Environmental Impacts of Ocean Disposal of CO₂

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Overview

One option to reduce atmospheric CO₂ levels is to capture and sequester power plant CO₂. Commercial CO₂ capture technology, though expensive, exists today. However, the ability to dispose of large quantities of CO₂ is highly uncertain. The deep ocean is one of only a few possible CO₂ disposal options (others are depleted oil and gas wells or deep, confined aquifers) and is a prime candidate because the deep ocean is vast and highly unsaturated in CO₂. The term disposal is really a misnomer because the atmosphere and ocean eventually equilibrate on a timescale of 1000 years regardless of where the CO₂ is originally discharged. However, peak atmospheric CO₂ concentrations expected to occur in the next few centuries could be significantly reduced by ocean disposal. The magnitude of this reduction will depend upon the quantity of CO₂ injected in the ocean, as well as the depth and location of injection.

Ocean disposal of CO₂ will only make sense if the environmental impacts to the ocean are significantly less than the avoided impacts of atmospheric release. Our project has been examining these ocean impacts through a multi-disciplinary effort designed to summarize the current state of knowledge. The end-product will be a report issued during the summer of 1996 consisting of two volumes: an executive summary (Vol I) and a series of six, individually authored topical reports (Vol II). A workshop with invited participants from the U.S. and abroad will review the draft findings in January 1996.

The six topical reports cover the following subjects:

- (1) CO₂ loadings/scenarios
- (2) near field perturbations
- (3) far field perturbations (performed under subcontract to SAIC, Inc.)

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- (4) impacts of CO₂ transport (performed under subcontract to UMass-Lowell)
- (5) environmental impacts of CO₂ release
- (6) policy and legal implications of CO₂ disposal

Each subject area is summarized briefly below with elaboration given to the near field perturbations and environmental impacts of a dry ice release.

CO₂ loadings/Scenarios

A 500 MW_e pulverized coal fired power plant is chosen as a reference. Without capture, this plant will emit CO₂ to the atmosphere at the rate of 115 kg/s (Herzog and Drake, 1993). With ocean disposal we assume 90% CO₂ capture efficiency and a 20% energy penalty. The energy penalty implies that net energy production with capture is reduced by 20% for a given energy input or, alternatively, that the required energy input for a given electrical output is increased by 25%. Considering a net electrical output of 500 MW_e, the effect of ocean disposal on a standard power plant is summarized below:

	Net Power	Release of Carbon Dioxide	
		To Atmosphere	To Ocean
Without Capture	500 MW _e	115 kg/s	0 kg/s
With Capture	500 MW _e	14.4 kg/s	130 kg/s

The emissions loadings are being studied as multiples of the standard power plant. The following matrix summarizes the scenarios that will be investigated:

	Number of 500 MW _e Power Plants (130 kg/s CO ₂ per plant)		
Analysis	One	Ten	One Hundred
Near Field (<25 km)	Five injection scenarios with generic ambient conditions	Five injection scenarios with generic ambient conditions	-
Mesoscale (25 km-2500 km)		3-5 specific sites off eastern U.S. with a generic injection at depth of 1000 m.	
Far Field (300 km-global)	-	-	One scenario: 50% injected at 1000 m off Tokyo & 50% injected at 1000 m off New York

One power plant is essentially the lowest level of disposal anticipated while the emissions from ten power plants represent an upper limit on the amount of emissions that are expected to be disposed of at a single point for reasons of economy of transport. One

hundred plants represents a loading of about 1.6% of the world's total anthropogenic CO₂ emissions and, as such, is a lower bound on the global amount of ocean disposal which could "make a difference" to atmospheric CO₂ levels.

For the near field analysis, five injection scenarios are considered:

- a droplet plume injected at 1000 m
- a CO₂ lake on the ocean bottom below 3700 m
- a dense CO₂ seawater plume injected at or below 500 m
- dry ice cubes released from the ocean surface
- a CO₂ hydrate plume injected at or below 500 m

Near Field Perturbations

The five injection scenarios are evaluated using separate models to describe 3-D concentration distributions of excess CO₂ and trace gases such as SO₂ and NO_x. The principal impacts of each scenario - the decrease in pH - are quantified using two criteria. First the spatial distribution of pH change is calculated. Then the range of time-histories of passive organisms traveling through the plume is calculated. Absolute pH is used in order to correlate the experiences with appropriate mortality data.

Far Field Perturbations

Far field perturbations refer to the change in total CO₂ concentration and associated pH at mesoscale and global scale.

Mesoscale simulations are being run for various locations along the eastern U.S.. The mesoscale dispersion model is a stochastic particle model driven by an externally calculated, time-dependent 3-D velocity field. "Particles" of CO₂ are continuously released at an injection site of 1000 m and tracked as they are advected by ocean currents, which include a mean current and turbulent fluctuations. The concentration of CO₂ at any one time can be plotted at a resolution of $1/4 \times 1/4$ degrees latitude and longitude.

A global carbon cycle model is being used to predict far-field long-term perturbations associated with one hundred 500 MW_e powerplants: 50 off of Tokyo and 50 off of New York. Injection depths of 1000 m will be used and simulations will run through the year 2500. The global discharge of anthropogenic CO₂ will be modeled as a simple logistics function of time. The global cycle model is based on the non-biological ocean circulation model of Mairer-Riemer and Hasselmann (1987), with biological carbon cycle components described by Bacastow and Mairer-Riemer (1990).

Environmental Impacts of CO₂ Transport Systems

Environmental impacts may occur at several stages of transport. The major impact of on-shore pipes occurs during construction when vegetation must be cleared and trenches dug. After construction, land and vegetation needs to be restored. In populated areas, it may be difficult to obtain rights-of-way. There is a remote chance of pipe rupture with the release of vaporized CO₂. CO₂ is not toxic, but is an asphyxiant. Models are being used to estimate the dispersal of this dense vapor and the risk to the surrounding environment.

The major impact of off-shore pipes will also occur during pipe-laying. The first few kilometers will be laid on the continental shelf which may include coral beds, sea vegetation and other marine habitats. Accidental rupture of the pipe would release CO₂

into the seawater, with partial dissolution. The rest of the released CO₂ would rapidly bubble up to the surface and reenter the atmosphere. The dissolved CO₂ will cause acidification of the seawater in the vicinity of the ruptured pipe.

The environmental impacts of tanker transport include (a) accidental releases with possible injury to the tanker crew; (b) release into the atmosphere of fuel combustion gases and particles. Both diesel and steam propelled tankers release into the atmosphere particles (flyash and soot), SO₂ and NO_x, and of course CO₂.

For pipe transport, on-shore facilities include a pumping station and storage tanks. Construction may require coastal land acquisition and disruption of coastal habitat. There is also a remote risk of accidental release of pressurized, liquid CO₂. For tanker transport, docking facilities will be required in existing harbors, or specially built ports.

If tanker transport is used for deep sea disposal, floating platforms must be used to unload CO₂ and pump it into a pipe extending from the platform. The floating platforms will cause minimal impact but may be a navigation hazard. The operating crew on the platform will be exposed to storms and other environmental hazards, as well as possible accidental release of pressurized, liquid CO₂. The vertical pipe should not cause significant impact on the marine environment.

Environmental Impacts of Ocean Disposal of CO₂

Marine life can be classified into four groups: phytoplankton, zooplankton, nekton, and benthos. The groups that will be affected by a CO₂ plume depend on the injection scenario and many scenarios preclude certain types of organisms from harm. The dry ice scenario is discussed below, but the methods and considerations are applicable to other scenarios.

Policy and Legal Implications of CO₂ Disposal

Important considerations relate both to site-specific discharges within or near a country's Exclusive Economic Zone as well as large scale worldwide CO₂ disposal. The Law of the Sea and the United Nations Environment Programme Agenda 21 are tone-setting and establish our commitment to curb CO₂ emissions. The London Dumping Convention, as well as other regional treaties, are more specific and classify materials, prohibiting the discharge of some to the ocean.

Worldwide CO₂ disposal would require international cooperation and funding. Presumably it would not be initiated without consensus that avoided impacts/risks of global change outweigh any impacts to the ocean. In opposition to this philosophy, international treaty language is moving toward a precautionary principle and frowns upon end of pipe solutions or solutions which transfer pollution from one medium (air) to another (water). Furthermore, the emotional response of non-governmental organizations (NGOs) can not be discounted.

Analysis for Dry Ice Disposal

The near field perturbations and associated environmental impacts for dry ice injection are considered as an example our methodology. Dry ice cubes must be as large as practical, to insure that only a small fraction of the dissolution occurs near the surface. Cubes with 3 meter sides released from a fixed point were chosen; one standard power plant requires the release of one cube every 320 seconds. CO₂ dissolution to the water column as a function of depth was based on Nakashiki *et al.* (1991).

To obtain a steady state solution the release was approximated as a continuous line source. Turbulence induced by the falling cube was added to a scale-dependent ambient

diffusivity (Okubo, 1973) to obtain the total diffusivity as a function of distance. The solution for the excess total CO₂ concentration is then given by

$$C(x, y, z) = \frac{\dot{M}/u}{\sqrt{2\pi}\sigma} \exp\left(\frac{-y^2}{2\sigma^2}\right)$$

where $\dot{M}(z)$ is the mass flux (kg/m-s) at depth z , u is the current speed (m/s), and $\sigma(x)$ is the lateral standard deviation (m) found from the total diffusivity.

Excess CO₂ concentrations due to the disposal of dry ice were calculated for the one and the ten plant scenarios for $u = 0.02$ and 0.10 m/s. Results for one plant with $u = 0.02$ m/s current are shown in Figure 1. The excess CO₂ was added to the ambient CO₂ to compute new pHs. A map of the change in pH can be seen in Figure 2.

The average ocean CO₂ concentration experienced by an organism passing through the region can be calculated by assuming that the organism is subject to the same diffusivity as the CO₂. Thus

$$\bar{C}(x, y_o, z) = \frac{C_{max}}{\sqrt{2}} \exp\left(\frac{-y_o^2}{2\sigma^2}\right)$$

where $\bar{C}(x, y_z)$ is the average excess CO₂ concentration experienced at location x and z by an organism that passes through the plume at a lateral distance y_o from the source, and $C_{max}(x)$ is the concentration at the centerline ($y = 0$) given above. $\bar{C}$ is used to calculate average pH as a function of time. At each depth, several lateral sections are selected and a representative experience is found based on the value of y_o at the middle of each section. Figure 3 shows the experiences at a depth of 900 m for ten power plants in a 0.02 m/s current.

The environmental impact assessment focuses on zooplankton and assumes conservatively that they have no CO₂ avoidance ability. Knowing the volume of water that will experience a given time history of pH, and knowing the population density of organisms in the water is sufficient to estimate the numbers of zooplankton affected by the CO₂.

Most studies on the effects of pH have been on fish in acidified lakes in response to acid rain concerns. Still, several useful studies have been performed on marine zooplankton in which either the animals were exposed to a constant pH, and mortality assessed at different times, or the animals were exposed to various pHs for a given time and mortality assessed (Grice *et al.*, 1973, Calabrese *et al.*, 1966, Havas and Hutchinson 1982 and Bamber 1987). Results from these studies have been superimposed on Figure 4 to give an approximate map of expected mortality as a function of pH and exposure time. ('Isomortality' curves are drawn for 0%, 50%, and 90% mortality as guides.)

Near field output such as Figure 3 can be discretized to yield the number of hours over which various sections of the plume experience different values of pH. The cumulative impact of a time-varying exposure can be estimated by using the isomortality curves to convert exposures into a common metric. For example, on Figure 4, an exposure of 50 hours at pH 6.0 causes roughly the same 10% mortality as an exposure of 15 hours at pH 5.5. Hence we can approximate an exposure of 50 hours at 6.0 plus 10 hours at 5.5 as 25 hours at 5.5. For such an exposure, the graph gives a mortality of 50%. Equivalently, converting the exposures to a metric of hours at 6.0 instead of 5.5, gives a total exposure of 90 hours corresponding to about 40% mortality. The table below illustrates this procedure using data from Figure 3 and compares it with an alternative method (Schubel, 1978).

Section width (m)	hrs. at pH 5.5	hrs. at pH 6.0	hrs. at pH 6.5	hrs. at pH 7.0	mortality % 1	mortality % 2
0-20	.417	2.71	5.97	14.8	0%	2.2%
20-60	0	.90	7.71	15.0	0%	1.3%
60-120	0	0	6.39	16.0	0%	1.0%
120-240	0	0	0	19.4	0%	0.5%

mortality % 1 = mortality using method described above. % 2 = mortality following Schubel (1978).

The section in the first row above is closest to the plume centerline and would experience the greatest effect; these data are plotted in Figure 4. It is clear that even the most severely affected organisms would scarcely be affected (method 2 by design will give non-zero mortalities since it assumes no threshold but these small numbers should be considered artifacts). Thus, we can safely expect little or no harm to pelagic organisms from the scenario of falling dry ice cubes. It should be mentioned that the dry ice cube scenario is expected to have the least impact because of the large dilution. We are in the process of studying other injection scenarios using similar methodology.

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Figure 1: Additional CO_2 concentrations due to the addition of the emissions of one standard power plant as 3 meter blocks of dry ice

Figure 2: Change in pH resulting from dry ice addition

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Figure 3: pH-Time experience for organisms at different distances from the plume centerline (conditions at a depth of 900 meters)

Figure 4: Mortality of zooplankton

ATTACHMENT III

Paper to be presented at the

**Eleventh Annual Coal Preparation, Utilization, and Environmental Control
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separate cycling at*