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

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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. This draft Discussion Paper is the result of the Task Force's activities.

Action Requested

The Technical Group is requested to review and consider 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 meeting of April 30, 2005 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."

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Discussion Paper:
Reviewing and Identifying Standards with Regards to Storage Capacity Measurement

Developed by a Task Force under the Technical Group of the Carbon Sequestration Leadership Forum (CSLF)

To be presented to the Technical Working Group Meeting of the Carbon Sequestration Leadership Forum on 30th April 2005, Oviedo, Spain.

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Abstract

A range of estimates for geological storage capacity of CO_2 have been published 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 work is required to refine terminology and definitions. A future report (Phase 2), if agreed to, 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 country and their region. 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

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 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 to calculate the available pore volume in a rock at a certain depth, temperature and pressure, applying it to a specific 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. Some of the largest potential capacity occurs in trapping mechanisms that are not directly dependant on the total pore volume available, but instead rely upon the rate of injection and migration, and the site specific pore water and rock chemistry. 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 variance 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. The views expressed in this report still need more work to reach a consensus and thus should be regarded as preliminary results only. If the suggestions coming from this work (now described as Phase 1) are accepted, a Phase 2 version of this report would be produced that can then assist 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.

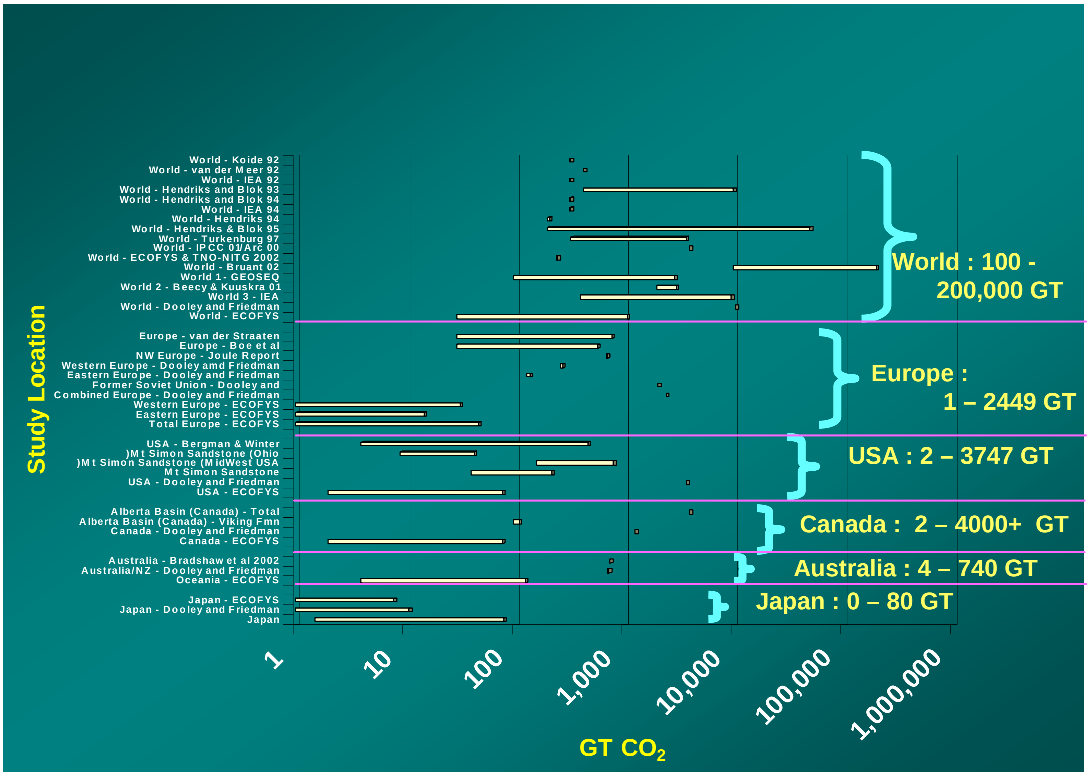


Figure 1. A listing of various estimates for CO_2 storage capacity for the world and regions of the world. Estimates are arranged by region, and ordered internally by date of completion of the estimates.

Figure 1 shows the range of many of the regional estimates for CO_2 storage capacity. 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 they contain more storage capacity than some world estimates. It is not 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. 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 discounted basins by assuming only 1% of any basin as being underlain by structural traps, or being 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 simulation or uncertainty modelling to probabilistically calculate the potential ranges in their estimates of meaningful values. Many estimates are poorly documented as to any of their detailed assumptions and methodology.

Figure 2 shows the relationship between the hydrocarbon resources that occur in major petroleum provinces of the world and the surface area of the basins. It is clear that there is no relationship between the surface area of a basin and petroleum accumulations. 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, evolutionary history and the respective timing of those factors. Many of these factors are common to 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.

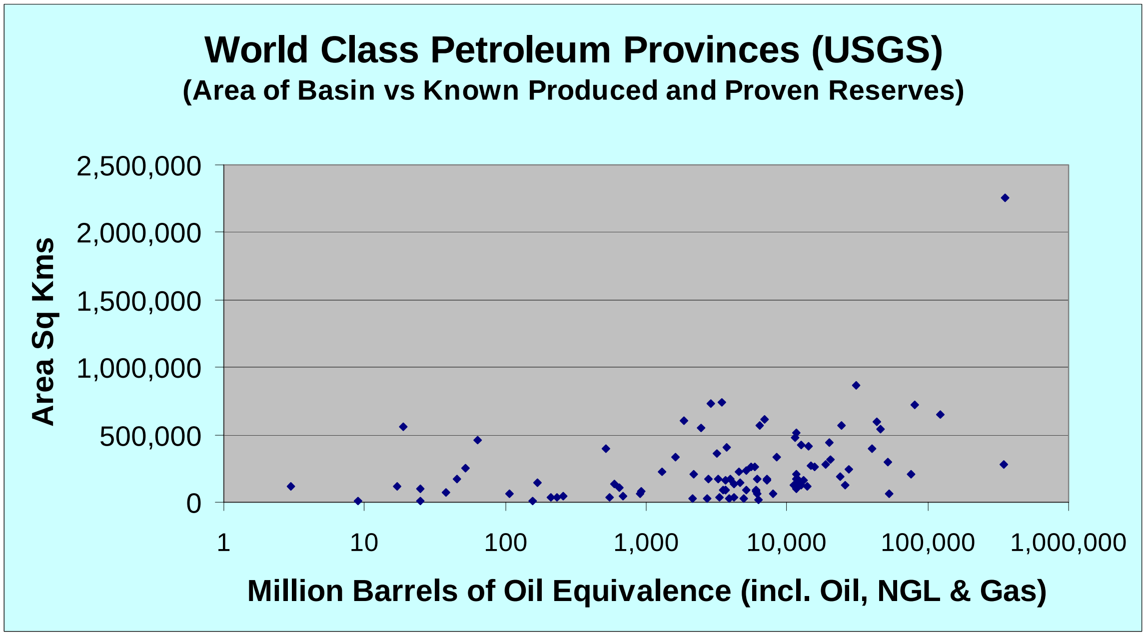


Figure 2. World class petroleum basins showing the relationship between the surface area of a sedimentary basin and the volume of hydrocarbon resources in that basin (USGS, 2000).

Given that no relationship exists between the surface area of a sedimentary basin and hydrocarbon resources, it is extremely difficult 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 the 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 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.

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 described below and in Appendix 1. In general, the surface area calculations are based solely on structural trapping methods only, ignoring or simplifying the role of dissolution, residual gas trapping and mineral trapping. 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.

Reserve vs. Resource

Part of the problem with the estimates of storage capacity relates to whether the assessments have been conducted at the reserve or resource level, and what assumptions have been 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 cuts 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 and In-Salah), many are not considered economic in the existing policy and economic environment. As a result, most potential sites around the world are not currently feasible, and thus would not classify as a reserve until the policy and economic conditions change. Figure 3 shows a resource pyramid for CO_2 storage. At the top of the pyramid are all the injection sites with good geological characteristics and which individually have large storage capacity that are located close by to sites with low costs of capture. At the base of the pyramid are the extremely difficult injection sites with problematic geological conditions with 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 that those at the top. Contradictory capacity estimate results have developed when assessments do not adequately define the boundary conditions and assumptions they have used, and so fail to describe where they are on the resource pyramid.

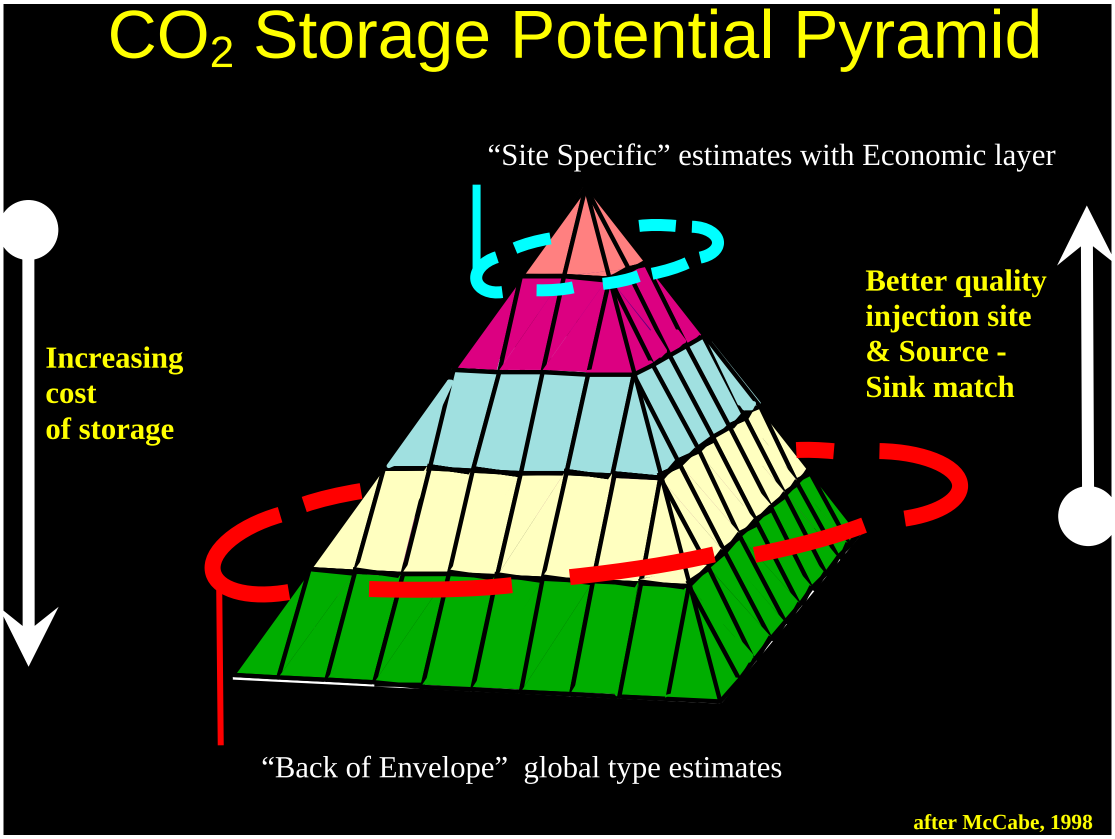


Figure 3. Resource pyramid for CO_2 storage showing source sink matches at the top with high quality injection sites located close to cheap large sources of CO_2, and low quality injection sites located long distances from expensive small sources of CO_2 at the base. Many of the global estimates are located towards the base of the pyramid, and the prospect style assessments are towards the top.

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 parts of the resource pyramid. (Note: The following nomenclature and definitions are preliminary and they will be refined during Phase 2 of the project.) They can be done to calculate:

- **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. This is an unrealistic number as in practice there always will be technical limitations across a region that prevent parts of the reservoir formation from being accessed, but it does give the maximum upper limit to a capacity estimate. This represents a physical limit of what the system can accept. It occupies the whole of the resource pyramid.

- **Realistic capacity** – applies a range of technical 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 the 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 –** assumes economic barriers to a capture and storage project by establishing the economics of sites using the technical detail available in the realistic capacity assessment. Detailed source/sink matching is done at this stage to match the best and nearest injection sites to emission sources. Cost curves may also be derived and Monte Carlo simulations calculated to help estimate the level of uncertainty and upper and lower ranges in the known and derived data versus the actual data that becomes available once a project is built and running. At this level of assessment, the capacity estimate can be quoted as a rate, not just a total volume. Because of the direct match of nearby suitable reservoirs to emissions sources has been made, 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 estimates are at the top of the resource pyramid.

In practice, all of these types of assessment have been done in the past, and examples of each exist in Figure 1. However, there is often no clear distinction at which level each assessment has been done. 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 also 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.

Storage Capacity vs. Supply Capacity

There is a need to clearly document whether storage capacity estimates are based upon source to sink matching (viable), or whether injection sites are being considered in isolation from economics and in isolation from the likely supply volume (theoretical/realistic). If the trap is not a clearly defined structural trap, and relies upon dissolution and residual trapping, then estimating the storage capacity will be highly dependant upon the supply volume coming from the source and where the injection wells are located. If it is mostly a dissolution trap, the volume and rate of dissolution relies upon the rate of supply, and whether it will match the reservoir performance for a sustainable period, or whether pressure will build up and whether the rock will become saturated with CO_2. Thus, if a reservoir is of poor quality in terms of permeability (and thus can only accept allow 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. This must limit its utility as a storage site as it will require large capital costs for many wells and compressors, and hence to quote such a site as having large storage capacity is extremely misleading.

Regional, Basin or Prospect Level Assessment

A range of methodologies exist that can be considered by countries that are embarking on assessments of their geological storage capacity. Depending at which level the assessment is 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 envisaged (discussed below and Appendix 1) as well as the outcomes that are desired from such an assessment. 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 province and could include several basins.

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 a numerical value forward of storage capacity. If a region is identified as having the correct geological characteristics, then more detailed numerical studies can commence. Simple comparisons of the regions 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 production, but which 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 assessment step because if a positive result is achieved, there will be an incentive for further detailed assessments across a 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" technical principles (surface area calculations) and derived numerical assessments without looking at the specific local or regional geology, except to say it is a sedimentary basin. 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. Such assessments might involve risk analysis of various factors to help further high-grade parts of a region 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, in order to optimise a selection process for further geotechnical 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 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.

a. For some of these (e.g. dissolution and residual gas trapping) reservoir simulations and specific source to sink matching will be required to more accurately predict capacity.
b. Given the intensive nature of such work, this style of assessment normally will only be done when sites are beginning to be chosen for storage, and not at the early conceptual stage of research in 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 Concepts

In the subsurface, CO_2 can occur in a free state as gas, or as a supercritical fluid like state. Its physical state will depend on pressure and temperature at which the CO_2 is injected, which in turn depend on depth. Supercritical CO_2 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 {capacity} than in the gaseous state). CO_2 can be trapped in the deep geological subsurface through structural (physical or buoyancy) trapping, dissolution into formation water, residual gas phase trapping, transformation into minerals, or adsorption onto coal. All of these options, except for coal adsorption, rely upon injection into porous rock.

The efficiency of trapping for many of the methods 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 and means with a variety of characteristics as described in Appendix 1. Estimates of storage capacity must take into account the diversity of trapping mechanisms that are envisaged, and the different geologic constraints on each trapping mechanism, as well as the fact that more than one method of trapping may occur at individual sites, and often with different timing rates for effective trapping. The complexity of these trapping mechanisms and the variations that occur within them individually and collectively demonstrates why simple capacity estimation methods will always be inaccurate. Furthermore, estimates of capacities 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.

Gaps Discussion

Many of the inaccurate and contradictory assessments of storage capacity are due to the desire 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, and nor should they be put in the public domain where they can be misunderstood and misused. Estimates need to clearly state the limitations that existed (data, time, knowledge) when making the assessment and suggest 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 important 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 input of that information to a reservoir simulation. Such simulation and model building are resource, time and data intensive, and often many potential storage sites lack critical data elements upon which the modelling is highly sensitive (e.g. relative permeability). Furthermore, 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 hydrology
- Establishment of methodologies and guidelines for capacity estimation
- Establishment and documentation of appropriate constraints for assessments, especially for the technical (geological) data
- Establishing reporting practices for storage capacity 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 do 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 predict storage capacity, including that many have a substantial time dependency
- Recognition of the fact that each trapping mechanism and means of geological storage requires a different methodology and data set
- Recognition that estimating CO_2 storage capacity is not just a static geometric volume calculation of available pore space, but is a dynamic system influenced by the injection rate. Thus, capacities need to be quoted as an estimate of the sustainable rate of CO_2 that is able to be injected relative to the volume of CO_2 that will be supplied from a region

- Recognition of the importance of the regional and basin assessment step to government policy setting and decision processes.

Future Directions

Many of the limitations of existing estimates of storage capacity discussed in this document 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 the recommendations of the Phase 1 report are accepted, the Phase 2 report will attempt to bring some sense and order to CO_2 storage capacity estimation. It will 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 will include regional, basin and prospect level assessments and will 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 will 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.

APPENDIX 1 - Trapping Methods

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

Structural Trapping

Structural trapping (Table A1) occurs when a gas or liquid phase is contained beneath impermeable layers (e.g. shale) where, despite the buoyancy forces driving the CO_2, it can not migrate vertically or laterally due to the impermeable layers. Structural traps include anticlines (large folds in the subsurface), fault blocks (tilted strata in the subsurface bounded by faults) and structural and stratigraphic pinch-outs (where dipping reservoir strata and/or porous strata is overlain by horizontal seal rocks). Storage in structural traps may be in traps that have previously held hydrocarbons or those that only contain non-hydrocarbon fluids (e.g. saline water). It is immediately effective as a trapping method.

Dissolution Trapping

Dissolution trapping (Table A1) occurs when the CO_2 dissolves into the formation water which it comes into contact with as it passes through the pores in the rock. CO_2 will move slowly within the formation water, and gradually dissolves into the formation water either fully or partially, depending on time and water saturation. 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 the exposure there is to “new” formation water the greater the rate of dissolution. Over time, as the CO_2 saturated water is denser than the surrounding formation water, it will migrate down, through gravity, back toward the basin centre, thus giving an effectively very large capacity compared with buoyancy trapping under a defined structural closure. The extent to which dissolution occurs will be dependent on whether highly permeable and thick reservoirs exist, and especially the presence of good vertical permeability. It occurs over a time range of 100s to 1000s of years.

Residual Gas Trapping

Residual gas trapping (Table A1) is where a proportion of the CO_2 passing through the rock is “permanently” trapped between the interstices of the pores between grains in the rock as a result of the surficial tension of the CO_2 bubbles. 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 operates over a time range of immediate to 10s to 100s of years. It will operate in conjunction with dissolution, and the CO_2 will eventually dissolve into the pore water.

Mineral Trapping

Mineral trapping (Table A1) will occur when the CO_2 reacts with the rock and formation water and precipitates “new” minerals in the rock. This is predicted to occur over 100s to 10000s of years, but is dependant on the mineralogy of the reservoir rock and the fluid types and interactions that occur. Depending on the composition of the minerals in the reservoir rock, the fraction of injected CO_2 that may be trapped as minerals may vary significantly. If limestone (carbonate) rocks are present, almost immediate chemical reactions will occur, whereas if sandstone rocks dominated by relatively stable quartz grains are present, very long time frames for reactions will exist. In some ways, this trapping 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.

Coal Adsorption

Coals are known to adsorb CO_2 more strongly than methane (which commonly occurs in coals) and to have a substantially greater capacity to store CO_2 than methane (at least twice as much). The storage capacity for coal seams can’t be calculated using pore volumes and gas compressibility as for conventional porous reservoirs, as the gas in coals is stored in the coal matrix on the surface of micropores, in a free state in the coal cleats or is dissolved in water. Calculation of CO_2 storage capacity in coals requires knowledge of the sorption isotherms and pressure, which vary for each coal type. There are concerns that storage of CO_2 in coals may not actually produce any greenhouse gas mitigation when it is associated with liberation of methane (21 times worse greenhouse gas than CO_2), as well as having limited capacity compared to injection into reservoirs that are porous 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. The trapping mechanism operates immediately.

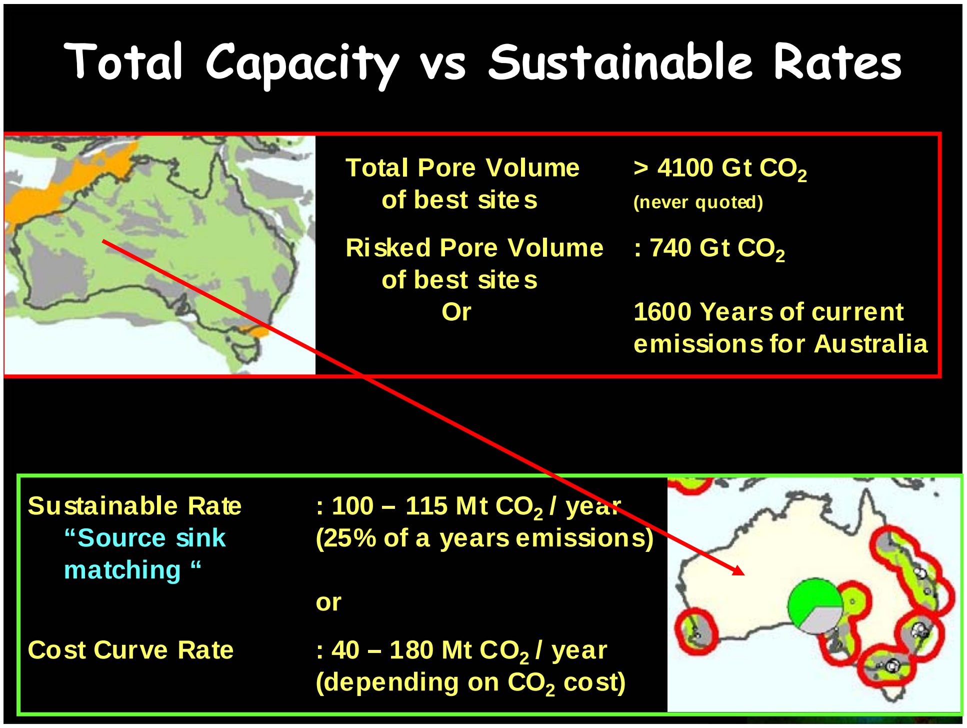
CHARACTERISTICS TRAPPING METHOD	NATURE OF TRAPPING	EFFECTIVE TIMEFRAME	AREAL SIZE	OCCURRENCE IN BASIN	ISSUES	CAPACITY LIMITATION / BENEFITS	POTENTIAL SIZE	CAPACITY ESTIMATION METHOD / REQUIREMENTS
STRUCTURAL (PHYSICAL OR BOUYANCY)	Anticline, fold, fault block, pinch-out. CO_2 remains as a fluid below 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 water (few percent) in reservoir. If open hydraulic system will have to displace formation water.	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
DISSOLUTION	CO_2 migrates through reservoir beneath seal and eventually dissolves into formation water	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 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 migrates 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
RESIDUAL	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. Depends on rock mineralogy and texture.	Can equal 15-20% of reservoir volume. Eventually dissolves into formation water.	Very large	Requires rock property data and reservoir simulation

MINERAL	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
COAL ADSORPTION	CO_2 preferentially adsorbs onto coal particles	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 Trapping Methods. Note the different time frames & range of issues. Most methods will operate alongside each other in each trap type.

APPENDIX 2 - Example of Appropriate and Inappropriate Capacity Estimation

In Australia, many of the storage capacity estimate steps described above have been produced and 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 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 that was 740 Gt CO_2 or 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: 740 Gt CO_2
Or
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 done in Australia from a theoretical capacity (in this case total pore volume) to a realistic capacity (in this case risked pore volume) to a viable capacity (in this case a sustainable rate and cost curve rate).

If instead of using a reliable and accurate methodology described above, Australia had however 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 21350 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 make them at all meaningful. Some exceed the 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.