UPDATE ON THE INTERNATIONAL EXPERIMENT ON CO_2 OCEAN SEQUESTRATION

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ABSTRACT

The specific objective of our project on CO_2 ocean sequestration is to investigate its technical feasibility and to improve the understanding of any associated environmental impacts. Our ultimate goal is to minimize any impacts associated with the eventual use of ocean carbon sequestration 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 2001 off the Kona Coast of Hawaii. At GHGT-4 in Interlaken, we presented a paper detailing our plans. The purpose of this paper is to present an update on our progress to date and our plans to complete the project. The co-authors of this paper are members of the project's Technical Committee, which has been formed to supervise the technical aspects and execution of this project.

OVERVIEW

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 option.

In December 1997 an agreement was signed by Japan, Norway and the US under the auspices of the Climate Technology Initiative under the Framework Convention on Climate Change to conduct an international field experiment for ocean carbon sequestration. Australia, Canada, CRIEPI (Japan) and ABB (Switzerland) have subsequently joined as sponsors. The authors of this paper represent the Technical Committee of this project. Two years ago at GHGT-4, we described the plans for this experiment (Adams *et al.*, 1999). In this paper, we present a progress report.

BACKGROUND

The two most discussed strategies for ocean carbon sequestration are direct injection of CO_2 into the deep ocean and iron fertilization. These two techniques have very different sets of technical and environmental challenges. Our effort is solely focused on the direct injection approach. In this method, liquid CO_2 is injected in the deep ocean, forming a buoyant plume. Sea water will be entrained into the rising droplet plume and transported upward to heights where the ambient water is less dense. Dissolution of CO_2 increases the density of the seawater in the plume. A thin, solid hydrate phase may form on the droplet surface that impedes, but does not prevent dissolution. At various points in its ascent, heavy, CO_2-enriched seawater peels away from the plume and subsides to a level of neutral buoyancy. This CO_2-enriched sea water subsequently is diluted and dispersed by ocean turbulence and currents. We are interested in the physics of the plume process (e.g., rise height, peeling process), CO_2-seawater chemistry (e.g., hydrate formation, CO_2 dissolution rates), the perturbations (e.g., pH changes), and the biological and ecological impacts.

In the laboratory, we can study plume physics at atmospheric pressures using a variety of fluids (e.g., oil or air discharged into seawater). However, to study the CO_2 dissolution and chemistry, we need high pressure tanks (over 50 bar). These exist on a small scale, but are not large enough to study plume dynamics. Therefore, a field experiment is required to simultaneously study the physics, chemistry, and biology of this process.

We envision that a series of field experiments will be required to obtain the knowledge to understand the potential for and the impacts of direct injection of CO_2 into the deep ocean. This first experiment was designed for small CO_2 discharges, which will result in minimal perturbations. A primary objective of this initial field experiment 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. This will let us predict how injection parameters (e.g., droplet sizes, flow rates) affect perturbations, which in turn impact on the biology and ecosystems. It is our hope to be able to engineer CO_2 injection systems to have minimum impacts.

We anticipate that 50-100 tonnes of liquid CO_2 will be released over a period of a week in a series of experiments. While this is a minimal amount to be able to see plume effects, it is significantly larger than any previous efforts. Most experiments will last several hours with CO_2 injection rates between 0.1 and 1.0 kg/s. Being the first experiment, we designed the scale to be as small as possible, but still resulting in perturbations we can measure. However, detecting biological changes will be much more difficult. Nonetheless, we have designed a biological component into this experiment.

As part of this project, we are preparing a proposal for future field experiments. Specifically, we are considering a type of experiment which 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. 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.

OCEANOGRAPHIC SURVEY

The location of the this first field experiment (contingent on receiving the necessary permits) will be about 3 km offshore of the Natural Energy Laboratory of Hawaii Authority (NELHA) at Keahole Point on the Kona coast of the Island of Hawaii. An oceanographic survey of the experimental site was conducted during the first week of August 1999. The objectives of the survey were: (1) to document the background currents and sea water chemistry and density, and to assess spatial and temporal variations of these quantities; (2) to investigate ambient bacterial production rates and their response to pH variations; (3) to characterize the local benthic communities; and (4) to evaluate the performance of three methods to measure pH: a conventional glass electrode on the CTD; a novel IS-FET (ion specific field effect transistor) instrument; and shipboard photometric analysis of sea water samples. Accurate and reliable measurements will be critical during the injection experiments, since pH is a primary indicator of the released CO_2.

During the survey, a series of CTD casts were performed and samples of seawater and sediment were collected for analysis. Two bottom-moored instrument arrays consisting of current meters and IS-FET pH sensors were deployed and retrieved after one month. These instruments recorded time histories of currents and pH over the period that they were submerged (Sundfjord and Golmen, 2000; Sundfjord *et al.*, 1999). A follow-up survey is scheduled for the fall of 2000.

EXPERIMENTAL INFRASTRUCTURE

The original concept for this experiment was to inject the CO_2 from shore through a pipe installed along the ocean bottom. This would allow the CO_2 to 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. Electrical and fiber optic cables harnessed to the pipe would bring electricity to the terminus, and allow monitoring of the plume from shore. The distance from shore to the pipe terminus at a depth of 800 m 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. 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.

As planning proceeded, several problems were encountered, which led to increasing costs. These included protecting the pipe in the surf zone, navigating around a coral reef, and negotiating an underwater cliff. Also, the system had to be designed for retrieval after the experiment was complete. Finally, with a bottom-mounted pipe, there was no opportunity to make repairs or modifications to the diffuser system during the experiment.

In response to the rising costs and other concerns about a bottom-mounted pipe, an alternative CO_2 discharge system has been adopted. We will now inject the CO_2 from a supply ship, which will house the CO_2 storage tanks and pumps. Coiled steel tubing will still be used to transport the CO_2 to depths of 800 m. At the end of the pipe will be a diffuser assembly, which will sit on the ocean floor. We will rest about 200 m of pipe on the ocean floor (see Fig. 1) to avoid entanglements with the ROV that will make measurements near the diffuser. While we will design this experiment to minimize the number of times we need to raise and lower the diffuser, it does allow us to make changes and repairs while at sea. We concluded this approach reduces both risk and cost compared to the original concept of the bottom-mounted pipe.

The delivery of a steady flow of liquid CO_2 to depths of 800 m gives rise to several engineering challenges in the area of flow control. The CO_2 will be liquid at the discharge point (pressure of 80 bar, temperature about 5°C). However, surface temperatures will make CO_2 a gas, resulting in two-phase flow in the pipeline. In general, it is much easier to control one-phase flow in pipes as opposed to two-phase flow. We can avoid two-phase flow in the pipe by pressurizing CO_2 at the pipe inlet to above its critical pressure of about 73 bar (this is how commercial CO_2 pipelines work). However, when we compress the inlet CO_2 to such a high pressure, it may result in large pressure drops (tens of bars) at the discharge point, which can complicate the nozzle design.

Regardless of whether we design for one-phase or two-phase flow, keeping a steady outlet flow will be difficult. CO_2 is a compressible fluid, so if we control the flow at the inlet, it is not necessarily the same flow at the outlet over one km away. While this may not be a problem for commercial operations, for a controlled experiment we need a steady, measured flow rate. As a worst case scenario, oscillatory flow may develop in the pipe with a frequency on the order of minutes. One way to avoid this problem is to meter the flow at the outlet (at 800 m under the sea), but this complicates the equipment design.

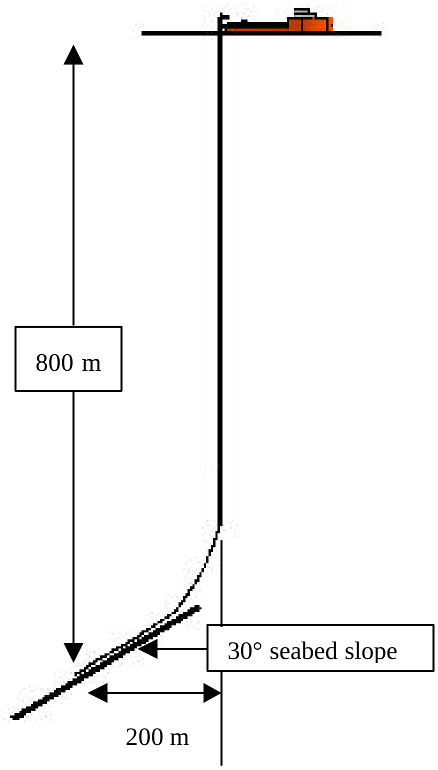

Figure 1: Schematic of layout for the field experiment, where CO_2 will be released at a depth of about 800 m from a supply ship.

Although anti-backflow valves will be installed immediately upstream of the nozzle discharge ports to prevent ingress of sea water, and the submerged conduit will be filled with dry gas during deployment, it is possible that some moisture will eventually intrude into the system. When CO_2 is dispersed in sea water, the hydrate phase typically is limited to a thin, often transient, film at the interface between the two fluids. When sea water is dispersed in CO_2, however, complete conversion of the water into a solid, stable hydrate crystal often occurs. In the present application, this may lead to blockage of the pipeline or nozzle assembly. Procedures are being developed to minimize the possibility of hydrate blockage during the field experiment. These procedures include purging and drying the inside of the pipeline after deployment with nitrogen gas and heating the nozzles when starting and terminating the flow of CO_2. If hydrate blockage does occur, it can be cleared by reducing system pressures by raising the diffuser assembly.

One final concern is what happens when the pipe is rapidly depressurized. If the CO_2 in the pipe is vented, it will flash into vapor and dry ice. The dry ice will plug the pipe and could take a substantial time (over a day) to sublimate. This type of delay is unacceptable, so procedures must be worked out to depressurize quickly without forming dry ice. Dry ice can be avoided if enough heat is added as we depressurize.

Members of the project team are conducting laboratory experiments to address flow instabilities, flow rate control, and hydrate blockage issues. Tests are being performed in pressure facilities at the Southwest Research Institute and the University of Hawaii.

EXPERIMENTAL DESIGN AND MEASUREMENTS

Data will be obtained on changes induced in sea water chemistry by the release of pure CO_2. A preliminary sampling of biota and a study of the effects of the discharged CO_2 on naturally occurring bacteria populations also are planned. This information will be directly applied to the development of models to assess marine environmental impact. The experimental objectives are:

- to investigate CO_2 droplet plume dynamics through qualitative flow visualization (using mobile video cameras) and quantitative measurements of velocity and pH in the plume and on its margins.

- to clarify the effects of hydrates on droplet dissolution through visualization of the droplet phase and measurements of the vertical extent of droplet rise using scalar indicators such as pH.

- to trace the evolution of CO_2-enriched sea water that peels from the plume by performing a three-dimensional mapping of the velocity and relevant scalar (pH and DIC) fields.

- to assess potential impacts on marine biota by quantifying variations in bacterial biomass, production, and growth efficiency associated with induced changes in seawater pH. We are hoping to expand this biological component to include impact studies on bottom living animals, sediments, and detritus by sampling and observations and on plankton by acoustic backscatter (ADCP) measurements, observations and sampling.

Data will be collected employing both fixed and mobile diagnostics. A research vessel (separate ship from the CO_2 supply vessel) will house an ROV (remotely-operated vehicle) and allow for CTD casts. A video system mounted on an ROV will provide flow images of the CO_2 droplet plume. Instruments will be moored on the sea floor along with the ROV transponders to monitor ambient conditions. These instruments will include pH sensors and acoustic current profilers. Detailed mapping of the scalar and velocity fields will be performed utilizing ROV-mounted instruments. The ROV will collect data along a three dimensional survey path through the droplet plume and the region of CO_2-enriched sea water generated by the discharge. The mobile instruments package has not been finalized but will include conventional salinity, temperature, and pH probes, as well as a modified ADV (acoustic Doppler velocimeter) to obtain point measurements of fluid velocities to evaluate turbulence structure. Water and sediment samples will be collected for chemical and biological analysis and CTD casts will be performed to supplement the data obtained with the moored arrays and ROV.

PERMITTING AND PUBLIC OUTREACH

In the U.S., the process of obtaining permits for CO_2 ocean sequestration activities is complicated by the issue of overlapping jurisdictions. In the case where CO_2 is transported to the deep ocean through a pipeline from shore, a host of regulatory agencies from the local, state, and federal governments will be involved in the permitting process. In general, the local government has authority down to the shoreline, the state government to a distance three nautical miles offshore, and the federal government beyond this point. For this reason, there seems to be potential advantages in avoiding the bottom mounted pipeline that crosses all three zones in favor of CO_2 injection from a ship. Currently, we are preparing applications to the appropriate agencies for submission by early summer. We hope to have approval by the fall.

The present field experiment is one of the first projects to bring the CO_2 ocean sequestration concept into full public view. The local community has responded in a variety of ways ranging from indifference to support to opposition. One concern is that the CO_2 will seriously harm marine biota. The possible impacts on marine organisms by injected CO_2 are a valid concern. Members of the research team have been attempting to communicate to the public that a primary objective of the project is to make a contribution towards evaluating these types of environmental issues. At the levels of CO_2 injected in this experiment, we do not expect to cause any harm to the marine biota. However, we will make biological observations to check the response.

Other concerns have been brought up about whether sequestration is an appropriate response to climate change concerns. We feel this reasoning is misguided as an argument against research. As scientists, we feel it is important not to be advocates. Our mission is to be objective in our work and research the facts so as a society we can make informed decisions. We feel that climate change presents enormous challenges and we will need a multi-faceted approach in our solution. It is too early in our understanding of climate change to rule out possible solutions. Since sequestration is being seriously considered as a mitigation option, it is to everyone's advantage to better understand its implications.

In order to better inform the public, an outreach effort is being pursued to educate the community about the project, CO_2 sequestration, and global climate change. Meetings with individuals and groups are underway. A web site has been established to disseminate information. The project has a policy of full disclosure and recommendations by the public regarding the scope and design of the experiment are considered. It has become clear that public outreach should be an important component of any existing or future CO_2 sequestration R&D program.

For more information about the project, we invite you to visit our web site at <www.co2experiment.org>

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