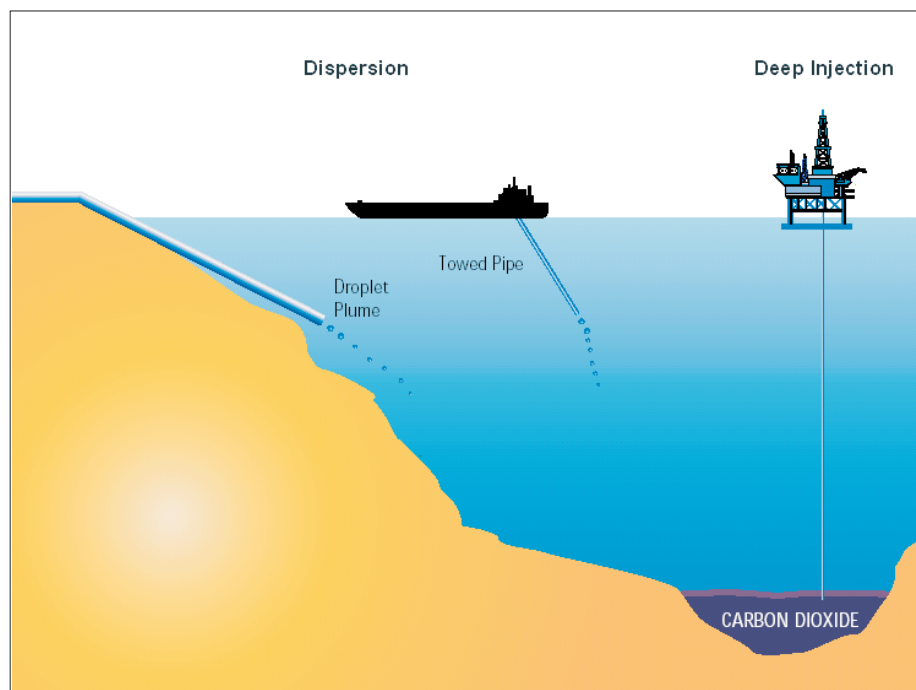


OCEAN STORAGE OF CO₂



Ocean storage concepts

This illustrates methods of dispersing CO₂ and injecting liquid at depth



This report has been produced by the IEA Greenhouse Gas R&D Programme.

Whilst every effort has been made to ensure the accuracy of information contained in this report, the conclusions reached and opinions expressed do not necessarily reflect those of the IEA Greenhouse Gas R&D Programme, its supporting organisations, its Operating Agent, or the International Energy Agency, each of which disclaims liability from the contents of this report.

This report has been compiled by W.G. Ormerod, P. Freund, and A. Smith.
Revisions made by J. Davison.

1st edition published February 1999 (ISBN 1 898373 25 6)

Cover image copyright © 1997 PhotoDisc, Inc.

© Copyright IEA Greenhouse Gas R&D Programme, 2002

2nd edition (revised) March 2002. ISBN 1 898373 30 2

INTRODUCTION

Storing carbon dioxide (CO₂) in the oceans may provide a useful means of limiting climate change caused by the burning of fossil fuels. This report explains the concept, provides a simple description of its scientific aspects and discusses the environmental implications. It also describes the further research that would be needed before this option for limiting the rise in atmospheric CO₂ concentration could be implemented.

There are several ways of utilising natural carbon reservoirs to reduce the impact of anthropogenic CO₂ emissions to the atmosphere. Of the three main reservoirs, the ocean carbon reservoir is by far the largest, being many times larger than the terrestrial reservoir, which in turn has greater capacity than the atmospheric reservoir. Currently, however, it is the atmospheric reservoir that is receiving the full brunt of fossil fuel CO₂ emissions, causing concern about climate change. Methods of enhancing the terrestrial carbon sink, for example by increased afforestation, have been developed and methods of storing CO₂ in natural (underground) reservoirs are now being proven. But methods of enhancing storage of carbon in the oceans are less obvious, as the process is more complex. Yet the potential to use the oceanic carbon reservoir to store (sequester) carbon is immense. Indeed, the ocean is the primary sink for CO₂ released to the atmosphere irrespective of whether additional interventions by man are undertaken.

There are at least two possible ways in which the ocean carbon reservoir could be used:

- 1) By capturing CO₂ from large industrial point sources and injecting it directly into the deep ocean.
- 2) By fertilising the oceans with additional nutrients to increase the draw-down of CO₂ from the atmosphere.

Although very different in concept, both these methods have the potential to significantly increase the rate of carbon storage in the ocean reservoir thereby reducing the burden placed on the atmospheric reservoir. Neither option offers a complete solution to the problem because there remains a need, if the connection between CO₂ emissions and climate change is proven, to reduce such emissions over the long term. However, these options do offer a way of buying time while emission reductions are made.

Of the two options, there exist greater uncertainties regarding the concept of ocean fertilisation. In addition, the science associated with the injection of CO₂ into the deep ocean, while still imperfect, is better understood. Consequently this report concentrates on the first of these options (for a short description of ocean fertilisation, see Appendix).

Beginning in 1995, the IEA Greenhouse Gas R&D Programme has sponsored a series of international expert workshops that have examined the state of knowledge about injection of CO₂ into deep ocean waters. A primary aim of these workshops was to determine what research needed to be done, to ensure that sufficient information was available to understand the benefits and consequences of ocean sequestration. To this end, the workshops concentrated on 4 specialist topics:

- 1) Ocean Circulation
- 2) Environmental Impact
- 3) International Links and Concerns
- 4) Practical and Experimental Approaches

Most of the information given in this report is derived from these workshops and the papers presented at them. This short summary is intended to make key information available to a wider audience, with the aim of stimulating discussion about the use of the oceans to sequester CO₂ in this way. Full reports of the workshops are available from the IEA Greenhouse Gas R&D Programme.

NATURAL CARBON STORAGE IN THE OCEANS

In pre-industrial times, before any significant release of CO₂ into the atmosphere from burning fossil fuels, the global carbon reservoirs were essentially in equilibrium. Although large carbon fluxes were exchanged between the atmosphere and the oceans and between the atmosphere and land, there were no net gains or losses from one reservoir to another. Since the industrial revolution, fossil fuels have become the major source of energy in the world and an increasing quantity of CO₂ is being discharged into the atmosphere from use of fossil fuels (currently 23 Gt CO₂/y, equivalent to 6 Gt C/y). The carbon reservoirs are now no longer in equilibrium. The concentration of CO₂ in the atmosphere has already increased from the pre-industrial concentration of 280 ppm to the present day value of 370 ppm. This disequilibrium has occurred because of the relatively slow rate of carbon assimilation by the deep ocean.

High quality measurements, used in conjunction with mathematical models, have built up a picture of the overall global carbon cycle that illustrates the difference between the present day situation and that existing before the large-scale use of fossil fuels. The two situations are illustrated in Fig. 1, which also shows the large size of the ocean carbon reservoir compared to the terrestrial and atmospheric reservoirs.

The Intergovernmental Panel on Climate Change (IPCC) has constructed scenarios that, in a business-as-usual situation, the atmospheric concentration of CO₂ will double during the next 100 years (Watson, 2001). Recoverable fossil-fuel resources are estimated to contain 4000 Gt C, compared to the quantity in the atmospheric reservoir of 750 Gt C (IPCC, 1994). There is therefore the potential to raise atmospheric CO₂ levels several fold. Increased concentrations of atmospheric CO₂, it is predicted, will have a significant effect on global climate.

The world's oceans are however working hard to alleviate this situation. The emissions of CO₂ into the atmosphere are accurately known from data on fossil fuel consumption and the increase in the concentration of CO₂ has been accurately measured at Mauna Loa, in Hawaii, and at the South Pole since 1958, and later at many other monitoring stations. These data show that the accumulation of CO₂ in the atmosphere amounts to 3.2 Gt C/y (12 Gt CO₂/y) whereas emissions from burning fossil fuels are almost double that amount. Table 1 shows that the oceans are, at the present time, successfully removing around 2 Gt C/y (6 Gt CO₂/y) from the atmosphere (although there is some uncertainty over exact amounts). Without the compensating effects of the ocean sink and the terrestrial sink, atmospheric CO₂ levels would be almost 100 ppm higher than they are today.

Table 1

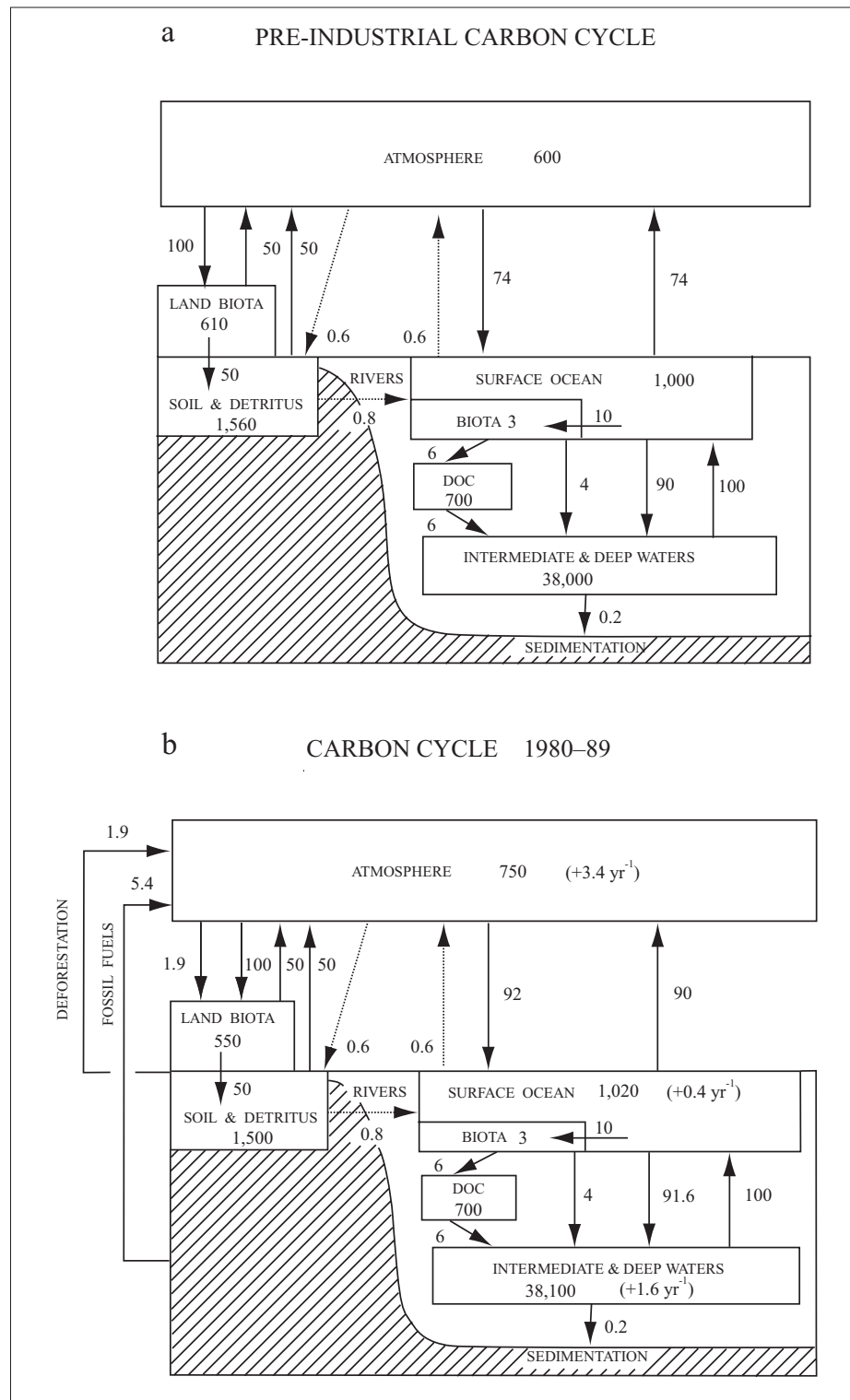
Net Annual Changes in Global Carbon Reservoirs (1990's) (Houghton et al, 2001)

	Gt C/year
Fossil fuel and cement production emissions	6.3 ± 0.4
Net terrestrial uptake	1.4 ± 0.7
Net oceanic uptake	1.7 ± 0.5
Net atmospheric storage	3.2 ± 0.1

Fig 1

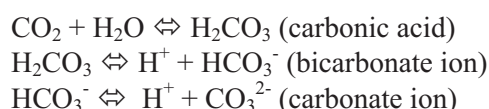
The global carbon cycle: reservoirs (GtC) and fluxes, (GtC/yr).

(Reprinted with permission from Nature, U. Siegenthaler and J.L. Sarmiento, 1993. Atmospheric carbon dioxide and the sea, Nature, 365:119. Copyright (1993) Macmillan Magazine, Limited.)



HOW DO THE OCEANS REMOVE CO₂ FROM THE ATMOSPHERE?

Transfer of CO₂ at the air-sea interface is rapid, especially when strong winds result in breaking waves and bubbles of air are entrained in the wind-mixed layer. CO₂ is much more soluble in seawater than in fresh water because the high pH of seawater (around pH~8) results in the following equilibria all being pushed to the right:



In seawater, only 1% of the CO₂ remains as molecular CO₂ and more than 90% is in the form of the bicarbonate ion. Together with the carbonic acid and the carbonate ions, these are referred collectively to as dissolved inorganic carbon (DIC).

The relatively warm surface waters of the sea are saturated with CO₂ but the colder deep waters of the world's oceans are unsaturated and have an enormous and under-utilised capacity to dissolve CO₂. For example, although the solubility of CO₂ in these deeper waters is twice the solubility in surface waters, the concentration of dissolved inorganic carbon (DIC) is only 12% higher in deep water than at the surface. This indicates substantial capacity for storing carbon in deeper water. Moreover, the high DIC content of the oceans (38 000 GtC) would be little changed even if it were to gain all the carbon in known fossil fuel reserves (4000 Gt C). This may be contrasted with the effect of introducing this amount of carbon into the atmospheric carbon reservoir (see above).

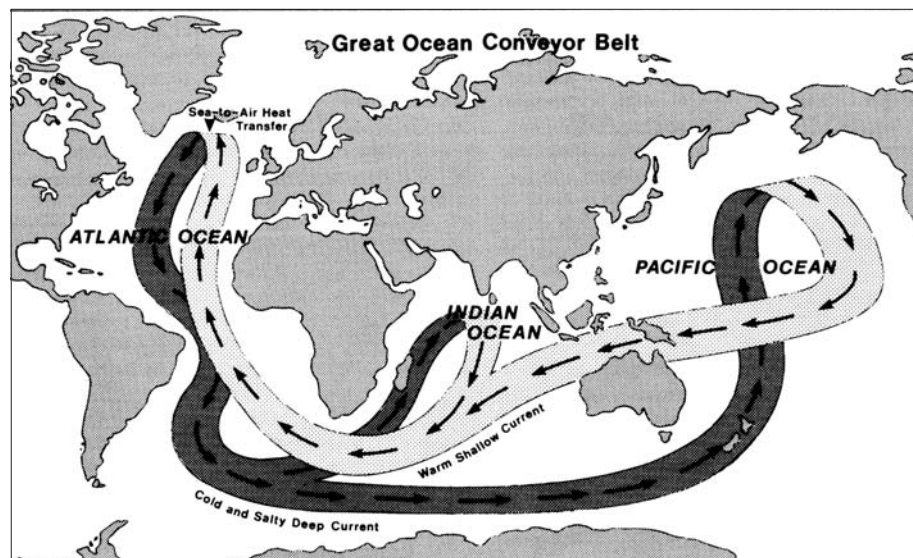
Unfortunately, from the point of view of removing CO₂ from the atmosphere, the transfer of carbon from surface water to the deep ocean is a slow process in most ocean areas. There are two mechanisms that 'pump' CO₂ from the atmosphere to deep waters:

Firstly, the 'solubility pump'.

CO₂ is highly soluble in the cold, dense water which, in high latitudes, sinks to the bottom of the ocean. This results in a 'thermohaline circulation' of seawater (fig. 2) whereby cold North Atlantic deep water (rich in CO₂) is 'conveyed' southwards nearly to Antarctica before eventually surfacing in the Indian Ocean and in the Equatorial Pacific. There, CO₂ escapes to the atmosphere again. Similarly, deep Antarctic waters circulate around Antarctica before resurfacing. The time interval, between water sinking at high latitudes and resurfacing in the tropics, is estimated to be around 1000 years.

Fig 2
The thermohaline conveyor.

(Reprinted with permission from Cambridge University Press "Climate Change 1995. Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses", 1996, pp271.)



Secondly, the 'biological pump'.

Plant life in the oceans, predominately phytoplankton, is produced by photosynthesis, utilising the CO_2 dissolved in the surface waters. The rate of phytoplankton growth and reproduction is often limited by the availability of nutrients. Phytoplankton are only 1-5mm in size and are rapidly grazed by zooplankton, which are in turn consumed by larger marine animals such as fish. Over 70% of this organic matter is recycled in surface waters but the balance is exported to the deep ocean waters, mostly by sedimentation of particulate organic matter. The biological pump therefore transfers CO_2 from the surface waters and effectively sequesters part of it in the deep ocean. Most of this organic material is remineralised by bacteria back to CO_2 , eventually returning to the surface waters (see diagram in Appendix). Again the time taken for the sequestered CO_2 to resurface from the deep ocean can be 1000 years.

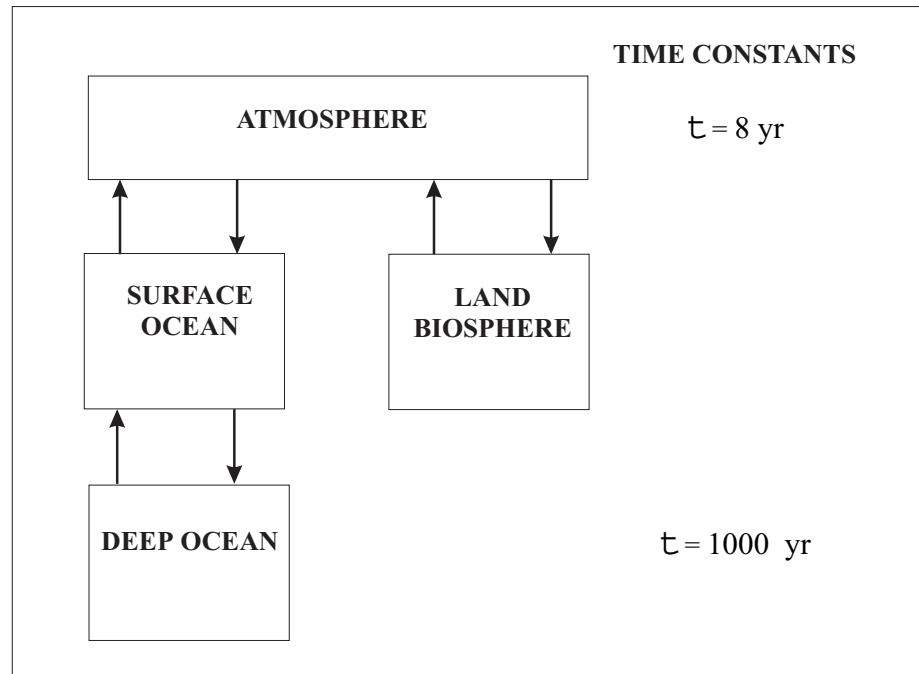
These two pumps have successfully moderated the rise in atmospheric CO_2 concentration. Mathematical models of the ocean carbon cycle indicate that, without either of these pumps operating, the atmospheric CO_2 concentration would now be twice as high as is seen today (Volk and Hoffert, 1985).

Accelerating the slow natural processes

The processes that return CO_2 from the depths of the ocean back to the surface are slow. Thus CO_2 can be retained by the ocean for periods of the order of a 1000 years. This lengthy residence time leads to the idea of a method of moderating the build-up of CO_2 in the atmosphere. Why not by-pass the slow, natural processes which transfers atmospheric CO_2 to the deep ocean, by injecting CO_2 directly into deep ocean? This idea is not new. It was first proposed by Marchetti in 1977 (Marchetti, 1977). He suggested that by injecting CO_2 into the higher density waters of the Mediterranean, as they spill through the Straits of Gibraltar, it would be transported into Atlantic deep water.

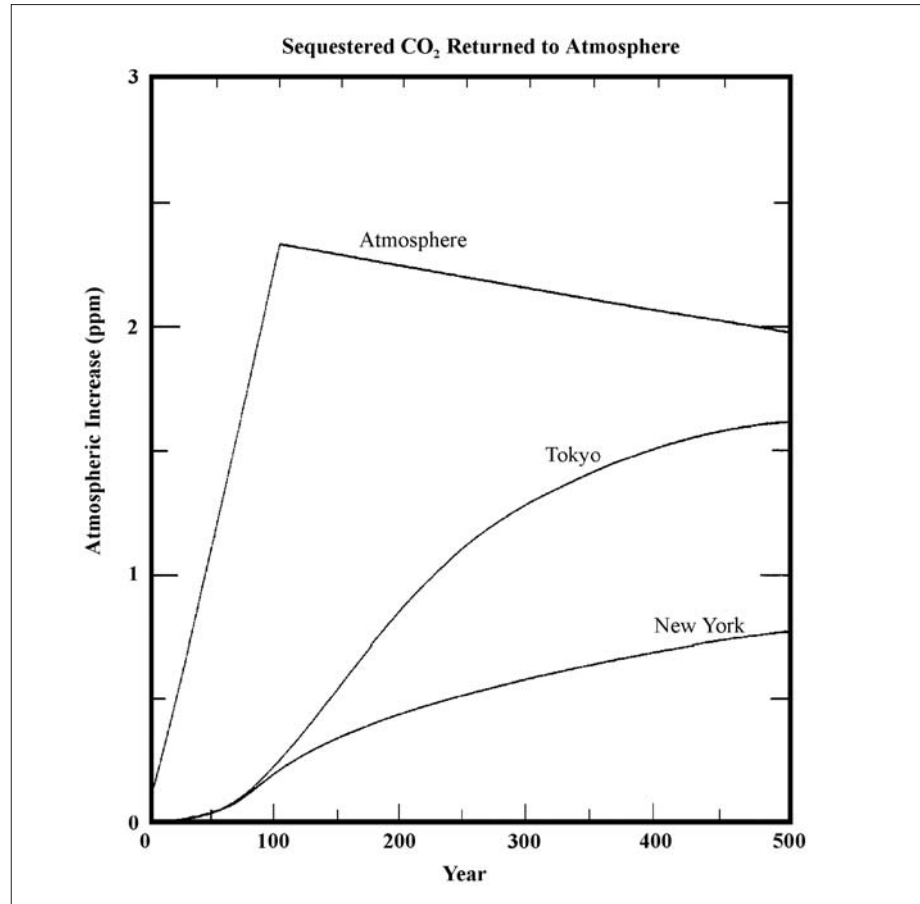
Simple ‘box’ models were initially used to demonstrate the principle of the method and these showed (fig. 3) that, although the end result will be the same in a thousand years or so, when atmospheric and ocean carbon sinks are again in equilibrium, the ocean would hold the CO₂ long enough to help reduce the rapid build-up of CO₂ in the atmosphere associated with the use of fossil fuels.

Fig 3
Box Model used to investigate ocean sequestration. This has 2 distinct boxes to represent different parts of the ocean. (Bacastow et al 1997)



The cycling of carbon within the ocean is a complex process. Although in the last 10 years a programme of oceanic measurements has been undertaken, under the auspices of the World Ocean Circulation Experiment (WOCE), much of our understanding of the natural oceanic carbon cycle is provided by mathematical models of the physical, chemical and biological processes taking place in the global ocean. One such global model, developed at the Max-Planck Institute in Hamburg, was reconfigured to track, over a 1000 year period, the fate of hypothetical deep water point sources of CO₂ sited at various locations (Bacastow and Dewey, 1996). The model is 3-dimensional and showed that the time taken for the CO₂ to return to the surface is quite sensitive to location; in certain locations some of the CO₂ will begin to surface within 100 years, whilst in others CO₂ will be isolated from the atmosphere for several hundred years (fig. 4).

Fig 4
Predicted return of sequestered CO₂ to atmosphere for 100 years of sequestration at depth between 900m and 1500m, at two locations (Bacastow and Dewey, 1996)



IS DIRECT INJECTION OF CO₂ A PRACTICABLE PROPOSITION?

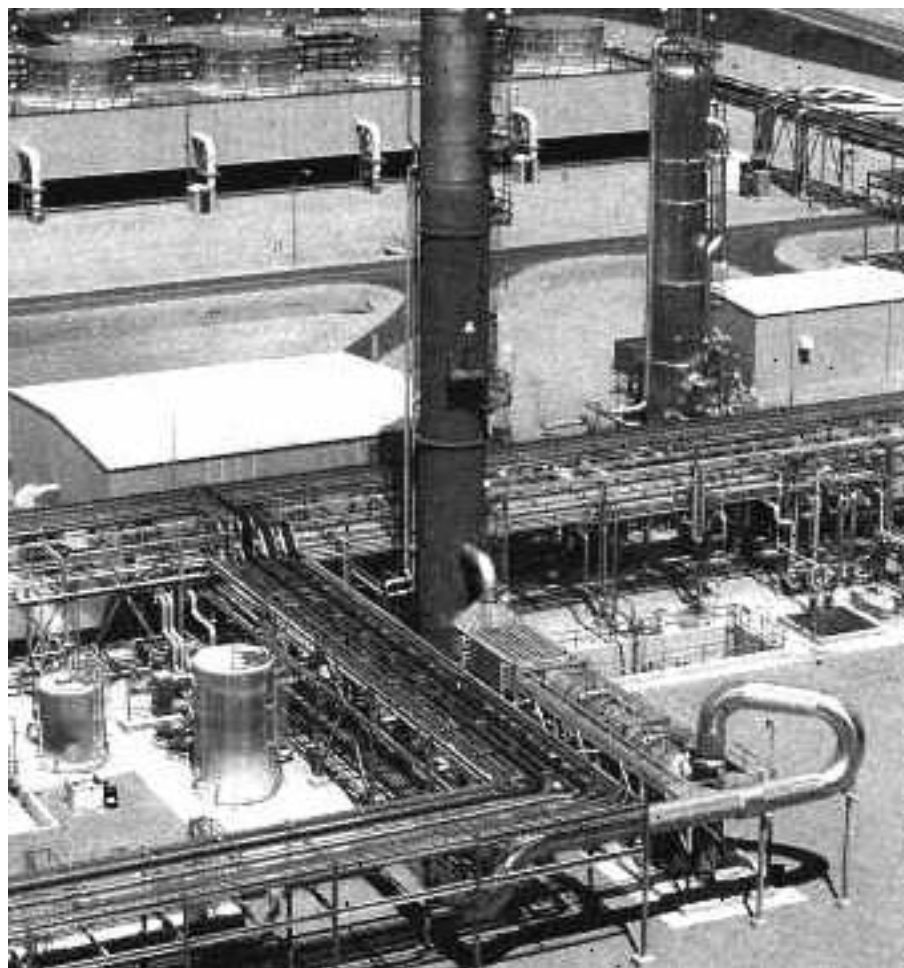
Direct injection of CO₂ into the deep ocean could be accomplished using proven technology, although it has never been attempted in practice. The method would be applied to large single sources of CO₂, such as a coal-fired power station, typically producing up to about 15Mt CO₂ per year (2GW_e).

Removal of CO₂

Technology for removing CO₂ from the exhaust gases of a power station is proven - it uses amine solvent 'scrubbing'. Such CO₂ separation plants have been demonstrated to achieve 98% removal of CO₂ (IEA GHG, 2001). As a result, a high pressure stream of concentrated CO₂ would be available for transportation to the sequestration site.

CO₂ capture plant

*(Courtesy of ABB
Lummus Crest)*



Transportation of CO₂ to injection site

The most suitable form in which to transport CO₂ to an injection site would be as a liquid or dense phase gas (this would be achieved by compression to above its critical point, 72.8 bar and 31°C). Transportation would not present any new design problems, according to petroleum engineers and naval architects speaking at one of the IEA Greenhouse Gas R&D Programme ocean storage workshops. It could be done either by undersea pipeline or by tanker.

Pipeline technology is sufficiently advanced that the oil and gas industry already constructs vertical risers in deep water and places seabed pipelines in depths down to 1600 m to transport oil and gas. Furthermore, a design study carried out on a proposed Oman to India pipeline, reaching depths of 3000 m, showed the project to be technically feasible. Overland pipelines for CO₂ have been operating in the USA for many years, over distances of up to 800 km; this is natural CO₂ which is used for enhanced oil recovery schemes but very similar principles would apply to captured CO₂. A 1m diameter pipeline would have the capability of transporting 70 000t CO₂/day, enough for 3GW_e of coal-fired power plant operating at full output.

Laying an oil pipeline

(© Copyright Statoil)



Alternatively the CO₂ could be transported by tanker to an injection platform. The design of a CO₂ tanker would be almost identical to those currently used to transport liquid petroleum gas (LPG). Refrigeration would be used to reduce the pressure requirement, with design conditions around -55 °C and 6 bar pressure.

A modern LPG carrier; CO₂ could be carried in a similar way

(Courtesy of Mitsubishi Heavy Industries Ltd.)



Dispersion of CO₂ at intermediate depths

To minimise the environmental impact in the productive surface waters of the ocean, CO₂ would have to be injected at depths of at least 1500m. Model studies suggest that, with careful site selection, retention times of several hundred years would be achieved by injection at 1500m. Such a depth is well within the capability of present day subsea pipeline technology. Several studies have modelled the dissolution of an ascending plume of liquid CO₂ droplets emerging from a diffuser (Liro *et al.*, 1992, Drange and Haugan 1992). These models predict that, with a suitably designed diffuser, all the CO₂ would be dissolved in the surrounding seawater within a height of 100 m above the injector. Thereafter the CO₂-rich seawater would be diluted as it disperses horizontally, aided by currents.

A method of achieving a more rapid dispersion of the CO₂-rich water involves injecting the CO₂ through a pipe hung vertically from a moving ship (Ozaki, 1997). Similar retention times would be achieved as with a fixed diffuser but with the advantage of minimising the impact on marine life.

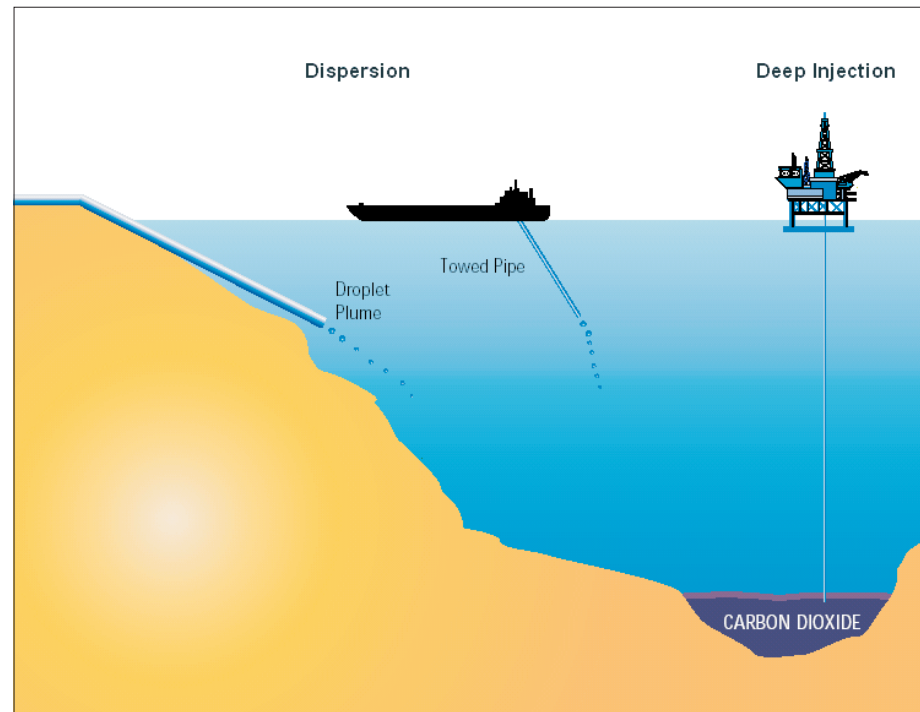
Injection of CO₂ at depths >3000 m

The density of liquid CO₂ exceeds that of water at depths greater than 3000m. This allows an alternative approach to dispersion of injected CO₂, whereby a submarine pool of liquid CO₂ could be formed in a hollow or trench on the seabed, thereby confining the impact to a small area of the seabed (Ohsumi, 1993). Dissolution of CO₂ into the overlying seawater would be reduced significantly by CO₂-hydrates, forming an ice-like combination of CO₂ and water. As a result, and because of the great depth, the retention time of CO₂ in the ocean would be even greater than in the previous examples.

A vertical pipe, attached to a platform, would be required to reach this depth. With only the top of the pipe supported, the axial strength of the pipe would have to withstand its full weight and the vertical motion of the platform. Design calculations indicate that, for pipe diameters of up to 1m, a pipe length of up to 5000m would be possible (Ozaki, 1995).

Ocean storage concepts

This illustrates methods of dispersing CO₂ and injecting liquid at depth



Use of solid CO₂

A simpler method, but logistically more difficult and more expensive, is to produce solid CO₂ blocks (Murray *et al*, 1996). Having a density of 1.5 t/m³, these would sink rapidly to the sea bed and, if shaped as a projectile, should penetrate into the sediment layer. Heat transfer calculations, supported by practical tests in Japan, have shown that, in free fall, 50% of a 4m cube of CO₂ would remain intact at 3000m depth.

IS OCEAN STORAGE AN EXPENSIVE OPTION?

Cost of capturing CO₂

Studies on the cost of CO₂ capture from power station flue gases (IEA GHG, 2001) suggest that application of current capture technology would increase electricity generation costs by about 50%. This is largely because capture of CO₂ with chemical solvents (and their subsequent regeneration) uses significant amounts of energy. Expressed in terms of avoided emissions of carbon dioxide, i.e. prevented from entering the atmosphere, capture costs are estimated to be about \$30-50/tCO₂ (\$110-180/tC) depending on the fuel and the type of plant. More advanced generation and capture technologies should, however, bring down the cost of CO₂ capture.

Transportation costs

The cost of transporting liquid CO₂ to a deep water site, either by pipeline or by tanker, can be estimated in broad terms. Comparable 0.5m diameter pipelines, recently installed in the North Sea and the Mediterranean, cost about \$1.6 million/km. Such pipelines would have capacity for 18 000 t/day, if carrying CO₂. The cost of transporting CO₂ for 500 km, by such a pipeline, would be around \$12/tCO₂ (\$45/t C), at 10% cost of capital. There would be a significant advantage in increasing the diameter of the pipeline. A 1.0m diameter pipe would be able to carry 4 times as much CO₂ but would be less than 4 times as expensive.

The costs associated with using a tanker to transport the CO₂ to a platform, from which it could be released through a vertical pipe into deep water, have also been quantified. Table 2 provides an example. The largest LPG tanker built to date has a capacity of 22 000 m³, costing \$50 million. Two such vessels would be required to handle the CO₂ produced by a 650 MW_e coal-fired power station. The logistics of such an operation are shown in Table 2.

Table 2

*Features of a tanker
for transporting liquid
CO₂*

Capacity of tanker	22,000	m ³
Design temperature	-55	°C
Design pressure	6	bar
Distance to discharge terminal	500	km
Speed of tanker	25	km/hr
Loading time	10	hrs
Discharge time	10	hrs
Round trip for tanker	3	days
Mean CO ₂ sequestration rate	7300	t/d

The transportation cost would therefore be around \$2/tCO₂ (\$7/tC), which is lower than for a pipeline, but there would be, in addition, expenditure on a CO₂ holding tank at the port, the platform, and the vertical pipe, as well as operating expenses. Even so, overall costs may be similar to those of the more conventional seabed pipeline.

The cost of dispersion through a vertical pipe from a moving ship should be broadly similar to using a static vertical pipe but the costs of generating solid CO₂ blocks or projectiles is likely to be prohibitive. Little information is available at present on the costs of these options.

Another method of carrying liquefied gases - an LNG carrier

(Courtesy of Mitsubishi Heavy Industries Ltd.)



IMPACT ON THE MARINE ENVIRONMENT

There is always concern at the prospect of using the oceans to store waste materials. Dumping hazardous substances in the ocean, such as nuclear waste, has been banned. But using the oceans to sequester more CO₂ would be different as the oceans already hold vast quantities of CO₂. In fact, what is being proposed with ocean sequestration of CO₂, is merely an acceleration of an existing natural process. This acceleration may assist in protecting the atmosphere and the terrestrial environment in which we live. Nevertheless, it is important to understand the effect that sequestration of CO₂ would have on the oceans.

Seawater pH changes

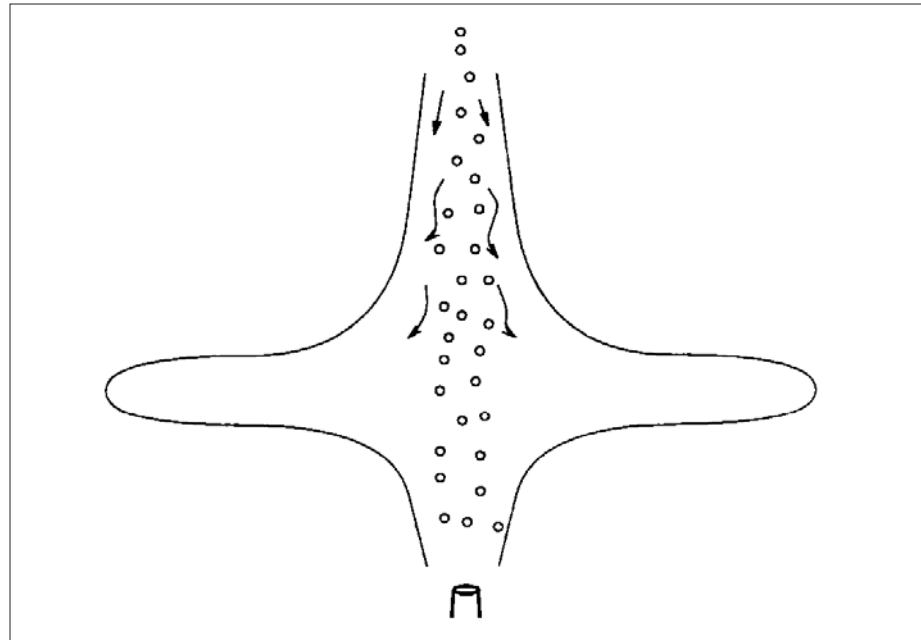
It is well known that dissolving CO₂ in sea water will decrease the pH of the water, due to the formation of bicarbonate and carbonate ions. It is also known that marine animals are, in general, intolerant to changes in the pH of the water in which they live (Knutzen, 1981). But how severe would the pH changes be from CO₂ sequestration, and what would be the impact on marine ecology?

The DIC concentration in surface ocean waters is already higher than in pre-industrial times as a result of the elevated CO₂ concentration in the atmosphere. Calculations show (Haugan and Drange, 1996) that there has been a decrease in pH of the ocean surface water of almost 0.1 pH-units due to the increase of atmospheric CO₂ from pre-industrial times. The 'spring bloom' in the North Atlantic and winter upwelling of deep (CO₂-rich) water in the North Pacific can cause changes in surface water pH of this magnitude, but other ocean areas see much lower seasonal variations. Indeed, below the euphotic zone (the top 100-200m, where there is enough light to support photosynthesis) the seasonal variation in pH is universally very small. The same calculations show that the current rate of increase in atmospheric CO₂ concentration (15ppm/decade) will cause a decrease in pH of 0.015 units/decade. This, by itself, could have a significant impact on the ecology of the productive surface waters of the oceans in the foreseeable future.

pH changes around a CO₂ injection site

A recent near-field modelling study (Adams *et al.*, 1997) has quantified the pH changes that would occur in the vicinity of a release of liquid CO₂ into seawater. The study predicted the steady state changes in pH from continuous injection of CO₂ at a rate equivalent to that produced by a 500MW_e coal fired power plant (130 kg/s CO₂). The simplest case considered was that of injecting all the liquid CO₂ through a single diffuser to form a droplet plume. The plume (fig. 5) rises as it dissolves and the saturated CO₂ solution spreads laterally into the (stratified) surrounding seawater. The results are illustrated in fig. 6.

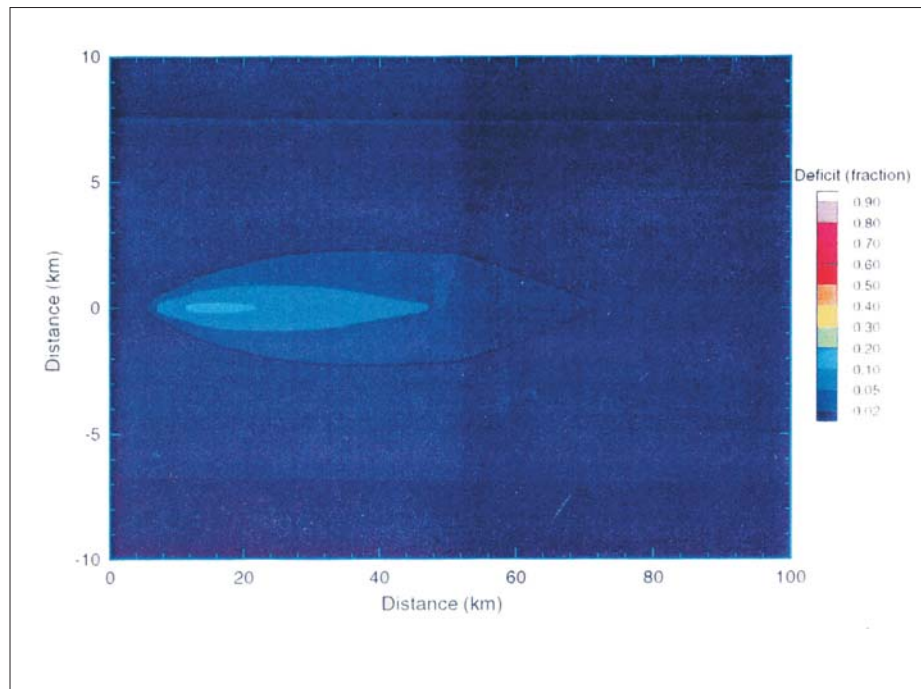
Fig 5
A droplet plume



This study predicts a reduction in pH of about one unit, from an ambient level of pH ~7.8, extending for several kilometres from the point of injection; this would have an impact on marine life. However, the study also showed a way in which the near-field environmental impact could be substantially reduced. This would be achieved by dispersing the CO₂ over large volumes of seawater so as to reduce the loading of CO₂ at any point in the ocean. A suitable engineering design could involve, for example, increasing the number of independent discharge points at which CO₂ is injected into the ocean. Other techniques have been examined which involve injecting liquid CO₂ through a vertical pipe housed on a moving ship. Both this technique and the dropping of solid blocks of CO₂ through the water column are efficient methods of dispersing the CO₂ and minimising pH changes; both procedures should, therefore, have minimum impact on the marine environment.

Fig 6
Reduction in pH
resulting from a
plume

(Calculation for a
single power plant.
Reprinted with
permission from
Adams and Herzog,
in "Environmental
Impacts of Ocean
Disposal of CO₂,
1996)



The greatest density of pelagic (i.e. swimming and floating) biomass occurs at depths between 500-1000m. Below that level, the amount of pelagic life decreases exponentially with depth although there is also a significant population of organisms living on/near the ocean floor (benthic organisms). By forming a pool of liquid CO₂/hydrate on the seabed at great depth, its impact would be localised to benthic organisms in a small area of the seabed. The impact in this small area would, however, be severe.

Effects distant from a CO₂ injection site

Although we can be confident that impacts can be reduced to very low levels, small changes in pH could have sub-lethal effects on marine animals and, over a period of time, affect the marine ecology. For example, reproduction and growth rates might be reduced. An important concern would be for those pelagic species that migrate vertically, either daily or seasonally, as a layer of low pH water could present a physiological barrier to such processes. It has also been established (Poertner, 1996) that pelagic species with high metabolic rates, such as squid, are much less tolerant to changes in pH than less active species, such as worms living in marine sediments.

Need for more information

More fundamental and observational data is required to understand all the possible effects of changes in seawater pH. A precautionary approach, minimising the impact on pelagic species, would be to confine CO₂ releases to depths greater than 1500 m.

WILL STORAGE OF CO₂ IN THE OCEAN BE PERMITTED?

There are legal and political obstacles to sequestration of CO₂ in the oceans. Many countries subscribe to the London Convention, 1972, that bans the dumping at sea of industrial waste and whose 1996 protocol prohibits dumping of all but 'approved' substances from ships or platforms. The UN Convention on the Law of the Sea puts an obligation on coastal states to control and regulate discharges from pipelines within their Economic Exclusion Zone. Moreover, a strict application of the 'precautionary principle', prevents an environmental option having potential hazards being put into operation until its impact is fully quantified. This will be a significant constraint on CO₂ sequestration in the ocean, not least because of the complexity of ocean ecology, especially aspects such as biodiversity, and the daily and seasonal migration patterns. Nevertheless, 'precaution' is similarly applicable in relation to the predicted adverse effects of rising levels of CO₂ in the atmosphere. Understanding the relative impacts in different sectors of the environment, in order to find the best mitigation options, requires good quality information about the different options and their implications.

CO₂ is a naturally occurring product and its overall impact on the ocean environment should be very small, because of the large size of the ocean carbon reservoir. Moreover, it is important to recognise that the CO₂ currently being emitted to the atmosphere is already being introduced into oceanic surface waters, indirectly, via the air-sea exchange. This gradual process of equilibrium poses its own risks; these waters support much more marine life than there is in the deep ocean; for this and other reasons, the human race is highly dependent on a well functioning marine ecosystem. In addition, direct injection of CO₂ into the deep ocean is not creating a new process; it is only accelerating a slow existing process and thereby mitigating some of the risks associated with climate change.

The arguments for sequestering additional CO₂ in the deep ocean are therefore strong, but further information is required to win acceptance of the concept as a valid method of controlling the rise in atmospheric CO₂ concentration. In particular, there would have to be convincing arguments made about the merits of ocean sequestration. This would require investment in research in order to obtain the necessary information and, eventually, a practical demonstration of the safety and feasibility of the method. It will be important to involve a wide range of interested parties in the formulation and review of such research programmes, and to discuss the results of this work openly.

PRIORITIES FOR FURTHER RESEARCH

The oceans have a controlling influence on world climate, so a good understanding is needed of the way they work. Most ocean waters are international and, because of the high cost of oceanographic research, there has been a history of international co-operation in marine research. In considering research needs associated with the concept of ocean sequestration of CO₂, it is important to make full use of existing research programmes and to try to integrate any new research into this international framework. Both the International Geosphere-Biosphere Programme (IGBP) and the World Climate Research Programme (WCRP) contain specific projects and tasks to elucidate the role that oceans play in regulating atmospheric CO₂ levels. These would be very relevant to understanding the concept of sequestering additional CO₂ in the oceans. In addition, links must be established with research on understanding the impact of CO₂ on marine ecology. Such links are relatively tenuous at present and new initiatives are required in this area.

It is clear from this report that there are many questions that have to be answered before any scheme to increase CO₂ sequestration in the oceans could be implemented. One of the primary aims of the expert workshops organised, by the IEA Greenhouse Gas R&D Programme, was to identify those research areas that should receive priority. A full description of these research needs can be found in the reports of those workshops but essentially three broad research areas were identified as meriting priority:

- 1) Development and comparison of global and regional ocean models :
 - to quantify the effectiveness and benefits of ocean sequestration;
 - to identify favourable sites; and
 - to determine the storage capacity.
- 2) Design and appraisal of engineering solutions that minimise environmental impact and are cost competitive with other CO₂ storage options.
- 3) Understanding the biological consequences of enhanced ocean sequestration of CO₂.

Progress is being made in all of these areas.

Ocean Models

Ocean modelling represents the only tool available to assess the effectiveness of enhanced sequestration of CO₂ in the oceans over the appropriate time-scale (i.e. centuries). Whilst there already exists a significant programme concerned with the development and validation of global ocean circulation models, there is a need to persuade the ocean modelling community of the need to specifically examine the concept of enhanced sequestration.

To this end, the IEA Greenhouse Gas R&D Programme is contributing additional funding to a European Union research programme (GOSAC)¹ to enable examination of the dispersion of CO₂ from point sources in the deep ocean. GOSAC is a model inter-comparison exercise, involving several 3-D global ocean models, and this additional work will increase our confidence in model predictions of the effectiveness of sequestering CO₂ in the deep ocean, and provide results for a variety of locations. Regional and basin scale modelling programmes will eventually be required and ocean measurement programmes that provide validation data for the models also deserve continued support.

Practical experiments

The chemical changes in sea water that would occur as a plume of CO₂-enriched water disperses, have been estimated by modelling. These ‘near-field’ models must be validated if environmental impacts are to be accurately predicted and the relative merits of the different methods assessed. This will require a significant programme of experimental work, both in the laboratory and in the ocean.

Plans are now being formulated for an internationally-supported experiment that will provide near field measurements of a range of physical parameters associated with a small scale release of CO₂ in the deep ocean.

Small scale releases of CO₂ in the deep ocean have been carried out, as shown in the image on the inside back cover

Biological data

Understanding the impact of enhanced ocean sequestration of CO₂ on the marine ecology represents perhaps the greatest challenge. Before any ocean sequestration scheme could be implemented, an environmental impact assessment would be required. This will necessitate research work at all levels to improve the knowledge base. The research work required ranges from fundamental laboratory work on the physiological responses of marine animals to elevated CO₂ levels in seawater, to field experiments concerned with the impact on community structure. Both pelagic and benthic species would have to be considered. Some work in this area is already being carried out but there is a need for a rational and coherent programme. Eventually this might require a significant field experiment, possibly in a contained environment such as a fjord.

Value of research

The expert workshops identified shortages of basic information in a number of key areas. Research such as that described above will help to remedy this. With data from this research, it should be possible to evaluate objectively the feasibility, benefits and risks of ocean sequestration, in order to compare it with the other options for preventing the build-up of CO₂ in the atmosphere.

1 GOSAC stands for Global Ocean Storage of Anthropogenic Carbon

CONCLUSIONS

Compared to the carbon reservoirs on land and in the atmosphere, the oceans have an enormous and under-utilised potential to sequester anthropogenic CO₂. The oceans are already naturally sequestering CO₂ from the atmosphere at a rate of about 2 GtC/y. The burning of all known reserves of fossil fuel carbon would only raise the dissolved inorganic carbon content of the oceans by 10%.

Global ocean modelling studies have predicted that CO₂, injected into the ocean at selected locations and at depths >1000m, will be isolated from the atmosphere for up to 1000 years. This would contribute to the alleviation of the expected peak in atmospheric CO₂ concentrations resulting from the continuing use of fossil fuels.

Capture of CO₂ from point sources, such as the exhaust gases of fossil-fuel power plants, has been commercially demonstrated. Dense phase transportation of CO₂ by pipeline is already in use on land. Seabed pipelines, 0.5m in diameter, have been constructed to handle gases and liquids at depths of 1600m; design studies have been undertaken for depths of 3000m; pipelines for CO₂ could be constructed in a similar way. Tankers could be designed and built to transport liquid CO₂ in the same way as LPG; these would transport CO₂ to an off-shore injection platform.

In the near to medium-term, dissolution and dispersion of CO₂ at intermediate depths (1500m) is the method most likely to be used to sequester CO₂ in the oceans, as it is readily achievable with present-day technology. However, vertical pipes, suspended from a platform, have the potential to reach depths greater than 3000 m, where liquid CO₂ would form a pool on the seabed, thereby prolonging oceanic retention times.

The total cost of the capture and transportation of CO₂ to a deep ocean site 500 km from shore, is estimated to be around \$40-60/tCO₂ (\$150-220/tC). Improvements in capture technology and the increased scale of operation should reduce these costs significantly.

Injecting liquid CO₂ into seawater causes a reduction in pH that could be harmful to marine life. However, near-field modelling studies predict that the impact could be reduced to a very low level by techniques that disperse the CO₂ and thus minimise transient increases in CO₂ concentrations. More fundamental and observational data are required to understand the possible sub-lethal impacts that could occur over longer periods of time.

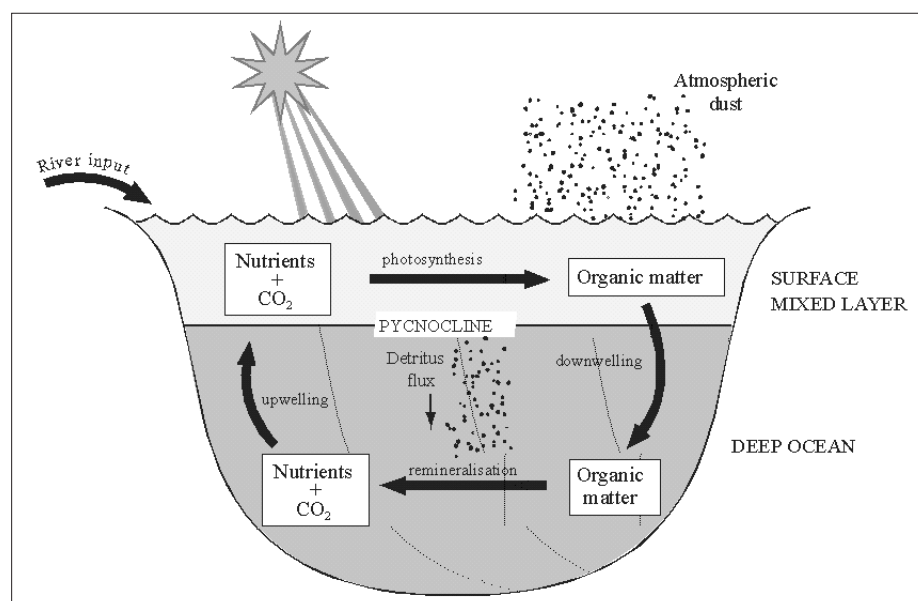
To remove any legal obstacles and ensure that sequestering additional CO₂ in the oceans is permitted, the benefits and possible impacts of the sequestering process must be openly debated. A comprehensive international research programme is required to provide information to support this debate.

APPENDIX - OCEAN FERTILISATION

An Alternative Sequestration Strategy

Ocean fertilisation would aim to increase production of biological material in the oceans, drawing-down additional CO₂ from the atmosphere. In considering this concept as a potential sequestration option, it is recognised that the 'biological pump' would transfer more carbon from the surface layers to deep water. Most of this organic carbon would be re-mineralised to inorganic carbon; much of the nutrients should also be recycled, and so be available for further biological production. Furthermore, it is argued that increasing biological productivity should also result in an increase in fish population, offering the prospect of increased fish catches and providing a route to offsetting some of the cost of carbon sequestration.

The biological pump



Three ocean fertilisation strategies have been proposed:

- 1) The general addition of macro-nutrients, such as nitrates and phosphates; this should be independent of the area of ocean selected.
- 2) The addition of iron, an essential micro-nutrient, to unproductive regions of the ocean where natural macro-nutrients are currently under-utilised (the so-called HNLC² areas).

Recent in-situ experiments in the equatorial Pacific Ocean (Martin *et al.*, 1994; Coale *et al.*, 1996) have indeed proved that addition of iron to an HNLC ocean area results in immediate use of the available macro-nutrients, with a corresponding reduction in the partial pressure of CO₂ in the surface water.

2 HNLC refers to high nitrogen low chlorophyll areas.

- 3) A third possible strategy is suggested by recent reports (Falkowski, 1997) that the absence of iron, and possibly other micro-nutrients, could also be restricting nitrogen fixation and therefore the supply of nitrates in the so-called LNLC³ ocean regions.

There are two major concerns about the implementation of such strategies. Firstly, there is the impact that such fertilisation could have on the marine community structure and the marine ecological balance. Secondly, modelling work (Orr, 1992) has indicated that, if applied on a very large scale, the amount of atmospheric-CO₂ sequestered could be significantly lower than might be expected from the increase in biological production.

A lack of information to answer these questions makes it unlikely that any large scale ocean fertilisation schemes will be implemented at present, but small pilot schemes are planned, primarily to investigate the potential for increasing fish catches. Increased levels of marine research are needed to clarify the understanding of the oceans and confirm the merits and net benefits offered by these proposed strategies.

3 LNLC refers to low nitrogen low chlorophyll areas.

REFERENCES

- Adams E.E., Caulfield A.J., Herzog H.J. and Auerbach D.I., 'Impacts of reduced pH from ocean CO₂ disposal: sensitivity of zooplankton mortality to model parameters' *Waste Management* **17**: 375-380, 1997
- Bacastow R.B. and Dewey R.K., 'Effectiveness of CO₂ sequestration in the post-industrial ocean' *Energy Convers. Mgmt.* **37**: 1079-1086, 1996
- Brewer P.G., Friederich G.E., Peltzer E.T., and Orr F.M., 'Direct experiments on the ocean disposal of fossil fuel CO₂'. *Science*, **284**: 943-945, 1999
- Bacastow R.B., Dewey R.K. and Stegen G.R., 'Effectiveness of CO₂ sequestration in the pre- and post-industrial oceans' *Waste Management* **17**, 5/6: 315-322, 1997
- Coale K.H., Johnson K.S., Fitzwater S.E., Gordon R.M., Tanner S., Chavez F.P., Ferioli L., Sakamoto C., Rogers P., Millero F., Steinberg P., Nightingale P., Cooper D., Cochlan W.P., Landry M.R., Constantinou J., Rollwagen G., Trasvina A. and Kudela R., 'A massive phytoplankton bloom induced by an ecosystem scale iron fertilisation experiment in the equatorial Pacific Ocean' *Nature* **383**: 495-501, 1996
- Drange H. and Haugan P.M., 'Carbon dioxide sequestration in the deep ocean: the possibility of injection in shallow water' *Energy Convers. Mgmt.* **33**: 697-704, 1992
- Falkowski D.G. 'Evolution of the nitrogen cycle and its influence on the biological sequestration of CO₂ in the ocean'. *Nature* **387**: 272-274, 1997.
- Haugan P.M. and Drange H., 'Effects of CO₂ on the ocean environment' *Energy Convers. Mgmt.* **37**, 1019-1022, 1996
- Houghton J. T., Ding Y., Griggs D.J., Noguer M., van der Linden P.J., Dai X., Maskell K., Johnson C.A. (Eds), 'Climate Change 2001: The Scientific Basis' Cambridge University Press 2001
- IEA GHG 'Putting carbon dioxide back in the ground' IEA Greenhouse Gas R&D Programme, 2001, ISBN 1 898373 28 0
- Knutzen J. 'Effects of decreased pH on marine organisms' *Marine Pollution Bulletin*, **12**: 25-29, 1981
- Liro C. R., Adams E.E. and Herzog H.J., 'Modelling the release of CO₂ in the deep ocean' *Energy Convers. Mgmt.* **33**: 667-674, 1992
- Marchetti C., 'On geoengineering and the CO₂ problem' *Climate Change* **1**: 59-68, 1977

Martin J.H., Coale K.H., Johnson K.S., Fitzwater S.E., Gordon R.M., Tanner S., Hunter C. N., Elrod V.A., Nowicki J.L., Coley T.L., Barber R.T., Lindley S., Watson A.J., Van Scoy K., Law C.S., Liddicoat M.I., Ling R., Stanton T., Stockel J., Collins C., Anderson A., Bidigare R., Ondrusek M., Latasa M., Millero F.J., Lee K., Yao W., Zhang J.Z., Friederich G., Sakamoto C., Chavez F., Buck K., Kolber Z., Greene R., Falkowski P., Chisholm S.W., Hoge F., Swift R., Yungel J., Turner S., Nightingale P., Hatton A., Liss P. and Tindale N.W., 'Testing the iron hypothesis in ecosystems in the equatorial Pacific Ocean', *Nature* **371**: 123-129, 1994.

Murray C.N., Visintini L., Bidoglio G., Henry B., 'Permanent Storage of Carbon Dioxide in the marine environment: the solid CO₂ penetrator' *Energy Convers. Mgmt.* **37**: 1067-1072, 1996

Ohsumi T., 'Prediction of solute carbon dioxide behaviour around a liquid carbon dioxide pool on deep ocean basins' *Energy Convers. Mgmt.* **34**: 1059-1064, 1993

Orr J.C. and Sarmiento J.L., 'Potential of marine macroalgae as a sink for CO₂: constraints from a 3-D general circulation model of the global ocean', *Water, Air and Soil Pollution*, **64**: 405-421, 1992.

Ozaki M., Sonada K., Fujioka Y., Tsukamoto O. and Komatsu M., 'Sending CO₂ into deep ocean with a hanging pipe from a floating platform' *Energy Convers. Mgmt.* **36**: 475-478, 1995

Ozaki M., 'CO₂ injection and dispersion in mid-ocean by moving ship' *Waste Management* **17**: 369-373, 1997

Poertner H-O. and Reipschlagel, A., 'Ocean disposal of anthropogenic CO₂ : physiological effects on tolerant and intolerant animals' In :Ocean Storage of Carbon Dioxide. Workshop 2 - Environmental Impact, IEA Greenhouse Gas R&D Programme, 1996, ISBN 1 898373 13 2

Volk T. and Hoffert M.I., 'Ocean carbon pumps: Analysis of relative strengths and efficiencies in ocean-driven atmospheric CO₂ changes.' *Geophys. Monogr.* **32**: 99-110, 1985

Watson R.T., 'Climate Change 2001: Synthesis Report'. Published for the Intergovernmental Panel on Climate Change. Cambridge University Press, 2001.

Ocean Storage Workshop Reports

Ormerod, W.G., 'Ocean Storage of Carbon Dioxide. Workshop 1 - Ocean Circulation' IEAGHG 1996, ISBN 1 898373 08 6

Ormerod, W.G., and Angel, M. 'Ocean Storage of Carbon Dioxide. Workshop 2 - Environmental Impact' IEAGHG 1996, ISBN 1 898373 13 2

Ormerod, W.G., 'Ocean Storage of Carbon Dioxide. Workshop 3 - International Links and Concerns' IEAGHG 1996, ISBN 1 898373 04 3

Wong, C.S., and Hirai, S., 'Ocean Storage of Carbon Dioxide. A Review of Carbonate and CO₂ Hydrate Chemistry' IEAGHG 1997, ISBN 1 898373 09 4

Ormerod, W.G., and Angel, M. 'Ocean Fertilisation as a CO₂ Sequestration Option' IEAGHG 1998, ISBN 1 898373 11 6

A large Pacific Grenadier Fish (Coryphaenoides acrolepsis) feeding close to CO₂ being released into a 20 inch diameter corral on the sea floor at 3600m depth; the fish is apparently unperturbed, however penetration of the thin boundary layer in direct contact with the CO₂ would result in a sharp avoidance reaction.

Photo © 2001 MBARI



(The low resolution of the image is due to it being a captured frame from video)