Programme Area: Carbon Capture and Storage

Project: Storage Appraisal

Title: Representative Structure Modelling of Aquifers with Identified Structure

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 A5.5

Representative Structure Modelling of Aquifers with Identified Structure

Conducted for

The Energy Technologies Institute

By

RPS Energy

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Date Released	28th October 2011 (final)

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Executive Summary

The project did not seek to collect structural data on saline traps, but some data were available for dome structures in the Bunter formation of the southern basin. As a result this storage type is the least numerous in the CarbonStore database, nonetheless its storage capacity is of particular interest, as such stores could combine the advantages of both open aquifers and pressure cells through structural containment with potentially less pressure restriction.

The storage capacity of the Bunter domes has been estimated previously on a volumetric basis, assuming a pore volume utilisation of 40%. The dynamic modelling work undertaken in this project improved these estimates by investigating pore volume utilisation and pressure interference between domes in a multi-injection scenario. The Bunter Formation was sub-divided into areal Zones and each of these Zones is classed as separate, but open, storage Units in CarbonStore. Zone 4 was selected for detailed study here as it contains the majority of the Bunter domes and so makes a significant contribution to the volumetric storage capacity in the Bunter domes.

The dynamic work on structural traps involved material balance Representative Structure modelling of CO_2 injection into all the Zone 4 domes described in this report and fine scale Exemplar modelling of injection into up to three selected neighbouring domes. Three versions of the Representative Structure model were constructed based on the minimum, most likely and maximum properties in CarbonStore. Most simulations assumed injection into all domes simultaneously. Injection was constrained by fracture pressure limits for each dome and the parent aquifer itself, set by data from CarbonStore. A rough optimisation of injection well numbers was performed as usually a point of diminishing added value was reached for additional wells.

Injection into a single dome to estimate the time required to fill the dome to the maximum assumed pore volume utilisation gave long filling times in excess of 100 years for large domes, despite using many wells. Injection into all domes simultaneously indicated significant pressure interference. Both these findings substantially reduced achievable storage capacities on likely project timescales, suggesting that these domes have achievable capacities substantially less than the maximum capacity indicated by the buoyant capacity limit.

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1 Introduction

The project did not seek to collect structural data on saline traps, but some data were available for dome structures in the Bunter formation of the southern basin. As a result this storage type is the least numerous in the CarbonStore database, nonetheless its storage capacity is of particular interest, as such stores may combine the advantages of both open aquifers and pressure cells. This type of store provides containment through structural trapping, which might be considered as more secure, for example, than dipping open aquifers. However, such stores are not fully confined, so in principle pressure can bleed off over time into the surrounding aquifer and pore volume utilisation may therefore be higher than for pressure cells, which are fully confined.

For the reasons above and because they lie in a convenient location relative to point sources of CO_2, see **Figure A1.1**, the Bunter domes have been studied before, for example, (Bentham, 2006). Bentham estimated the storage capacity of these domes on a volumetric basis, assuming a pore volume utilisation of 40%. The dynamic modelling work undertaken in this project has improved these estimates, both by investigating pore volume utilisation and pressure interference between domes in a multi-injection scenario. The Bunter Formation was sub-divided into areal Zones using structural features such as salt walls, faults and dykes as boundaries. Each of these Zones is classed as separate, but open, storage Units in CarbonStore. Zone 4 (CarbonStore Unit 139.000) was selected for detailed study as it contains 15 of the 29 Bunter domes and so makes a significant contribution to the volumetric storage capacity in the Bunter domes.

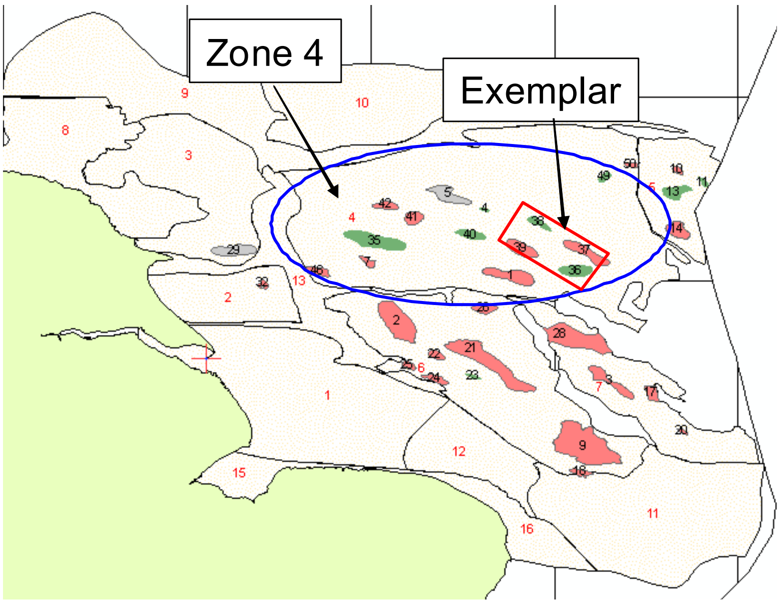

Figure A1.1: Domes in Bunter Formation

The dynamic work on structural traps involved material balance Representative Structure modelling of CO_2 injection into all 15 Zone 4 domes and fine scale Exemplar modelling of the region around Bunter closures (domes) 36, 37,38 and 39, primarily injecting into 36. These closures were selected based on a lower likelihood of faulting, whilst enclosing significant pore volume. The properties of Zone 4 domes are given in section 2.

An ECLIPSE100™ material balance type model of the Bunter Zone 4 and all its 15 domes was constructed with just a single cell representing each dome. This is described in section 3. Three versions of the model were produced based on the minimum, most likely and maximum properties in CarbonStore.

For comparison purposes, it is useful for structural traps to calculate two extreme capacity estimates, a pressure capacity (calculated from compressibility) and a capacity based upon the assumption that the structure could be 'filled-to-spill' with buoyant CO_2:

$$S_{pressure\,capacity} = PV\left(c_w + c_f\right)\Delta P\,\rho_{CO_2}$$

$$S_{buoyant\ capacity} = PV\left(1 - S_{wirr}\right)\mu\,\rho_{CO_2}$$

where S_{wirr} is the irreducible water saturation and μ is a sweep ("fill") efficiency.

The range of 'static' capacities for the structures considered, (i.e. those initially filled with saline water), is given by the 'pressure capacity' at the low end, and 'buoyant capacity' at the high end. The Representative Structure material balance models were used to investigate both dynamic timing effects from limited injectivity and interference effects between neighbouring structures to estimate exploitable capacity. The analysis of these cases is presented in section 4, including comparisons with the Exemplar model results. Recommendations for estimating the storage capacity of closures in CarbonStore are given in section 5. A discussion of results in terms of results from other studies is presented in section 6. The main conclusions are listed in section 7.

2 Bunter Zone 4

The location and extent of Bunter Zone 4 (CarbonStore Unit 139.000) is shown in **Figure A1.1**.

Properties for Bunter Zone 4 and its associated daughter Units were extracted from CarbonStore on 10 March 2011. A summary of the most likely unit properties is given in **Table A2.1**. Whilst these properties were subject to further revision, it was assumed that they provide an adequate representation of interference between closures for this study.

Bunter Zone 4 contains 15 closures and 6 hydrocarbon fields. The hydrocarbon fields were ignored for this study. The closures represent approximately 10% of the total pore volume. The distribution of pore volume among the closures can be seen in **Figure A2.1**.

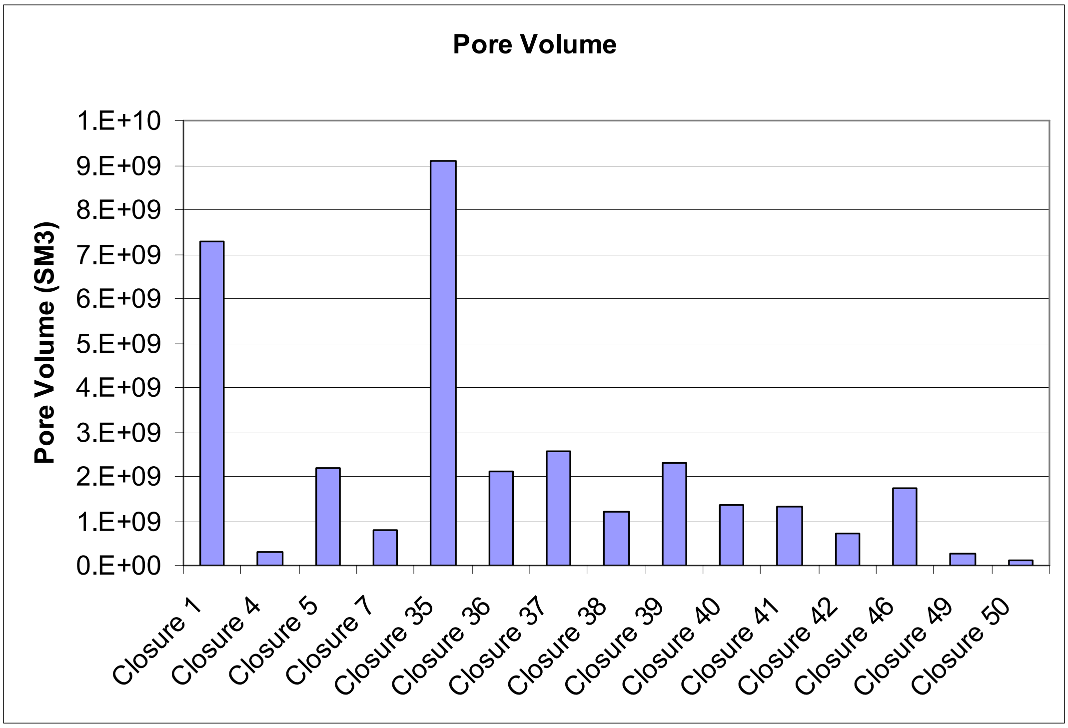

Figure A2.1: Distribution of Pore Volume Among Closures

Clearly closures 1 and 35 are very large whilst closures 4, 7, 42, 49 and 50 are small.

Unit	Description	Porosity	Pore Volume (10^6 m^3)	Shallowest Depth (m)	Centroid Depth (m)	Estimated Relief (m)	Temperature at Shallowest Depth (ºC)	Normal Hydrostatic Pressure at Shallowest Depth (MPa)	Storage Formation Permeability (mD)
139	Zone 4	0.14	279,837	65	1591	2854	12	0	100
139.007	Closure 1	0.29	7,266	725	1,297	876	35	1,937	100
139.008	Closure 4	0.21	287	1,339	1,457	60	57	4,956	100
139.009	Closure 5	0.2	2,199	1,207	1,377	193	52	4,010	100
139.011	Closure 7	0.14	801	1,359	1,540	41	58	4,922	100
139.015	Closure 35	0.26	9,078	1,012	1,385	501	45	3,096	400
139.016	Closure 36	0.15	2,124	1,211	1,569	495	52	2,425	50
139.017	Closure 37	0.15	2,576	1,403	1,660	301	59	5,004	50
139.018	Closure 38	0.22	1,221	1,605	1,751	96	66	5,310	100
139.019	Closure 39	0.14	2,320	1,172	1,567	538	51	2,739	100
139.020	Closure 40	0.14	1,341	1,547	1,739	157	64	5,795	100
139.021	Closure 41	0.19	1,320	721	1,102	581	35	1,324	100
139.022	Closure 42	0.16	726	889	1,067	214	41	1,945	100
139.026	Closure 46	0.15	1,742	828	1,138	285	39	1,709	100
139.029	Closure 49	0.14	250	1,857	1,932	42	75	7,453	15
139.030	Closure 50	0.14	98	2,054	2,113	46	82	8,303	15

Table A2.1: Bunter Zone 4 Most Likely Properties

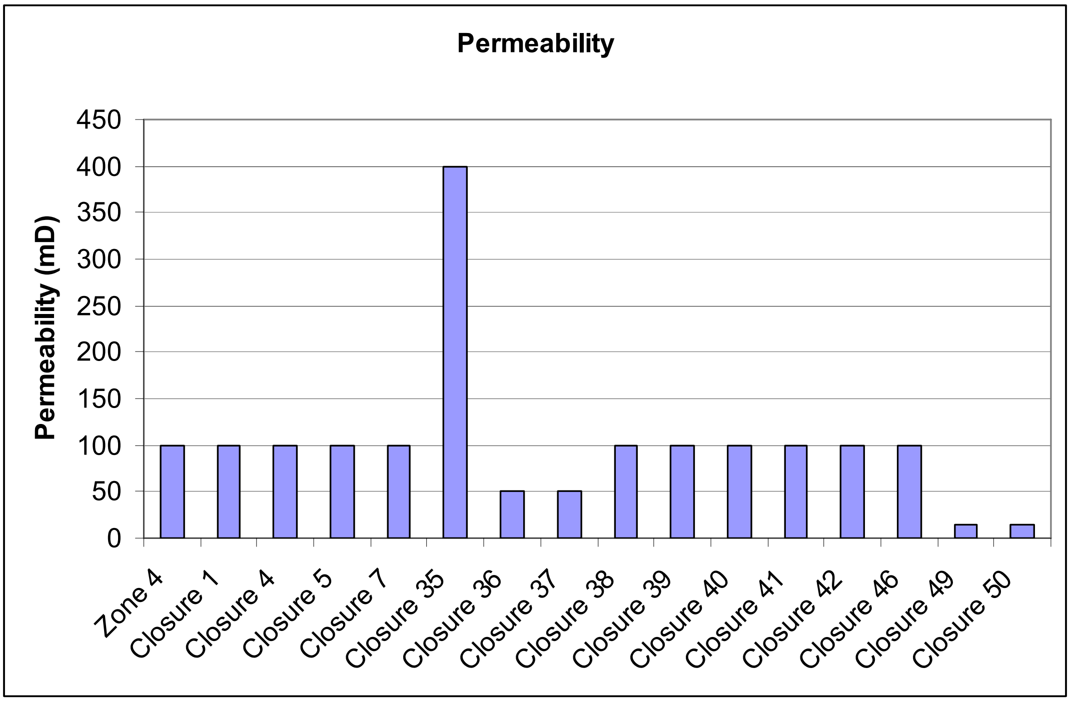

Figure A2.2: Permeability of Zone 4 and Its Closures

The most likely permeability of each closure is shown in **Figure A2.2**. Closure 35 has much higher permeability than the other closures, whereas closures 36, 37, 49 and 50 have lower permeability, reflecting the variation in properties seen across Zone 4.

There is quite a range of shallowest depth across the closures as shown in **Figure A2.3**. This is important because the pressure capacity of the seal increases with depth which affects the rate at which CO_2 can be injected into a closure. The impact on pore volume utilisation is discussed in section 4.1.

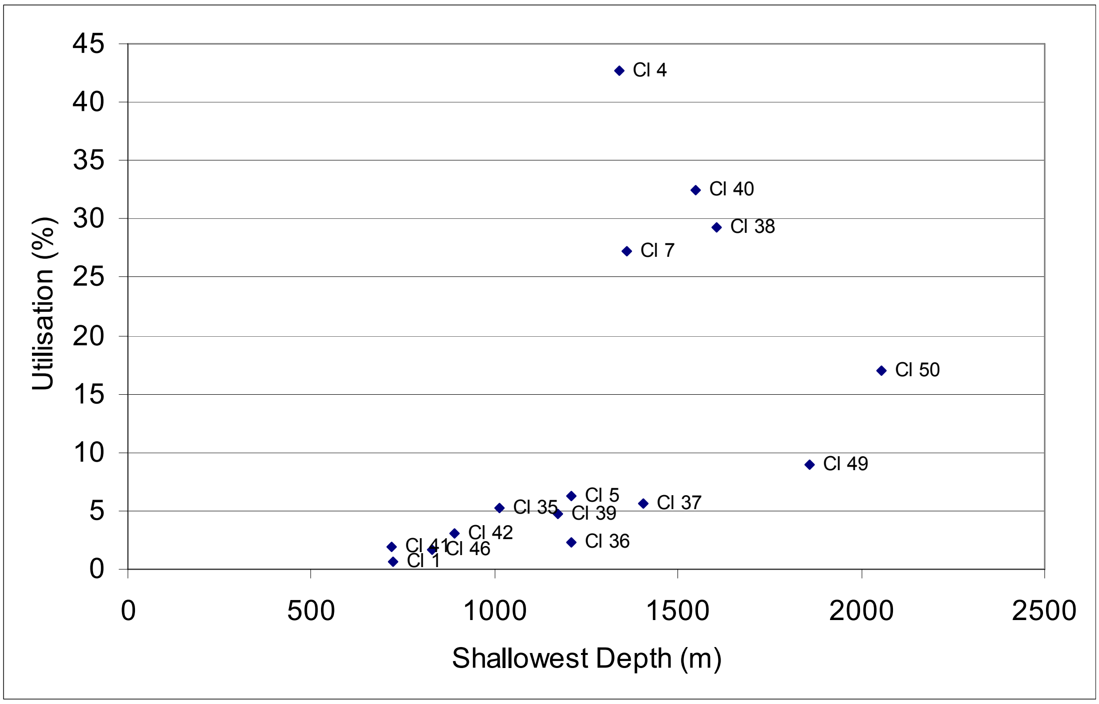

Figure A2.3: Shallowest Depth of Each Closure

The parent unit both sub crops to the sea bed and is hydraulically connected to other Bunter zones.

The 'static' storage capacity for each unit in CarbonStore, calculated from compressibility (as of 10 March 2011) is shown in **Figure A2.4**, on which capacity has been plotted using a log axis. This is contrasted with the 'fill to spill' capacity assuming an interim value of the most likely sweep efficiency of 48% from the Exemplar study. Using this value for the closures gave a total "fill to spill" capacity of 6,963 Mt for the closures. The static capacity of the closures in CarbonStore (as of 10 March 2011) was 270 Mt derived mostly from compressibility based calculations. The capacity of closures 1 and 41 is from the 2% pore volume rule, as their shallowest depth is above 800 m. The capacity of the parent was 1807 Mt.

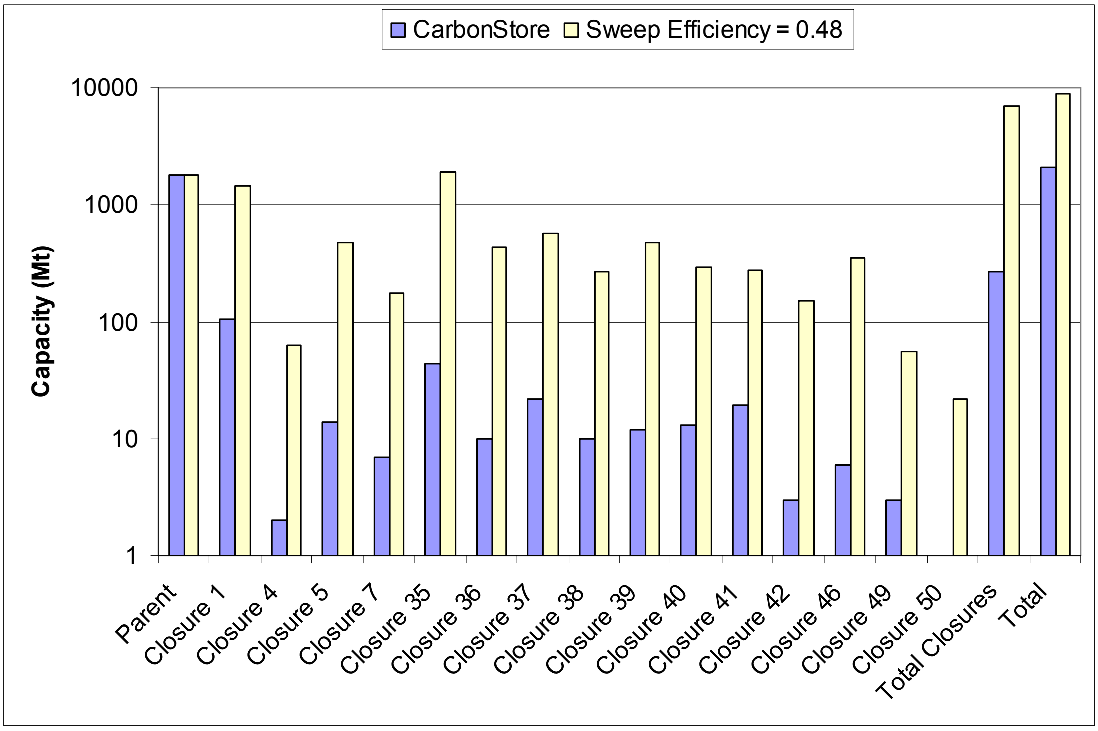

Figure A2.4: CarbonStore Static Capacities of Bunter Zone 4 Closures

3 Material Balance Model Construction

A material balance model of Zone 4 was constructed with one block (tank) used to represent each closure, one to represent the parent and finally one to represent the external world. The software used for this work was ECLIPSE100™ as recommended from a previous phase of this project, see Appendix on Dynamical Scoping Studies. A black oil representation was used but CO_2 dissolution and brine vaporisation were not permitted because of the coarse nature of the model. The PVT data was generated from the TOUGH2-ECO2N module. In this model the brine is represented by the oil component and the CO_2 by the gas.

Individual PVT tables were assigned to each block to capture variations in both temperature and salinity. The blocks were connected together by assuming that the closures are concentric circles at the centre of a circular parent as shown in **Figure A3.1**.

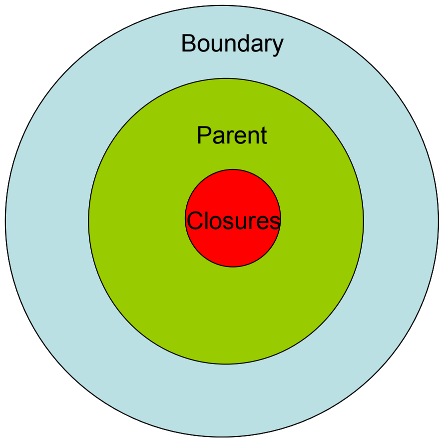

Figure A3.1: Approximation of Units in Zone 4 as Concentric Circles

Each closure was only connected to the parent with the connectivity calculated using the ECLIPSE radial transmissibility formula, (Schlumberger, 2009). The parent was also connected to a boundary block to recognise that it is connected to other Bunter units plus sub crops to the sea bed.

A quiescent initialisation was performed to ensure that there was no initial flow between closures.

A modified Viking 2 relative permeability curve was used for this work as recommended in the Appendix on Dynamical Scoping Studies. The critical gas saturation was rescaled to ensure that CO_2 did not exit any closure until the fill criterion had been met.

CO_2 was injected through vertical well(s) which had a minimum economic rate of 0.1 Mt/yr and a maximum rate of 2 Mt/yr. The maximum well bottom hole pressure was limited to 90% of fracture pressure at shallowest depth for closures. For the parent it was set to 90% of fracture pressure at the centroid depth of the parent otherwise, it is not possible to inject because the parent subcrops to the sea bed which gives an effective pressure capacity of zero.

A generic well lift table was constructed and a maximum well head pressure limit of 25 MPa imposed. However, this limit was never invoked during any of the simulations.

CO_2 was injected into the domes simultaneously with an intention to inject the "fill to spill" capacity into the domes over 40 years to investigate pressure interference effects between the closures. The potential to subsequently inject CO_2 into the parent zone was investigated by attempting to inject its CarbonStore static capacity during years 41 to 80. The pressure was typically monitored for another 20 years after injection.

The pressures in each closure were monitored to ensure that 90% of the fracture pressure at the shallowest depth was not exceeded at any time

The purpose of the simulations was to determine the mass of CO_2 injected plus a rough estimate of well count needed to inject it. The mass injected was used to estimate the fraction of the total capacity which can be exploited over typical project life times.

Three models were constructed representing minimum, most likely and maximum values from CarbonStore. This typically involved changing permeability and pore volume, however the pressure seal capacity also varied as there is uncertainty in the shallowest depth. The properties for each model are listed in section 10.

Complementary Exemplar studies calculated an interim most likely single dome sweep efficiency of 48.2%. This sweep efficiency corresponds to a storage factor of 27.5% of pore volume assuming the irreducible brine saturation of 0.423 from the Viking 2 relative permeability. Using this value for the closures gave a total "fill to spill" capacity of 6,963 Mt for the closures. This interim Exemplar "most likely" sweep efficiency of 48% was used for the minimum and most likely models.

Earlier project scoping work on injection into domes suggested a "maximum" sweep efficiency of 65% for a 200 Mt homogeneous dome. However, other factors such as rate, heterogeneity, relief etc. may affect this capacity. The 65% sweep efficiency corresponds to a pore volume utilisation of 37.5%, assuming the irreducible brine saturation of 0.423 from the Viking 2 relative permeability. The sweep efficiency of 65% was used for the maximum model as the final Exemplar minimum and maximum values were unavailable at the time.

The final minimum and maximum sweep efficiencies from the Exemplar study were 12% and 65%. The final "most likely" sweep efficiency was 33% corresponding to a pore volume utilisation of 19.1%. This sweep efficiency is only exceeded for the very smallest closures in the results reported in section 4.1 and so the overall pore volume utilisation would be largely unaffected if cases were rerun with the final value.

4 Analysis

4.1 Most Likely Cases

The mass of CO_2 injected into the most likely model is shown in **Figure A4.1**. The total injected was 1,448 Mt into the closures and 228 Mt into the parent unit. The CarbonStore capacity for each unit is the compressibility based value (as of 10 March 2011).

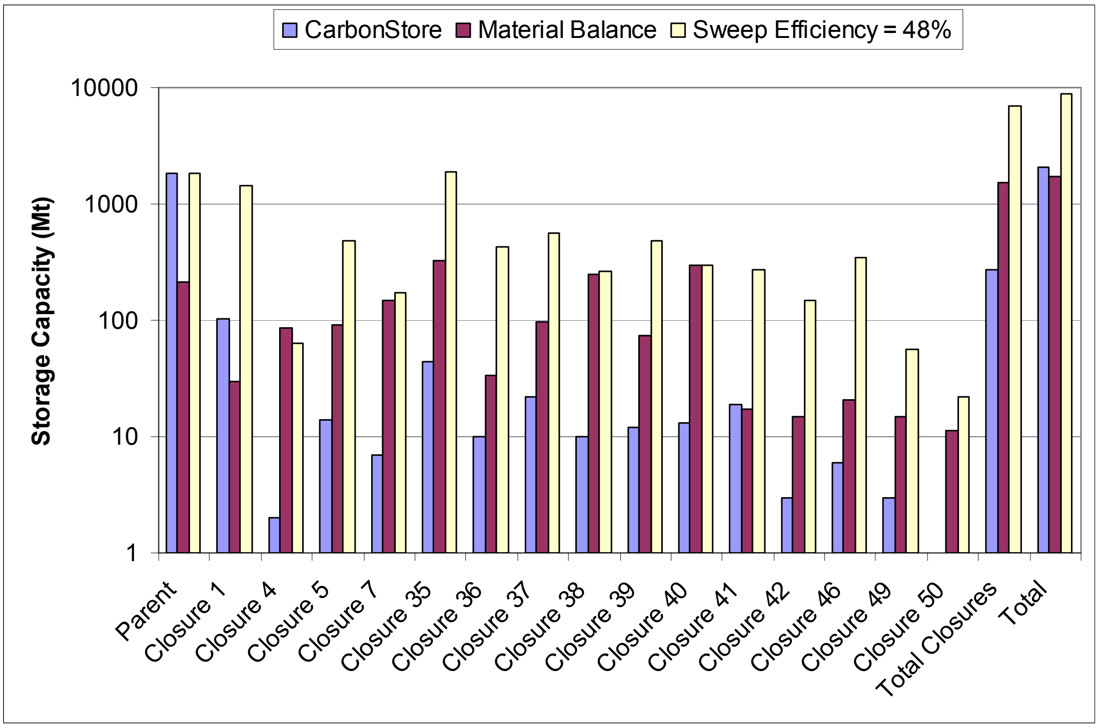

Figure A4.1: Storage Capacity for the Most Likely Model

The closure pore volume utilisations (final closure CO_2 saturation) are shown in **Figure A4.2**.

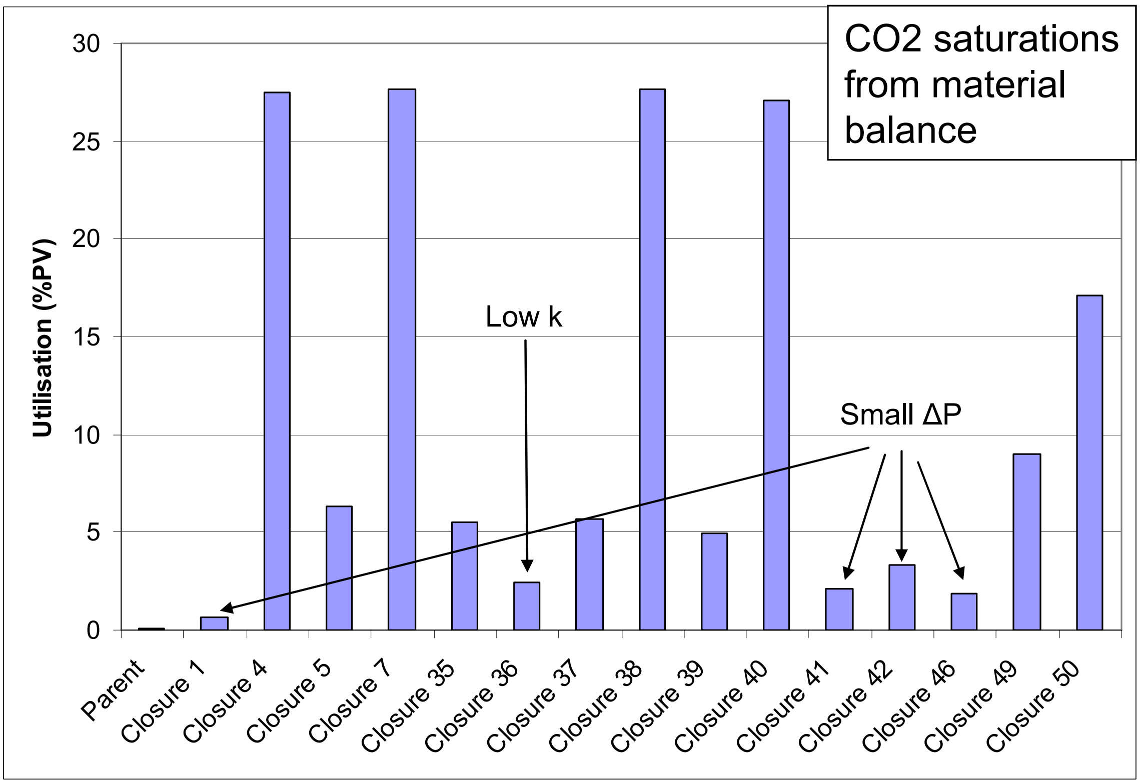

Figure A4.2: Closure Pore Volume Utilisation for Most Likely Model

The simulation attempted to "fill to spill" the closures within 40 years which would have resulted in a CO_2 saturation of 0.275. Clearly high saturations were only achieved in closures 4, 7, 38 and 40, which are some of the smallest closures. Other closures with low utilisation are closures 1, 41, 42 and 46, which are all relatively shallow (**Figure A2.3**). Typically shallower units have lower pressure seal capacities and so it is not possible to utilise a large pressure differential to expel the brine from the closure leading to lower injection rates. Closure 36 has low utilisation due to having a lower permeability (**Figure A2.2**). The remaining units typically have a utilisation of around 6% of the pore volume which corresponds to a sweep efficiency of approximately 10%. The variation of utilisation with pore volume is shown **Figure A4.3**.

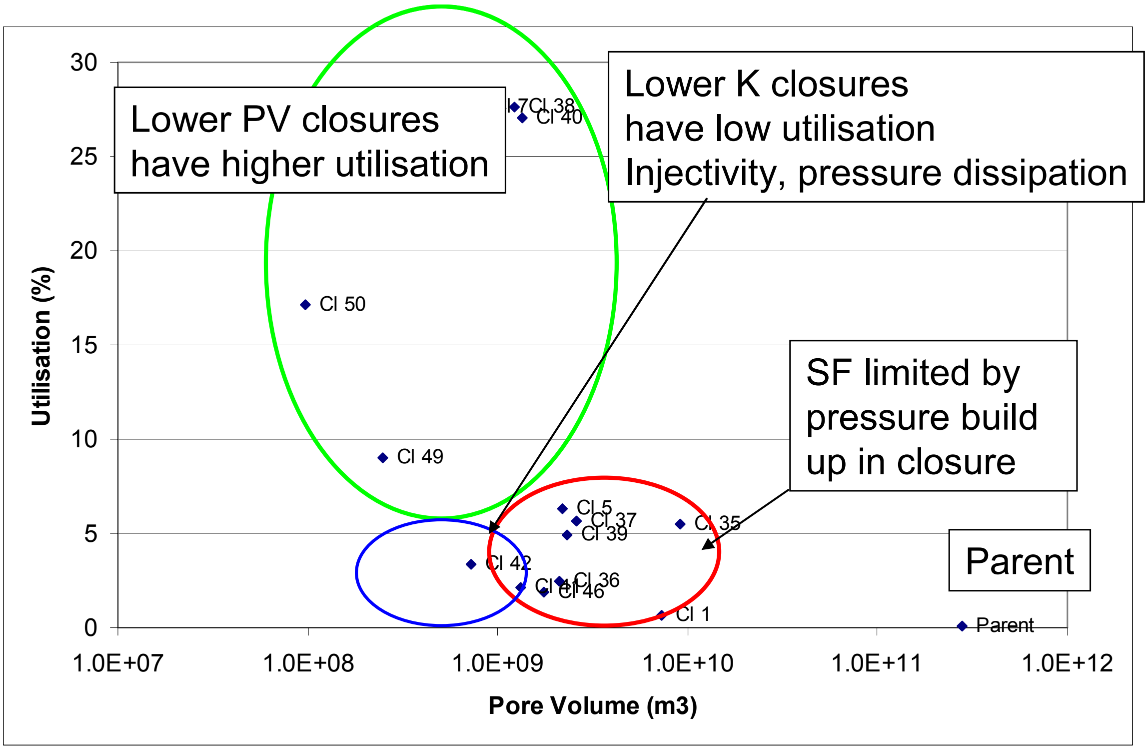

Figure A4.3 Variation of Utilisation with Pore Volume

The higher utilisation of smaller units may be partly understood by considering the geometry of the model. Each closure is considered to be circular. The volume of a closure increases as its radius squared, whilst the area available to flow between it and its parent increases only in proportion to the radius. Thus larger volume closures have "smaller" connectivity/pore volume resulting in backing up of pressure during injection. This results in lower injection per pore volume.

The pressure at the shallowest depth in each closure is shown in **Figure A4.4**. Typically the pressure in each closure rises during the injection phase (first 40 years) and then falls whilst injecting into the parent. The parent shows a significant rise in pressure during the first 40 years which dissipates slowly afterwards. This pressure rise limits the amount of CO_2 which can be injected into the parent.

The pressure change in the large high permeability closure can be seen to differ from the other closures. Initially it rises much faster due to better injectivity but then becomes pressure constrained such that the pressure increases slowly as injection declines. With the exception of the shallowest closures, the pressure falls fairly quickly after injection ceases but remains well above the initial hydrostatic value.

The pore volume averaged utilisation for all closures was 6.4%. However this was significantly affected by the very large shallow closure 1, but if this were excluded, the pore volume averaged utilisation would be 8.0%.

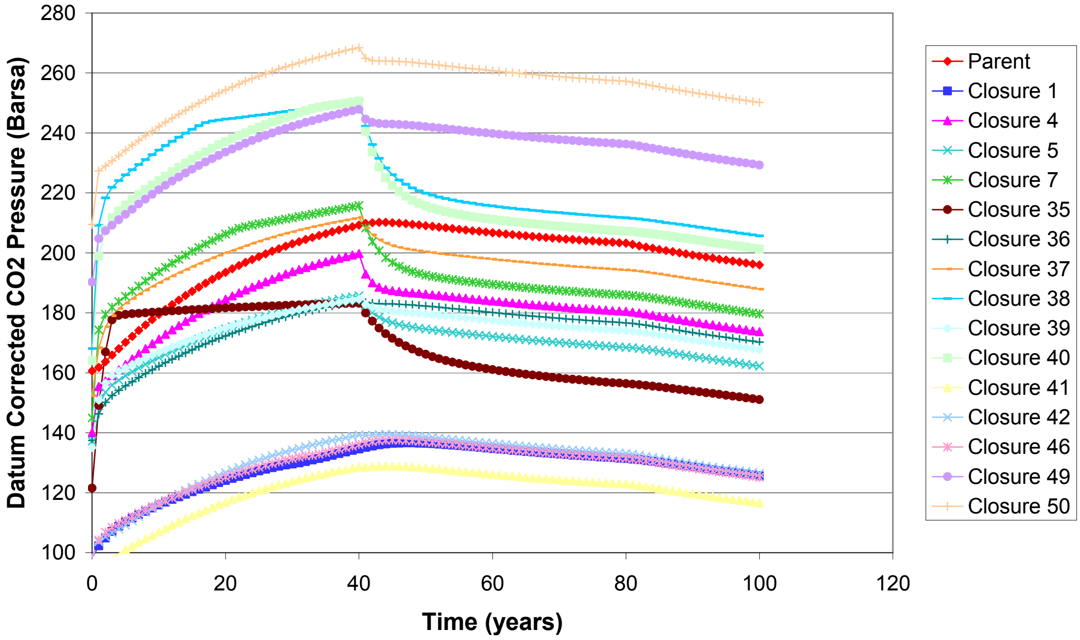

Figure A4.4 Datum Corrected Pressure in Each Closure under Simultaneous Injection

4.1.1 Injection into Closure 35

A simulation was performed injecting into just the largest dome, Closure 35. The pressure behaviour is shown in **Figure A4.5**. The pressure in all closures can be seen to rise significantly. This pressure interference has a major impact on injectivity when injecting into several closures simultaneously. A dip occurs in the pressure after about 300 years which corresponds to the time at which CO_2 starts to migrate into the parent unit. This point also corresponds to a significant reduction in the CO_2 injection rate into closure 35 due to relative permeability effects at the boundary.

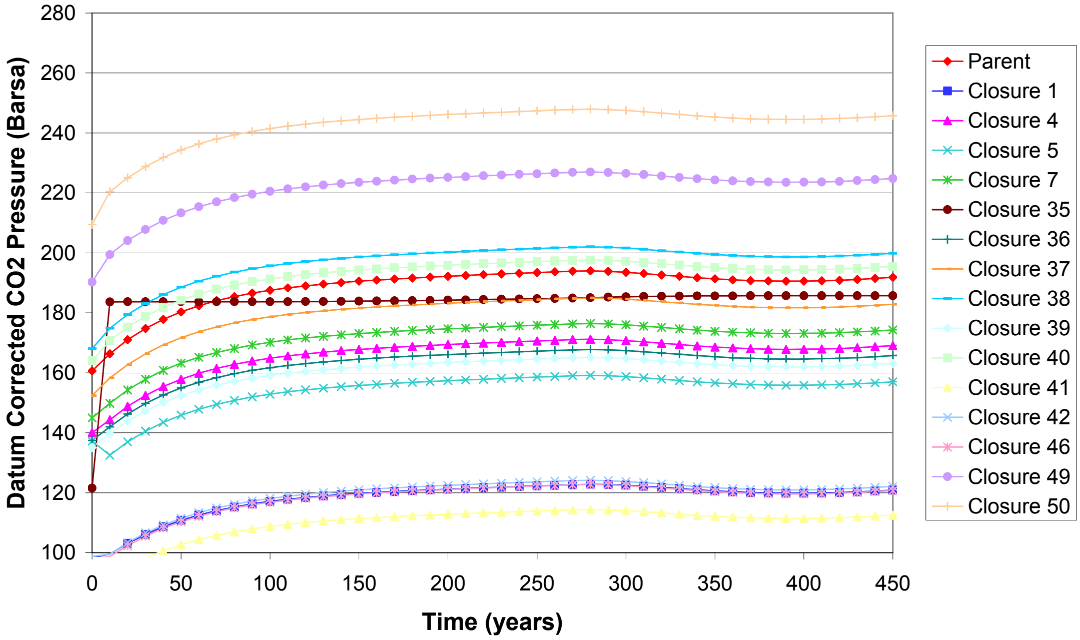

Figure A4.5: Change in Pressure in Closures When Injecting into Closure 35

The well flow rates and the pressure build up in the closure are shown in **Figure A4.6**.

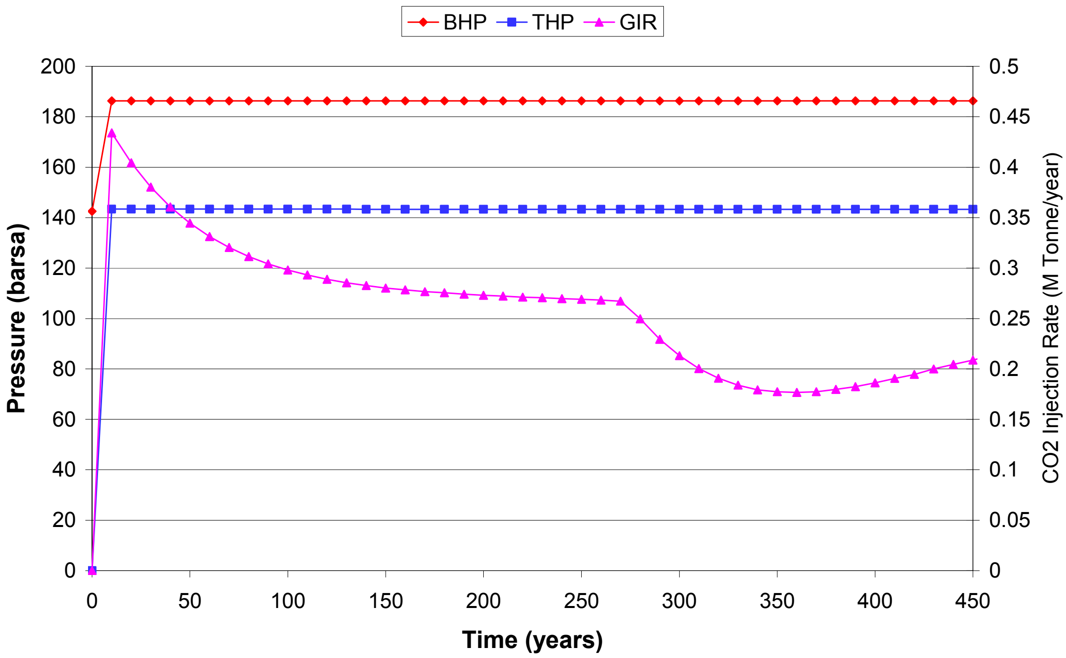

Figure A4.6: Well Injection Rate and Bottom Hole Pressure For Injection into Closure 35

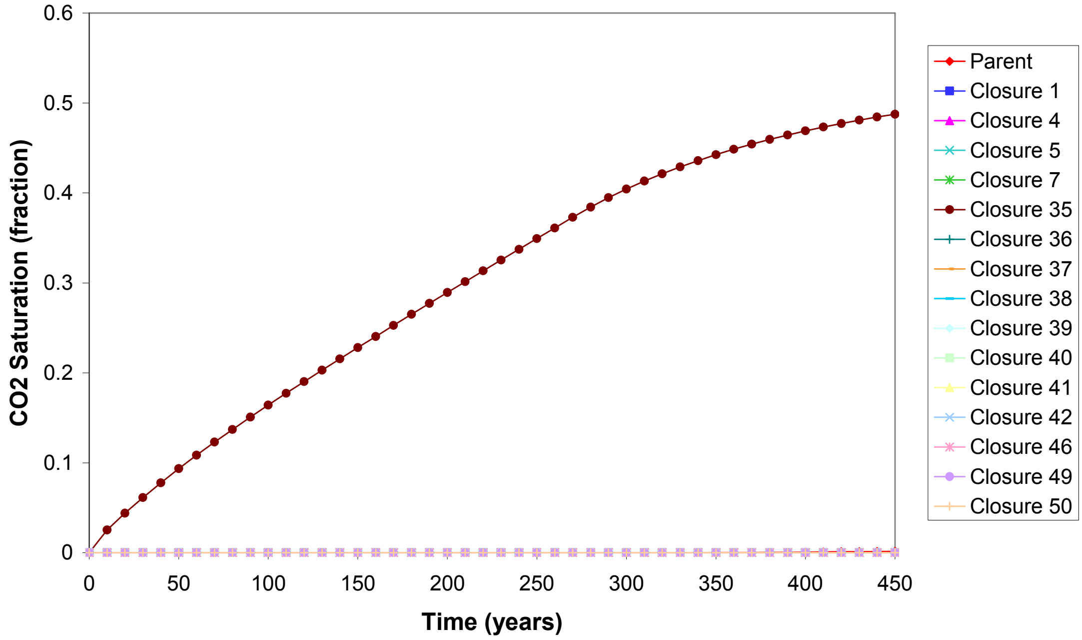

Figure A4.7: CO_2 Saturation in Closure 35

The CO_2 pore volume utilisation is equivalent to the CO_2 saturation for the material balance model. The rate at which closure 35 fills is shown in **Figure A4.7**. For this simulation, the closure has been filled assuming a spill saturation of 37.5% corresponding to a sweep efficiency of 65%. This occurs after approximately 280 years. The time to fill to the “most likely” spill utilisation of 27.5% is approximately 190 years. The closure fills approximately linearly for most of this time. The factor affecting how long the dome takes to fill is its connectivity to the parent which limits how quickly brine can be expelled from the closure.

4.1.2 Comparison with Exemplar Modelling

The Exemplar model base case injects into closure 36 only, so an equivalent Representative Structure simulation was performed. The properties in the Exemplar model are from a detailed geologic model and differ from those downloaded from CarbonStore on 10 March 2011. To ensure compatibility, the pore volume of closure 36 was set to $2.542x10^9$ m^3 and the permeability was calculated from the average well permeability-thickness product as approximately 400 mD. CO_2 was injected for 100 years. The pore volume utilisation is shown in **Figure A4.8** and was 10% after 20 years rising to 19% after 43 years. The final utilisation in the Exemplar modelling was 19% after 20 years of injection, after which CO_2 started to spill from the closure. These results are in rough agreement on the 40 year economic timeframe, bearing in mind that the material balance approach can only model an assumed spilling point.

The well performance is shown in **Figure A4.9**.

Figure A4.10 shows the pressure increase in neighbouring closures. This is typically 2 MPa which is comparable to the values found in the Exemplar base case of 1.4 to 2.6 MPa.

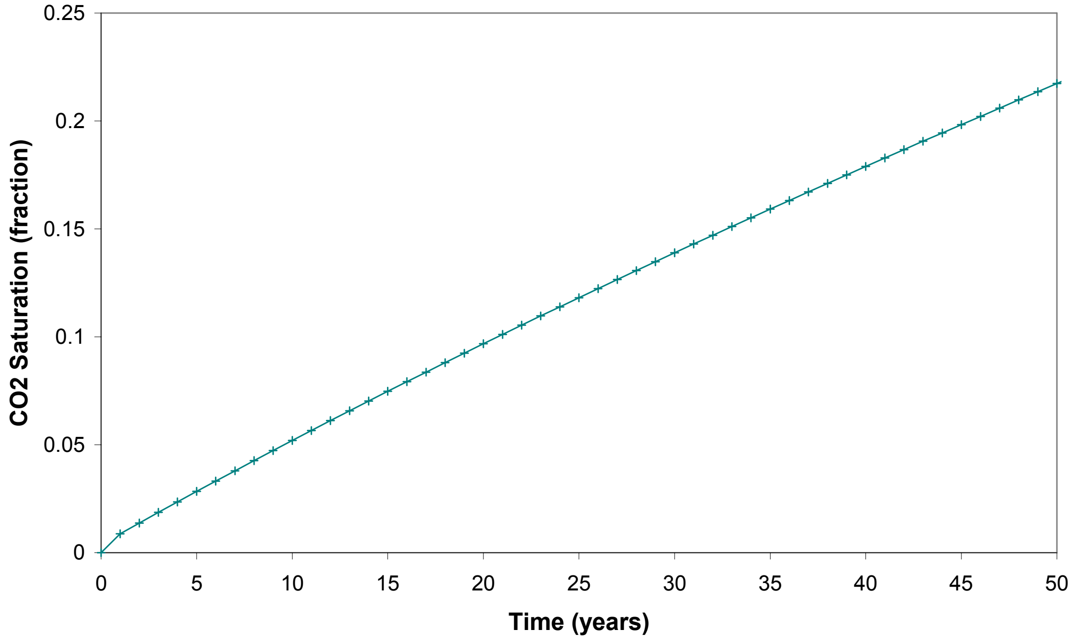

Figure A4.8: CO_2 Saturation for Injecting into Closure 36 Only

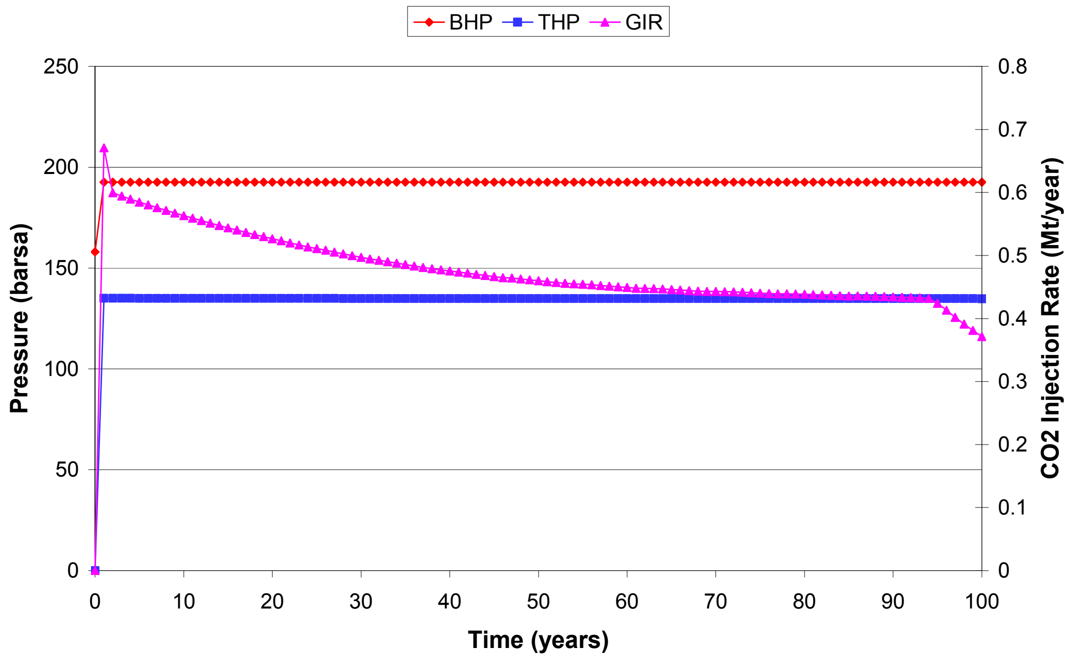

Figure A4.9: Well Injection Rate and Bottom Hole Pressure for Injection into Closure 36

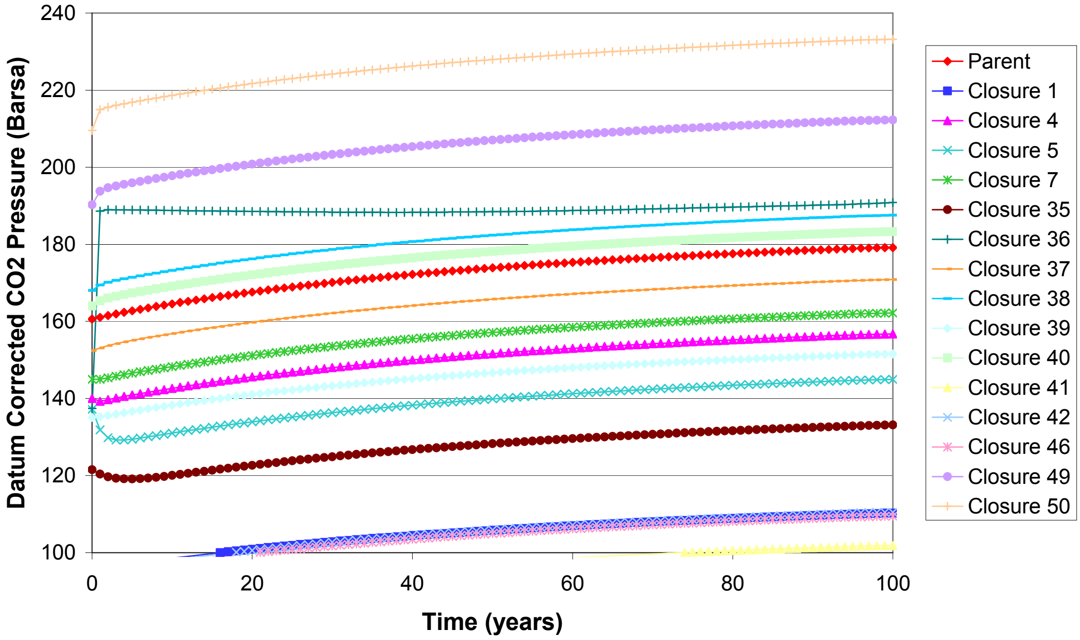

Figure A4.10: Rise in Pressure in Closures Due to Injection into Closure 36

4.1.3 Impact of Outer Boundary Condition

The impact of the outer boundary condition was investigated. The effect of a closed parent was investigated by removing the tank representing the external world. The effect of modelling a larger external world was also investigated by multiplying the pore volume of its tank by 1000. The impact on utilisation is shown in **Figure A4.11**. It should be noted that a fill to spill saturation of 37.5% was assumed for these calculations.

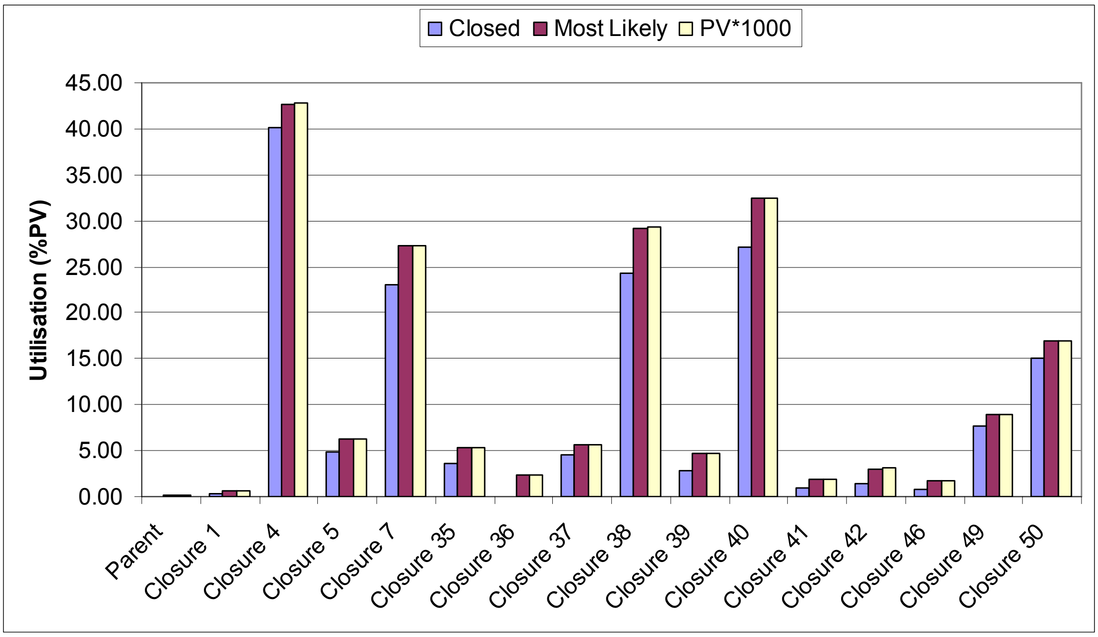

Figure A4.11: Impact of Outer Boundary Condition on Utilisation

The impact of increasing the pore volume of the boundary block was small resulting in slightly higher utilisation. The overall mass of CO_2 injected into both the closures and the parent was comparable to the base case.

However, the closed boundary condition resulted in a drop of 21% in the amount injected into the closures. For Bunter Zone 4 the closures represent 10% of the total pore volume. For most units the closures are probably a smaller fraction and so it is expected that the impact of a closed boundary will have a smaller effect on the amount which can be stored in the closures. The amount injected into the parent also decreased by 58% demonstrating that much of a closed (pressure cell) unit's potential might be taken up by storing CO_2 in its closures.

4.1.4 Sensitivity to Number of Closures

The Exemplar study modelled CO_2 injection into one to three closures, 36, 37 and 39. Some Representative Structure simulations were run modelling CO_2 injection into three, five and ten closures to understand how utilisation might vary with the number of closures. The particular choice of closures was made to provide a consistent transition between the Exemplar and RS simulation studies. The Exemplar study contains a small number of closures of similar size, whilst the RS contains 15 closures with widely varying pore volumes. The three closure case used the same closures as the Exemplar. The five closure case included two more domes, 5 and 46, of comparable size to the Exemplar ones. The ten dome case excluded the two very large domes, 1 and 35, and the three smallest closures, 4, 49 and 50. For the modelled closure selection, the pore volume range increased as the number of closures increased. Though alternative closure selections might produce different results, it is essential here to merge the Exemplar and Representative Structure results consistently.

The utilisation within each closure and the final pore volume averaged utilisation are shown in **Figure A4.12 and Figure A4.13**.

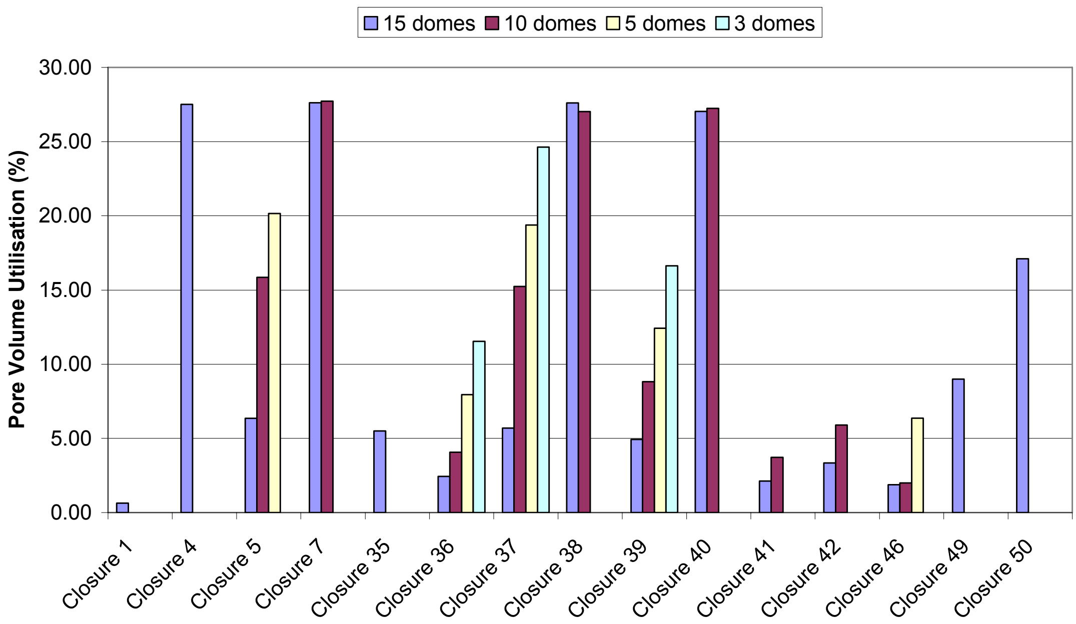

Figure A4.12: Individual Closure Pore Volume Utilisation for 3 to 15 Closures

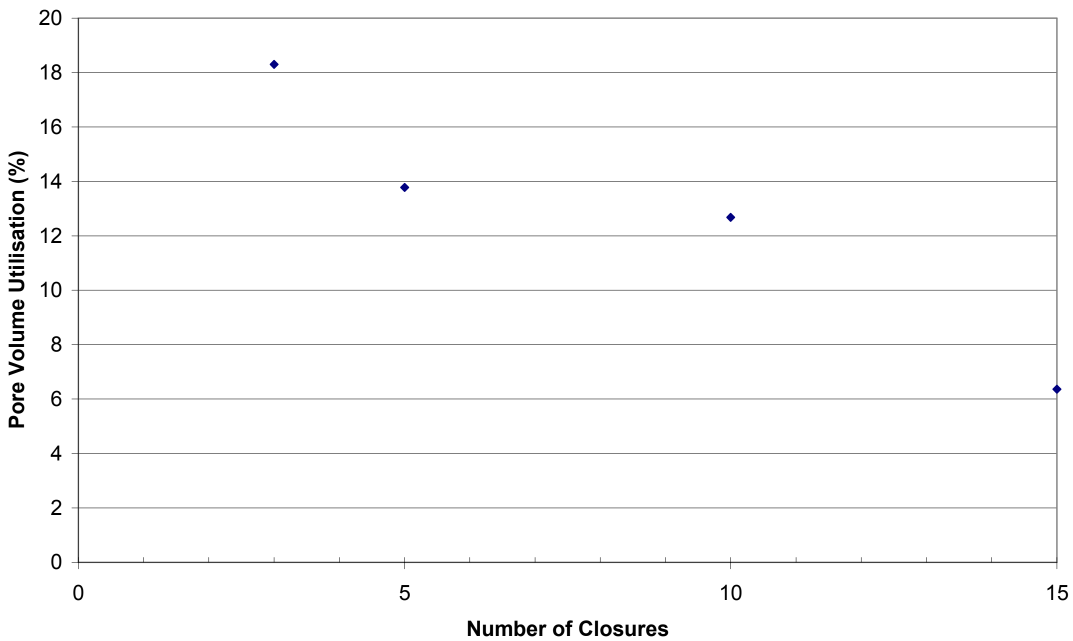

Figure A4.13: Pore Volume Utilisation for 3 to 15 Closures

Figure A4.12 shows that typically the utilisation of a closure decreases significantly with the number of closures undergoing injection. For example, the utilisation of closures 36, 37 and 39 is reduced by approximately two-thirds as the number of closures increases from 3 to 15. This occurs because of pressure interference between the neighbouring injection sites.

The three closure utilisation of 18.3% is in close agreement with the Exemplar value of 18.1%.

The injection into each closure is shown in **Table A4.1**. The injection into each closure in the base case (15 closures) is given in **Table A4.2**.

Number of Closures	**3**				**5**				**10**			
	CO_2 Injected (Mt)	No. of Wells	Mass inj/well (Mt)	Utilisation (%)	CO_2 Injected (Mt)	No of Wells	Mass inj/well (Mt)	Utilisation (%)	CO_2 Injected (Mt)	No of Wells	Mass inj/well (Mt)	Utilisation (%)
Parent	385	12	32	0	343	12	29	0	235	12	20	0
Closure 1	0	0	0	0	0	0	0	0	0	0	0	0
Closure 4	0	0	0	0	0	0	0	0	0	0	0	0
Closure 5	0	0	0	0	295	15	20	20	236	10	24	16
Closure 7	0	0	0	0	0	0	0	0	150	3	50	28
Closure 35	0	0	0	0	0	0	0	0	0	0	0	0
Closure 36	165	25	7	12	114	10	11	8	59	4	15	4
Closure 37	420	30	14	25	331	15	22	19	264	10	26	15
Closure 38	0	0	0	0	0	0	0	0	227	6	38	27
Closure 39	259	30	9	17	195	10	19	12	140	6	23	9
Closure 40	0	0	0	0	0	0	0	0	251	10	25	27
Closure 41	0	0	0	0	0	0	0	0	33	2	17	4
Closure 42	0	0	0	0	0	0	0	0	29	2	14	6
Closure 46	0	0	0	0	75	5	15	6	24	1	24	2
Closure 49	0	0	0	0	0	0	0	0	0	0	0	0
Closure 50	0	0	0	0	0	0	0	0	0	0	0	0
Closure total	843				1011				1412			
Total Injected	1229				1354				1648			
Total no of wells		97				67				66		
Mass Injected /well (Mt)			13				20				25	

Table A4.1: Summary of Simulation Results for Varying Number of Closures

4.2 Minimum and Maximum Models

Minimum and maximum models were constructed using the properties given in **Table A10.2** and **Table A10.3**. The utilisation for these models is shown in **Figure A4.14**.

The minimum model predicted a large drop in utilisation for nearly all of the closures. This is due to worse injectivity (lower permeability) combined with significant backing up of pressure (lower pore volume and worse connectivity). However, the utilisation in Closure 50 actually increased due to less pressure interference. In some units it was not possible to achieve the minimum economic rate. The total injected into the closures dropped from 1448 Mt to just 43 Mt. The total injected into the parent also fell significantly from 228 Mt to 30 Mt.

The maximum model resulted in much higher utilisation in all closures. The total injected into the closures increased to 10,064 Mt. The increase was due to better injectivity (higher permeability) combined with better dissipation of pressure (higher pore volume and connectivity). The mass of CO_2 injected into the parent increased to 1810 Mt. The mass injected into each closure is shown in **Figure A4.15**.

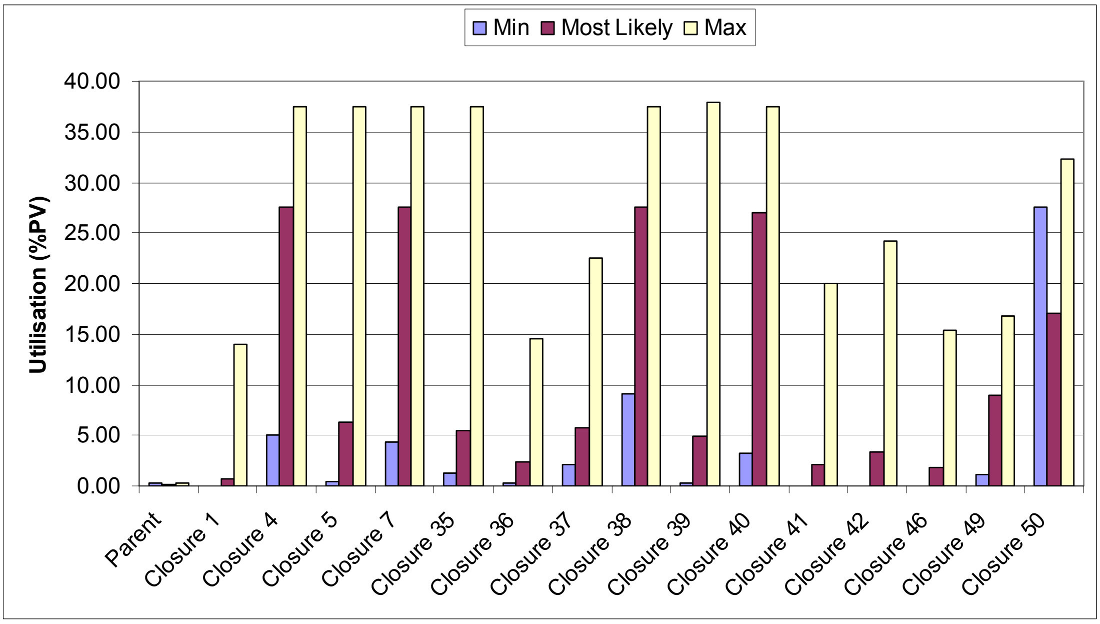

Figure A4.14: Variation in Utilisation with CarbonStore Properties

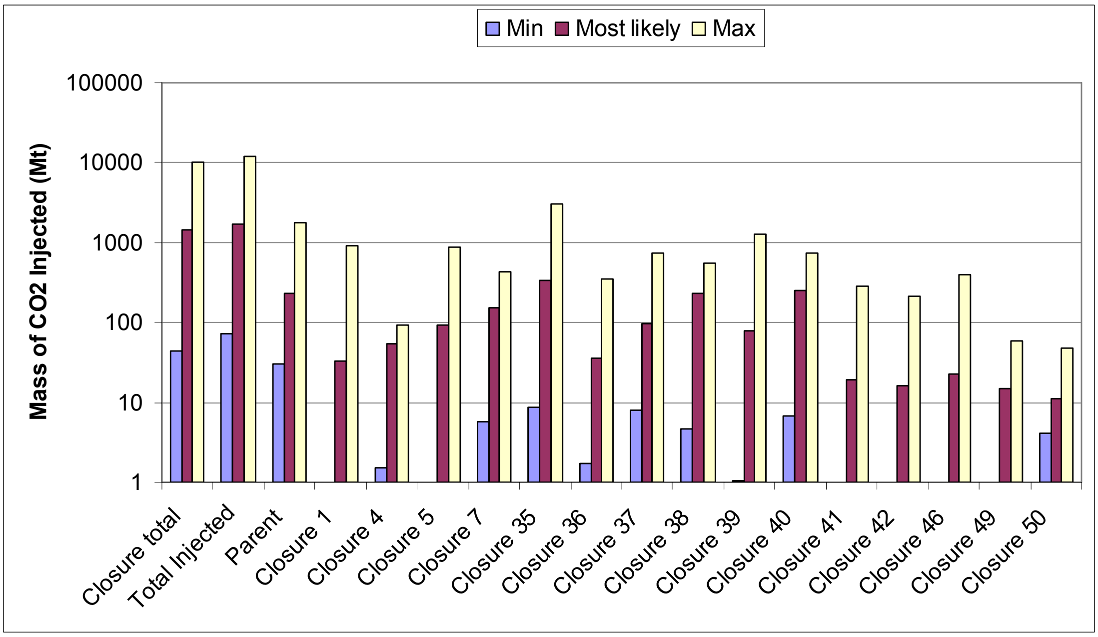

Figure A4.15: Mass of CO_2 Injected in all Models

The average pore volume utilisation of the closures was 27.6% for the maximum model whilst for the minimum model it was 1.1%.

The total mass injected into each closure for the three models is shown in **Table A4.2** along with other key simulation results.

	Minimum				Most Likely				Maximum			
	CO_2 Injected (Mt)	No. of Wells	Mass inj/well (Mt)	Utilisation (%)	CO_2 Injected (Mt)	No of Wells	Mass inj/well (Mt)	Utilisation (%)	CO_2 Injected (Mt)	No of Wells	Mass inj/well (Mt)	Utilisation (%)
Parent	30	2	15	0	228	12	19	0	1810	30	60	0
Closure 1	0	1	0	0	32	2	16	1	927	20	42	14
Closure 4	2	1	2	5	55	2	27	28	94	2	56	38
Closure 5	1	1	1	0	94	2	47	6	861	15	70	38
Closure 7	6	1	6	4	150	2	75	28	426	7	74	38
Closure 35	9	1	9	1	340	10	34	6	3081	45	76	38
Closure 36	2	1	2	0	35	2	18	2	350	7	42	15
Closure 37	8	1	8	2	98	2	49	6	750	10	74	23
Closure 38	5	1	5	9	232	5	46	28	557	9	72	38
Closure 39	1	1	1	0	78	2	39	5	1270	16	79	38
Closure 40	7	1	7	3	249	5	50	27	752	12	74	38
Closure 41	0	1	0	0	19	1	19	2	282	4	66	20
Closure 42	0	1	0	0	16	1	16	3	209	3	65	24
Closure 46	0	1	0	0	23	1	23	2	398	6	60	15
Closure 49	0	1	0	1	15	1	15	9	59	1	59	17
Closure 50	4	1	4	28	11	1	11	17	48	1	48	32
Closure total	43				1448				10064			
Total Injected	74				1676				11874			
Total no of wells		17				51				188		
Mass Injected /well (Mt)			4				33				63	

Table A4.2: Summary of Simulation Results

5 Application to CarbonStore

The material balance model produced a wide range of closure utilisations which can be understood by considering how they vary with pore volume, permeability and shallowest depth (**Figures A5.1 and A5.2**).

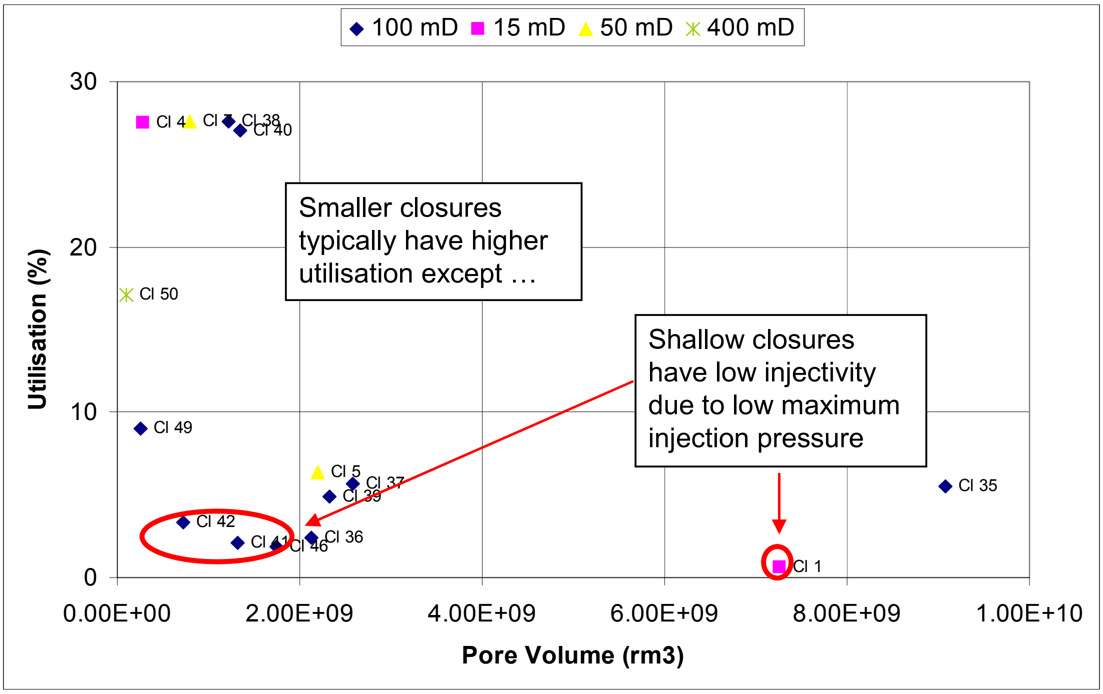

Figure A5.1: Impact of Permeability and Pore Volume on Utilisation

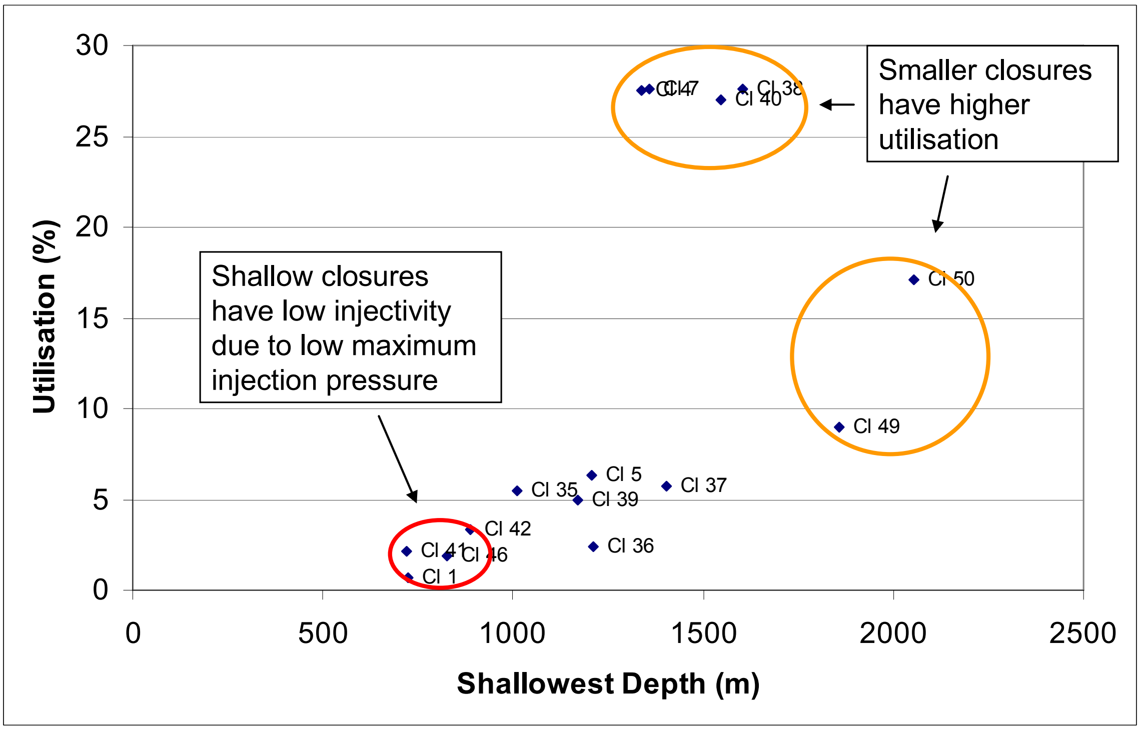

Figure A5.2: Impact of Depth on Utilisation

Typically high utilisation is only found for small closures with pore volume less than 2 x 10^9 m^3 or for closures with high permeability, as for the maximum model described in section 4.2. Closures which are very shallow become pressure constrained and it is difficult to achieve high utilisation over project lifetimes. For the larger closures, the utilisation is typically around the 6-8% of pore volume for the most likely model. To avoid skewing the results by the smaller closures, it is recommended that a pore volume average of all the closures is used to estimate capacities in CarbonStore.

It is recommended that the Exemplar values be used for small numbers of closures as these are derived from detailed models which predict, rather than assume spill capacity. Combined with the cases run in section 4.1.4, this leads to a progressive reduction in the utilisation of each closure as more closures are included. A linear fit was found acceptable to match the most likely values as shown in **Figure A5.3**.

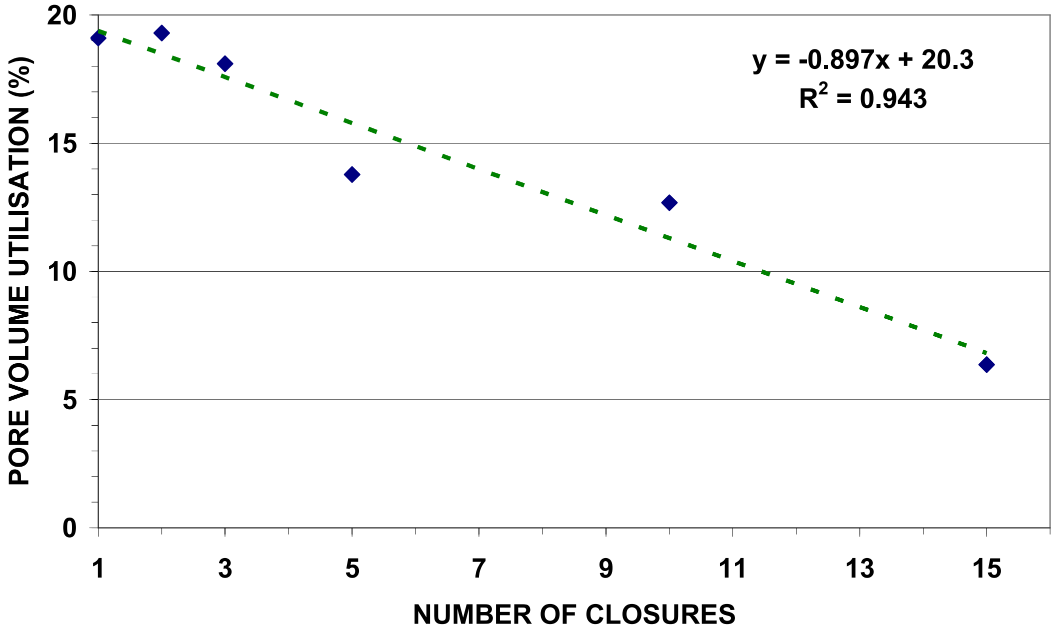

Figure A5.3: Linear Fit to Multiple Closure Utilisation

The minimum and maximum utilisations from Exemplar simulation for a single dome were estimated to be 3.9% and 33% respectively, whereas from material balance they were 1.1% and 27.6%. A straight line fitted to the two points could be used to define the minimum and maximum values for intermediate numbers of domes. However, a more pragmatic approach would use the maximum and minimum of these numbers to capture the wide range of uncertainty. Therefore it is recommended that a minimum of 1% and a maximum of 33% is used regardless of the number of domes. This simple assumption may result in the Monte Carlo based capacity calculation implemented in CarbonStore giving higher than otherwise mean values for units with many closures The recommended distribution is shown in **Table A.5.1**.

Minimum (% PV)	Most Likely (% PV)	Maximum (% PV)
1	Max(20.3-0.897N_{Trap}, minimum value)	33

Table A5.1: Minimum, Most Likely and Maximum Utilisation Values for CarbonStore Probability Distribution

The storage potential of the parent should be calculated using the appropriate algorithm for an open aquifer or pressure cell. If the parent is a pressure cell, the combined capacity of the parent and daughters should not exceed that of the parent.

6 Discussion of Results

A material balance approach was used to estimate the approximate impact of simultaneously injecting CO_2 into a large number of closures within a parent saline aquifer. This indicated that pressure interference between injection wells/ sites may be significant. A detailed Exemplar model of three domes supports this conclusion. Exemplar modelling was also used to estimate sweep efficiency for a single closure.

Simulation suggests that pressure interference significantly reduces storage capacity for injection into several closures, assuming they are not remote from each other.

Other studies have assessed potential for the Bunter domes. A report by the Tyndall Centre for Climate Change Research estimated capacities for the major Bunter closures assuming 40% of the pore volume could be filled with CO_2 (Bentham, 2006). A subsequent review by Senior CCS Solutions discounted these by up to 50% (Senior CCS Solutions, 2010) which corresponds to a closure pore volume utilisation of 20%. The original 40% utilisation was based on computer simulation of closed structures in the Bunter sandstone (Obdam, 2002).

The range of 20 to 40% is almost consistent with the most likely and maximum values for the single dome (19% and 33%). However, the most likely utilisation for a region containing three or more domes was found to be lower than either of these values because of pressure interference effects neglected in the earlier studies. The minimum reported here (1.1%) is based on much less favourable reservoir properties.

Other studies have also considered the impact of the pressure footprint. Smith et al consider the impact of boundary conditions on CO_2 Capacity Estimation in Aquifers (Smith, 2010). They reported that pressure footprints of individual wells overlap to generate higher pressures and larger footprints. Where wells are closely spaced this may affect injectivity. Injection models indicate that this is the case for both open and closed systems and so a regional assessment with regards to pressure evolution is required. It was also noted that shallower structures may exceed the maximum pressure limit, despite being remote from the injection wells. Smith also reports capacity estimates using an impermeable cap rock are conservative.

The UKSAP capacity estimates for units containing structural traps are likely to be conservative compared to these studies.

7 Conclusions

A material balance model representing CO_2 injection into 15 structural closures in Zone 4 of the Bunter Sandstone Formation was constructed. Maximum, most likely and minimum estimates of pore volume utilisation were made from the range of property variations in CarbonStore. The results were shown to be in reasonable agreement with those from a more detailed Exemplar model, which considered CO_2 injection into up to three of these closures.

The material balance model predicted significant pressure interference when injecting CO_2 into multiple closures simultaneously, assuming they are not remote from each other. This interference substantially reduced the fraction of the storage capacity which might be utilised on likely project time scales of a few decades. For example, the estimated most likely pore volume utilisation for CO_2 injection into all 15 Zone 4 Bunter domes from material balance was 6.4%. This is substantially lower than the most likely Exemplar estimate of pore volume utilisation for injection into dome 36 only of 19.2%.

The minimum pore volume utilisation found in the material balance study was 1.1% and the maximum was 27.6%. This range is similar to that found in the Exemplar study.

These CO_2 pore volume utilisations are consistent with those from other relevant Bunter studies when account is taken of the significant effect of pressure interference in multiple closure injection scenarios.

The individual closure pore volume utilisations were found to depend most on shallowest depth permeability, and pore volume. The shallowest depth has a major impact through the pressure seal capacity of the closure. Shallower closures have significantly reduced maximum injection pressures, which limits the rate at which brine can be expelled from the closure, reducing pore volume utilisation on likely project time scales. Similarly, lower permeability both impacts the rate at which CO_2 can be injected and brine expelled from a closure. Larger pore volumes could also be difficult to utilise, as the effective area available to expel brine from the closure does not increase in proportion to the pore volume, making it harder to expel brine at the same fractional rate of pore volume, when compared to a smaller closure.

It is found that the Exemplar and Representative Structure ‘most likely value’ pore volume utilisation results can be acceptably approximated by a linear function of the number of water-bearing closures into which CO_2 is simultaneously injected.

Minimum, most likely and maximum pore volume utilisations were derived for the CarbonStore Monte Carlo storage capacity calculations by combining the results of the Exemplar and Representative Structure studies. The recommended minimum value of 1% is derived from the most pessimistic Representative Structure multi-closure injection case. The recommended maximum of 33% is derived from Exemplar simulation into a single homogeneous closure. The most likely pore volume utilisation is calculated from the linear function of the number of closures injected into, referred to in the paragraph above.

8 References

1. Bentham, M, 2006. An assessment of carbon sequestration potential in the UK – Southern North Sea case study, Tyndall Centre Working Paper No. 85.
2. Obdam, A, van der Meer, L, May, F, Kervevan, C, Bech, N and Wildenborg, A, 2002, Effective CO2 Storage Capacity in Aquifers, Gas Fields, Oil Fields and Coal Fields, in Gale,J and Kaya, J, (eds.), Greenhouse Gas Control Technologies, Proceedings of the 6th International Conference on Greenhouse Gas Control Technologies, 1-4 October 2002, Kyoto, Japan.
3. Schlumberger, 2009. ECLIPSE 100 Technical Description, Chapter 70, 2009.2.
4. Senior CCS Solutions Ltd, 2010, CO2 Storage in the UK - Industry Potential.
5. Smith, D.J., Bentham, M, Holloway, S, Noy, D.J., Chadwick, R.A., 2010, The Impact of Boundary Conditions on CO2 Capacity Estimation in Aquifers, British Geological Survey, Ninth Annual Conference On Carbon Capture And Sequestration - May 10 - 13, 2010.

9 Glossary

Variable	Meaning	Units
ΔP	Change in pressure	MPa
μ	Sweep efficiency	Fraction
ρ	Density	Kg/m^3
c_f	Formation compressibility	1/MPa
c_w	Brine compressibility	1/MPa
N_{Trap}	Number of traps (e.g. Bunter domes)	
PV	Pore volume	m^3
$S_{buoyancycapacity}$	Storage capacity from fill to spill	Mt
$S_{pressurecapacity}$	Storage capacity from compressibility	Mt
S_{wirr}	Irreducible brine saturation	fraction

10 Material Balance Model Parameters

Name	Pore Volume m^3	Gross thickness m	NTG	Permeability (mD)	Porosity (fraction)	Dtop m	Dcentroid m	cr 1/MPa	Salinity (ppm)	Temperature °C	Pressure MPa	90% Fracture Pressure MPa	Transmissibility cp m3/day/bar	Swc	Sweep Eff	CO_2 density kg/m^3	Static Capacity Mt	Injection Time years
Boundary	3.7016E+12	199	0.91	100	0.14	65	1591	0.00062	180000	66	161							
Zone 4	2.7984E+11	199	0.91	100	0.14	65	1591	0.00062	180000	66	161	6*	732	0.423		323	1807	40
Closure 1	7.2655E+09	270	0.89	100	0.29	725	1297	0.00045	180000	57	131	131	431	0.423	0.48	719	1959	40
Closure 4	2.8713E+08	175	1	100	0.21	1339	1457	0.00052	180000	61	147	249	264	0.423	0.48	791	85	40
Closure 5	2.1991E+09	147	0.9	100	0.20	1207	1377	0.00053	180000	58	147	225	364	0.423	0.48	785	647	40
Closure 7	8.0093E+08	321	0.91	100	0.14	1359	1540	0.00062	180000	64	155	253	323	0.423	0.48	786	236	40
Closure 35	9.0778E+09	245	0.91	400	0.26	1012	1385	0.00047	180000	59	143	186	545	0.423	0.48	759	2583	40
Closure 36	2.1237E+09	221	0.91	50	0.15	1211	1569	0.00060	180000	65	158	193	327	0.423	0.48	730	581	40
Closure 37	2.5758E+09	212	0.94	50	0.15	1403	1660	0.00060	180000	68	167	261	338	0.423	0.48	782	755	40
Closure 38	1.2210E+09	195	0.88	100	0.22	1605	1751	0.00051	180000	71	177	288	326	0.423	0.48	785	359	40
Closure 39	2.3197E+09	251	0.91	100	0.14	1172	1567	0.00062	180000	66	158	195	397	0.423	0.48	739	642	40
Closure 40	1.3412E+09	227	0.91	100	0.14	1546	1739	0.00062	180000	71	175	290	358	0.423	0.48	791	397	40
Closure 41	1.3203E+09	182	0.93	100	0.19	721	1102	0.00054	180000	50	111	132	339	0.423	0.48	738	365	40
Closure 42	7.2590E+08	142	0.99	100	0.16	889	1067	0.00059	180000	48	107	144	314	0.423	0.48	738	200	40
Closure 46	1.7417E+09	335	0.97	100	0.15	828	1138	0.00060	180000	51	114	134	363	0.423	0.48	722	471	40
Closure 49	2.4955E+08	107	0.91	15	0.14	1857	1932	0.00062	180000	78	195	350	109	0.423	0.48	803	75	40
Closure 50	9.7890E+07	73	0.91	15	0.14	2054	2113	0.00062	180000	84	213	387	80	0.423	0.48	805	29	40

Table A10.1: Most Likely Material Balance Model Properties

*The Zone 4 fracture pressure limit was replaced by the value at the centroid, 25.9 MPa.

Name	Pore Volume m^3	Gross thickness m	NTG	Permeability (mD)	Porosity (fraction)	Dtop m	Dcentroid m	cr 1/MPa	Salinity (ppm)	Temperature °C	Pressure MPa	90% Fracture Pressure MPa	Transmissibility cp m3/day/bar	Swc	Sweep Eff	CO_2 density kg/m^3	Static Capacity Mt	Injection Time years
Boundary	1.4989E+13	388	1	500	0	115	1611											
Zone 4	1.1928E+12	388	1	500	0.24	115	1611	0.00107	180000	72	158	6*	7863			755	1807	40
Closure 1	9.9614E+09	296	1	500	0.29	775	1313	0.00072	180000	61	127	141	4118	0.423	0.65	719	2686	40
Closure 4	3.7605E+08	180	1	500	0.24	1389	1461	0.00086	180000	66	142	266	2463	0.423	0.65	791	112	40
Closure 5	3.5689E+09	162	1	500	0.24	1257	1385	0.00088	180000	63	144	236	3267	0.423	0.65	785	1051	40
Closure 7	1.7523E+09	335	1	500	0.24	1409	1543	0.00107	180000	70	150	268	3182	0.423	0.65	786	517	40
Closure 35	1.2616E+10	279	1	1500	0.26	1062	1396	0.00076	180000	64	139	199	5453	0.423	0.65	759	3590	40
Closure 36	3.6352E+09	258	1	100	0.18	1261	1581	0.00103	180000	71	154	206	1787	0.423	0.65	730	995	40
Closure 37	5.1474E+09	224	1	100	0.24	1453	1668	0.00103	180000	75	163	272	1654	0.423	0.65	782	1509	40
Closure 38	2.2032E+09	205	1	500	0.3	1655	1801	0.00084	180000	80	177	309	3067	0.423	0.65	785	648	40
Closure 39	5.0166E+09	259	1	500	0.24	1222	1617	0.00107	180000	73	158	209	3721	0.423	0.65	739	1390	40
Closure 40	2.9821E+09	241	1	500	0.24	1597	1789	0.00107	180000	80	175	308	3387	0.423	0.65	791	885	40
Closure 41	2.1525E+09	196	1	500	0.24	771	1152	0.00091	180000	54	111	141	3139	0.423	0.65	738	596	40
Closure 42	1.3479E+09	157	1	500	0.24	939	1114	0.00100	180000	53	107	154	2825	0.423	0.65	738	373	40
Closure 46	3.8681E+09	406	1	500	0.24	878	1187	0.00103	180000	55	114	143	3621	0.423	0.65	722	1047	40
Closure 49	5.4335E+08	111	1	50	0.24	1907	1982	0.00107	180000	87	195	372	515	0.423	0.65	803	164	40
Closure 50	2.2633E+08	81	1	50	0.24	2104	2163	0.00107	180000	95	213	414	385	0.423	0.65	805	68	40

Table A10.2: Material Balance Model Properties Using Maximum Values From CarbonStore

* The Zone 4 fracture pressure limit was replaced by the value at the centroid, 26.2 MPa.

Name	Pore Volume m^3	Gross thickness m	NTG	Permeability (mD)	Porosity (fraction)	Dtop m	Dcentroid m	cr 1/MPa	Salinity (ppm)	Temperature °C	Pressure MPa	90% Fracture Pressure MPa	Transmissibility cp m3/day/bar	Swc	Sweep Eff	CO_2 density kg/m^3	Static Capacity Mt	Injection Time years
Boundary	2.9351E+11	49	0.91	10	0.05	15	1572	0.00038	180000	59	164							
Zone 4	1.6401E+10	49	0.71	10	0.05	15	1572	0.00038	180000	59	164	5*	16			323	1807	40
Closure 1	8.2936E+08	251	0.71	10	0.05	675	1282	0.00029	180000	53	134	122	9	0.423	0.48	719	224	40
Closure 4	4.1972E+07	170	0.71	10	0.05	1289	1453	0.00033	180000	56	151	232	6	0.423	0.48	791	12	40
Closure 5	3.4439E+08	131	0.71	10	0.05	1157	1370	0.00033	180000	53	150	209	9	0.423	0.48	785	101	40
Closure 7	1.8872E+08	304	0.71	10	0.05	1309	1537	0.00038	180000	58	160	236	7	0.423	0.48	786	56	40
Closure 35	9.8723E+08	199	0.71	200	0.05	962	1373	0.00030	180000	54	146	173	11	0.423	0.48	759	281	40
Closure 36	1.1085E+09	207	0.71	15	0.12	1161	1557	0.00037	180000	59	162	179	9	0.423	0.48	730	303	40
Closure 37	5.4391E+08	200	0.71	15	0.05	1353	1652	0.00037	180000	62	171	243	9	0.423	0.48	782	160	40
Closure 38	7.1582E+07	184	0.27	10	0.05	1555	1701	0.00032	180000	63	177	268	7	0.423	0.48	785	21	40
Closure 39	5.5899E+08	244	0.71	10	0.05	1122	1517	0.00038	180000	58	158	181	9	0.423	0.48	739	155	40
Closure 40	2.9868E+08	203	0.71	10	0.05	1497	1689	0.00038	180000	63	175	269	8	0.423	0.48	791	89	40
Closure 41	2.2221E+08	171	0.71	10	0.05	671	1052	0.00034	180000	45	111	123	8	0.423	0.48	738	62	40
Closure 42	1.3683E+08	134	0.71	10	0.05	829	1017	0.00036	180000	43	108	134	7	0.423	0.48	738	38	40
Closure 46	1.8016E+08	159	0.71	10	0.05	778	1088	0.00037	180000	46	114	124	7	0.423	0.48	722	49	40
Closure 49	5.8887E+07	102	0.71	5	0.05	1807	1882	0.00038	180000	68	195	325	6	0.423	0.48	803	18	40
Closure 50	2.1377E+07	64	0.71	5	0.05	2004	2063	0.00038	180000	74	213	360	5	0.423	0.48	805	6	40

Table A10.3: Material Balance Model Properties Using Minimum Values From CarbonStore

- The Zone 4 fracture pressure limit was replaced by the value at the centroid with is 25.6 MPa.