Development of Storage Coefficients for Carbon Dioxide Storage in Deep Saline Formations

Millie Basava-Reddi[1], Charlie Gorecki[2], and Neil Wildgust[1]

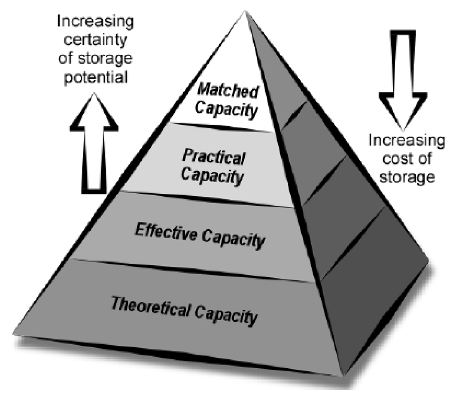
[1] IEAGHG, [2] EERC

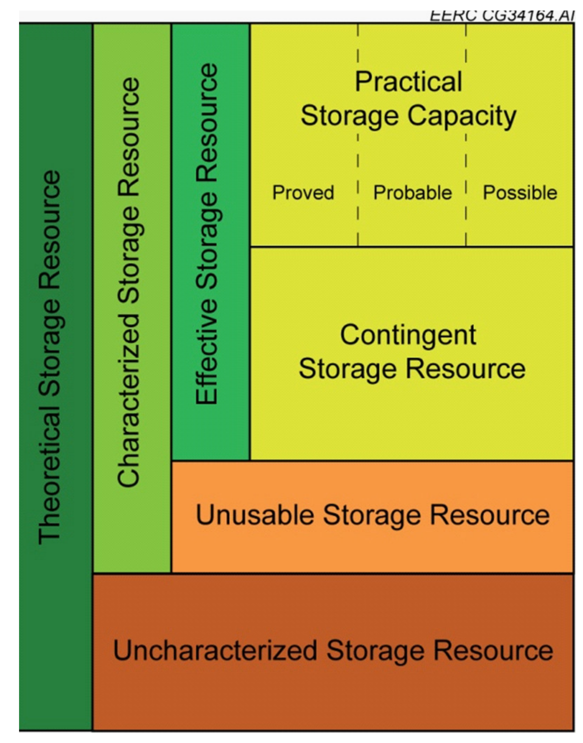
Background to the Study

The IEA Greenhouse Gas R&D Programme commissioned the Energy and Environmental Research Centre, from the University of North Dakota, to undertake a study to develop storage coefficients for CO_2 storage in deep saline formations. The project was co-sponsored by the US Department of Energy.

The aim was to define a series of storage coefficients, which can be applied to regional calculations to provide more realistic estimates.

Storage Resource Classification





The study considered 4 existing CO_2 storage resource classification schemes:

- The CSLF Techno-Economic Resource-Reserve Pyramid;
- The US DOE classification scheme
- The probabilistic assessment methodology being developed by the USGS
- The CO2CRC classification system

The CSLF and US DOE classification schemes, with elements of the CO2CRC scheme, were considered as the most appropriate basis for development of storage capacity coefficients. In relation to the storage coefficients developed by the study, the key definitions are:

Theoretical Storage Resource – The upper limit of storage resource; includes pore volume that can be used to store CO_2 in separate phase, dissolved phase, and mineral phase.

Effective Storage Resource – Estimated resource after technical constraints have been applied. It is the pore volume in known storage sites into which it is technically feasible to inject and store CO_2.

DoE and CSLF Methodologies

The basic equation for the US DOE approach is:

$$G_{CO_2} = A * h * \phi * \rho_{CO_2} * E$$

Where, the mass of stored CO_2 is (G_{CO2}) based on investigational area (A), formation thickness (h), porosity (ϕ), CO_2 density (ρ_{CO2}) and the application of a storage coefficient (E).

The CSLF main equation is:

$$V_{CO_2T} = V_{trap} * \phi * (1 - S_{wirr}) = A * h * \phi * (1 - S_{wirr})$$

Where the theoretical volume of stored CO_2 (V_{CO2T}) is based on a geometric volume of a trap, (V_{trap}) the area (A), average thickness (h), porosity (ϕ) and the irreducible water saturation (S_{wirr}). The capacity coefficient C_c, which incorporates the cumulative effects of trap heterogeneity, CO2 buoyancy, and sweep efficiency, is then multiplied by to derive an effective storage capacity.

The two storage coefficients can be related by the following equation, provided that the same assumptions concerning storage conditions are applied:

$$E_E = C_C * (1 - S_{wirr})$$

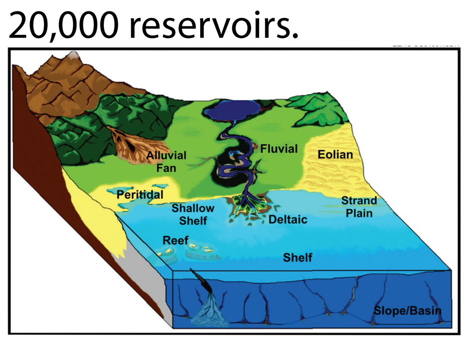
Development of Coefficients for Effective Storage Capacity

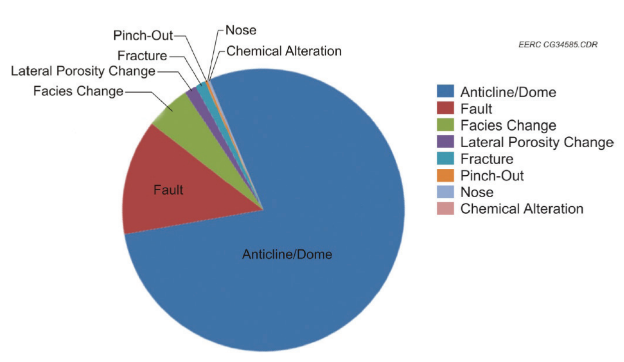
Methodology

Depleted oil and gas reservoirs are generally well characterised from exploration/ production data and have proven capacity to retain buoyant fluids over geological timescales. These storage resources can be readily assessed using mass balance considerations rather than through coefficients and so the study focussed on deep saline formations (DSF).

A literature review of actual CO_2 storage projects showed that these are of insufficient numbers to adequately representative all possible DSF scenarios, therefore, a simulation approach was adopted.

To construct the models, the Average Global Database was constructed by using hydrocarbon reservoir properties as a proxy for DSF characteristics (due to the general paucity of data available for DSF). This was compiled through use of existing US databases and an extensive literature review for other regions and contains details of over 20,000 reservoirs.





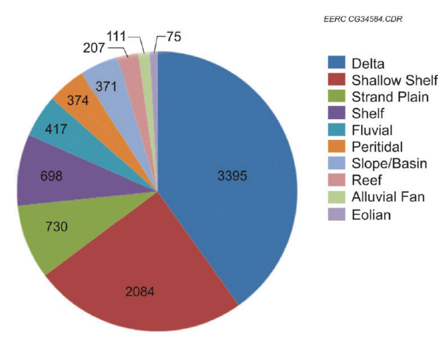


Figure 9. Depositional environments from the AGD.

A uniform injection and evaluation scheme was developed as a base for all of the modelling runs undertaken:

- Coefficients were calculated at the projected time when injection stopped;
- CO_2 injection volumes were set at 1Mt over 1 year for homogeneous models and 1Mt over 5 years for heterogeneous models;
- Areal dimensions of the models were set at 3.2km by 3.2km, thickness at 26m, whilst models were divided into 204,000 grid cells;
- Trapping was dominated by physical containment, but solution and residual trapping were also accounted for even though they were relatively minor contributors to trapping over the projected timescales of injection;
- Plumes were defined by the extent of free-phase CO_2.

First stage - Series of simulations using homogeneous models, constructed with average properties derived from the AGD, enabling an assessment of the sensitivity of calculated coefficients to various key input parameters.

The results of this assessment showed that tightly closed structures, increased depth, lower temperatures, low ratios of vertical to horizontal permeability and high injection rates, all increased storage efficiency and the value of the calculated coefficient. Effects of relative permeability and irreducible water saturation appeared to be much less pronounced.

Calculation of Storage Coefficients

Heterogeneous models were developed for the various lithologies, depositional environments and structures, to derive ranges of storage capacity coefficients. Statistical distributions from the AGD were employed for key input parameters including porosity and permeability.

The issue of scale was considered in detail, in particular whether calculation of coefficients and storage resource at localised scales can be applied to entire formations. Site-specific storage coefficients were developed from 195 simulations using heterogeneous models, before attempting to extrapolate these results to the formation level. The resulting values for storage coefficient, E_E ranged from 4% to 17% with an 80% confidence interval. Structural setting was found the exert the largest influence of any parameter on the results, with storage coefficients for effective resource exceeding 25% in some cases.

Table 13. P10, P50, and P90 Storage Coefficients E_E and $C_C * (1 - S_{wirr})$ Calculated for the Site-Specific Scale for Different Lithologies (A_n/A_t is fixed at 0.8)

Lithology	Depositional Environment	P10, %	P50, %	P90, %
Clastics	Not applicable	4.62	6.79	14.92
Dolomite	Not applicable	6.57	7.91	14.92
Limestone	Not applicable	4.24	6.13	9.82
Clastics	Alluvial fan	4.35	6.22	13.97
Clastics	Delta	4.96	6.70	14.03
Clastics	Eolian	5.64	7.44	15.86
Clastics	Fluvial	5.13	6.44	12.50
Clastics	Peritidal	4.12	6.06	15.41
Clastics	Slope basin	4.89	7.39	16.98
Clastics	Shallow shelf	5.41	7.67	15.62
Clastics	Shelf	4.07	6.23	17.23
Clastics	Strand plain	5.40	6.72	12.90
Limestone	Peritidal	4.45	5.61	9.41
Limestone	Reef	4.09	5.31	9.00
Limestone	Shallow shelf	4.70	7.47	10.59

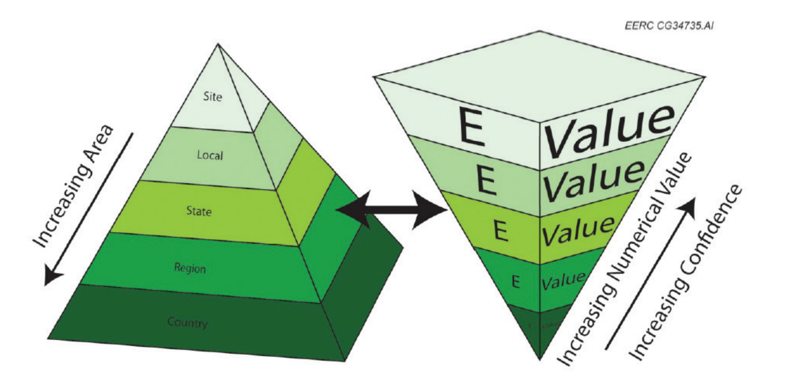


Figure 20. Relationship between the site of the assessment and the resulting storage coefficient. At the site-specific scale the value of the storage coefficient will increase as well as the confidence in the result, because of increased knowledge of the site.

General Formation Properties for the AGD.

Percentile Value	Depth, m	Salinity, ppm	Temp Grad, °C/m	Reservoir Thickness, m
10	900	8,200	0.020	3.4
50	2,300	53,000	0.025	26
90	3,800	170,000	0.033	190

The site-specific results were then extrapolated to the formation scale.

Storage Coefficients calculated at formation level by Lithology

Lithology	P10, %	P50, %	P90, %
Clastics	1.86	2.70	6.00
Dolomite	2.58	3.26	5.54
Limestone	1.41	2.04	3.27
All	1.66	2.63	5.13

In order to assess effective storage resource at the basin level, resources in individual DSF units should be assessed using the methodology outlined, and then results aggregated.

Conclusions and Recommendations

The study has successfully built upon earlier work by CSLF and US DOE, confirming the similarities of the two methodologies and more importantly, establishing an ease of comparison of storage coefficients employed and resources calculated for deep saline formations.

The modelling work showed the relative influence of various parameters on the efficiency of storage, and allowed the derivation of probabilistic ranges of storage coefficients for calculation of effective storage resource at both site-specific and formation levels, the overall mean value for all lithologies being 2.6% at the formation level.

The analysis and conclusions presented by the study are based on theoretical modelling. As experience and data is gained from increasing numbers of actual injection projects, the results of this study and the storage coefficients derived should be re-assessed at an appropriate point in the future using real-world data.