistic assumption set, diverging for lower net thicknesses and permeabilities, see **Figure A4.12**. It was found however, that very good agreement could be retained by setting the endpoint CO_2 relative permeability to 1 in the analytic formula, see. This effectively allowed for brine vaporisation into CO_2, or 'dryout', around the well. These conclusions were the same for each model size. It was recommended therefore that the analytic solution with this adjustment be used for direct calculation of dynamic capacities for each pressure cell in CarbonStore.

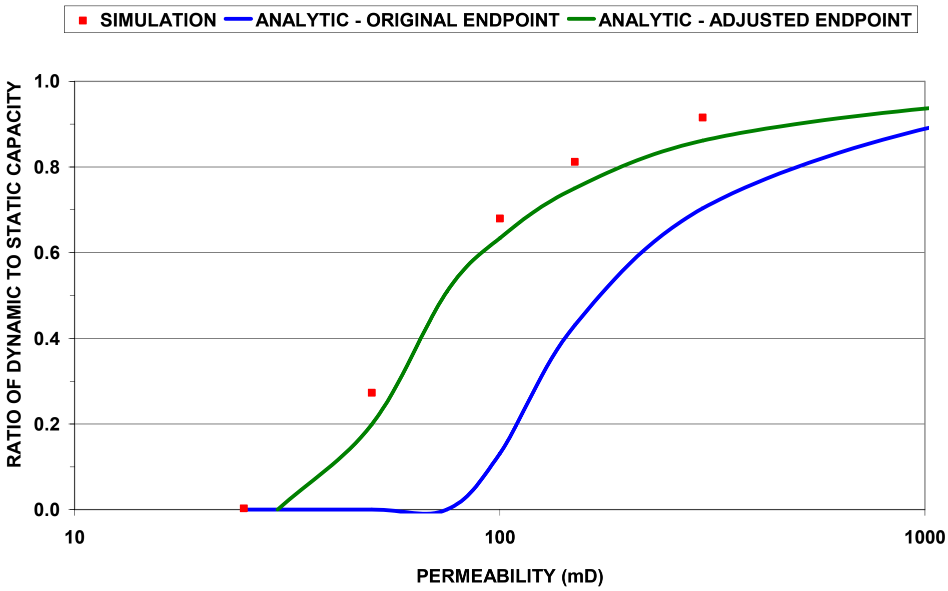

Figure A4.12: Capacity as a function of permeability, 'realistic' simulation compared with analytic model

5 Simulation of a Large Pressure Cell

A numerical simulation model was constructed to be typical of the six largest pressure cells in CarbonStore, all of which have static capacities greater than 1 Gt. The range of static capacities is 1.2 to 6.1 Gt. These pressure cells extend over large areas, typically 9 to 16 thousand km^2, though one thicker unit covered less than two thousand km^2.

5.1 Input Data

Table A5.1 lists the typical large pressure cells properties which defined the simulation model. The PVT data input was similar to the medium size simulation model but used typical values of salinity and temperature. The relative permeability data was the standard Viking 2 set.

Model Parameters	Values
Depth at centroid, m	3,000
Fracture pressure gradient, psi/ft	0.8
Hydrostatic pressure gradient, psi/ft	0.433
Percentage fracture pressure limit, %	90
Model thickness, m	300
Model Area, km^2	10,000
Temperature at reference depth, ^oC	90
Brine salinity, ppm	100,000
Formation permeability, mD	40
Formation porosity, fraction	0.164
k_v/k_h	0.1
Rock compressibility, MPa^{-1}	4E-05
Net-to-gross, fraction	1
Connate water saturation, fraction	0.423
Surface ρ_{CO2} , kg/m^3	1.873
Residual water saturation, fraction	0.423
Maximum CO_2 relative permeability, fraction	1
CO_2 relative permeability @ (S_{wr}), fraction	0.2638
Target injection duration, years	57.3
Dip, degree	1
Area aspect ratio	1:1
Static storage capacity, Mt	3,436
Assumed minimum economic CO_2 well injection rate (Mt/year)	0.5
Maximum CO_2 well injection rate (Mt/year)	2.0

Table A5.1: Large Pressure Cell Model Input Data

Two cases of the simulation model are listed below, one with dip and another without. The symmetry element modelling approach modelled only 1/8th of the full store with reduction in one direction only. The static capacity of the model element was 375 Mt from four horizontal wells located 20 km apart from updip to downdip, **Figures A5.1 and A5.2**. The maximum CO_2 injection rate was 1.875 Mt/yr/well in order to give an even number of wells, to apply the element modelling approach.

- Case V5A – No dip
- Case V6A – 1^0 dip (in one direction only)

As these models possessed large static capacities, in order to estimate the full storage potential, the cases were allowed to run for up to 100 years or until the fracture pressure limit was reached in some gridblock. Injector bottom hole pressures were limited to the fracture pressure limit.

The temperature at the centroid depth assumed a geothermal gradient of $30^{0}C$ / 100 m. All the large pressure cells are normally pressured, so the initial model pressure assumes a hydrostatic pressure gradient.

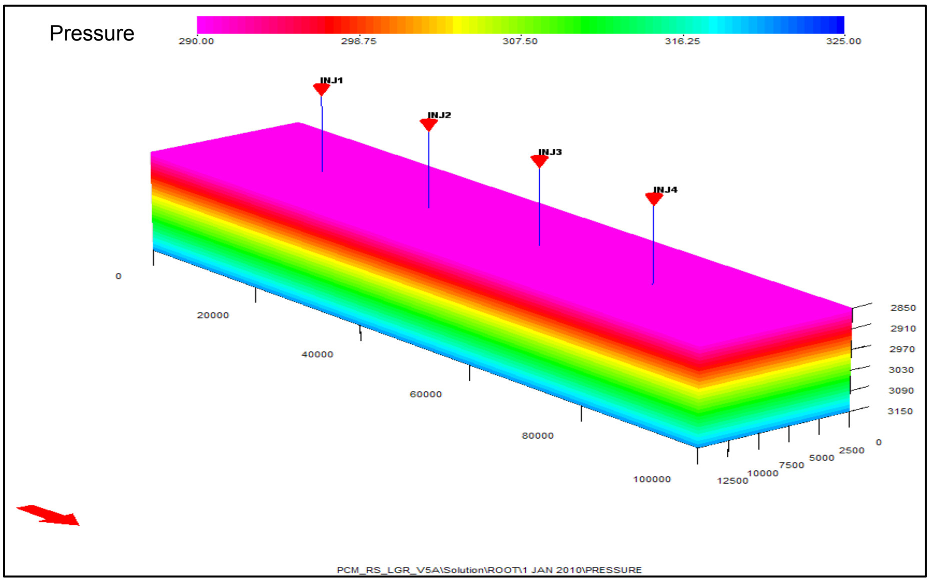

Figure A5.1: Well Locations in Case Without Dip

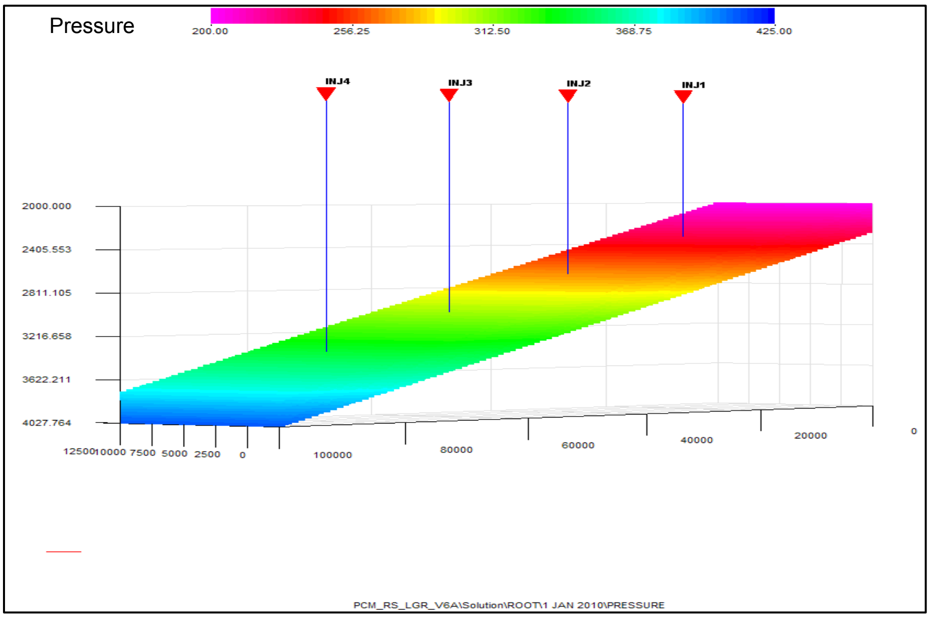

Figure A5.2: Well Locations in Dipping Case

5.2 Model Gridding

A coarse simulation grid of 1 km by 1 km by 10 m was used to model the representative pressure cell because of the size of the element model. For the $1/8^{th}$ element model this gives a grid dimension of 100x13x30 and a total number of 39,000 global grid blocks. One of the edge grids in the y-direction was 0.5 km. The coarse grid was combined with some local grid refinements (LGR) around wells in order to ensure modelling accuracy of pressure dissipation and CO_2 migration from the injection points.

The CO_2 envelopes were not expected to extend beyond about 5 km radius of the injection points, so the horizontal local grid refinement was limited to an area of about 120 km^2 around the wells. The global grid size of 1 km square was reduced to 200 m square. The number of simulation layers was increased from 30 to 60 by refining the global vertical grid thickness from 10 m down to a minimum of 2.5 m, see **Table A5.2**. The number of grid blocks in each LGR was 181,500, which gave a total of 765,000 active grid blocks in the simulation model.

Global Layers	Thickness, m	LGR Layers	Thickness, m
1 – 30	10	1 – 20	2.5
		21 – 50	5
		51 – 60	10

Table A5.2: Vertical Grid Refinement for Large Pressure Cell

5.3 Initialisation of the Dipping Model

The model with no dip was initialised assuming hydrostatic equilibrium using the hydrostatic gradient in **Table A5.1**, however this approach could not be applied to the dipping model. The model is very long, 100 km, so a dip angle of 1º increased the vertical interval between the shallowest and deepest depths to over two km, preventing the gas pressure equilibration calculation from converging in ECLIPSE100™.

It was therefore decided to initialise the dipping case by explicitly defining the initial pressure and saturation of the brine. At the initial conditions there is no injected CO_2 so the PVT data was modified by removing the saturated data. In order to calculate the initial brine pressure distribution in the model, the modified PVT data was first used to initialise the model with the undersaturated brine. The brine pressure distributions were then extracted for all the gridblocks in the model and used as input for a non-equilibrium initialisation. The initial CO_2 saturation was set to zero for all the gridblocks.

5.4 Simulation Results

The dynamic storage performances for the two cases with and without dip are shown in **Table A5.3**. The total number of horizontal wells equivalent to the full model was 32. With no dip and a target injection rate of 1.875 Mt/year/well, about 88% of the static storage capacity was utilised in just under 43 years, when the fracture pressure limit was reached. However, with a 1^0 dip the storage factor was reduced by more than a quarter as the fracture pressure limit was reached 9 years earlier, because of the effect of dip on this limit for the updip wells. The shallowest depth increased by 850 m for the dipping case. The ratio of dissolved to the total CO_2 injected was about 1:10 in most of the cases.

Cases	SF. Frac.	Time, yrs	Total CO_2 (Mt)	Free CO_2 (Mt)	Dissolved CO_2 (Mt)	Dissolved CO_2 (%)
No dip	0.88	42.7	3019	2706	313	10.4
1^0 dip	0.63	33.5	2163	1928	236	10.9

Table A5.3: Simulation Results of a Representative Large Pressure Cell

Various profiles are now presented, but note these include injection for up to 100 years, far beyond the fracture pressure limit for both the dipping and non-dipping cases. The field injection profiles of the both cases are compared in **Figure A5.3**. For the dipping case a pronounced spread of injection rates and BHP profiles for the four simulated wells are shown in **Figure A5.4** and **Figure A5.5**.

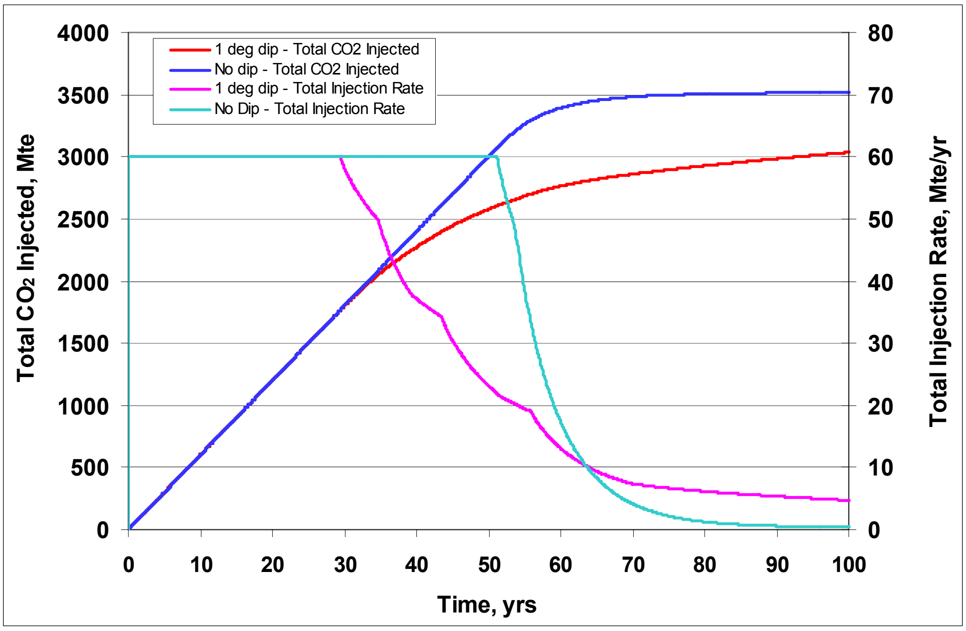

Figure A5.3: Field Injection Profiles for the Large Pressure Cell Model

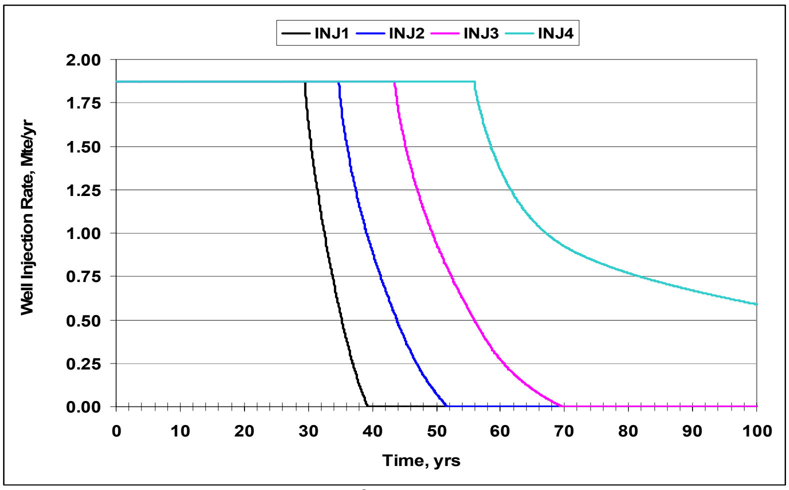

Figure A5.4: Case 1^0 Dip Well Injection Rates

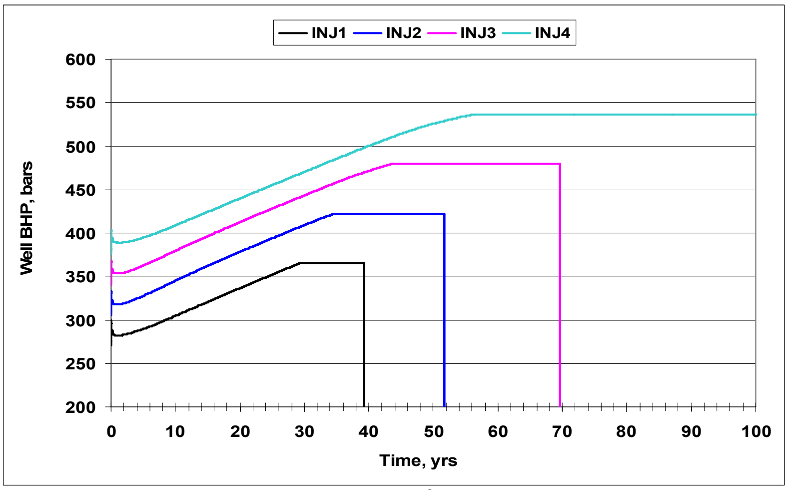

Figure A5.5: Case 1^0 Dip Well BHP

Figure A5.6 shows pore volume utilisations for both free and dissolved CO_2. At the fracture pressure limit the pore volume utilisations of free CO_2 are 0.6% and 0.4% for the non-dipping and dipping cases respectively.

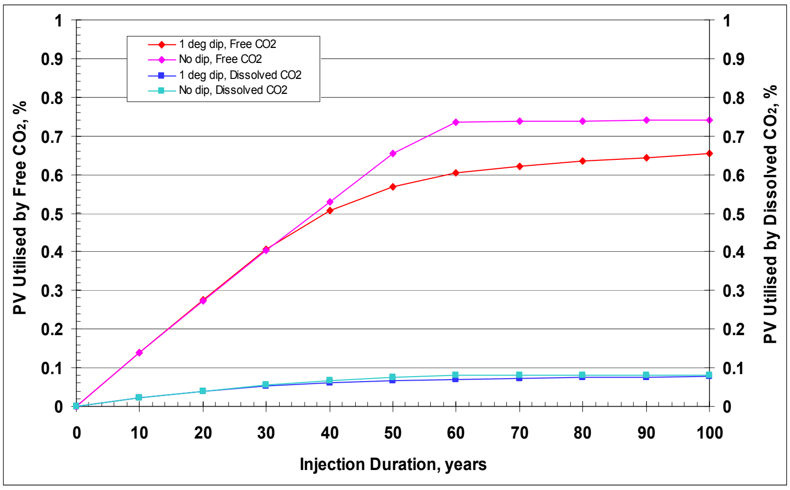

Figure A5.6: Pore Volume Utilisations for the Large Pressure Cell Models

Figure A5.7 shows the time at which the fracture pressure limit is reached for various well number scenarios calculated by the analytic model. This suggests that it would take 32 vertical wells each injecting at 1.875 Mt/year for 57.3 years to fill the large pressure cell.

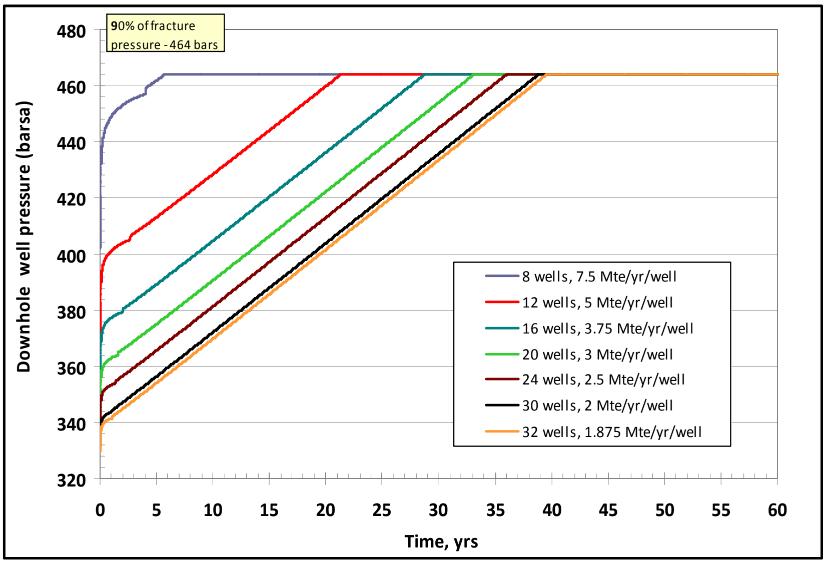

Figure A5.7: Analytic Model Predictions of Time to Reach Fracture Pressure Limit

Figure A5.8 compares the storage factor predicted by the analytic model with that from simulation, assuming 32 horizontal wells, for both the dipping and non-dipping cases. The storage factor for the non-dipping case including only free CO_2 agrees well with the analytic prediction, but is significantly higher when dissolved CO_2 is included. The storage factor for the dipping case is significantly below the analytic prediction.

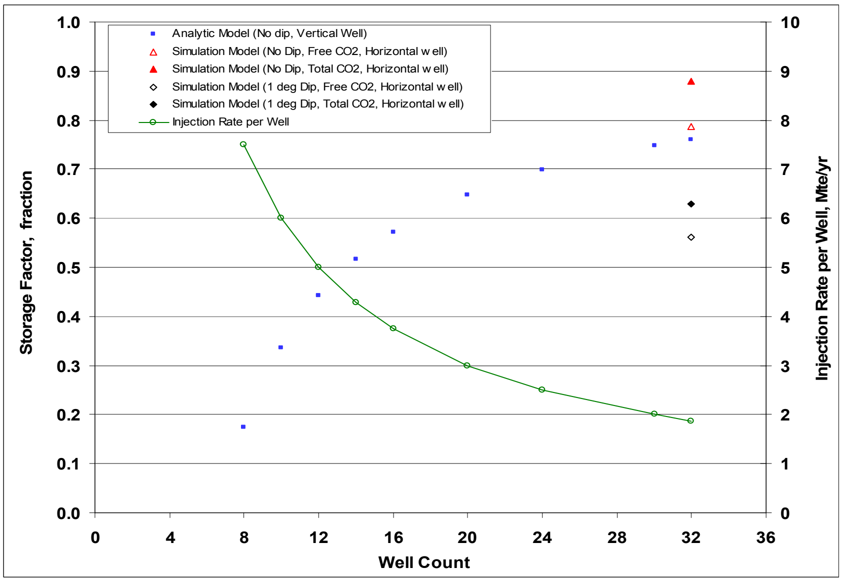

Figure A5.8: Storage Factor Comparisons for 32 Wells

The conclusions from these larger models are consistent with those from the medium size models.

6 Conclusions

For a simple set of modelling assumptions, closer to those required by the analytic solution, the numerical simulation agrees well with the analytic solution.

For the more realistic set of assumptions including relative permeability data, the numerical simulation suggests that the analytic model as originally implemented will significantly underestimate dynamic capacities for lower permeability and net thickness. This is due to neglecting brine vapourization into CO_2, 'dryout', around the well and can be effectively compensated for by setting the endpoint CO_2 relative permeability to 1 in the analytic formula.

With the revised implementation suggested above, the analytic model can be used to adequately estimate dynamic CO_2 storage capacities of pressure cells in CarbonStore.

Dynamic capacities are typically a large fraction of static capacities unless the product of permeability and thickness is low or there are too few wells to fill the store.

Typically during injection up to about 10% of injected CO_2 dissolves in brine in these simulations.

An unfavourable aspect ratio may reduce dynamical storage capacities, but this effect is not large, typically less than 10%, so may be able to be removed with engineering optimisation.

A dipping structure may also have reduced dynamical storage capacity, due to lower fracture pressure limits updip reducing injectivity. However, this effect is not large and might be able to be removed with engineering optimisation.

Consistent results were obtained for numerical simulation of both the medium and large pressure cells.

7 References

1. Mathias SA, Gonzalez GJ, Thatcher KE & Zimmerman RW 2012. Pressure buildup during CO_2 injection into a closed brine aquifer. *Transport in Porous Media,* In Press

2. Mathias, SA, Hardisty, PE, Trudell, MR & Zimmerman, RW 2009. Approximate Solutions for Pressure Buildup During CO2 Injection in Brine Aquifers. *Transport in Porous Media* **79**(2): 265-284.

3. National Institute of Standards and Technology online database, http://webbook.nist.gov/chemistry/name-ser.html, Sampled 2010.

8 Glossary of Terms and Abbreviations

BHP	bottom hole pressure
CO_2	carbon dioxide
cp	centipoise
C_f	rock compressibility
C_w	water compressibility
C_t	total compressibility
Gt	Giga tonnes
kg	kilogram
km	kilometres
km^2	square kilometres
k_v/k_h	ratio of vertical permeability to horizontal permeability
M	million
mD	permeability in millidarcies
m^3	cubic metres
m^3/d	cubic metres per day
Mt	millions of tonnes
MPa	mega pascals
NTG	net to gross ratio
^oC	degree centigrade
phie	porosity fraction
ppm	parts per million
ρ_{CO2}	density of CO_2
psi	pounds per square inch
psia	pounds per square inch absolute
psi/ft	pounds per square inch per feet
PV	pore volume
PVT	pressure volume temperature
SC	static capacity
SF	storage factor
ϕ	porosity
UKSAP	UK storage appraisal project