AN INTERNATIONAL EXPERIMENT ON CO_2 OCEAN SEQUESTRATION[1]

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ABSTRACT

The ocean represents the largest potential sink for anthropogenic CO_2. In order to better understand this potential, Japan, Norway, and the United States signed a Project Agreement for International Collaboration on CO_2 Ocean Sequestration in December 1997; since that time, Canada and ABB (Switzerland) have joined the project. The objective of the project is to investigate the technical feasibility of, and improve understanding of the environmental impacts from, CO_2 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. A Technical Committee has been formed to supervise the technical aspects and execution of this project. The members of this committee are the co-authors of this paper. In this paper we discuss key issues involved with the design, ocean engineering, measurements, siting, and costs of this experiment.

BACKGROUND AND MOTIVATION

One potential option to mitigate atmospheric CO_2 levels is to capture and sequester power plant CO_2. Commercial CO_2 capture technology, though expensive, exists today. However, the ability to sequester large quantities of CO_2 is uncertain. The deep ocean is one of only a few possible CO_2 disposal options (others include depleted oil and gas wells, coal beds, or deep saline aquifers), so it is important that we understand as much as possible about this strategy.

As indicated by recent international conferences on the subject (e.g., Handa and Ohsumi, 1995; Herzog, 1996; Ormerod, 1997), much has been learned about ocean CO_2 sequestration in the past half-dozen years. Of necessity, however, most of our knowledge has resulted from theoretical or laboratory studies. As we learn more, these studies must be validated and complemented with field studies.

In December 1997 an agreement was signed authorizing the first step in this direction: an international, pilot scale, field experiment scheduled to take place off of Hawaii during the summer of the year 2000. The agreement was signed by Japan, Norway and the US under the auspices of the Climate Technology Initiative under the Framework Convention on Climate Change; Canada and ABB (Switzerland) have recently joined as sponsors.

We envision a series of three types of field experiments studying ocean sequestration at increasingly larger scales. The current project focuses on ***pilot scale tests.*** The primary objective of these experiments is to learn more about the physical-chemical processes which occur between seawater and CO_2 discharged as a buoyant liquid at ocean depths of order 1000 m in order to gain insights concerning the technical feasibility of this method and to better understand any associated environmental impacts. A number of tests will be performed at an open ocean site, over

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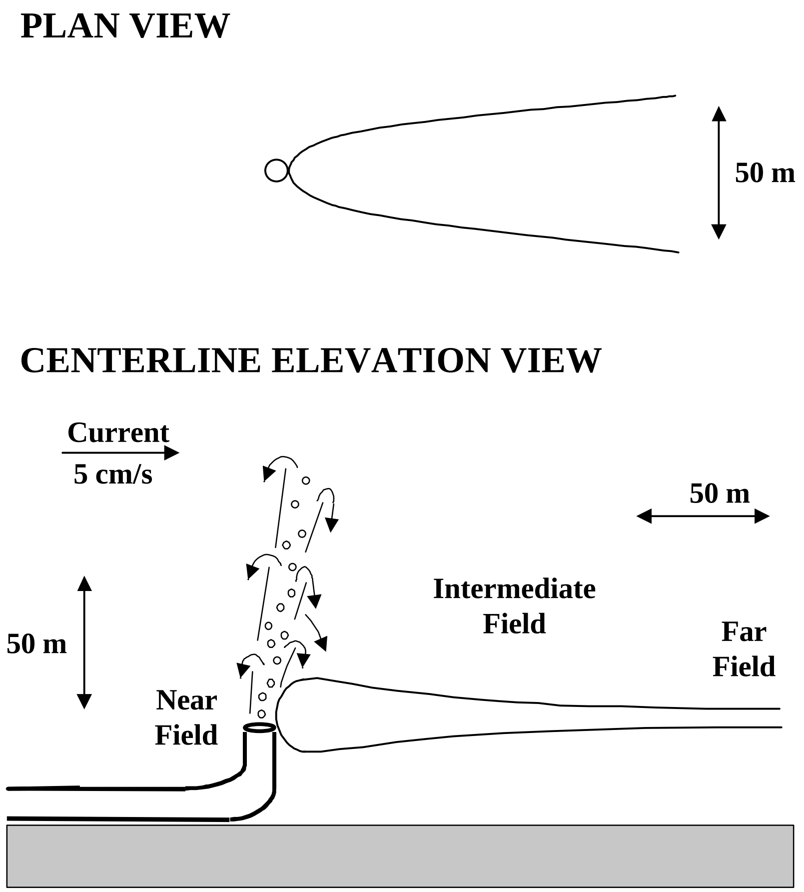
a relatively short duration (one month), and at a significantly reduced scale (e.g., with a CO_2 loading of 0.1 to 1 kg/s). Possible follow-on experiments include:

- ***Longer term tests of environmental impact.*** The second type of experiment would focus on environmental impacts--both acute and chronic, including those expected in the water column and the seafloor--associated with the CO_2 discharge. In order to constrain the spatial dimensions of the experiment, tests could be conducted in a semi-enclosed body such as a fjord, as long as the hydrographic and biological conditions were similar to those of potential open ocean sites. However, the tests would need to be conducted over a sufficient time frame to be consistent with the lifetimes of impacted organisms (e.g., at least a year for many pelagic species). Extensive measurements would need to be taken before and after the release, as well as during the CO_2 release, in order to assess both change and recovery.

- ***Full scale tests.*** Before CO_2 ocean disposal can be accepted as a commercial technology, field tests will need to be conducted at full scale. Because of the substantial costs involved in producing large quantities of CO_2, a logical step in this direction would be to conduct an open ocean experiment using a "free" source of CO_2. Possible sites include the Norwegian Sea or the Gulf of Mexico, where CO_2 produced with natural gas is routinely vented to the atmosphere.



PLAN VIEW

CENTERLINE ELEVATION VIEW

Figure 1: Views of a CO_2 plume from a pilot scale release using modeling approach of Caulfield *et al*. (1997). The modeling assumes a concentrated release of CO_2 at a rate of 1 kg/s from a single jet at a depth of about 1000 m in a stratified ambient ocean with uniform current speed of 5 cm/s. The initial droplet radius is 0.7 cm, and no account has been taken of reduced mass transfer due to possible hydrate formation. The near field, intermediate field, and far field regions proposed for experimental study are identified in the Centerline Elevation view.

EXPERIMENTAL OBJECTIVES

The major objectives of our pilot scale field experiment are to:

- better understand the physical-chemical processes affecting the transport and fate of CO_2 released as buoyant liquid droplets at water depths of order 1000 m.
- evaluate the technical feasibility of this method.
- allow development and validation of transport and fate models, which are critical in predicting environmental impact.
- help establish CO_2 delivery techniques and field monitoring methodologies that will help in future experiments.

The physical-chemical interactions which need study are described below as a function of the scale of interaction. See also Figure 1. Note that while the experiment entails releasing the CO_2 droplets from a pipe on the ocean bottom, results should be applicable to the “moving ship” concept currently being investigated in Japan (Ohsumi, 1995).

CO_2 injection and droplet formation

The CO_2 will be injected through one or more nozzles and will form droplets upon its release. Important issues for nozzle design are the distribution of droplet sizes, interactions among droplets near the nozzle (e.g., aggregation/breakup), and the possibility of hydrate clogging at the nozzle. These characteristics will depend on nozzle design and, in particular, whether the design results in a jetting or atomization mode of droplet formation. Research on this topic is underway at several laboratories including the University of Hawaii (Masutani and Nihous, 1997), but field observations are needed for verification.

Droplet dynamics

Perhaps the most important technical uncertainty with the droplet plume option is whether or not hydrates will form on the rising droplets of a turbulent droplet plume. Hydrate "skins" will affect the rate of CO_2 dissolution and droplet rise velocity. The combined effects will influence the elevation within the water column at which the CO_2 ultimately comes to rest, and hence the efficiency of sequestration. Some experimental work on hydrate formation for individual, stationary droplets in a moving flow field has been conducted recently (e.g., Hirai *et al.*, 1996), and further laboratory experiments are planned at the University of Hawaii, but conditions may be different for a collection of free droplets in a highly turbulent plume. Field measurements to test the influence of hydrate formation will include direct observations of liquid CO_2 droplets at different elevations within the plume, and indirect measurements based on the vertical extent of pH perturbations and the concentration of tracers (e.g., fluorescent dye) injected with the CO_2.

Droplet/plume interaction

The behavior of a droplet plume in a stratified ambient is complicated by the fact that the core of the plume is positively buoyant, while the edge is negatively buoyant because the plume has entrained ambient water from lower depths and because a solution of CO_2 in seawater is denser than ambient water. The heavier solution tends to peel off as the plume rises. Model predictions suggest that the location and magnitude of the peeling affects the ultimate level and thickness of the CO_2 plume (Caulfield *et al.*, 1997; Thorkildsen and Alendal, 1997), but this effect needs more rigorous study, especially in the presence of ambient currents. Some understanding can be gleaned from experiments conducted in atmospheric pressure tanks (e.g., using air bubbles in salinity-stratified tanks), but a more complete confirmation requires field testing where the physical-chemical properties of CO_2 can be simulated at realistic pressures. Field tests will consist of observations of the plume flow field using video cameras, as well as 3-D velocity measurements. Additional measurements may be taken inside and outside the plume of other properties such as pH and the concentration of injected tracers (e.g., fluorescent dye).

Intrusion dynamics

Once CO_2-enriched water peels from the plume, it is expected to sink while intruding into the stratified ocean. Because of ambient density stratification, the CO_2-enriched seawater collapses vertically and spreads horizontally as it is advected by ocean currents. The intrusion is complicated by multiple peelings from the same plume, and multiple plumes from a multi-port injection. Theoretical and experimental data are available to describe gravitational intrusion under idealized conditions (e.g., mass injected at a point in a linearly stratified, or a two-layer ambient; Akar and Jirka, 1995) but field validation is necessary. Properties to be measured include the width and thickness of the intrusion layer as a function of distance from the injection. These properties will be determined by measuring pH and the concentration of an injected tracer. Vertical profiles of velocity at various positions will also help establish the lateral extent of the intruded plume.

Ambient diffusion

At some distance from the point of injection, gravitational spreading will effectively cease, but the CO_2-enriched seawater will continue to diffuse due to passive ocean turbulence. Although much slower than plume-induced mixing near the point of injection, ambient diffusion is important for diluting plume contaminants and hence determining the distances required for plume concentrations and pH to return to background levels. Indeed, model sensitivity studies suggest that ambient diffusion is one of the most important variables affecting the impact on zooplankton passing through a CO_2-enriched plume (Adams *et al.,* 1997).

Many field experiments have been conducted to measure horizontal and vertical ambient diffusion in near surface waters (e.g., Okubo, 1971), but fewer data are available to describe such mixing at greater depths. Of particular importance would be measurements near the sea floor, where ambient turbulence (particularly in the vertical) may be considerably enhanced due to the proximity of the bottom boundary layer (Thorpe *et al*., 1990). Several recent experiments with SF_6 have shown an influence of boundary mixing (Ledwell and Hickey, 1995; Ledwell and Bratkovich, 1995), and a recent near bottom tracer observation by CRIEPI has shown enhanced vertical mixing in very deep waters off the coast of Japan. However, additional measurements conducted near the bottom of the thermocline where we anticipate injecting the CO_2 would be helpful.

SITE SELECTION FOR PILOT SCALE EXPERIMENTS

A number of factors were considered in selecting a site. The four most important were:

- ***Proximity to deep water***. The site needs to have relatively deep water (i.e., 1000 m depth) in close proximity to shore (i.e., <10 km) in order to minimize the costs of transporting CO_2 from shore.
- ***Representative hydrography***. The vertical profile of temperature and density gradient should be representative of ocean sites where a "real" CO_2 injection might someday occur.
- ***Shoreline support facilities***. The site should have the infrastructure to handle large CO_2 tanks, be near transportation facilities for emergency supplies, be able to house researchers, and, most importantly, have trained personnel to support the experiment.
- ***Licensing considerations***. Although the environmental impacts of the pilot scale CO_2 experiment will be negligible, permission to conduct the experiment must be obtained from appropriate jurisdictions.

We reviewed several sites adjacent to deep water which have been considered previously in connection with Ocean Thermal Energy Conversion (OTEC) plants. These sites, and the approximate distance from shore to water of a depth of 1000 m, included: the Kona coast of the big island of Hawaii (3 km); Punta Tuna in southeastern Puerto Rico (4 km), the north shore of St. Croix, US Virgin Islands (3 km), the west coast of Mexico (5 km), the west coast of Luzon, Philippine Islands (6 km) and Guam (7 km). Waters off the northeast coast of Bermuda were also strongly considered; although 1000 m is not reached until a distance of about 12 km, the Bermuda Biological Station for Research (BBSR) could supply excellent shoreline support. We ultimately chose the Hawaiian site, in large part because of the strong technical and scientific support from the University of Hawaii, the Natural Energy Laboratory of Hawaii Authority, and the Pacific International Center for High Technology Research.

We also looked into oil rigs in the Gulf of Mexico, some in water depths approaching 1000 m. Some of the shallower rigs are abandoned and are currently being used for marine research. However, oil companies were understandably reluctant to give us permission to share any of the active rigs which were located in deeper water.

Finally, we considered conducting our experiments in a deep fjord, where water depths tend to drop off rapidly and conditions are generally calmer than the open ocean. A survey of Norwegian fjords (Golmen *et al*., 1997) indicates that several have sufficient depth. However, fjords were not pursued in great detail for this initial pilot test because of the possible delay in obtaining required environmental permits.

EXPERIMENTAL DESIGN

Scale of the experiment

The scale of the experiment refers to the duration of tests and the magnitude of the CO_2 loading. We envision a series of approximately 10 tests, each lasting from several hours to a day, performed over a period of several weeks.

The CO_2 loading should be sufficient for full scale simulation of a single nozzle; as such, loadings in the range of 0.1 to 1.0 kg/s are contemplated. The loading from a 500 MW_e coal-fired power plant is about 130 kg/s (Herzog *et al*., 1996), so these tests will simulate the behavior from one nozzle out of an array of 100 to 1000 nozzles serving a large power plant.

CO_2 will be released from sufficient depth so that the liquid CO_2 droplets will dissolve before they rise to about 500 m, where they would flash into a vapor. To allow for the study of relatively large droplets with possible hydrate skins, a discharge depth of 700-1000 m is envisioned. It is desirable to discharge the CO_2 from at least two elevations above the ocean floor in order to observe the influence of the bottom boundary layer on plume transport and mixing.

While the CO_2 injection, droplet formation, and droplet dynamics will be simulated at full scale, the processes of droplet/plume interaction, intrusion dynamics and ambient diffusion will clearly be reduced in scale. The choice of CO_2 loading reflects a trade-off between measurement resolution (i.e., the ability to detect the CO_2 at various distances from the injection) and the cost of supplying CO_2. The cost of CO_2, including transportation and storage, could be as high as $500 per tonne. At a loading of 1 kg/s, ten experiments, each lasting eight hours, would require about 300 tonnes of CO_2 costing $150,000.

CO_2 Delivery

We considered the following options for discharging CO_2 at a depth of 1000 m.

- from a pipe constructed along the ocean bottom.
- from a vertical pipe attached to an oil platform.
- from a pipe towed by a ship or barge.
- from a submerged tank.

A bottom pipeline was selected as the easiest option because the CO_2 would be handled on shore, and any troubleshooting of the delivery system could be conducted before the start of the experiments, minimizing interruptions to researchers and research vessels on site. In addition, the pipe will be semi-permanent, allowing follow-on tests to be conducted if desired. Electrical and fiber optic cables harnessed to the pipe will bring electricity to the terminus, and allow monitoring of the plume from shore.

The distance from shore to the pipe terminus at the Hawaiian site is about 3 km. A pipe designed to deliver CO_2 at a rate of 1 kg/s over this distance requires a diameter of about 3-5 cm and, in order to avoid phase changes, must withstand pressures as high as 170 bar. Steel pipe of the appropriate strength and flexibility is available commercially in lengths up to 10 km, coiled on large diameter reels. The typical cost of such a pipe is less than $10,000 per km, but the larger cost comes in pipe deployment which requires the support of a pipe laying ship or barge and possibly a submersible to help anchor the pipe, attach risers, etc. Traditional pipe laying involves attaching straight pipe sections, but because of the small pipe diameter, the coiled pipe will simply be unreeled. We are currently comparing the various options which include:

- reel on shore, end of pipe fixed on vessel, pipe unreels as vessel moves away from shore;
- reel on vessel, end of pipe fixed on shore, pipe unreels as vessel moves away from shore;
- reel on vessel, end of pipe fixed at sea terminus, pipe unreels as vessel moves toward shore;

To test the performance of different nozzles, and the effect of discharge at different heights above the bottom boundary layer, a riser system will be attached to the end of the pipe. A manifold will allow the nozzles to branch from the riser and be controlled remotely by solenoid valves. Anti-back flow valves installed near the nozzles and an "electric blanket" will prevent seawater from intruding into the risers and potentially clogging the pipe with hydrates.

Measurements

Below we subdivide our experiments into three sub-sets encompassing the near, intermediate and far fields. See Figure 1 for approximate dimensions for a pilot scale experiment. While these experiments address the objectives of a "first experiment", we remain open to participation by other researchers who may avail themselves of the basic set-up to perform complementary studies.

- ***Near field experiments*** would be designed to test nozzle designs and observe droplet behavior. Observations will be made with a system of lights and tilt/pan video camera mounted on the seafloor near the diffuser section.
- ***Intermediate field tests*** will study droplet/plume interaction and intrusion dynamics at distances of order 100 m downstream from the discharge point. The principal measurement platform will be a remotely operated vehicle (ROV) which can maneuver precisely along a three-dimensional survey path measuring parameters such as pH, plume velocity, and concentrations of fluorescent dye. We will also collect discrete water samples which will be analyzed for temperature, salinity, and carbon chemistry aboard a supporting research vessel. Vertical arrays of pH sensors and an acoustic doppler current profiler will document ambient conditions.
- ***Far field experiments*** will measure ambient diffusivity. For the range of experimental release rates being considered, excess CO_2 concentrations, and hence perturbations in pH, will be too small to detect after several days. Hence, we plan to inject and measure a fluorescent tracer *in situ* with the aid of a sonar drifting buoy.

SCHEDULE

Our project began in December 1997 and will formally last through March 2002. A technical committee comprised of members of the participating countries (and co-authors of this paper) meets twice a year and reports bi-annually to a steering committee representing the project’s sponsors. Our first task was site selection, which was completed in early 1998. Background surveying of bathymetry and currents will start in early 1999. Design of all measurement systems will be completed in 1999, and the actual experiments will be conducted in the summer of the year 2000. The remaining time will be spent analyzing the data and documenting our results.

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