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TECHNICAL GROUP

DRAFT

Discussion Paper from the Task Force for Reviewing and Identifying Standards with Regards to CO_2 Storage Capacity Measurement

(Version 2)

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Note by the Secretariat

Background

At the meeting of the Technical Group in Melbourne, Australia on September 15, 2004, a Task Force was created to review and identify standards with regards to CO_2 storage capacity measurement. This Task Force consists of Australia (lead), Canada, the European Commission, France, Norway, and the United States. It was instructed to produce a Discussion Paper that would then undergo review and be presented at a full Technical Group meeting. A first version of this discussion paper was presented at the meeting of the Technical Group in Oviedo, Spain, on April 30, 2005. This second version of the Discussion Paper is a continuation of the Task Force's activities.

Action Requested

The Technical Group is requested to review and consider the second version of the Discussion Paper presented by the Task Force for Reviewing and Identifying Standards with Regards to CO_2 Storage Capacity Measurement.

Conclusions

The Technical Group is invited to note in the Minutes of its next meeting that:

> "The Technical Group reviewed and considered the Discussion Paper presented by the Task Force for Reviewing and Identifying Standards with Regards to CO_2 Storage Capacity Measurement."

CSLF-T-2005-9
15 August 2005

Discussion Paper on CO_2 Storage Capacity Estimation (Phase 1) ; "Version 2"

"A taskforce for review and development of standards with regards to storage capacity measurement"

Prepared by the Storage Capacity Estimation Taskforce for the Technical Working Group of the Carbon Sequestration Leadership Forum

Version 1 Presented to the Technical Working Group Meeting of the Carbon Sequestration Leadership Forum on 30th April 2005, Oviedo, Spain, and Version 2 to be presented to the Technical and Policy Working Group Meeting of the Carbon Sequestration Leadership Forum in Berlin in September 2005.

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Abstract

A range of estimates for the capacity for storage of CO_2 in geological media have been published since the early 1990s for the world, various regions, and countries. The range of the estimates in some cases varies widely. Also, there is considerable discrepancy amongst the estimates due to the different methods that have been used, some of which have relied upon questionable approaches. Assessment methodologies vary at the regional, basin and prospect (local) level, with differing degrees of accuracy and precision for each level. For each geological trap type and means of CO_2 storage, there are a variety of parameters that impact on the efficiency of storage of CO_2, many of which act independently whilst some act in opposite directions. The effectiveness of each trapping mechanism occurs over widely different time ranges (immediate to 10,000s to 100,000s years). This complexity, as well as that a single trap type often involves multiple trapping mechanisms, makes capacity estimation a multifaceted task. If governments are to have reliable capacity estimates for geological storage of CO_2, a series of proper definitions and consistent and accepted methodologies for estimating CO_2 storage capacity need to be established to allow policy decisions to be made with the best resource assessments possible. This report (Phase 1) documents the nature of the problem, but further and ongoing work will be required to refine terminology and definitions. A proposed future report (Phase 2) will document existing studies from around the world that are considered to have used reliable and technically viable methodologies. It will aim to establish a set of definitions and terminology so that results can be compared and contrasted, and will assist in the setting of future government policy directions in regard to greenhouse gas mitigation, especially as it relates to geological storage of CO_2.

Introduction

Governments around the world are searching for options to make deep cuts into greenhouse gas emissions, and the geological storage of CO_2 is one option that shows significant promise both in terms of capacity and immediate applicability. However, governments are dependant on reliable estimates of CO_2 storage capacity and insightful indications of the viability of geological storage in their respective jurisdiction. Similarly, industry needs reliable estimates for business decisions. If these estimates are not reliable, and decisions are made based on poor estimates and advice, then valuable resources and time could be wasted. Policies that have been put in place to address CO_2 emissions could be jeopardised.

Background

The main storage mechanisms of CO_2 in geological media are briefly listed here, and explained more in detail in Appendix 1. In the subsurface, CO_2 can occur in a free state as gas, a liquid or as a supercritical fluid-like state. Its physical state will depend on in situ pressure and temperature, which in turn depend on depth. Dense CO_2 (liquid or supercritical) will be up to 500 times denser than in the gaseous state at the surface and so will occupy less volume (i.e., much greater storage efficiency than in the gaseous state). Carbon dioxide can be trapped in the deep geological subsurface through physical processes: structural or stratigraphic trapping, and residual gas phase trapping; and through chemical processes: dissolution into formation water or reservoir oil, precipitation into carbonate minerals, or adsorption onto coal and kerogen-rich shales. Hydrodynamic trapping is a combination of physical and chemical processes acting on different time scales

Estimation of the capacity of a geological reservoir to store CO_2 is not a straightforward or simple process. Some authors have tried to simplify estimates at the regional or global level, but have largely been unsuccessful, as evidenced by the widely conflicting results (Figure 1). At the worldwide level, estimates of the CO_2 storage potential are often quoted as “very large” with ranges for the estimates in the order of 100s to 10,000s Gt of CO_2. Although in principle capacity estimation relies on a simple series of algorithms that depend on the storage mechanism under consideration to calculate the available capacity in a certain volume of sedimentary rock at a given depth, temperature and pressure, applying them to a specific region or site is complex. It is particularly difficult due to the various trap types and trapping mechanisms that can occur, the different time frames over which trapping becomes effective, and the different physical states in which the CO_2 might occur. All of these parameters affect the effectiveness of geological storage of CO_2, often in different directions. The highly variable nature of geological settings, rock characteristics, and reservoir performance combine to make some results unreliable when they have used methodologies that generalise the inputs for potential storage capacity.

Given the significant variability that exists in many estimates and in their underlying criteria, it is necessary to document the limitations of many of the assumptions used so far, and to make suggestions and give examples of how better and more reliable estimates can be determined. At the same time a series of definitions needs to be established to enable more consistency between capacity estimates and in understanding and comparing various capacity figures. This preliminary work provides some guidance on a number of issues associated with storage capacity estimation, and should be followed by further work clarifying terminology discrepancies and putting forward improved and agreed methodologies for capacity estimation. If this occurs, it will assist member countries to establish their own estimates of CO_2 storage capacity for their region, or to understand the limitations of estimates that are already in the public domain.

Existing Capacity Estimates

A large proportion of existing capacity estimates are highly variable and in many instances are contradictory. Although geoscience professionals are able to examine the details and underlying assumptions of each report (if documented) to see if they have used appropriate methodologies, non-geoscientists will often only look at the final “bottom line” number and can be misled or subsequently mislead others if they use the values in a way for which they were never intended. This phenomenon is not uncommon in resource assessments of mineral and fossil fuel resources.

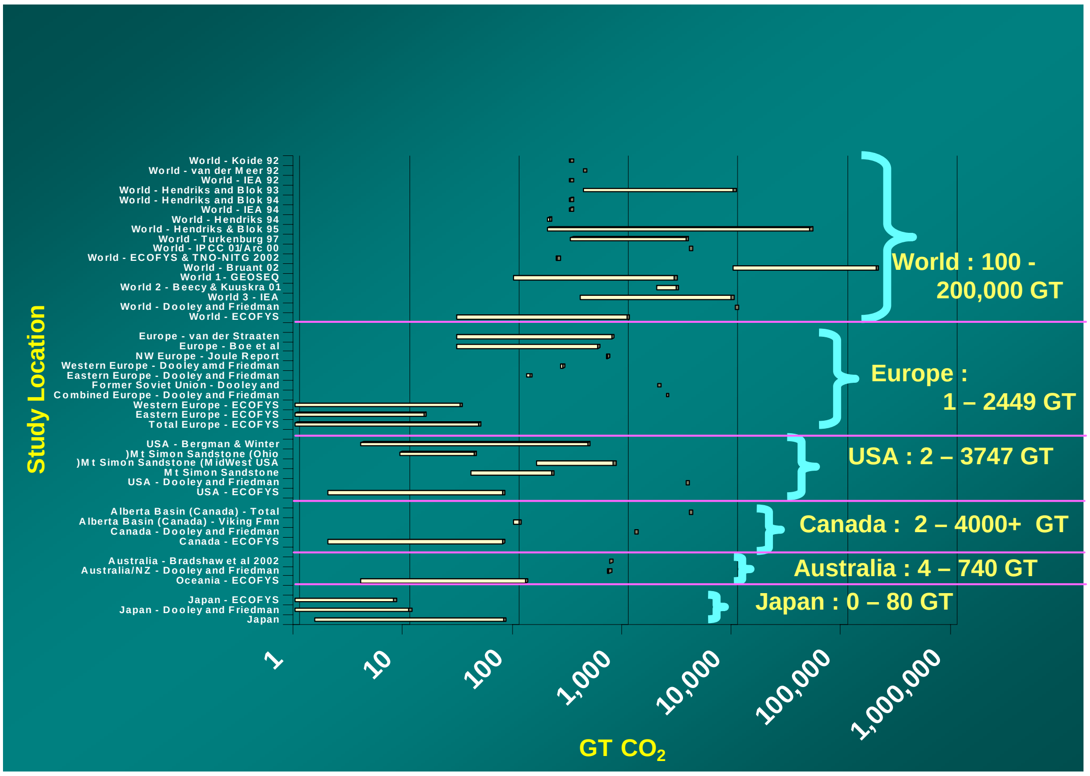

Figure 1. A listing of various estimates for CO_2 storage capacity for the world and regions of the world. Estimates are arranged by region, and ordered internally by date of completion of the estimates.

Figure 1 shows the range of many of the regional estimates for CO_2 storage capacity in geological media. They are ordered by region and by date, and show many instances where the estimates are at great variance, within a region and for the world. Some estimates for individual regions suggest that they contain more storage capacity than some world estimates. It is not necessarily correct to assume that more recent estimates are more accurate or reliable than earlier estimates, as the underlying assumptions and methods need to be carefully examined.

Initial estimates for the world during the early to mid 1990s used simplistic methods which relied upon the surface area of sedimentary basins to make their estimates of storage capacity of CO_2 in free phase in the rock pore space. They estimated the area of all sedimentary basins in the world, then assumed an average thickness of reservoir rock and an average porosity (i.e. pore space – voids between grains in a rock) and thus derived a total pore volume available. Some estimates worked from the premise that only structural traps were relevant and thus reduced the potential total volume by assuming that only 1% of the area of any basin comprised structural traps, and thus was viable for CO_2 storage. The main problem with this methodology is that it relies entirely on the premise that the surface area of a sedimentary basin is directly related to the available resources that it contains. It also relies on an assumption that an “average basin” exists, or can be estimated. None of these estimates applied Monte Carlo simulations or uncertainty modelling to probabilistically calculate the potential ranges in their estimates of meaningful values. Many of these estimates are poorly documented in regard to their detailed assumptions and methodology.

To illustrate the lack of a relationship between the size of a sedimentary basin and its contained resources, Figure 2 shows the relationship between the hydrocarbon resources that occur in major petroleum provinces of the world and the surface area of these basins. It is clear that there is no relationship between the surface area of a basin and petroleum accumulations. The generation, accumulation and volume of hydrocarbons in a basin are dependant on the basin type, the source rock quality, reservoir quality, seal characteristics, structural trapping mechanisms, burial and tectonic history, and the respective timing of those factors. Many of these factors are common to the geological storage of CO_2, with the exception that timing is important mostly in terms of the preservation of traps rather than of the generation of fluids relative to traps.

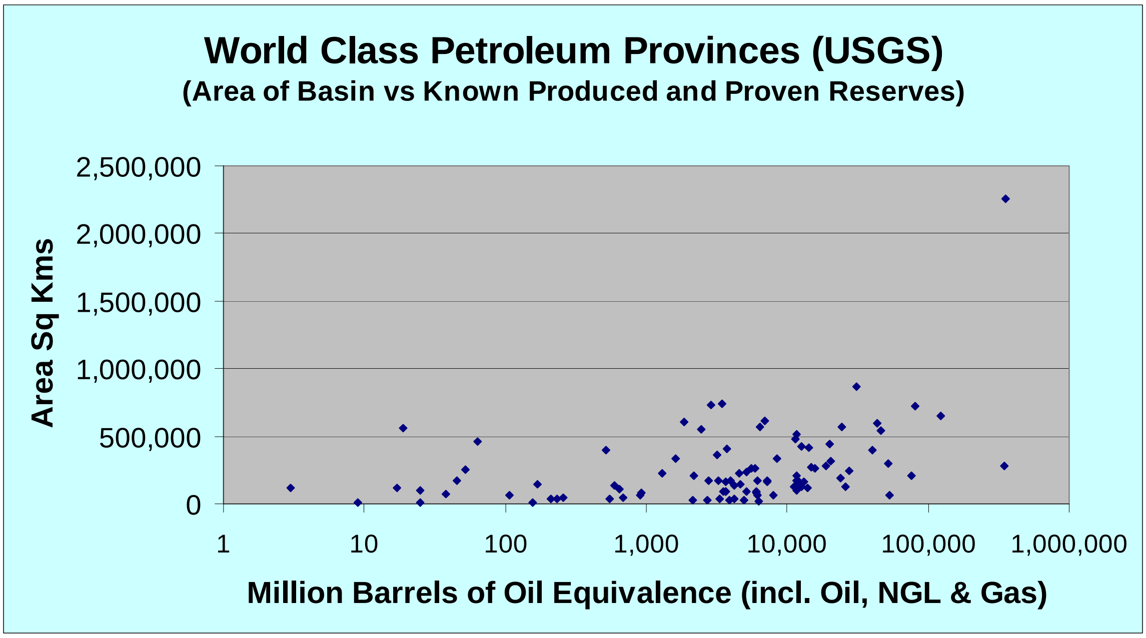

Figure 2. Relationship between the surface area of a sedimentary basin and the volume of hydrocarbon resources in that basin for world class petroleum basins (data from USGS, 2000 – World Petroleum Assessment).

Given that no relationship exists between the surface area of a sedimentary basin and hydrocarbon resources, it is difficult and wrong to conclude that such a relationship would exist for CO_2 storage capacity. One of the logic flaws in utilising the surface area of a basin in capacity calculations is that hydrocarbons are found in traps that are a subset of the capacity estimates used in the surface area calculations. Additionally, many estimates of CO_2 storage capacity of a region rely in part upon a calculation of the replacement of the storage space previously occupied by hydrocarbon resources. So, if hydrocarbon accumulation volumes are not related to the surface area of a basin, then the CO_2 storage capacity can't be related to the surface area of a basin. Some of the assumptions being used are such gross simplifications that they become meaningless when examined in any detail. For example, the assumptions used in surface area calculations do not allow for vertical stacking of reservoirs (assuming only 1 reservoir per basin), nor do they recognise that many large and aerially extensive basins can be very shallow with no reservoir/seal pairs (combination of a seal overlying a reservoir rock), nor that many narrow basins are often quite deep, with numerous stacked reservoir/seal pairs. In both of these examples, the storage capacity would have been respectively grossly overestimated and underestimated.

One of the other problems with estimates that are only based on surface area is apparent from examination of the complexity of the various trapping methods. In general the surface area calculations are based solely on structural trapping methods on the assumption that a porous geological formation is considered as a continuous and homogeneous entity. This ignores or simplifies the role of stratigraphic trapping (a reservoir formation is generally a discontinuous and heterogeneous formation), dissolution, residual gas trapping and mineral trapping when CO_2 is injected in deep saline aquifers, or of adsorption trapping when CO_2 is injected in coal seams and potentially organic-rich shales. Many estimates inadequately document how they deal with these trapping methods, or simply make technically unjustified assumptions (e.g. 1% of a basin is viable for trapping). Where the world estimates are in the 1000s Gt CO_2 range or 100s to 1000s Gt CO_2 at the regional level in Figure 1, they have probably included elements of dissolution trapping in their estimates. Given that dissolution and residual gas trapping probably account for well over 90% of the trapping potential, both regionally and globally, it can be seen that gross underestimates will be derived by ignoring these trapping methods. These and many other similar issues have been raised by Manancourt and Gale (2004), leading them to the conclusion that detailed basin analysis and extensive research is required before reliable storage capacity estimates can be determined.

Reserve versus Resource

Additional problems with the estimates of storage capacity relate to whether the assessments were conducted at the reserve or resource level, and the assumptions that were made to discriminate between these two tiers of assessment. A reserve is usually defined as those quantities of a commodity which are anticipated to be commercially accessible from known accumulations from a given date forward, whereas resources are those quantities of a commodity which are estimated, on a given date, to be potentially accessible from known accumulations, but which are not currently considered to be commercially recoverable. Traditionally in assessment of a commodity a clear definition of both these levels is first made, normally including such factors as economic cut-offs (e.g. $/ton), proven extent, reliability of assessment data, and whether a technology barrier exists (e.g. located in deep water or needs a breakthrough in processing techniques). Although a few sites are genuinely operating as CO_2 storage sites in the current economic conditions (e.g. Sleipner in the North Sea and In-Salah in Algeria), many are not considered economic in the existing policy and economic environment. As a result most potential sites around the world would not classify as a reserve until the policy and economic conditions change.

Another possible thought process in considering storage capacity for CO_2 could perhaps be to examine the way unconventional resources such as oil shale, gas trapped in very poor low permeability and porosity reservoirs (“tight gas”), or even extraction of uranium from seawater) are treated today. Each of these resources can be technically extracted but mostly do not figure in reserve calculations (although this will change as resources become scarcer and prices increase). Such unconventional resources often are assessed based on the perceived commercial and technological efficiency of the extraction process in the future relative to the prevailing value of the commodity, and are usually grossly uneconomic compared to conventional resources. Coal bed methane is another energy commodity that is facing challenges in developing an appropriate resource assessment methodology to convert a potential resource into an accurate reserve estimate. Some of the issues are that the data are often very scant and uncertain, and a large numbers of wells might be required before it would be possible to reliably predict sustainable flow rates and volumes. In a similar way, CO_2 storage potential in deep saline reservoirs, especially where it lies at the base of the resource pyramid (see next section) or takes a significantly long time before it is effectively trapped (e.g. dissolution - see Appendix 1), could be quoted with additional qualifiers in terms of conventional and unconventional resources.

Resource Pyramids

The concept of resource pyramids was advanced by McCabe (1998) as a method to describe the accumulation around the world of hydrocarbons in different categories. This concept is proposed here to represent the similar issue of capacity for CO_2 storage in geological media. Because of the multi-faceted aspects of this issue, three resource pyramids are proposed, representing a) High Level, b) Techno-Economic and c) Trap Type and Effectiveness aspects.

High Level

Figure 3 shows the High Level resource pyramid for CO_2 storage. At the top of the pyramid are all the storage sites with good geological characteristics and that individually have large storage capacity, which are located close by to sites with low costs of capture. At the base of the pyramid are the extremely difficult sites, with problematic geological conditions, small storage capacity and that are located a great distance from sources with large capture costs. However, the total potential storage capacity of the sites at the base of the pyramid is very much greater than those at the top. Contradictory capacity estimate results have developed when assessments do not adequately define the boundary conditions and assumptions that have been used, and so fail to describe their position on the resource pyramid.

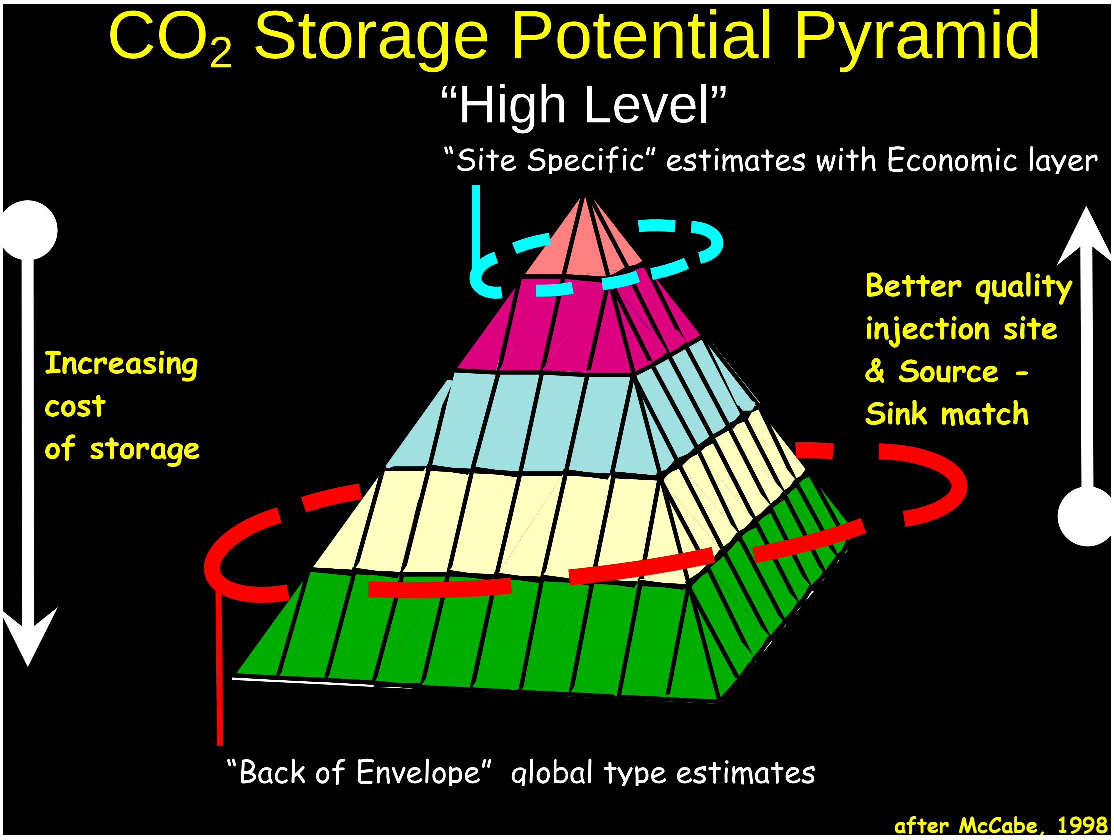

Figure 3. High level resource pyramid for CO_2 geological storage, showing at the top good sites with large individual capacity located close to cheap large sources of CO_2, and at the base low quality and/or small sites located long distances from expensive small sources of CO_2. Many of the current global estimates include sites that are situated towards the base of the pyramid, while the detailed prospect style assessments are positioned towards the top.

Techno-Economic Resource Pyramid

Figure 4 shows an example of a techno-economic resource pyramid that adds additional complexity to the high level resource pyramid. When calculating capacity, several types of estimates can and often are made, depending on the nature and purpose of the assessment, and they all lie across different regions of the resource pyramid. The following nomenclature and definitions are a preliminary guide that should form the basis of further work. This pyramid considers 3 technical and economic categories, being;

- **Theoretical capacity** – assumes that the whole of a reservoir formation is accessible to store CO_2 in its pore volume, or the whole of the formation water in a reservoir formation is available to have CO_2 dissolved into it, or the whole mass of coal is available to adsorb and store CO_2. This provides a maximum upper limit to a capacity estimate, however it is an unrealistic number as in practice there always will be technical and economic limitations across a region that prevent parts of the reservoir formation from being accessed and/or fully utilized. This represents the physical limit of what the geological system can accept. It occupies the whole of the resource pyramid.
- **Realistic capacity** – applies a range of technical (geological and engineering) cut-off limits to elements of an assessment such as quality of the reservoir (e.g. permeability and porosity) and seal, depth of burial, pressure and stress regimes, size of the pore volume of the reservoir and trap, and whether there may be other competing interests that could be compromised by injection of CO_2 (e.g., existing resources such as oil, gas, coal, water, national parks). This is a much more pragmatic estimate that can be done with some degree of precision, and gives important indications of technical

viability of CO_2 storage. These estimates are within the main body of the resource pyramid, but exclude the basal parts of the resource pyramid.

- **Viable capacity** –is the capacity arrived at by also considering economic, legal and regulatory barriers to CO_2 geological storage, and thus builds upon the realistic capacity assessment. Detailed source/sink matching is performed at this stage to match the best and nearest storage sites to large emission sources. The source/sink matching should extend beyond just geotechnical aspects, and include social and environmental aspects of locating storage sties. Cost curves may also be derived and Monte Carlo simulations performed to help estimate the level of uncertainty and upper and lower ranges in the known and derived data versus the actual data that become available once a project is built and running. At this level of assessment, it may be possible to also express the capacity estimate as an injection rate, not just as a total volume. Because the direct match of nearby suitable sites to emissions sources has been performed, the figures quoted become an annual sustainable rate of injection, where economics, supply volume and reservoir performance are integrated to define the viability of the resource. These capacity estimates are at the top of the resource pyramid.

All of these types of assessment have been performed in the past, and examples of each exist in Figure 1. However there is often no clear indication of the level of the assessment. Some have actually calculated a total theoretical capacity, then acknowledged that it is an unrealistic estimate, and so applied an arbitrary discount factor (e.g., 1%) across all sites to attempt to bring them back to a more realistic estimate. Applying an arbitrary discount factor is not realistic, given that the highest variability is actually in the geological data themselves within each basin and at specific sites. An example of applying a range of these methodologies to the same data set is described in Appendix 2.

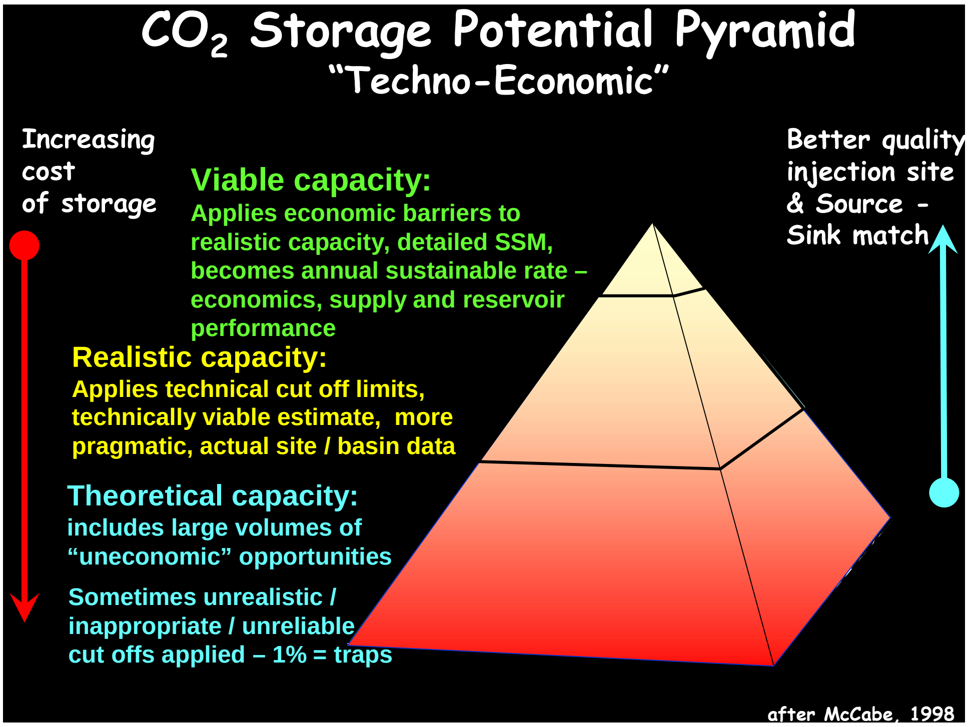

Figure 4. Techno-Economic Resource Pyramid for capacity for CO_2 geological storage, showing the three levels of Theoretical, Realistic and Viable estimates. Theoretical includes the entire pyramid, Realistic the top two portions and Viable only the top portion.

Trap Type and Effectiveness Resource Pyramid

This version of the resource pyramid (Figure 5) attempts to represent the relationships between the reservoir quality and trap types (left vertical axis), trapping mechanisms (bottom axis) and the timing effectiveness of trapping (right horizontal axis). The characteristics of the trapping mechanisms are described in detail in Appendix 1. At least 3 qualifiers need to be documented in this resource pyramid to explain which storage capacity estimate method has been used. At any time at a particular storage site, some of these trapping mechanisms might be mutually exclusive (e.g. dissolution into the fluids and displacement of fluids), whilst others may partially act simultaneously (e.g. residual gas saturation and compression of fluids and the rock matrix with increasing pressure), and others will compete against each other (e.g. simple compression of fluids such as occurs in a closed system versus displacement of pore fluids in an open system). Over the long term “geological” life of a storage site, many of the trapping mechanisms may actually participate in the eventual trapping mechanism history.

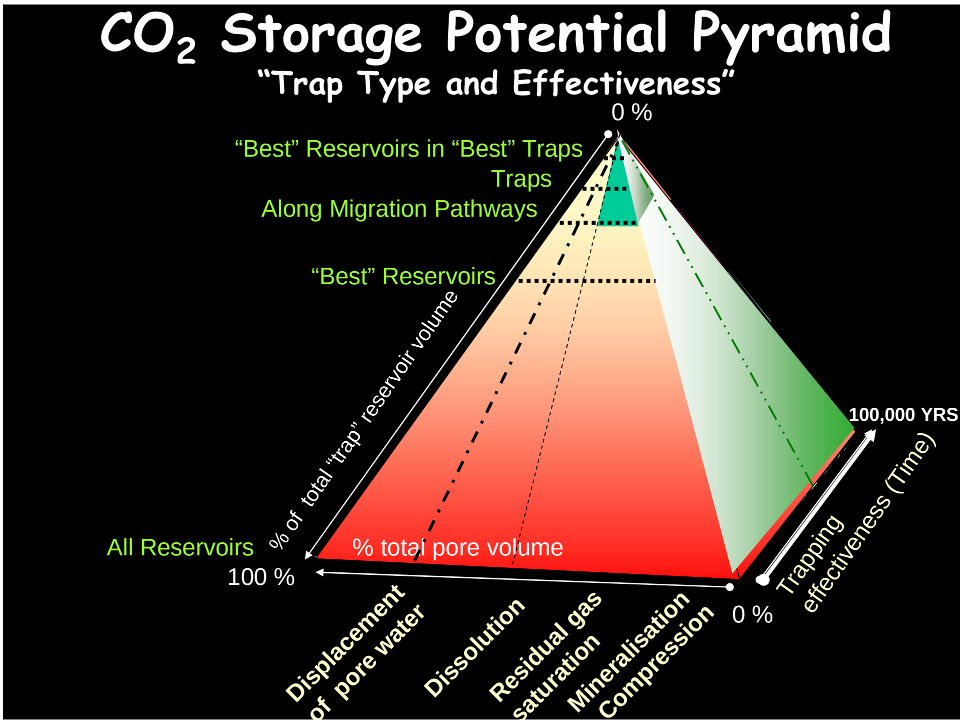

Figure 5. Trap type and effectiveness resource pyramid showing the relationships between different trap types, trapping mechanisms and their effectiveness in terms of time (years). The highlighted green inset pyramid corresponds to the proportion of the total resource pyramid that relates to dissolution trapping (see Appendix 1) that occurs along migration pathways over an effective time frame of up to 10,000s years.

Effect of Supply Volume and Injectivity on Storage Capacity

As described for the Techno-Economic Resource Pyramid, there is a need to clearly document whether storage capacity estimates are based upon source to sink matching (viable capacity), or whether injection sites are being considered in isolation from economics and in isolation from the likely supply volume (theoretical and realistic capacity). If the trap is not a clearly defined structural trap that is immediately effective, and relies upon dissolution and residual trapping, then the Trap Type and Effectiveness Resource Pyramid needs to be considered to conceptualise what capacity estimate method is being described If a site is of poor quality in terms of permeability (and thus can only accept small rates of injection), but has a lot of pore space and potential storage volume, then there will be a limit to the rate at which the CO_2 can be injected for each well. This may limit its utility as a storage site because it will require large capital costs for many wells and compressors, and, hence, quoting such a site as having large storage capacity may be extremely misleading. As such, describing this capacity by expressing it in terms similar to the documentation of unconventional resources could help indicate that it might not be an economically or technically efficient option.

Regional, Basin or Prospect Level Assessment

A range of methodologies exist that can be considered by jurisdictions and/or organizations that are embarking on assessing the CO_2 geological storage capacity available to them. Depending on the level of the assessment being undertaken, different constraints will apply to the methods used to estimate capacity. Methodologies will also differ for some regions due to the different trapping mechanism under consideration (discussed below and Appendix 1), and also depending on the outcomes that are desired from such an assessment. Assessments should be broadly based in their methodology to extend beyond just geotechnical components and consider the environmental and social parameters in site selection. The levels at which assessments can occur would include regional, basin and prospect (local) assessments.

Regional

Regional assessments are done at a high level when knowledge is required of which sedimentary basins in a region are suitable for CO_2 storage, especially when there is a need to determine whether there is likely to be sufficient storage capacity to match the region's emissions profile. A region may be defined by a geographic or political entity and could include several basins. The following are characteristics of regional-scale assessments.

a. Such an assessment can be done fairly rapidly if there is a regional dataset in place and can simply high grade a region's potential without putting forward a numerical value of storage capacity. If a region is identified as having the correct geological characteristics, then more detailed numerical studies can commence. Simple comparisons of a region's total pore volume occupied by known and produced hydrocarbons compared to the regional CO_2 emissions profile can provide insights as to a region's storage potential. However there are many instances of basins with no hydrocarbon resources and/or production that have excellent CO_2 storage potential.
b. If a regional dataset does not exist, then the primary data must be assembled and analysed at the regional level to make an assessment
c. This is an important initial assessment step because, if a positive result is achieved, there will be an incentive for further detailed assessments across the region, and presents a government with potential opportunities for reduction of CO_2 emissions.
d. It is this level that dominates assessments at the global level, and to date has in many instances used “questionable” principles and methodologies (e.g., surface area calculations) and derived numerical assessments without looking at the specific local or regional geology, except only for acknowledging that a sedimentary basin exists. The production of numerical capacity assessments where detailed and specific data are not available is extremely questionable. To date this level of assessment has produced highly variable and inconsistent results.
e. Given the importance of this assessment step and process to government decisions, the inaccuracies and contradictions in regional assessments need to be remedied and standards and definitions put forward.

Basin

Assessment at the basin level examines many of the geological settings that occur across an area, and whether there may be specific technical benefits or limitations in utilising storage sites in that region. These assessments should include an evaluation based on geology, hydrogeology, geothermal regime, pore space, end existence of energy and mineral resources, and their level of production. Such assessments might also involve risk analysis of various factors to help further high grade parts of a basin by defining where the greatest potential exists, as well as what technical issues might arise.

a. Such assessments may involve economics and detailed source to sink matching so as to optimise a selection process for further studies.

b. Basin assessments may include parts of the assessment methodology used in prospect assessment.

Prospect

Prospect level work at the local scale will involve detailed methodologies for estimating storage capacity at various sites within a basin. It requires different approaches depending on the trapping mechanism that is envisaged (dissolution, depleted hydrocarbon fields, deep saline reservoirs in geological structures) and whether such structures are closed or open in terms of hydrodynamics. It also must take into account the effects on the lithosphere (e.g. integrity of the cap rock) and the biosphere (e.g. effects on the ecological equilibrium of microorganism population, environmental risks derived from possible leakages).

a. For some of these (e.g., dissolution and residual gas trapping) reservoir simulations and specific source to sink matching will be required to predict capacity more accurately.
b. Given the intensive nature of such work, this style of assessment normally will only be done when sites are chosen for storage (at the specific site selection stage), and not at the early conceptual stage of evaluation of a region. However, some storage sites may be obvious candidates in the early screening process, and will rapidly accelerate to this detailed scale of assessment.

Trapping Efficiency and Timing

The efficiency of trapping for many of the mechanisms described in Appendix 1 and Table A1 depends upon the migration rate of the CO_2, which itself is highly dependant on the rock and fluid properties and geological characteristics of each site. The conceptual geological settings that constitute the largest potential storage volumes are (in decreasing potential capacity) deep saline reservoirs, depleted oil and gas fields, and coal beds. Trapping of CO_2 in geological formations in the subsurface can occur through various mechanisms that have characteristics as described in Appendix 1. Estimates of storage capacity must take into account the range of trapping mechanisms that are possible at each site, the different geological constraints on each mechanism, and the fact that different trapping mechanisms operate on different time scales that range from instantaneous to 10,000's of years. Figure 5 attempts to show these relationships. The complexity of these trapping mechanisms and the variations that occur within them individually and collectively demonstrate why simple capacity estimation methods will always have a range of uncertainties. Furthermore, estimates of storage capacity at specific sites may be highly sensitive to geological parameters that are poorly known or even unknown (such as relative permeability), requiring clear descriptions of the surrogate values used in the calculations for each site.

A related issue in estimation of CO_2 storage capacity is that of timing of availability and operation. Some trapping mechanisms operate immediately during and after injection. This is the case for physical trapping mechanisms that operate in porous and permeable rocks, e.g., structural, stratigraphic, residual-gas, and hydrodynamic trapping, and adsorption trapping which operates in coals. Chemical trapping mechanisms such as dissolution and mineral precipitation, operate on much longer time scales, sometimes up to centuries, millennia and even longer. From a practical viewpoint, storage capacity is required during this century, therefore capacity that effectively becomes operational or available only after this time frame might need to be considered differently in a regulatory perspective. However, dissolution and mineral precipitation, even if they do not provide immediate capacity, theoretically increase the storage security because CO_2 that is dissolved in formation water or reservoir oil, or that changes into a mineral, will not return to the atmosphere even if buoyancy related leakage flow paths are available.

Another issue associated with storage capacity is that oil and gas reservoirs (stratigraphic and structural traps where hydrocarbons have accumulated) may not be immediately available, even if storage becomes operational as soon as CO_2 injection commences. This is because oil and gas reservoirs still in production are unlikely to be used for CO_2 storage until they are depleted, unless CO_2 based enhanced recovery methods are used. With the increasing price of oil and gas, the life of oil and gas reservoirs may be extended beyond what is currently considered as economic. Thus, situations may arise when, while CO_2 viable capacity exists in the vicinity of large stationary CO_2 sources, it may not be accessible until years or decades in the future, in which case alternate storage sites must be found.

Gaps Discussion

Many of the contradictory assessments and errors in calculated storage capacity are due to the desire or need to make quick assessments with limited or no data. Such assessments might have a place, but they should not be used in setting forward looking strategy or for making investment decisions, nor should they be released in the public domain where they can be misunderstood and misused. Estimates need to clearly state the limitations that existed (data, time, knowledge) at the time of making the assessment and indicate the purpose and future use to which the estimates should be applied. Assessments that lack documentation of constraints (or justification for their use) cannot be easily compared with other assessments. This is the most common reason for contradictory results that can't be reconciled.

There are many levels of uncertainty within assessments of storage capacity. The different levels of assessment require extensive datasets from multiple disciplines that must be integrated to develop the most meaningful assessments. The most accurate way to estimate storage capacity is through construction of a geological model and use of that information in reservoir simulations. Such simulation and model building are resource, time and data intensive. Often many potential storage sites lack critical data elements upon which the modelling is highly sensitive (e.g. relative permeability). Furthermore, detailed reservoir simulations can only be done at the prospect level.

Thus some of the main gaps include;

- Lack of clear and accepted definitions that are meaningful across a range of geoscience disciplines, including geology, reservoir engineering and hydrogeology.
- Establishment of consistent and accepted methodologies and guidelines for capacity estimation.
- Establishment and documentation of appropriate constraints for assessments, especially for the technical (geological and reservoir engineering) data.
- Establishing reporting practices for storage capacities that are on par with modern practices in the other resource industries.
- Recognition of the data and knowledge required to undertake a meaningful assessment and the need to perform a thorough technical assessment if the estimates are to be relied upon.
- Recognition of the importance of the variability of the trapping mechanisms and the complexity within each mechanism in trying to estimate storage capacity, including the fact that many have a substantial time dependency.
- Recognition of the fact that some trapping mechanisms and levels at which geological storage assessment are done will require slightly different methodology and data sets in their assessment process.
- Recognition that estimating CO_2 storage capacity is not always just a simple static, geometric volume calculation of available pore space (as done in most past estimates), but can be a dynamic system that will evolve over time.
- Recognition that estimating CO_2 storage capacity must take into account environmental impacts of potential storage sites at early stages in the assessment process
- Recognition of the importance of the regional and basin assessment step to government policy setting and decision processes.

Future Directions

Many of the existing estimates of storage capacity discussed in this document and quoted in literature elsewhere were made at the global and regional level. However, there are several examples in the literature of correctly applying proper methodologies to arrive at estimates that can be reported in a meaningful manner to governments and policy makers. These include work done in Australia, Canada, Europe and the USA. If a Phase 2 report is produced, it should attempt to bring some sense and order to CO_2 storage capacity estimation. It should document valid examples and put forward some guidelines and definitions that can be used at the various levels in which storage capacity estimates can be undertaken. This should include regional, basin and prospect level assessments and should draw upon practical examples like acid gas injection and gas storage to show how prospect level assessment works at the local scale, and how exploration concepts such as “prospect and play analysis” can be applied to regional CO_2 storage capacity analysis. It should also discuss the importance of using Monte Carlo modelling to produce probabilistic estimates of storage capacity, which is the only reliable way to document and deliver resource estimates where there are high degrees of uncertainty in knowledge and information.

References

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APPENDIX 1 - Trapping Mechanisms

Listed below and in Table A1 are descriptions of the various trapping mechanisms that can occur in the subsurface.

Structural and Stratigraphic Trapping

Structural and stratigraphic trapping (Table A1) occur when a fluid in gas or liquid phase is contained in a static position beneath impermeable layers (e.g. shale) and can not flow. In the case of CO_2, despite its buoyancy, it can not migrate vertically or laterally due to these impermeable layers. These traps include anticlines (large folds in the subsurface), fault blocks (tilted/shifted strata in the subsurface bounded by faults) and structural and stratigraphic pinch-outs (where dipping reservoir strata and/or porous strata are overlain by horizontal seal rocks). Storage in such traps may be in traps that have previously held hydrocarbons (oil and gas reservoirs) or in those that contain only formation water (brackish water or brine). This trapping mechanism is immediately effective when CO_2 is injected.

Residual Gas Trapping

Residual gas trapping (Table A1) occurs when a proportion of the CO_2 migrating through the rock is “permanently” trapped between the interstices of the grains in the rock as a result of the surface tension of the CO_2 phase. It results from isolated “drops” of CO_2 being left in the pore space as the main mass of CO_2 passes through the rock matrix. The more rock the CO_2 passes through, the more residual gas trapping will occur, and it operates over a time range of immediate to 10s to 100s of years. For this trapping mechanism to operate, the CO_2 has to migrate and water has to re-imbibe the porous space previously occupied by CO_2. This mechanism operates in conjunction with dissolution, and the CO_2 will eventually dissolve into the pore water.

Dissolution Trapping

Dissolution trapping (Table A1) occurs when the CO_2 dissolves into the formation water or reservoir oil which it comes into contact with as it passes through the pores in the rock. Carbon dioxide will gradually dissolve into the formation water either fully or partially, depending on time and CO_2 saturation of the water. The quantity of CO_2 dissolved and rate of dissolution into the formation water depends on the water chemistry and the rate of contact of the CO_2 with unsaturated formation water. The higher is the exposure to “new”, unsaturated formation water, the greater is the rate of dissolution. Over time, as the CO_2 saturated water is denser by ~1% than the surrounding formation water, it may migrate downward, driven by gravity, back toward the basin centre, thus providing an effectively very large capacity compared with buoyancy trapping under a defined structural or stratigraphic closure. The extent to which dissolution occurs depends on whether highly permeable and thick reservoirs exist, and especially the presence of good vertical permeability. Dissolution trapping occurs over a time range of 100s to 1000s of years.

Mineral Trapping

Mineral trapping (Table A1) occurs when CO_2 reacts with the rock and formation water and precipitates carbonate minerals in the rock. This is predicted to occur over 100s to 10,000s of years, but it strongly depends on the mineralogy of the formation rock and the fluid types and interactions that occur. The fraction of injected CO_2 that may be trapped as precipitated minerals varies significantly, depending on the composition of the minerals in the reservoir rock. If limestone (carbonate) rocks are present, almost immediate chemical reactions will commence, whereas if sandstone rocks dominated by relatively stable quartz grains are present, chemical reactions might not take place or perhaps will only occur over very long time frames. In some ways this trapping mechanism can be considered to approach a state of “permanent” trapping, but in most scenarios will probably operate on longer time frames than other trapping methods.

Hydrodynamic Trapping

Hydrodynamic trapping occurs when CO_2 is injected below confining strata in deep saline aquifers whose formation water migrates in long, regional and basin scale flow systems. The typical velocity of the flow in these systems is in the order of cm/year, while their length scale is in the order of tens and hundreds of km. If CO_2 is injected in such systems, although no structural or stratigraphic trap exists locally to impede its lateral movement, it migrates along the dip of the strata at such low velocity, driven by buoyancy, that it would take tens of thousands to millions of years to reach the shallow strata at discharge areas. During this time, other trapping mechanisms such as residual gas trapping, dissolution and mineral precipitation, will act, with the net result that no free-phase CO_2 will ever reach the shallow strata. Furthermore, migrating CO_2 may be trapped in structural or stratigraphic traps along the migration path. This trapping mechanism operates immediately, being similar to structural and stratigraphic trapping except that the lateral migration of CO_2 at the injection site is not impeded.

Coal Adsorption

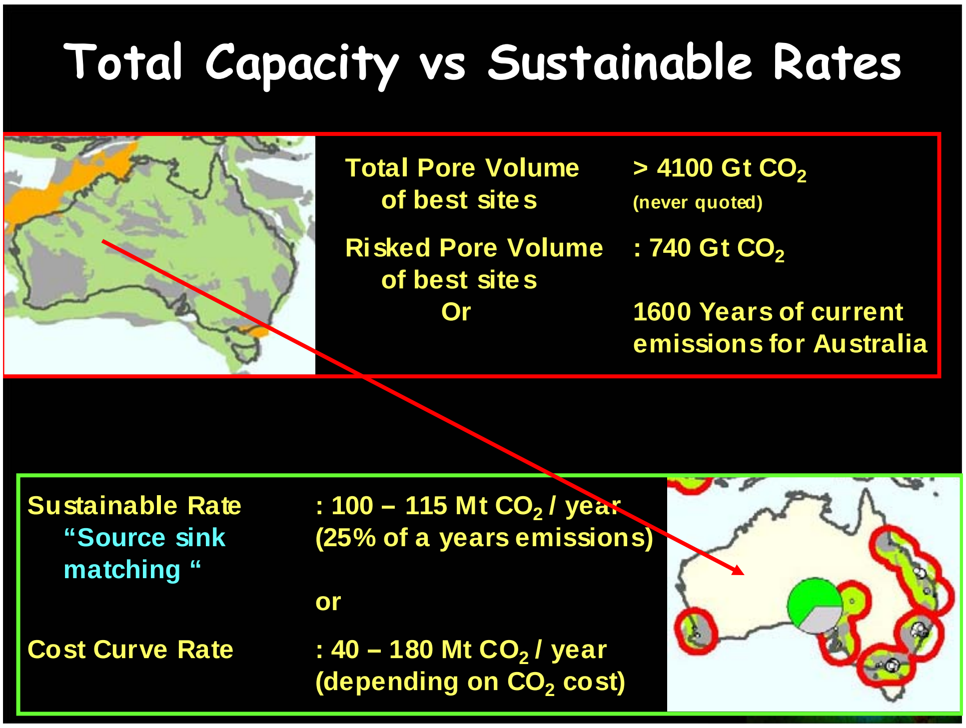
Coals have higher affinity to, and hence adsorb CO_2 more strongly than methane and other hydrocarbon gases (which commonly occur in coals) and, therefore, have a substantially greater capacity to store CO_2 (at least twice as much). The CO_2 storage capacity of coal seams can't be calculated using pore volumes and gas compressibility in a manner similar to conventional porous reservoirs, because the gas is stored in the coal matrix adsorbed onto the surface of micropores, in a free state in the coal cleats, or it is dissolved in the water contained in the coal. To calculate the CO_2 storage capacity in coals requires knowledge of adsorption isotherms and pressure, which vary for each coal type. Concerns have been expressed that the storage of CO_2 in coals may not actually lead to any reduction in greenhouse gases when there is a risk associated with liberation of even a small proportion of the contained methane to the atmosphere (which has a radiative effect 21 times stronger than CO_2). Furthermore, CO_2 storage in coals is limited by significant reductions in coal permeability with depth and with CO_2 (coal swelling). Also, CO_2 storage in coals is effective as long as the pressure regime in the coal is not lowered, otherwise the CO_2 will be released. In addition, coals that are deemed today as uneconomic and, therefore, fit for CO_2 storage, may become economic for mining or for in situ gasification at some time in the future. Generally, coals have limited CO_2 storage capacity in comparison with formations that are conventional porous sedimentary rock. Storage of CO_2 in coals is an emerging science, and more research is required to fully understand the processes and interactions involved, such as the effect of swelling of coals during injection of CO_2. This trapping mechanism operates immediately.

CHARACTERISTICS **TRAPPING MECHANISM**	**NATURE OF TRAPPING**	**EFFECTIVE TIMEFRAME**	**AREAL SIZE**	**OCCURRENCE IN BASIN**	**ISSUES**	**CAPACITY LIMITATION / BENEFITS**	**POTENT-IAL SIZE**	**CAPACITY ESTIMATION METHOD / REQUIREMENTS**
STRUCTURAL & STRATIGRAPHIC	Anticline, fold, fault block, pinch-out. CO_2 remains as a fluid below physical trap (seal)	Immediate	~ 10s km^2 to 100s km^2	Dependent on basins tectonic evolution. 100s of small traps to single large traps per basin	Faults may be sealed or open, dependant on stress regime and fault orientation and faults could be leak/spill points or compartmentalise trap	If closed hydraulic system then limited by compression of fluid (few percent) in reservoir. If open hydraulic system will have to displace formation fluid.	Significant	Simple volume calculation of available pore space in trap, allowing for factors that inhibit access to all the trap – eg sweep efficiency, residual water saturation
RESIDUAL GAS	CO_2 fills interstices between pores of the grains in rock	Immediate to 1000s years	basin scale - e.g. 10000s km^2	Along migration pathway of CO_2	Will have to displace water in pores. Dependant on CO_2 sweeping through reservoir to trap large volumes.	Can equal 15-20% of reservoir volume. Eventually dissolves into formation water.	Very large	Requires rock property data and reservoir simulation
DISSOLUTION	CO_2 migrates through reservoir beneath seal and eventually dissolves into formation fluid.	100s to 1000s of years if migrating - >10000s years if gas cap in structural trap - and longer if reservoir is thin and has low permeability	basin scale - e.g. 10000s km^2	Along migration pathway of CO_2, both up dip and down dip	Dependant on rate of migration (faster better) and contact with unsaturated water, and pre-existing water chemistry (less saline water better). Rate of migration depends on dip, pressure, injection rate, permeability, fractures, etc.	Once dissolved, CO_2 saturated water may migrate towards the basin centre thus giving very large capacity The limitation is contact between CO_2 and water, and having highly permeable (vertical) and thick reservoirs.	Very large	Requires reservoir simulation and need to know CO_2 supply rate and injection rate
MINERAL PRECIPITATION	CO_2 reacts with existing rock to form new stable minerals	10s to 1000s of years	basin scale - e.g. 10000s km^3	Along migration pathway of CO_2	Dependant on presence of reactive minerals and formation water chemistry. Could precipitate or dissolve.	Rate of reaction slow. Precipitation could "clog" up pore throats reducing injectivity. Approaches "permanent" trapping.	Significant	Requires rock mineralogy
HYDRODYNAMIC	CO_2 migrates through reservoir beneath seal, moving with or against the regional ground water flow system, whilst other physical and chemical trapping mechanisms operate on the CO_2.	Immediate	basin scale - e.g. 10000s km^2	Along migration pathway of CO_2, with or against the direction of the flow system that may move at rates of cm's / year	Dependant on CO_2 migration after the injection period, being so slow that it will not reach the edges of the sedimentary basin where leakage could occur.	No physical trap may exist and thus totally reliant on slow transport mechanism and chemical processes. Can include all other trapping mechanisms along the migration pathway.	Very large	Requires reservoir simulation and regional reservoir flow model
COAL ADSORPTION	CO_2 preferentially adsorbs onto coal surface	Immediate	~ 10km^2 to 100km^2	Limited to extent of thick coal seams in basins that are relatively shallow	Coals can swell reducing injectivity. Difficult to predict permeability trends. CO_2 adsorption not 100% effective which raises issue of leakage if no physical seal is present.	Injectivty poor due to low permeability. Effective at shallower depths than porous sedimentary rocks, but not at deeper depths due to permeability issues. Many injection wells required. If methane liberated might not be net GHG mitigation.	Low	Requires gas sorption data and knowledge of permeability trends and coal "reactivity" to CO_2

Table A1: Characteristics of physical and chemical trapping mechanisms. Note the different time frames & range of issues. Most mechanisms will operate alongside each other in each trap type.

APPENDIX 2- Example of appropriate and inappropriate capacity estimation

Many of the steps in storage capacity estimation described above have been produced in Australia, and they can be used as an illustrative example (Figure A1). An original screening study across the continent examining just the best sites in each viable sedimentary basin (i.e. of sufficient depth [>1000m] with adequate reservoir / seal pairs and potential traps) produced a total pore volume value (equivalent to theoretical capacity) of over 4100 Gt CO_2. This number was never published because it was known to be meaningless if it was used on its own. Each of the sites (over 100) had an individual risk applied to specific parameters such that a risked pore volume value (equivalent to realistic capacity) was calculated, resulting in a capacity of 740 Gt CO_2, equivalent to 1600 years of Australia's emissions. When detailed source/sink matching was applied to the dataset, a sustainable rate of injection was derived (equivalent to viable capacity) of 100 – 115 Mt CO_2/yr, or ~ 25% of Australia's annual total emissions. Following cost curve analysis, a rate of injection of 40 – 180 Mt CO_2/yr was derived, depending upon the value assigned to a tonne of carbon dioxide.



Total Capacity vs Sustainable Rates

Total Pore Volume of best sites	> 4100 Gt CO_2 (never quoted)
Risked Pore Volume of best sites Or	: 740 Gt CO_2 1600 Years of current emissions for Australia

Sustainable Rate "Source sink matching "	: 100 – 115 Mt CO_2 / year (25% of a years emissions) or
Cost Curve Rate	: 40 – 180 Mt CO_2 / year (depending on CO_2 cost)

Figure A1. Example of the levels of assessment performed in Australia from theoretical capacity (in this case total pore volume) to realistic capacity (in this case risked pore volume) to viable capacity (in this case a sustainable rate and cost curve rate).

If, instead of using a reliable and accurate methodology as described above, Australia had used an inappropriate surface area method to calculate storage capacity, a vastly different capacity would have been derived. Using known data constraints for porosity, thickness and expansion factors from the best 44 out of Australia's 300 sedimentary basins, and assuming just 1 reservoir/seal pair for each basin would give estimates for storage capacity of: minimum 40 Gt CO_2, maximum 21,350 Gt CO_2, average 3370 Gt CO_2, and best estimate of 1270 Gt CO_2. These numbers are clearly unreliable, have huge error bars and uncertainty factors associated with them, and would need probability values assigned to them to render them meaningful. Some exceed estimates for the entire world's CO_2 storage capacity, and the maximum value exceeds the more appropriate method that generated the realistic estimate quoted above by nearly 30 times, whilst the minimum is nearly 20 times less. They are quoted here solely to document the unreliability of such inappropriate methods.