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CHAPTER 6

Can the Kyoto Goals be Achieved Using the Oceans as Sinks?

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Summary

This chapter outlines technological proposals to accelerate the sequestration of the main greenhouse gas, carbon dioxide, into oceanic reservoirs, either through direct disposal of fossil fuel-derived CO_2 in the water column or at the seabed or through attempts to enhance biological uptake through large-scale ocean fertilization programmes. These proposals are evaluated against a number of criteria necessary for acceptance of ocean disposal/sequestration as a sustainable contribution to the goals and commitments of the Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC), as well as consistency with other international legal instruments. The chapter concludes that the ultimate objective of the UNFCCC, namely stabilization of greenhouse gas concentrations at levels that would prevent dangerous interference with the climate system, cannot be met through such Although theoretically capable of reducing atmospheric CO_2 levels in the coming century to a similar level as an emission reductions at source strategy, CO_2 disposal in the ocean will result in higher CO_2 levels, and hence larger climate changes and sea level rise in future centuries. Given the threat these technologies present to effective implementation of the Kyoto Protocol and to sustainable energy and waste management more broadly, efforts should be made to ensure that ocean disposal/sequestration of CO_2 cannot be used to offset against commitments to emissions reductions for greenhouse gases.

Introduction

In 1992, following the United Nations Conference on Environment and Development (UNCED, Rio de Janeiro, June 1992), 166 nations signed the United Nations Framework Convention on Climate Change (UNFCCC 1992). The Convention established the objective to achieve "*stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous interference with the climate system*". The Kyoto Protocol to this Convention, adopted in 1997 (UN 1997), sets legally binding commitments to reductions and/or limitations in emissions of greenhouse gases specific to each of the industrialized countries listed in Annex B to the Protocol. The ratifications of Poland, Canada and New Zealand during December 2002 brought the number of Parties to the Protocol to beyond 100 (see http://unfccc.int), though without the ratification of the Russian Federation, the total of industrialized country CO_2 emissions covered remains short of the 55% required for entry into force of the Protocol.

Although many gases arising from anthropogenic activity contribute to climate forcing, CO_2 is quantitatively by far the greatest contributor (60% of the total radiative forcing of the well mixed greenhouse gases[1] and set to rise further).

Despite the key intention of the Kyoto Protocol being the reduction of emissions at source, a number of proposed approaches to climate change mitigation rely instead on the development of technical mechanisms for the "management" of anthropogenic CO_2 in the environment. In broad terms, such approaches endeavour to limit the magnitude of atmospheric increases in CO_2 concentration through attempts either to influence the partitioning of carbon between different environmental compartments or to isolate generated CO_2 from the atmosphere over long time-scales. Beyond the manipulation of terrestrial carbon stocks through management of land-use changes, proposed strategies include direct disposal of liquid or solid CO_2 at sea (both above and beneath the seabed) and the enhancement of uptake of CO_2 by natural biological processes in the oceans (through ocean "fertilisation"). In each case, these sea-based techniques involve a high degree of intervention with ecosystems and with the global carbon cycle, involving manipulations on the scale of "planetary engineering".

At best these proposals are subject to enormous uncertainties regarding their likely effectiveness in stabilizing atmospheric CO_2 concentrations, while having the potential for adverse impacts at local, regional and global level. Some nevertheless regard them as necessary contributions towards combating climate change (e.g. Hoffert et al. 2002). At worst they are portrayed not merely as measures to mitigate climate change to which we are already committed but also as permitting continued exploitation of fossil fuel reserves, with the attendant environmental problems.

This chapter focuses on issues of technical feasibility, environmental impact and legality under existing international law of ocean related storage proposals for CO_2. It asks whether such interventions with the oceanic component of the climate system should be employed as a contribution to meeting the goals and commitments laid down in the Framework Convention on Climate Change and its Kyoto Protocol.

The UNFCCC and its Kyoto Protocol

In order to put this latter question in context, it is first necessary to understand what the ultimate objective of the UNFCCC and its Kyoto Protocol is, and to review the mechanisms envisaged in order to meet this goal. Article 2 of the Convention sets the objective of stabilizing greenhouse gas concentrations at levels that would prevent dangerous interference with the climate system, with the latter being defined as "the totality of the atmosphere, hydrosphere, biosphere and geosphere and their interactions". The specific reduction target of 5% against 1990 emissions for industrialised countries set for the first commitment period of the Kyoto Protocol (2008-2102) is generally recognised as only the beginning of what will need to be much more substantial cuts in emissions in future commitment periods if the objective of the Convention itself is to be met.

Under Articles 3.3 and 3.4, the Protocol permits the limited use of terrestrial carbon offsets (i.e. verifiable changes in terrestrial carbon stocks) against emissions commitments, though this has been, and is likely to remain one of the most controversial aspects of the Protocol. Significantly, these provisions mean, for example, that an ocean fertilisation "sink" cannot be counted towards Annex B Parties' obligations to limit emissions.

Articles 3.1 and 3.2 of the Protocol specify that industrialised Parties listed in Annex B must limit or reduce their emissions of greenhouse gases according to an agreed schedule. The manner in which sinks can be used to offset emissions is set out in subsequent Articles 3.3 and 3.4. Article 3.3 limits this to:

> *"direct human-induced land-use change and forestry activities, limited to afforestation, reforestation and deforestation since 1990".*

Moreover, removal by such sinks must be amenable to quantification and reporting in a "transparent and verifiable manner" (in a legally binding regime developed under Articles 5, 7 and 8 of the Protocol). Article 3.4 provides for additional sink activities to be agreed by the Conference of the Parties (COP) to the FCCC (serving as the meeting of the Parties to the Protocol), but these are still limited to:

> *"additional human-induced activities related to changes in greenhouse gas emissions by sources and removals by sinks in the agricultural soils and the land-use change and forestry categories".*[2]

Theoretically, certain other provisions of the Protocol could allow the use of oceanic storage of carbon for credits. These include Article 6 of the Protocol, which permits Joint Implementation projects between industrialized countries for credits and the Clean Development Mechanism under Article 12, which allows for developed countries to purchase credits from projects done in developing countries. In each case, however, specific enabling decisions of the Parties would be required, and this is unlikely without a full review of the issues. An IPCC special report on CO_2 storage technologies is now in preparation, including a section on the implications of carbon capture and storage for emission reporting and monitoring provisions of the Convention and Protocol.

An increasing body of research has focused on strategies to reduce the scale of further atmospheric increases in CO_2 concentration through large-scale human intervention in oceanic carbon cycles. As noted above, these schemes involve either direct introduction of fossil-fuel derived CO_2 or enhancement of biological uptake of CO_2 from the atmosphere to the oceans. In the most part, proposals have been developed largely as engineering concepts, with a focus on technical and economic feasibility and with relatively little regard either for adverse impacts on the receiving environment or for the existing legal instruments within which they would necessarily operate. This legal regime includes not only the provisions of the Kyoto Protocol outlined above, but also those of Conventions established to ensure protection of the marine environment from human activities (specifically the 1972 London Convention on dumping of wastes at sea and, more generally, the UN Convention on Law of the Sea (UNCLOS)).

The attractiveness of ocean disposal and/or sequestration strategies for climate change mitigation is based primarily on the scale of the oceans as a reservoir of carbon and, therefore, as an apparent sink for further emissions. Indeed, the scale of the ocean carbon reservoir relative to terrestrial and atmospheric reservoirs is often cited as a justification for the pursuit of such technological approaches (Table 6.1). The importance of the oceans as a reservoir and ultimate sink of carbon is recognised by both the UNFCCC and the Kyoto Protocol, and is not in dispute. What is questionable, however, is whether human interventions of the nature proposed, ostensibly designed to accelerate uptake of anthropogenic CO_2 emissions by the oceans, are consistent with the requirements under Article 2 of the UNFCCC to prevent dangerous interference with the climate system and Article 4.1 (d) to "sustainable management...conservation and enhancement" of the ocean carbon reservoir:

> *"promote sustainable management, and promote and cooperate in the conservation and enhancement, as appropriate, of sinks and reservoirs of all greenhouse gases not controlled by the Montreal Protocol, including biomass, forests and oceans as well as other terrestrial, coastal and marine ecosystems;"*

Whilst proponents of ocean carbon sequestration see this as a mandate for pursuing their research under the Convention (e.g. Adams et al. 2002), it could well be argued that ocean disposal/sequestration of CO_2 is neither sustainable in concept or practice nor consistent with the conservation or enhancement of marine ecosystems. Under Article 2, two issues arise:

- the deliberate direct addition of CO_2 to the oceans constitutes a potentially dangerous source of interference to the climate system;
- a sizeable fraction of this CO_2 will reappear in the atmosphere over centuries, leading to higher CO_2 concentrations than would have occurred had emissions been reduced at source[3]:

Table 6.1. Estimates of carbon reservoirs of different biosphere compartments and order of magnitude estimates of potential capacities for carbon sequestration (adapted from Herzog 2001)

Reservoir size	**Gt (billion tonnes) carbon**
Oceans	44 000
Atmosphere	750
Terrestrial	2 200
Sequestration potential	**Gt (billion tonnes) carbon**
Oceans	1000s
Deep saline formations	100s-1000s
Depleted oil and gas reservoirs	100s
Coal seams	10s-100s
Terrestrial	10s

From a more technical viewpoint, it is also questionable that the capacity of ocean sinks can be related in such a simplistic way to the estimated scale of the global carbon reservoir the oceans represent. Most proposals under consideration necessarily involve introductions of large quantities of CO_2 at specific sites, or fertilisation to increase atmospheric drawdown within a particular region, such that the specific characteristics of those locations will have a substantial impact on the fate of the carbon so introduced.

Moreover, despite increasing research and knowledge, our understanding of oceanic carbon cycles, and therefore the manner in which such interventions would interact with and impact upon them, remains limited. In short, it is difficult to see how claims that ocean disposal/sequestration of CO_2 merely represents an acceleration of the natural uptake of CO_2 from the atmosphere can be verified and justified given the current state of knowledge of ocean carbon fluxes.

Outline of the ocean disposal and sequestration technologies proposed

Characteristically the technologies proposed involve very large scale projects designed either to prevent carbon dioxide reaching the atmosphere (CO_2

disposal and or storage) or to sequester carbon from the atmosphere. Proposals fall into three distinct categories:

- The fertilisation of open waters to increase primary production and hence to absorb more carbon in fixed form which will eventually be incorporated into the ocean sediments
- Disposal of captured carbon dioxide directly into oceanic waters.
- Injection of captured CO_2 into sub-seabed geological formations.

All of these technologies would need to be implemented on a global scale to achieve their designed effect on the working of the planet as whole (Marland, 1996) as they are designed to modify, through human intervention, the operation of global scale biogeochemical cycles, in this case the carbon cycle. For the purposes of this chapter, which specifically addresses the applicability of the oceans as sinks under Kyoto, discussion is focused primarily on the first two of these concepts, involving interaction with the ocean carbon reservoir itself.

Ocean Fertilisation

Fertilisation with iron

Iron is a limiting micro-nutrient for algal growth in some large areas of the worlds oceans. Ocean fertilisation with iron has been theoretically and, to an extent, practically explored. A series of experiments conducted in the Equatorial Pacific Ocean (IRONEX) were designed to assess the scope for increased algal production through supply of the limiting nutrient over an area of 64 km^2. In response to a single introduction of iron to these high nitrate/low chlorophyll waters, a biological response was observed. A second experiment in which multiple iron additions were made showed that both particulate and dissolved organic carbon did increase, while dissolved CO_2 concentrations decreased. Significantly, the researchers stated that the experiments were "not intended as preliminary steps to climate manipulation". Inevitably, however, these studies have been discussed in relation to their applicability to climate change mitigation (Ormerod & Angel, 1998) and modelling studies have been carried out based upon the concept.

Models have shown (see: Ormerod & Angel, 1998) that the largest effect of iron fertilisation would be in the Southern Ocean, where a doubling of primary production could take place (albeit concentrated over a small proportion of the total area). However, the draw-down of atmospheric carbon dioxide would be less than that implied by the amount of new primary production generated since some of the carbon dioxide would be supplied by changes in the seawater bicarbonate equilibrium. Efficiency may also be impacted by unpredicted secondary effects on planktonic community structure and/or food webs as a result of fertilisation.

Moreover, the nature, scale and permanence of the fertilisation operation required to sustain increased carbon assimilation likely render it infeasible in practical terms. It has been estimated, for example, that for this approach to sequester 0.5 Gt carbon *per annum* would require 2700 ships or 200 aircraft to treat 1.7×10^7 km^{-2} of sea surface with around 470,000 tonnes of iron per year (Sarmiento & Orr, 1991) and on a continuous basis.

Fertilisation with macro-nutrients

Addition of the macro-nutrients, nitrate and phosphate to seawater has also been proposed (e.g. Shoji & Jones 2001). The concept has been investigated in practical terms through the Norwegian MARICULT project, geared primarily to increase supplies of food and natural raw materials (Ormerod & Angel, 1998). Nonetheless, the idea that this might increase oceanic uptake of CO_2 has not gone unrecognised. Most of the potential impacts of this strategy are common to the iron fertilisation concept. In the case of macro-nutrients, however, many of these impacts have been observed in natural systems impacted by nutrients introduced *via* sewage or agricultural sources. Ecosystem changes, anoxic waters and the appearance of nuisance species have all been documented in coastal waters subject to enhanced macro-nutrient loading (see: Johnston et al., 1998). Ultimately, the effectiveness of such approaches in enhancing carbon sequestration in the longer term are highly uncertain, while the risks of undesirable secondary impacts are substantial (Trull et al. 2001).

Disposal of CO_2 into ocean waters

Mitigation of climate change impacts by means of the direct introduction of fossil fuel-derived carbon dioxide into marine waters was first proposed in 1977. Thus far, proposals for ocean disposal of carbon dioxide involve one of three methods of introduction:

- Introduction by pipeline into deepwater followed by dissolution (see Drange et al. 2001)
- Dispersion following discharge of dry-ice blocks or liquid CO_2 from a ship
- Formation of a lake of liquid CO_2 in the deep ocean (see Brewer, 2000)

These concepts are illustrated in Figure 6.1a-c.

In practice, the discharge of dry-ice blocks is likely to prove much more expensive than production of liquid carbon dioxide. It costs around twice as much to produce solid as opposed to liquid CO_2 (Golomb, 1993). The solid material would tend to sink; it has been calculated that cubes of 3-4m dimension would sink below 3000m before 50% of the CO_2 dissolved. One idea which has grown from this is to use shaped part solid/part liquid penetrators, 4-5m in diameter and 20-40m in length which sink and embed

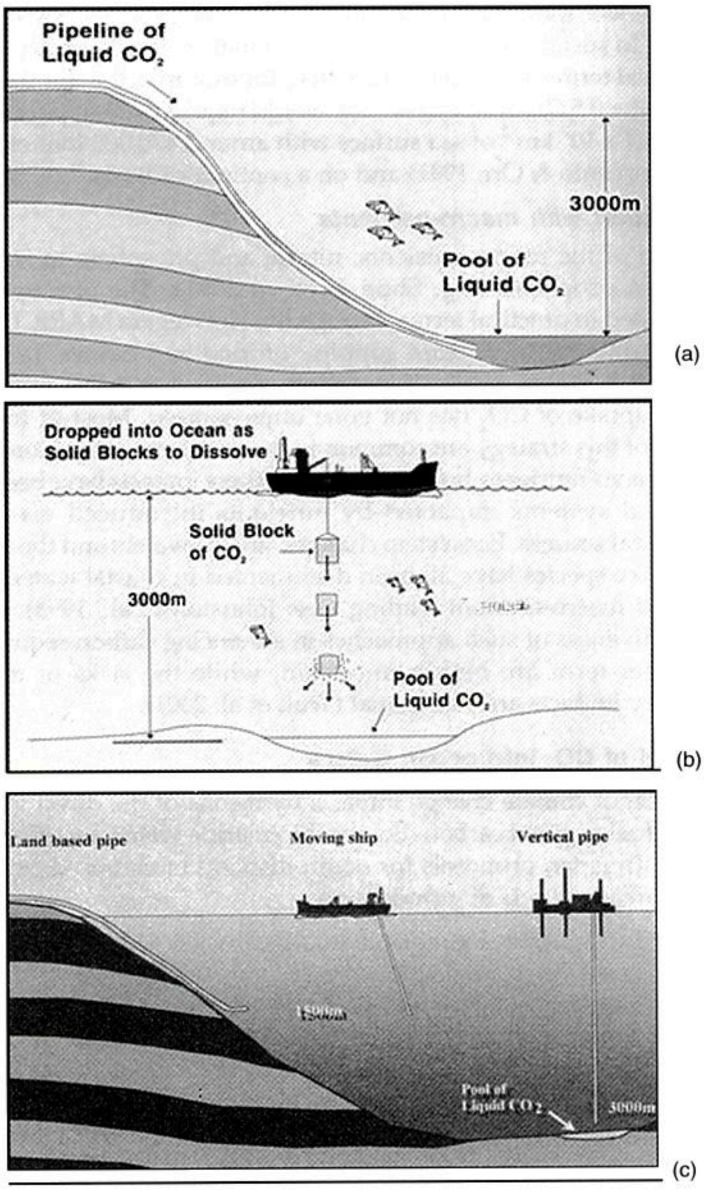

Fig. 6.1a-c: Concepts for the deep-sea disposal of carbon dioxide captured from power and industrial plants. These involve the discharge of liquid carbon dioxide from land based pipelines into deep water (Figure a) or the disposal of blocks of dry ice directly from vessels (Figure b). Figure (c) shows the proposed disposal of liquid carbon dioxide from a towed pipeline into midocean waters and the discharge of liquid carbon dioxide onto the seabed from a fixed platform.

themselves in the sea-floor (Guevel et al., 1996). Once again, the energy penalty is likely to be high and a large infrastructural cost is implied given that capacity will need to exist to handle the approximately 500 tonnes of CO_2 produced by a 500MW coal fired power plant each hour.

Most research effort has focused on the introduction of CO_2 by pipeline. At depths of less than 500m, introduction of CO_2 will create bubble plumes since, at ambient pressures and temperatures, carbon dioxide exists as a gas. These bubbles will dissolve in the seawater and, it is suggested, become trapped below the ocean thermocline. Although in engineering terms this is a relatively simple option, the retention time of the gas would be relatively short (around 50 years).

At prevailing temperatures and pressures between 500m and 3000m, carbon dioxide exists as a positively buoyant liquid. Hence, it will form a droplet plume, perhaps with the droplets covered in film of hydrate which could slow dissolution. Below 3000m, it is anticipated that CO_2 will form a dense liquid plume which could ultimately form a lake of liquid CO_2 on the sea bottom (Adams et al., 1995) with a clathrate surface. Retention times in these cases should be much greater since deep water exchanges with surface water at a much lower rate than surface water interacts with the atmosphere in the upper mixed layer of the sea. Calculations have suggested that a lake of CO_2 on the deep ocean floor derived from 1GW of coal fired power plant over ten years of operation could cover 654,500m^2 of sea floor to a depth of 80.9m and contain 58 million tonnes of the liquefied gas (Wong & Hirai, 1997). The assumption that the pool would remain 80.9m in depth is merely a hypothetical construct to operate the mathematical model. Unless constrained by local topography, it seems reasonable to assume that, in practice, the liquid CO_2 would spread out to form a thinner layer over a much wider area, with the consequence of more widespread impacts.

Ocean disposal/sequestration: a sustainable strategy?

A diversity of concerns arise in relation to the proposals outlined above to exploit the oceans as a "storage" or disposal site for continued anthropogenic emissions of CO_2. To be justifiable as measures contributing to the attainment of Kyoto commitments, ocean disposal and sequestration programmes would need to satisfy a number of key criteria, which may be summarised as below:

1. **consistent** with Article 2 of the UNFCCC - the measure must not contradict or prejudice the stabilization of greenhouse gas concentrations at levels that would prevent dangerous climate change;
2. **predictable and effective** – they would need to be founded upon an understanding of marine circulation patterns and carbon cycles sufficient to allow reliable prediction of behaviour and effects

following intervention and to guarantee containment over effective timescales;

3. **sustainable** – such programmes should not conflict with basic principles of sustainability, including intergenerational responsibility, avoiding systematic changes in chemical composition and maintenance of the bases of biological diversity and productivity (including at the abyssal seafloor);
4. **verifiable** –the amounts of carbon sequestered would need to be quantifiable and verifiable;
5. **legal** – all such sea-based activities would clearly need to be consistent with other legislative instruments governing the use and protection of the marine environment;
6. **efficient** – the additional costs of such operations, in terms of CO_2 generated, must not in themselves significantly add to the equilibrium concentrations of CO_2 in the atmosphere by contrast with other measures, either in the short or the long-term; and
7. **complementary** – the pursuit of any such measures must not restrict the availability or effectiveness of other measures to address climate change, especially the reduction of CO_2 generation and emissions at source through development of alternative technologies and energy sources.

These criteria provide a framework against which the acceptability of current proposals for the direct ocean disposal and/or enhanced biological uptake of CO_2 through ocean fertilisation can be evaluated. It must be said, however, that to date, the development of the ocean disposal/sequestration concept has taken place largely within a technological nimbus, seemingly insulated from these more holistic considerations, despite the magnitude of the questions and uncertainties that surround them.

Do we know enough about ocean carbon cycles for ocean disposal/ sequestration of CO_2 to be predictable and effective?

An understanding of the role of the oceans in the carbon cycle is central to any evaluation of the likely impacts of ocean disposal of CO_2 and associated storage techniques. Dominating global carbon reserves, the oceans play a large part in the carbon cycle. In simple terms, it is the equilibrium which exists between ocean carbon dioxide concentrations and those in the atmosphere, and the way in which this equilibrium is driven, that governs atmospheric carbon dioxide concentrations in the long term. The uncertainties and limitations to knowledge of the global carbon cycle, and of the specific role of the oceans, have recently been highlighted by Falkowski et al. (2000). In large part these limitations are due to poor spatial and temporal resolution of understanding of these processes in the ocean despite the data generated by large ocean research programmes on this topic and to the resultant inadequacies of the mathematical models applied to such studies (Follows et al., 1996; Ormerod, 1996). CO_2 uptake from the oceans has largely been inferred from calculations based upon sparse total inorganic carbon measurements. Improving the precision of these estimates by suitably intense sampling programmes is likely to be some decades into the future (Goyet et al., 1997).

Uncertainties in the capacity of the ocean "sinks"

Even with the current uncertainties which exist in relation to the size of carbon reservoirs and fluxes, simple calculations based upon the actual concentration of CO_2 and the theoretical saturation achievable in deep ocean waters indicate a notional capacity for several million Gt of CO_2. In practical terms, this is constrained by the amount of carbonate ion available to neutralise the carbonic acid formed by dissolved carbon dioxide if environmentally significant excursions in overall oceanic pH values are to be avoided. Estimates for carbonate available in deep ocean sediments range between only 1,600 Gt and 4,920 Gt, with dissolved carbonate in waters deeper than 500m at 1,320 Gt. While it must be stressed that these values are highly speculative due to the paucity of empirical data (see: Wong & Hirai, 1997), the actual capacity is clearly likely to be orders of magnitude less than notional values.

Recently, Rau and Caldeira (1999) and Caldeira and Rau (2000) have proposed carbon capture/sequestration schemes which employ additional reactions with carbonates (e.g. limestone) prior to ocean disposal in an attempt to circumvent this constraint. Although reducing the potential for pH changes resulting from direct CO_2 injection, such approaches (described simply as "accelerated weathering") fail to solve many of the more conceptual and ethical problems surrounding human intervention with the ocean carbon cycle on this scale, aside from the almost unimaginable scale of the infrastructure necessary in order to put such measures in to practice.

Uncertainties in the timescales of containment

In addition to uncertainties and unknowns relating to overall capacity, fluxes and even immediate fate of artificially introduced CO_2, major questions surround the timescales over which sequestered carbon will remain isolated from the atmosphere. These questions of retention time are central to the viability of ocean disposal schemata, with timescales of 500-1000 years considered necessary for "effective" containment (ignoring longer-term considerations).

Broadly speaking, the retention time for CO_2 disposed of to the ocean is assumed to increase with the depth at which it is discharged (Wong & Matear, 1993; GESAMP, 1997), though with considerable regional variations related to ocean circulation patterns (Bacastow et al., 1995; Ormerod, 1996). Of course, the disposal of liquid CO_2 in the water column would be subject to ocean circulation processes to a far greater extent than that deposited on the sea floor in solid or liquid form. Eventually, however, ocean processes will dissolve all forms of dumped CO_2 and transport it towards the surface. It has been estimated that at a depth of >3000m a pool of CO_2 containing 58.4 Mt would dissolve into the deep water over approximately 240 years. Various values for the dissolution and movement of CO_2 in the deep sea have then been derived through the use of observations and models, though the models have acknowledged limitations (Ormerod, 1996) and hence these predictions are subject to a high degree of uncertainty.

Indeed, some previously held assumptions regarding residence times for deep ocean waters have recently been challenged. Furthermore, the potential for climate change (even to the extent to which we are already committed) to modify these residence times through impacts on circulation drivers and patterns have been largely overlooked.

For example, assumptions that the age of the water in some deep ocean basins of the North Pacific was in excess of 1000 years have been challenged through the use of passive tracers such as chlorofluorocarbons, tritium and radiocarbon. Turnover time for deep water in the basins around the margins of the North Pacific (the Okhotsk, Japan and Bering Seas) is now estimated at only 100 years or less as opposed to the previously accepted values of up to 1300 years. Similarly, the basins of the Arctic Ocean may ventilate within only 75-300 years (see: Wong & Matear, 1996). This obviously throws into serious question the presumed utility of these basins for CO_2 disposal which had previously been assumed to be possible. Although other regions may turn over more slowly than previously thought, the general picture is one of limited understanding of circulation patterns, hardly a reliable basis for assuming predictable and effective containment of CO_2.

In addition, there appears to be extreme uncertainty about how rapidly vertical mixing takes place, with widely divergent values cited in the literature (Wong & Matear, 1996). No deep measurements are available for the crucial parameter (diffusivity) which may, in any case, vary according to ocean floor topography on a site specific basis. Areas with steep structures on the ocean floor (e.g. seamounts) have diffusivities much higher than accepted "background" values, lending weight to the hypothesis that such topography-induced turbulence may dominate deep ocean mixing (Munk & Wunsch, 1998, Chiswell & Sutton, 1998). Wind driving is also considered to be highly important (Wunsch, 1998). The rate of vertical mixing of deep Pacific water is, accordingly, a subject of debate. Based upon ^{13}C and ^{14}C tracer studies, a mixing rate of 30 m y^{-1} has been inferred, implying that dumped CO_2 could reach surface waters in 140-200 years instead of the 1000-1500 years suggested in earlier literature. Overall, a great deal of uncertainty exists concerning the mechanisms of ocean circulation and heat exchange. Mixing is unlikely to be uniform, but may take place at localised active regions, such as well stirred bottom slopes (see: Killworth, 1998).

It appears to date that none of the analyses of the fate of the CO_2 have considered the fact that the ocean circulation patterns could change either as a result of natural variability or as a result of climate change. Indeed, it has been suggested (Sarmiento et al., 1998) that ocean circulation changes modelled under a global warming scenario could have very significant implications for oceanic CO_2 uptake in the future. As one possible example, while the basic phenomena associated with the El-Niño-Southern Oscillation are known, the deep oceanic changes associated with it are much more poorly understood. Moreover, complex land-ocean interactions in carbon budgets which occur during ENSO events are only now beginning to be documented. For example, the Amazon Basin, which normally acts as a substantial sink of carbon, may, in ENSO years, act as a significant carbon source (Tian et al., 1998).

Similarly, the modelled predictions that North Atlantic thermohaline circulation, the process whereby surface water is drawn into deep water in the North Atlantic, may weaken or stop under changed climatic conditions, are also of significance (Rahmstorf, 1995; DETR, 1998; Schlosser et al., 1991). There appears to be an intricate and intimate relationship between the North Atlantic Oscillation (NAO) and the physical properties and behaviour of deep currents flowing in the Denmark Strait (between Greenland and Iceland). The NAO is the dominant recurrent mode of atmospheric behaviour in the North Atlantic Sector (Dickson, 1998; Dickson et al., 1999), and yet none of the CO_2 disposal studies appear to have considered the consequences of impacts on this process which could arise from changes in sea-ice cover under a changed climatic regime (Yang & Neelin, 1993; Hunt et al., 1995).

Indeed, there is some evidence in the palaeorecord to suggest that changes in deep ocean circulation could have acted as a climate "switch" in the past (MacLeod & Huber, 1996). Changes in deep water circulation affecting waters where large quantities of carbon dioxide have been disposed of could, therefore, lead to a much more rapid return of carbon dioxide to the atmosphere than is predicted in the various studies which have not considered these factors. At the very least a rapid efflux of disposed CO_2 from deep waters would render the supposed rationale for ocean disposal completely irrelevant. Even relatively small changes in the pattern or location of oceanic upwelling could lead to disposed CO_2 reaching the ocean surface much faster than anticipated.

Finally, it must be remembered that under conditions of changed climate there could be changes in the frequency and intensity of storms and in the strength of prevailing winds (IPCC 1996). A direct coupling exists between wind and ocean circulation. According to modelling exercises supported by observations (Wunsch, 1998), much of the work done by wind occurs in the Southern Ocean. Changes in wind intensity and consequent impacts upon ocean-atmosphere CO_2 exchange could be of considerable importance in determining the residence time of CO_2 in the ocean. Similarly, other research has shown that the depth of convection in the oceans is increased as more heat is removed from surface waters by wind action (Curry et al., 1998).

Clearly, the significance of all these phenomena for oceanic CO_2 cycling is not known. Such studies, however, are making it clear that chemical and physical properties of deep water masses are far from immutable and that the signatures of sea surface conditions are translated, in time, to deep waters and vice versa. The uncertainties which arise as a result of these findings do not appear to have been taken into consideration in analyses of CO_2 disposal (see: Wong & Hirai,1997).

Is ocean disposal/sequestration of CO_2 sustainable?

Perhaps the most generic formulation of the concept of sustainability is that captured within the Rio Declaration arising from the UN Conference on Environment and Development (UNCED 1992):

> *"the right to development must be fulfilled so as to equitably meet developmental and environmental needs of present and future generations"*

From the preceding discussion, it is already apparent that proposals for large-scale human intervention in oceanic carbon cycles could be seen to fall foul of this concept of intergenerational equity, especially as assumptions regarding effectiveness in space and time are highly questionable. The timeframes over which some interventions, especially fertilisation programmes, would need to be conducted carry considerable trans-generational responsibilities to continue the process. In the case of iron fertilisation of the Southern Ocean, for example, models suggest that if the exercise was stopped after 50 years, a significant proportion of the carbon fixed in this way would simply return to the atmosphere as CO_2 over the subsequent half century (Ormerod & Angel, 1998).

Issues such as energy penalties incurred in implementing such interventionist approaches and their potential to inhibit progress towards carbon-neutral, renewable alternatives may be seen to reduce further the consistency of these schemata with sustainable practice. These additional concerns are addressed further below.

An alternative description of sustainability, though by no means inconsistent with the concept above, is provided by the list of first order principles set out by Cairns (1997). Of these four principles, three may provide a useful metric against which the sustainability of CO_2 disposal/

sequestration proposals can be evaluated, namely that neither i) man-made nor ii) natural substances should be permitted to accumulate systematically in the biosphere and that iii) the fundamental bases for productivity must not be systematically depleted. The potential for CO_2 disposal or ocean fertilisation operations to impact systematically on the diversity and productivity of natural systems is of concern. Although the stated purpose of ocean disposal/sequestration is to reduce catastrophic impacts on marine and terrestrial systems resulting from CO_2 otherwise being released directly to atmosphere, it must be recognised that the schemata proposed can lead to unpredictable and essentially irreversible impacts of their own.

All proposed oceanic CO_2 disposal/sequestration schemes have potential to cause considerable ecosystem disturbance. Considerable uncertainty surrounds the impacts of ocean fertilization on marine ecosystems. A series of experimental introductions of iron into the Southern Ocean promoted a bloom of phytoplankton (Boyd et al, 2000) but in doing so, produced significant changes in community composition and the microbial food web (Hall & Safi, 2001). These changes are disturbances of the marine ecosystem. If ocean fertilization was implemented on a larger scale, there are concerns that these changes could alter the oceans' food webs and biogeochemical cycles (Chisholm et al., 2001) causing adverse effects on biodiversity. There are also possibilities of nuisance or toxic phytoplankton blooms and the risk of deep ocean anoxia from sustained fertilization (Hall & Safi, 2001).

In the case of CO_2 introduced directly at depth, seawater pH values will be altered, with potential adverse consequences for marine organisms (Ametistova et al., 2002). It has been predicted that the fall in pH associated with a CO_2 plume could disrupt marine nitrification and lead to unpredictable phenomena at both the ecosystem and community level (Huesemann et al. 2002). Organisms unable to avoid regions of low pH because of limited mobility will be most affected, layers of low pH water could prevent vertical migration of species and change the composition of particles, affecting nutrient availability (Ametistova et al., 2002). Deep-sea organisms are highly sensitive to changes in pH and CO_2 concentration (Seibel & Walsh, 2001). Thus, even small changes in pH or CO_2 could have adverse consequences for deep-sea ecology and hence for global biogeochemical cycles that depend on these ecosystems (Seibel & Walsh, 2001). CO_2 introduced upon seamount ecosystems raises further concerns. Benthic fauna in these ecosystems exhibit high degrees of endemism and where fish congregations are of highly adapted (K-selected) species (Koslow et al. 2000; de Forges et al. 2000).

The overall ecological and biodiversity implications of ocean CO_2 disposal are very likely to be negative, especially to benthic systems, although there is a lack of detailed knowledge of the faunal assemblages likely to be impacted, and the extent of the areas affected (Seibel and Walsh 2001). There is a need, for example, to obtain precise information on the responses of deep sea animals to elevated CO_2 exposure over their whole life-cycle under realistic conditions (Omori et al., 1996).

In order generally to justify large scale ocean dumping activities, it has been suggested (Angel & Rice, 1996) that large scale in situ experiments should be conducted to investigate impacts. The suggestion has been repeated in connection with the CO_2 ocean disposal option by Ormerod & Angel (1996), who state that the biological impacts of large-scale discharges (of CO_2) can only be adequately assessed by a careful manipulation of a total ecosystem. This may be true, but the ecosystem concerned needs to be fully understood at the outset of the experiment. Under current circumstances, therefore, it is difficult to see what such an experiment would achieve since the ecosystems in question are so poorly characterised. Hence only the grossest effects are likely to be detected and the more subtle, but equally important, changes forced upon ecosystem structure and function are likely to be overlooked. Such an experiment, conducted without rigorous preparation over many years and followed up by many years of subsequent observation, would be scientifically worthless.

Could quantities of carbon sequestered in oceans be verified?

It is noted above that, while it is true that Articles 3.3.and 3.4 of the Kyoto protocol explicitly allow for the offsetting of sequestration into "sinks" against commitments to emission reductions, the clear intention is that this should apply to management of terrestrial carbon reserves only. Moreover, Article 3.3 requires that any such offsetting must be "reported in a transparent and verifiable manner". As Caldeira (2002) notes:

> *"such a system of credits or debits cannot rely on trust alone; there must be some independent way of verifying carbon stored by a sequestration project"*

This reporting requirement, vital to the environmental effectiveness, proper governance and evaluation of Kyoto Protocol implementation, will nevertheless undoubtedly be subject to enormous operational difficulties and measurement uncertainties. Extending such a concept to the marine environment, the transparent and verifiable reporting of increases in oceanic carbon reserves seems inevitably to run up against insurmountable problems. Aside from the scale of uncertainties and lack of understanding of the fate of introduced carbon (or indeed the effectiveness of fertilisation schemes in enhancing draw-down), Caldeira (2002) stresses that reabsorption from the atmosphere will add further complexity, since it will be essential that such reabsorbed carbon is not included in offset calculations. Even if the other substantive issues surrounding ocean disposal/ sequestration of CO_2 could be resolved, therefore, it would appear that the fundamental barriers to quantification and verifiability for carbon so sequestered would render its offsetting against emission reduction commitments difficult in the extreme, if not impossible.

Do ocean disposal/sequestration proposals conflict with other existing legal instruments?

Before governments commit themselves to continue to invest in research into the technical feasibility of disposing of fossil fuel generated CO_2 to the oceans there is a need seriously to consider the practicability and feasibility of such options under elements of international law other than the Kyoto Protocol and the FCCC.

For example, unless the international regime governing the dumping of wastes at sea, both above and under the seabed (the 1972 London Convention), is made the subject of drastic revisions, the direct disposal of fossil fuel-derived CO_2 from vessels and platforms would violate international law. The possibility of such revisions is neither realistic nor desirable, particularly as acceptance of CO_2 dumping could open the door to reconsideration of dumping as an option for other industrial wastes. In the words of the UN Group of Experts of Scientific Aspects of Marine Environment Protection (GESAMP 1997):

> *"For technical and financial reasons CO_2 (dry ice) disposal appears to be an unattractive option unless it is to be dumped from vessels. Dumping from ships, however, comes under the aegis of the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Convention, 1972). In 1993 Contracting Parties to this Convention adopted a prohibition on dumping of industrial wastes…at sea that took effect on January 1st 1996. It therefore seems unlikely unless the Convention can be amended to permit the dumping of CO_2, from ships, that any of the current Parties to the Convention…could give approval to such a practice. It should be further noted that the same conclusion would apply to liquid CO_2 disposal from vessels and platforms which would also fall within the purview of the London Convention 1972".*

GESAMP (1997) was correct to point out that that the dumping of CO_2 at sea is a concept that is not in accordance with existing international law. In addition to dumping at sea from ships, aircraft, platforms and other man-made structures at sea, the Convention also covers the disposal of wastes and other matter under the seabed. This was agreed by the Thirteenth Consultative Meeting of Contracting Parties to the London Convention (1990) which adopted by vote Resolution LDC.41 13 to this effect. Six years later, in adopting the 1996 Protocol to the London Convention, the Contracting Parties unanimously agreed that:

> *" 'Dumping' means: any deliberate disposal into the sea of wastes or other*

> *matter from vessels, aircraft. Platforms or other man-made structures at sea; [….as well as] any storage of wastes or other matter in the seabed and the subsoil thereof from vessels aircraft platforms or other man-made structures at sea." (Article I, 4.1.1 and I, 4,1,1.2 of the 1996 Protocol to the London Convention)*

According to Article XV 2 of the London Convention 1972, any amendments to the Convention require a two thirds majority of those Contracting Parties in attendance at the time of the vote and:

> *"will be based on scientific or technical considerations."*

The prohibition on the dumping of industrial waste at sea on or under the seabed is legally binding on all Contracting Parties to the London Convention (78 countries by the end of 2002) and also upon all Contracting Parties to the United Nations Convention on the Law of the Sea (UNCLOS, 1982). This is in accordance with Article 210.6 ("Pollution by Dumping") of UNCLOS, which states that:

> *"National laws regulations and measures shall be no less effective in preventing reducing and controlling such pollution than the global rules and standards".*

The acceptability under international law of disposing of CO_2 via a pipeline from the shore into the marine environment remains an open question. In the preambular text to Resolution LC. 49 (16), banning the dumping of industrial waste at sea, Contracting Parties to the London Convention:

> *"Reaffirm[ed] further the agreement that a better protection of the marine environment by cessation of dumping of industrial waste should not result in unacceptable environmental effects elsewhere."*

This statement was primarily addressing the need to give priority to waste avoidance and clean production and also to avoid wastes previously dumped at sea being placed in land-based dumps in a manner which could not be considered to be environmentally sound. Nevertheless, the need to avoid wastes that could be dumped at sea entering the marine environment via land based sources and activities was also very much present in the minds of the negotiators.

Moreover, in adopting the 1996 Protocol to the London Convention, Contracting Parties reiterated in Article 2 of the Protocol their obligation to:

> *"individually and collectively protect and preserve the environment from ALL SOURCES of pollution".*

Further they also agreed in Article 3.3 of the Protocol that:

"In implementing the provisions of this Protocol, Contracting Parties

> shall act so as not to transfer, directly or indirectly, damage or likelihood of damage from one part of the environment to another or transform one type of pollution into another".

The most recent expression of the universal trend to eliminate the dumping and land based discharge of wastes to the marine environment is contained in the 1998 Sintra Statement which was adopted unanimously by the Environment Ministers of the countries bordering the North East Atlantic, together with the European Commissioner for the Environment (OSPAR, 1998). The signatories to this statement:

> *"reemphasise[d] [their] commitment to prevent the sea being used as a dumping ground for waste, whether from the sea or from land based activities".*

In common with GESAMP (1997) the Independent World Commission on the Oceans (IWCO 1998), established to consider thoroughly all issues of ocean science, ocean conservation and ocean governance, noted that the dumping of CO_2 at sea is banned by the London Convention and that, furthermore:

> *"The Framework Convention on Climate Change and its Kyoto Protocol do not provide for Parties to dump or store CO_2 in international waters and thereby to offset their emissions".*

The provisions of existing Conventions, coupled with the current political reality, would seem, therefore, to rule out the consideration of oceanic disposal of anthropogenic CO_2 as a potential strategy to address current and future emissions. Indeed, it was questions concerning the legality of ocean disposal of CO_2 under the more regional (North East Atlantic) OSPAR Convention (1992) which led the Norwegian Environment Ministry to refuse a permit for an experimental release planned in the Norwegian Sea during the summer of 2002 (Adams et al. 2002, Burke 2002).

Is the energy penalty for capture and disposal or for fertilisation acceptable?

Many proposals to dispose of CO_2 in to deep ocean waters have been predicated upon the assumed possibility to capture clean CO_2 from the majority of the world's power stations and transport it for disposal. This strategy clearly carries with it a significant energy penalty from the outset. A typical capture scheme involves absorbing CO_2 from flue gases into a solvent (e.g. commonly monoethanolamine, MEA) followed by steam stripping. Disposal of the complete flue gas is unlikely to be viable since the carbon dioxide content ranges from about 3% in the case of gas turbine plant (Langeland & Wilhelmsen, 1993), similar to a natural gas combined cycle plant (3.6%), to flue gas concentrations of around 14% for a coal fired power plant. In the case of some specialised petrochemical processes this may be as high as 80% (Bailey & McDonald, 1993) while coal based plant with oxygen fuel and CO_2 recycle could reach 92%.

Current energy penalties, in other words the reduction in utility output as a result of using the process, range from between 15 and 24% for gas-fired plant to between 27-37% for conventional coal fired plant. Advanced coal plant attracts an energy penalty of 13-17% (Herzog et al., 1997). These figures do not include liquefaction and disposal penalties. These estimates are broadly supported by other estimates (Leci, 1996) suggesting absolute reductions in efficiency of up to 35%. Effectively, capture alone would reduce the thermal efficiency of a typical power plant from around 35% to 25% (GESAMP, 1997) accounting for around 30% of the total energy content of the coal used as fuel. Some improvements envisaged for the future suggest penalties could be brought down to between 9% and 15%. This energy penalty effectively results in a reduced efficiency of the plant.

A further 10% of the fuel value of the coal would be required to liquefy and compress the carbon dioxide to a pressure enabling deep-water discharge (150 Atm) (Golomb, 1993). Other estimates (Haugen & Eide, 1996) include liquefaction and disposal penalties with those from capture. These suggest that for a 500MW power station the electricity consumption for the MEA process amounts to between 18 and 24MW. In addition the steam requirement for stripping the solvent equates to between 70 and 140 MW and is smallest for gas fired power stations. In order to prepare the stripped CO_2 for disposal it must be liquefied, pressurised and purified. Assuming injection into an aquifer, this will require an additional 55-60MW for a coal fired plant and about 30-40MW for a gas fired plant. Transport of CO_2 from a pulverised coal plant over 100 km would require a further 3MW and, if

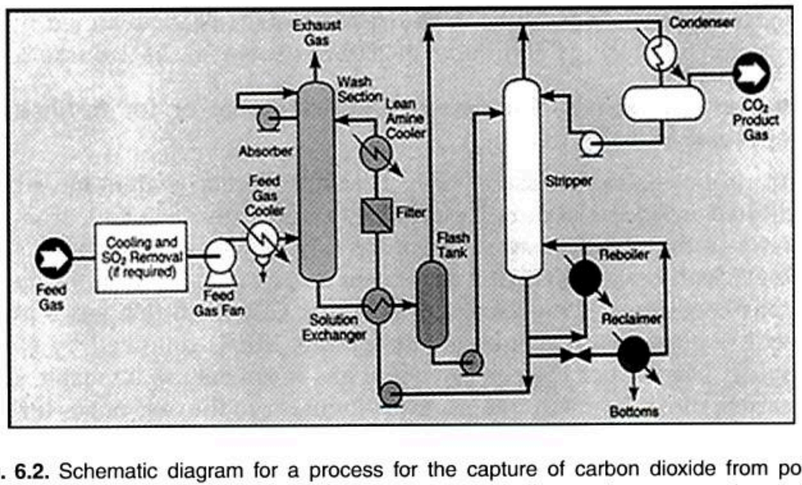

Fig. 6.2. Schematic diagram for a process for the capture of carbon dioxide from power station/industrial process flue gases. This indicates the energy demanding components of the process and the waste streams generated as a result.

the full capacity of a large diameter pipe were used, the total energy required for this phase would be 12-14MW.

Accordingly, the total electricity loss from a 500MW facility capturing and disposing of CO_2 can be expected to amount to at least 80MW (16%) while heat losses due to steam consumption account for at least 70MW. A total penalty of 25%-45% can, therefore, be expected on the basis of current technology. This will inevitably result in greater quantities of carbon dioxide being generated for a given unit of energy produced.

This reduction in efficiency has considerable long-term implications for the concept of ocean dumping of carbon dioxide in the context of Article 2 of the UNFCCC. As noted above, a dumping strategy would reduce the transient peak of CO_2 over the next century (as would an emission reduction strategy aimed at the same CO_2 concentrations within that timeframe) but ultimately would result in CO_2 levels approaching those expected had no emissions reductions been undertaken. If the emissions from energy used in the capture and disposal processes are taken into account, the long term stabilisation value could perhaps even be significantly higher than under a "business as usual" scenario (depending upon the precise mix of fossil fuels used in energy generation and their relative carbon intensities). Hence, the assertion (Herzog et al., 1997) that ocean disposal represents simply a short circuit of natural processes is somewhat disingenuous since it does not appear to accommodate the fact that adoption of the strategy will lead in the longer term to higher CO_2 concentrations than would otherwise have been the case. This has been recognised in modelling exercises which have shown that, where marine disposal systems are used, the long term atmospheric concentrations ultimately exceed those from systems without controls using disposal to ocean (Flannery et al., 1993).

Will the pursuit of ocean disposal/sequestration impact negatively on the development of source-oriented and carbon neutral solutions?

It has been observed that technical progress in carbon management is outpacing consideration of its limitations and potential risks. Large-scale adoption of such strategies would constitute a major technological and societal choice that would be difficult to reverse. There is a strong risk that this choice will be made without adequate reflection upon its implications (Parson & Keith, 1998) given the current slow political progress on genuine abatement through *inter alia* the development of renewable energy resources.

In turn, this suggests the potential for a serious conflict within corporations and governments regarding allocation of resources for onward investment in energy technologies. There are finite resources available in the corporate and public domains to direct at development of sustainable (renewable) energy technologies and the associated infrastructure. Carbon management strategies designed to maintain fossil fuel consumption and use into the future are diametrically opposed in philosophy and intent to the development of renewable energy resources and of highly efficient technologies and transport systems. Given that a highly significant component of investment in renewable energy development is being made by multinational oil companies, there is the very real prospect that such investment will be held hostage to the development of expensive carbon management technologies. There also appears to be a presumption in the energy industry that the relatively low cost "least regrets" options which include improvements to energy supply, end-use efficiency, substitution with less carbon intense fuels and inexpensive renewables will not solve the medium to long term problem. Accordingly, it has been argued that technologies to capture and remove CO_2 could have a central role to play in the future. Crucially, they are seen by some in the energy industries as a long term option which allows for continued large scale use of fossil energy resources (Herzog et al., 1997).

In the light of the numerous legal and political uncertainties that would surround any proposal to dump CO_2 in the marine environment or artificially to enhance uptake through fertilisation on a massive scale, along with the considerable scientific and technical problems and uncertainties outlined elsewhere in this document, it would appear that further investment in such options would represent a wasteful drain on available resources. These resources might be much better utilised in the research, development and promotion of renewable energy alternatives and the implementation of effective energy efficiency programmes. Such an approach would clearly be more consistent with the conclusions expressed by the IWCO (1998)

Summary and Conclusions

The first commitment period reduction targets of the Kyoto Protocol are widely seen as a significant first step in reducing CO_2 and other greenhouse gas emissions. The 5% reduction target for industrialized countries is by no means adequate to achieving the ultimate objective of the Convention (WRI, 1998) and further and deeper emission reduction commitments by the industrialized countries will be essential in the second commitment period (2013-2017) and beyond. Developing countries will need to switch more rapidly to energy efficient technologies and environmentally sound renewable energy supply sources. In this context ongoing development of unsustainable ocean disposal/sequestration strategies will continue to draw vital resources away from the research, development and implementation of energy efficiency programmes and renewable energy alternatives.

The potential for unpredicted, and possibly serious or even irreversible, effects on current or future generations resulting from the various ocean disposal strategies outlined above is indisputable and threatens to violate the principle of sustainability established as a result of the first UN

Conference on Environment and Development (UNCED 1992). At the same time, the assumption that ocean sequestration or disposal of CO_2 will be effective in combating climate change and in particular meeting the ultimate objective of the UNFCCC, stabilization of greenhouse gas concentrations at levels that prevent dangerous interference with the climate system, remains very much open to debate. Indeed, the use of such strategies to meet the provisions of the Kyoto Protocol would undermine its environmental effectiveness and, by loading longer term increases of CO_2 into the atmosphere in future centuries, contradict the principal of intergenerational responsibility. In other words, use of "ocean sinks" in meeting short-term emission targets in the coming decades would be at the expense of further climate change in the future.

The optimistic view (Herzog et al., 1997) that CO_2 disposal strategies allow for wide scale use of fossil fuels into the future can be challenged on fundamental grounds. It makes little difference to the final long-term level of CO_2 achieved in the atmosphere. Furthermore, the seemingly widely held assumption that:

> *"From a long term perspective (i.e. at the time scale of a millennium) the question of ethics of using the ocean does not arise because the fate of most CO_2 discharged to the atmosphere will be to finish up in the deep ocean" (Angel, 1998)*

...is quite wrong. The ocean disposal of CO_2 raises very deep ethical questions indeed, particularly since the strategy likely carries with it a commitment for future generations to a worse equilibrium state than would be the case by reducing emissions at source or even in some case continuing to emit on a "business as usual" basis. As carbon cycle modellers have noted, the CO_2 does not disappear and that "ignoring the truly long-term effects is a political and ethical choice" (Tans, 1997).

Although CO_2 disposal in the oceans may diminish the extent of the transient peak in atmospheric CO_2 concentrations over the coming century it certainly would bequeath to future generations most likely unacceptable levels of climate change. Such an outcome could only be averted via technologies that extracted CO_2 direct from the atmosphere, to soak up the flux of anthropogenically injected CO_2 outgassing from the oceans in future centuries. In effect, the strategy simply delays the full impact of climate change to a point in the future. This key trans-generational failing is not addressed by proponents of the strategy (*e.g.* Herzog et al., 1997). Since the final CO_2 stabilisation value will be key determinant of the ambient climate of the time, the ocean disposal option effectively shifts a substantial burden of the responsibility (perhaps 30-50%) into the future at which point it will not be recoverable or avoidable.

In 1998, the Independent World Commission on the Oceans (IWCO) considered the implications of CO_2 disposal at sea, concluding that:

> *"In the context of global warming, the importance of ocean-atmosphere interactions, the role of the oceans as a CO_2 sink and the precautionary principle, it is imperative that people and governments exploit as a first priority, the manifold opportunities that exist for reducing carbon emissions and consider only with circumspection the potential of the oceans as a site for CO_2 disposal".* (IWCO 1998)

From the analysis presented above, it seems clear that the position of the IWCO on this issue has substantial merit. It can only be hoped that the "people and governments" to whom their concluding statement was addressed will take due note and will not look to the oceans as a convenient "sink" to allow Kyoto commitments to be met in accounting terms while failing to address the underlying problem of the unsustainable fossil-fuel economy.

Footnotes

[1] See Table 6.1 of IPCC TAR WGI for summary of radiative forcing from 1750-1998 of main greenhouse gases.

[2] Essentially these were defined in the Bonn and Marrakech Accords of 2001 to included restricted volumes of forest management credits, cropland and grazing land management and revegetation (see FCCC/CP/2001/13/Add.1 at *www.unfccc.int*) and are beyond the scope of this chapter to elaborate).

[3] This could, for example, render impossible the future attainment of climate protection goals such as those set by the European Union of limiting warming below 2oC increase above pre-industrial levels.

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