

# OCEAN SEQUESTRATION OF CO<sub>2</sub> — AN OVERVIEW<sup>1</sup>

Howard J. Herzog  
Massachusetts Institute of Technology (MIT) Energy Laboratory

## ABSTRACT

The ocean represents the largest potential sink for anthropogenic CO<sub>2</sub>. Discharging CO<sub>2</sub> directly to the ocean would accelerate the ongoing, but slow, natural processes by which over 90% of present-day emissions are currently entering the ocean *indirectly* and would reduce both peak atmospheric CO<sub>2</sub> concentrations and their rate of increase. This paper discusses the options for finding ocean sequestration strategies that are environmentally sound, economically viable, and technically feasible. In addition, some current research projects in this area are highlighted.

## INTRODUCTION

The ocean represents the largest potential sink for anthropogenic CO<sub>2</sub>. It already contains an estimated 40,000 GtC (billion tonnes of carbon) compared with only 750 GtC in the atmosphere and 2,200 GtC in the terrestrial biosphere (IPCC, 1996). As a result, the amount of carbon that would cause a doubling of the atmospheric concentration would change the ocean concentration by less than 2%.

Worldwide anthropogenic emissions of carbon to the atmosphere are about 7 GtC. The ocean-atmosphere flux is about 90 GtC per year, with a net ocean uptake of  $2 \pm 0.8$  GtC (IPCC, 1996). On a time-scale of a thousand years, over 90% of today's anthropogenic emissions of CO<sub>2</sub> will be transferred to the ocean. Discharging CO<sub>2</sub> directly to the ocean would accelerate this ongoing, but slow, natural process and would reduce both peak atmospheric CO<sub>2</sub> concentrations and their rate of increase. This is shown schematically in Figure 1.

The focus of this paper is ocean sequestration of CO<sub>2</sub> by direct injection. This assumes a relatively pure CO<sub>2</sub> stream has been generated at a power plant, from an industrial process, etc. An alternative approach to ocean sequestration of CO<sub>2</sub> is to enhance the net oceanic uptake from the atmosphere, such as through iron fertilization (Martin *et al.*, 1994; Coale *et al.*, 1996).

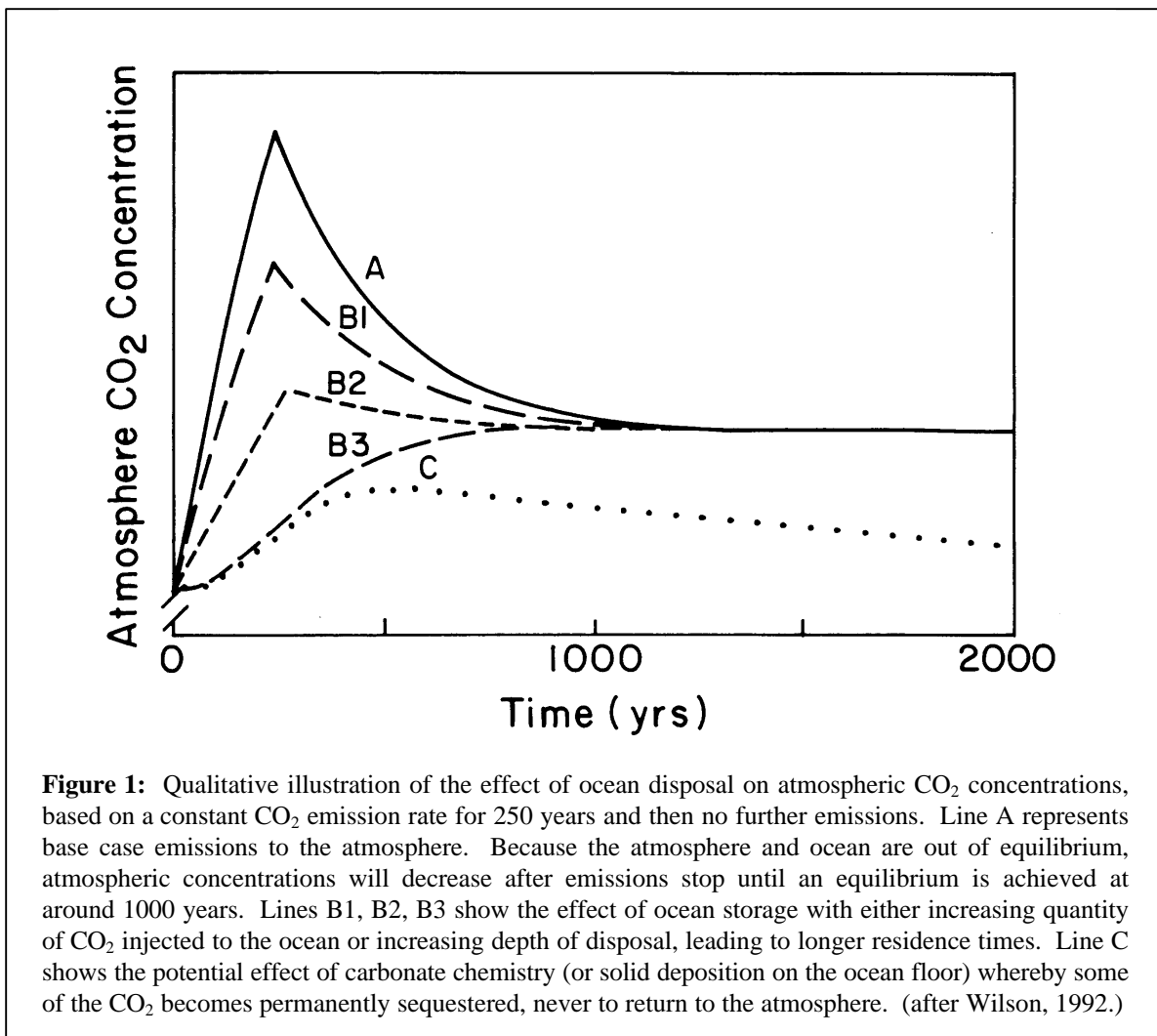
## BACKGROUND

In order to better understand the opportunities and challenges involved in direct injection of CO<sub>2</sub> into the ocean, a simplified view of the ocean and the properties of CO<sub>2</sub> are presented here. The exact temperature and density profiles in the ocean vary with season and location. In general, the vertical profile of the oceans are characterized by three strata: an upper mixed layer about 100 m deep, a thermocline region extending to about a depth of 1000 m, and a deep region. The upper mixed layer features near-constant density and temperature profiles over the depth and gaseous concentration levels in equilibrium with the atmosphere. The thermocline is stably stratified by large temperature and density gradients that inhibit vertical mixing. The deep ocean has near-constant temperatures in the range of 2-5°C. Pressure at any depth can be approximated by assuming a 1 bar pressure rise for every 10 m of depth.

At typical pressures and temperatures that exist in the ocean, pure CO<sub>2</sub> would be a gas above approximately 500 m and a liquid below that depth. In seawater, the liquid would be positively buoyant (i.e., it will rise) down to about 3000 m, but negatively buoyant (i.e., it will sink) below that depth. At about 3700 m, the liquid becomes negatively buoyant compared to seawater saturated with CO<sub>2</sub>. In seawater-CO<sub>2</sub> systems, CO<sub>2</sub> hydrate (CO<sub>2</sub>•nH<sub>2</sub>O, 6<n<8) can form below about 500 m depth depending on the relative compositions. CO<sub>2</sub> hydrate is a solid with a density about 10% greater than that of seawater.

---

<sup>1</sup> Presented at the Fourth International Conference on Greenhouse Gas Control Technologies, August 30 - September 2, 1998, Interlaken, Switzerland.



## RESEARCH CHALLENGES

In assessing strategies for implementing ocean sequestration of CO<sub>2</sub>, several key research topics need to be addressed. Some of the key areas are discussed below.

**Sequestration efficiency**, which is very site-specific, refers to how long the CO<sub>2</sub> will remain in the ocean before ultimately equilibrating with the atmosphere (see Figure 1). The use of ocean general circulation models are required to determine sequestration efficiencies. Results to date suggest that CO<sub>2</sub> can be effectively sequestered for hundreds of years or longer, depending on the exact location and depth of the injection (Dewey *et al.*, 1997).

**Environmental impacts** must be viewed at two different scales. *On a global scale*, direct injection of CO<sub>2</sub> to the ocean can be considered environmentally beneficial compared to our present trajectory. Our current anthropogenic emissions of CO<sub>2</sub> to the atmosphere will cause a gradual decline in average ocean pH of about 0.5 units over the next several centuries. Direct injection of CO<sub>2</sub> to the ocean will only perturb the system by less than another 0.1 pH unit. However, the increased acidity due to the direct addition of CO<sub>2</sub> will occur primarily in the deep ocean, while acidification of the more productive surface waters would actually be mitigated (Haugan and Drange, 1995). Furthermore, by lowering atmospheric peak concentrations and slowing their growth rates, direct injection of CO<sub>2</sub> to the ocean will reduce the chance of catastrophic events, such as the shutting down of the ocean's thermohaline circulation (Stocker and Schmittner, 1997; Broecker, 1997). *On a local scale*, the most significant environmental

impact is derived from lowered pH as a result of the reaction of CO<sub>2</sub> with seawater (Magnesen and Wahl, 1993; Kollek, 1993; Auerbach *et al.*, 1997). Carbonate dissolved in seawater and in benthic sediments at shallow depths will provide a buffer, but depending on the method of release, pH can be expected to vary from as low as 4 very near the injection point, to its ambient value of about 8. Impacts would occur principally to non-swimming marine organisms (e.g., zooplankton, bacteria and benthos) residing at depths of about 1000 m or greater and their magnitude will depend on both the level of pH change and the duration of exposure (Auerbach *et al.*, 1997). However, available data suggest that impacts associated with pH change can be completely avoided if the injection is properly designed to disperse the CO<sub>2</sub> as it dissolves (Caulfield *et al.*, 1997).

**Public outreach.** The viability of ocean storage as a greenhouse gas mitigation option will also hinge on social and political considerations. In view of public precaution toward the ocean, the strategy will require that all parties (private, public, non-governmental organizations) be included in ongoing research and debate (Kildow, 1998).

### **Box 1. IEA Ocean Disposal Workshops**

Between August 1995 and October 1996 the IEA Greenhouse Gas R&D Programme sponsored four workshops in which international experts convened to discuss the necessary steps toward demonstrating the feasibility of ocean disposal. The major conclusions of these workshops were:

**Workshop 1 -- Ocean Circulation.** Sequestration efficiency and large scale environmental impacts will depend on predictions from ocean global circulation models (OGCMs). To improve their reliability we must:

- involve the ocean modeling community more widely in the ocean storage concept.
- initiate an OGCM inter-comparison exercise on point sources of CO<sub>2</sub> in the deep ocean.
- support measurement programs which can provide validation data.

**Workshop 2 -- Environmental Impacts.** The concept of ocean storage requires that impacts to the marine environment be substantially less than avoided impacts of continued emissions to the atmosphere. To better quantify marine impacts we must:

- develop basic guidelines for biological acceptability.
- improve understanding of the physiological response of organisms through laboratory experiments under pressurized conditions and ultimately through *in situ* field experiments.
- collaborate with relevant existing marine biology research programs.
- research the impact of the business-as-usual scenario.

**Workshop 3 -- International Links and Concerns.** Global change is a worldwide problem requiring worldwide mitigation efforts and worldwide acceptance of these efforts. To facilitate this acceptance, we should:

- establish an international strategic advisory group consisting of science and technology experts, including representatives from other interest groups.
- involve other ongoing programs (e.g., International Geosphere-Biosphere Programme (IGBP), World Climate Research Programme (WCRP), IPCC).
- define processes for seeking legal and public acceptance.
- identify and involve stakeholders.
- learn from past examples.

**Workshop 4 -- Practical and Experimental Approaches.** In order to advance the concept of ocean disposal to the level of demonstrated technology, we must:

- develop experimental programs on biological impact (to gain understanding and acceptability) and near field plume behavior (to validate impact modeling).
- improve global/regional modeling to quantify benefits and identify sites.
- develop engineering solutions to refine injection options (sites, modes of discharge) and quantify costs and impacts.
- develop legal case and educate public.
- forge links with existing international science programs.

**Engineering analysis**, in terms of what technology exists and what must be developed, is an important consideration. Led in part by the oil industry, great strides have been made in undersea off-shore technology. It is becoming routine to work in depths approaching 2000 m. However, many technical challenges still exist in going deeper. At the injection point, understanding is needed of the physical-chemical interactions between CO<sub>2</sub> and seawater, including the likelihood of hydrate formation on surfaces of CO<sub>2</sub> droplets contained in droplet plumes, and the interaction between CO<sub>2</sub>-enriched seawater and stratified receiving water. Hydrates will affect mass transfer between CO<sub>2</sub> and seawater, and hence the elevation within the water column at which CO<sub>2</sub> is dissolved (Masutani *et al.*, 1995). Plume/ambient interaction will affect the elevation at which the CO<sub>2</sub>-enriched seawater is ultimately sequestered and, in particular, whether or not the plume will impact more environmentally sensitive benthic organisms. Finally, engineering analysis is required to estimate the costs of the various injection pathways.

The IEA Greenhouse Gas R&D Programme sponsored a series of four international expert workshops addressing each of the four research challenges described above. Their findings, including recommendations for further research, are presented in Box 1. A number of their recommendations have already been implemented, including an on-going OGCM inter-comparison on point sources (see Workshop 1) and an initial meeting of an international strategic advisory group (see Workshop 3). The full proceedings from these workshops are available through the IEA Greenhouse Gas R&D Programme (<http://www.ieagreen.org.uk/> or Stoke Orchard, Cheltenham, Gloucestershire, GL52 4RZ, United Kingdom).

### INJECTING CO<sub>2</sub> INTO THE OCEAN

In the near-term, a consensus is developing that the best strategy is to discharge the CO<sub>2</sub> below the thermocline at depths of 1000 - 1500 m. The technology exists today to implement such a strategy. The injection can be achieved with minimal environmental impacts. The cost is low compared to most other ocean injection strategies and is much smaller than anticipated capture costs. The major question revolves around sequestration efficiency.

To implement the above strategy, two methods of injection have been proposed. One is to transport the liquid CO<sub>2</sub> from shore in a pipeline and discharge it from a manifold lying on the ocean bottom, forming a rising droplet plume about 100 m high (Liro *et al.*, 1992). Alternatively, the liquid CO<sub>2</sub> could be transported by tanker and then discharged from a pipe towed by the moving ship (Ozaki *et al.*, 1995). Although the means of delivery are different, the plumes resulting from these two options would be quite similar and, therefore, research on these two injection methods should be considered complementary.

Another approach to CO<sub>2</sub> ocean sequestration is to inject the CO<sub>2</sub> as deeply as possible in order to maximize the sequestration efficiency. In order to accomplish this, new technology would need to be developed, with unknown costs. One such idea is to inject the liquid CO<sub>2</sub> to a sea floor depression forming a stable "deep lake" at a depth of about 4000 m (Ohsumi, 1995).

Two other ideas that have been discussed for injecting CO<sub>2</sub> include dry ice released at the ocean surface from a ship (Nakashiki *et al.*, 1991) and a dense CO<sub>2</sub>-seawater mixture created at a depth of between 500 and 1000 m forming a sinking bottom gravity current (Haugan and Drange, 1992). The former is probably too expensive due to the production and handling of dry ice, while the later has many questions concerning environmental impact due to the highly concentrated nature of its plume. Table 1 summarizes the different injection strategies outlined in this section.

**TABLE 1. Comparison of Ocean Sequestration Injection Options**

| Option               | Development Required | Cost       | Environmental Impact | Leakage to Atmosphere |
|----------------------|----------------------|------------|----------------------|-----------------------|
| Droplet Plume        | Low                  | Low        | Low-Medium           | Medium                |
| Towed Pipe           | Medium               | Low-Medium | Lowest               | Medium                |
| CO <sub>2</sub> Lake | Highest              | High?      | Low                  | Lowest                |
| Dry Ice              | Lowest               | High       | Low                  | Low-Medium            |
| Dense Plume          | Medium               | Lowest     | Highest              | Medium                |

## SELECTED RESEARCH ACTIVITIES

Listed below is a description of several recent or on-going research efforts into ocean sequestration of CO<sub>2</sub>.

**International field experiment.** Many of the important physical, chemical and biological processes related to ocean sequestration of CO<sub>2</sub> cannot be scaled, which means that more experimental research must eventually be conducted in the field. To this end, Japan, Norway, and the United States signed a Project Agreement for International Collaboration on CO<sub>2</sub> Ocean Sequestration in December 1997; since that time, Canada and ABB (Switzerland) have joined the project (Adams *et al.*, 1998). The objective of the project is to investigate the technical feasibility of, and improve understanding of the environmental impacts from, CO<sub>2</sub> ocean sequestration in order to minimize the impacts associated with the eventual use of this technique to reduce greenhouse gas concentrations in the atmosphere. The project will continue through March 31, 2002, with a field experiment to take place in the summer of 2000 off the Kona Coast of Hawaii. The implementing research organizations are the Research Institute of Innovative Technology for the Earth (Japan), the Norwegian Institute for Water Research (Norway), and the Massachusetts Institute of Technology (USA). The general contractor for the project will be the Pacific International Center for High Technology Research in Hawaii. Based on the results of this effort, a Phase II may be initiated to investigate longer-term acute and chronic biological impacts conducted at a semi-enclosed site such as a fjord.

**Near field impacts from ocean sequestration of CO<sub>2</sub>.** The MIT Energy Laboratory carried out a comprehensive analysis of near field impacts for the US Department of Energy (Auerbach, 1997; Caulfield, 1997). In that study, a methodology was developed to quantify impacts by marine zooplankton passing through a CO<sub>2</sub>-enriched sea water plume. Predicted impact depends on injection mode, with scenarios which disperse the CO<sub>2</sub> showing the least impact. The conclusion was that impacts associated with exposure to low pH can be avoided by properly dispersing the CO<sub>2</sub> and keeping the plume off of the seabed.

**The CO<sub>2</sub> ocean sequestration project in Japan.** In April, 1997, a five year national program looking at ocean sequestration of CO<sub>2</sub> began in Japan. Annual funding is in excess of 10 million USD per year. The lead research institutes for this program are the Research Institute of Innovative Technology for the Earth (RITE) and the Kansai Environmental Engineering Center (KEEC). The R&D agenda includes behavior of liquid CO<sub>2</sub> released in the ocean, an engineering system for CO<sub>2</sub> injection, impacts of CO<sub>2</sub> on marine organisms, a near field environmental impact assessment model, and participation in the international field experiment (Masuda, 1998).

**Comparison of ocean carbon cycle models.** A European research program entitled GOSAC (Global Ocean Storage and Anthropogenic Carbon) is participating in the Ocean Carbon-cycle Model Intercomparison Project (OCMIP), an international project devoted to improving marine carbon cycle models by comparing them with each other and by evaluating them using observational data sets. Thanks in part to some additional funding provided by IEA Greenhouse Gas R&D Programme, GOSAC will also look at global scientific aspects of the deep-ocean CO<sub>2</sub> sequestration issue. Specifically, they will do a model comparison of dispersion of CO<sub>2</sub> from seven hypothetical point sources in order to get a better understanding of sequestration efficiency.

**Experiments at the Monterey Bay Aquarium Research Institute (MBARI):** In April 1998, MBARI successfully carried out a controlled experiment with a 9 liter liquid CO<sub>2</sub> release at a depth of 3650 m (in-situ temperature about 1.6°C) from their ROV *Tiburón*. For several hours they imaged the hydrate formation process, obtaining some “amazing and unusual” results. A paper documenting this experiment is now in preparation (Peter Brewer, MBARI, personal communication, 1998). Earlier experiments are described in Brewer *et al.* (1988) and Brewer (1988). Future plans call for a series of biological response experiments starting in November of this year.

## CONCLUSIONS

The ocean has the largest potential as a sink for anthropogenic CO<sub>2</sub>. In order to take advantage of this opportunity, much research must be done in the areas of ocean modeling, environmental assessment, engineering analysis, and public outreach. Several significant efforts are underway, but we are just at the beginning of the journey.

## REFERENCES

- Adams E, M Akai, L Golmen, P Haugan, H Herzog, S Masuda, S Masutani, T Ohsumi and CS Wong, "An International Experiment on CO<sub>2</sub> Ocean Sequestration," these proceedings (1998).
- Auerbach DI, JA Caulfield, EE Adams and HJ Herzog, "Impacts of Ocean CO<sub>2</sub> Disposal on Marine Life: I. a toxicological assessment integrating constant-concentration laboratory assay data with variable-concentration field exposure," *Environmental Modeling and Assessment*, **2**, pp. 333-343 (1997).
- Brewer, PG, FM Orr Jr., G Friederich, KA Kvenvolden and DL Orange, "Gas Hydrate Formation in the Deep Sea: In Situ Experiments with Controlled Release of Methane, Natural Gas, and Carbon Dioxide," *Energy and Fuels*, **12**(1), pp. 183-188 (1998).
- Brewer, PG, "Experiments on the controlled release of carbon dioxide in the deep sea using ROV technology," *EOS, Transactions Am. Geophys. Union*, **79** (supplement), p.OS58 (1998).
- Broecker WS, "Thermohaline Circulation, the Achilles Heel of Our Climate System: Will Man-Made CO<sub>2</sub> Upset the Current Balance?," *Science*, **278**, pp. 1582-1588 (1997).
- Caulfield, JA, EE Adams, DI Auerbach and HJ Herzog, "Impacts of Ocean CO<sub>2</sub> Disposal on Marine Life: II. probabilistic plume exposure model used with a time-varying dose-response model," *Environmental Modeling and Assessment*, **2**, pp. 345-353 (1997).
- Coale KH *et al.*, "A massive phytoplankton bloom induced by an ecosystem scale iron fertilisation experiment in the equatorial Pacific Ocean," *Nature*, **383**, pp. 495-501 (1996).
- Dewey RK, GR Stegen and R Bacastow, "Far-Field Impacts Associated With Ocean Disposal of CO<sub>2</sub>," *Energy Convers. Mgmt* **38**(Suppl.), pp. S349-S354 (1997).
- Haugan PM and H Drange, "Sequestration of CO<sub>2</sub> in the Deep Ocean by Shallow Injection," *Nature*, **357**, pp. 318-20 (1992).
- Haugan P and H Drange, "Effects of CO<sub>2</sub> on the Ocean Environment," *Energy Convers. Mgmt* **37**(6-8), pp. 1019-1022 (1995).
- IPCC, *Climate Change 1995 The Science of Climate Change* Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change, JT Houghton, LG Meira Filho, BA Callander, N Harris, A Kattenberg and K Maskell, Eds., Cambridge University Press, Cambridge, England (1996).
- Kildow, JT, "Policy Protocols for Building a Partnership between the Public and Marine Scientists: The Ocean Sequestration of CO<sub>2</sub> Experiment," these proceedings (1998).
- Kollek R, "Carbon Dioxide Disposal: Evaluation of a Scheme for Disposing of the CO<sub>2</sub> Product from a 2 GW<sub>e</sub> Coal-Fired Power Station in the Ocean at a Depth of 500 m," IEA Greenhouse Gas R&D Programme Report IEA/93/OE13, Cheltenham, UK (1993).
- Liro C, E Adams and H Herzog "Modeling the Release of CO<sub>2</sub> in the Deep Ocean," *Energy Convers. Mgmt* **33**(5-8), pp. 667-674 (1992).
- Magnesen T and T Wahl, "Biological Impact of Deep Sea Disposal of Carbon Dioxide," The Nansen Environmental and Remote Sensing Center (NERSC) Technical Report No. 77A, Bergen, Norway (1993).

Martin JH *et al.*, "Testing the iron hypothesis in ecosystems in the equatorial Pacific Ocean," *Nature*, **371**, pp. 123-129 (1994).

Masuda S, "The CO<sub>2</sub> Ocean Sequestration Project in Japan," these proceedings (1998).

Masutani SM, CM Kinoshita, GC Nihous, H Teng, LA Vega and SK Sharma, "Laboratory Experiments on CO<sub>2</sub> Injection into the Ocean," in: *Direct Ocean Disposal of Carbon Dioxide* (Handa and Ohsumi, ed.), pp. 239-252 (1995).

Nakashiki N, T Ohsumi and K Shitashima, "Sequestering of CO<sub>2</sub> in a Deep Ocean -- Fall Velocity and Dissolution Rate of Solid CO<sub>2</sub> in the Ocean," CRIEPI Report (EU 91003), Japan (1991).

Ohsumi T, "CO<sub>2</sub> Disposal Options in the Deep Sea," *Marine Technology Society Journal*, **29**(3), pp. 58-66 (1995).

Ozaki M, K Sonoda, Y Fujioka, O Tsukamoto and M Komatsu, "Sending CO<sub>2</sub> into Deep Ocean with a Hanging Pipe from Floating Platform," *Energy Convers. Mgmt.* **36**(6-9), pp. 475-78 (1995).

Stocker TF and A Schmittner, "Influence of CO<sub>2</sub> emission rates on the stability of the thermohaline circulation," *Nature*, **388**, pp. 862-865 (1997).

Wilson TRS, "The Deep Ocean Disposal of Carbon Dioxide," *Energy Convers. Mgmt.*, **33**(5-8), pp. 627-33 (1992).