INTERNATIONAL COLLABORATION ON CO_2 SEQUESTRATION

2nd Annual Report
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The main focus of our work during this time period was to carry out laboratory and numerical studies on CO_2 plumes to support the experimental design, as well as to work with the international team through the technical committee (TC) to help design the infrastructure and the scientific plan for the field experiment.

During this period, key events included:

- 4th TC Meeting, October 4-5, 1999 in Cambridge, MA hosted by MIT.
- 5th TC meeting, March 6-8, 2000 in Nagasaki Japan. Attended by Howard Herzog and Eric Adams.
- 6th TC meeting, August 9-10, 2000 in Cairns Australia. Attended by Howard Herzog and Eric Adams and Scott Scolofsky.
- The Fifth International Conference on Greenhouse Gas Control Technologies (GHGT-5) held August 13 - 16, 2000 in Cairns Australia. A paper on this project was presented.

This report is directed into five main components:

I. Paper giving project overview presented at GHGT-5, August 2000 (pages I.1 — I.6)

II. Paper summarizing our laboratory studies on plumes

III. Paper summarizing our laboratory studies on plumes

IV. Preliminary Design for Injection of CO_2 from a Ship (pages IV.1 — IV.17)

V. Our input into the Field Experiment Design (pages V.1 — V.3)

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^oC). 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.

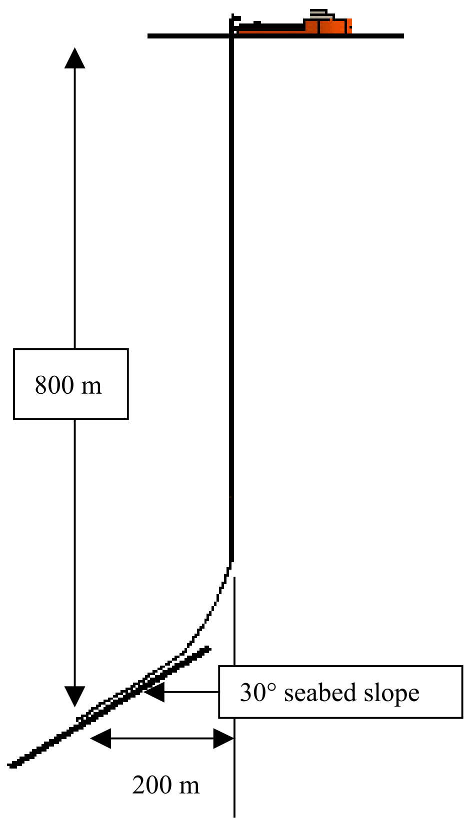

Figure 1: Schematic of layout for the field experiment, where CO_2 will be released at a depth of about 800 m from a supply ship.

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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Bubble and Droplet Plumes in Stratification 1: Laboratory Studies

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1. Abstract

This paper describes laboratory experiments of steady-state plumes in linear stratification driven by a buoyant dispersed phase, such as bubbles or droplets. The experimental results are applied to deep-ocean plumes, where bubble expansion is negligible over the natural length scale of the plume and the depth can be neglected. Experimental techniques include visualization using LASER-induced fluorescence and flow quantification using pre- and post-profiles of salinity and dye tracer. Plume behavior (known as plume Type) and intrusion depths and fluxes are correlated with U_N, the ratio of the bubble slip velocity, u_s, to the characteristic plume fluid rise velocity, $(BN)^{1/4}$, where B is the buoyancy flux and N is the Brunt-Vaisälä buoyancy frequency.

2. Introduction

Recent interest in bubble and droplet plumes resulting from proposed carbon dioxide sequestration (Adams et al. 1997) and potential oil-well blowouts (Yapa & Zheng 1999) requires a better understanding of the behavior of multi-phase plumes in the deep ocean (> 800 m). As these plumes rise, they experience a linear ambient stratification, forming a layered system of intrusions as the dense, entrained fluid periodically separates, or peels, from the rising bubble column. This and the companion paper (Crounse et al. 2000) help predict the potential environmental impacts of these plumes by studying the dynamics of the detraining fluid.

An important feature of deep-ocean droplet plumes is that bubble expansion is negligible over the characteristic plume length scale, and plume behavior should be independent of the depth, H. Much of the existing analysis of multi-phase plumes, however, derives from reservoir destratification and aeration (e.g. Asaeda & Imberger 1993, Lemckert & Imberger 1993, Baines & Leitch 1992, Wüest et al. 1992, McDougall 1978, Kobus 1968), where H is typically of the order of the atmospheric pressure head, H_A = 10 m. As a result, bubble expansion has always been included as an important process affecting plume dynamics, and existing correlations present plume characteristics as functions of H.

This paper presents a dimensional analysis to find correlation parameters independent of H and presents laboratory experiments to extend and support the new parameters. The laboratory experiments were conducted with air bubble and oil droplet plumes in a 1.2 m square by 2.4 m tall tank. Fluorescent dye tracer marked the levels of intrusion. By measuring changes in the dye and salinity profiles during an experiment, pumping rates into the intrusion layers were quantified. The companion paper uses these results to calibrate an integral model and apply it to a prototype CO_2 sequestration scenario.

3. Dimensional Analysis

We would like to predict three plume descriptors: the trap heights of intrusions, the volume fluxes (dilution) into the intrusions, and the characteristic plume behavior. We use trap height as the dependent variable in this section to illustrate the dimensional analysis. A similar analysis could also be conducted

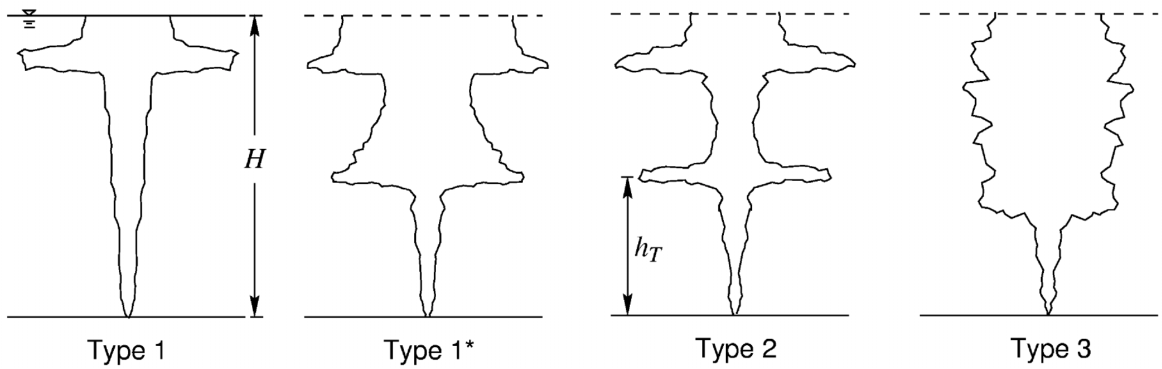

Figure 1. Schematic of characteristic two-phase plume behavior in stratification.

for the intrusion layer flux (we present the result in Section 6). Characteristic plume behavior extends the work of Asaeda and Imberger (1993) for reservoir plumes in which three plume types were defined (see Figure 1): Type 1 plumes have no intermediate intrusion (only a surface intrusion), Type 2 plumes have one or more distinct sub-surface intrusions, and Type 3 plumes have continuous detrainment forming a random, finger-like set of intrusions. The dimensionless variables identified in this section are used in Section 5 to differentiate among plume types.

Starting simply, consider a single-phase plume in linear stratification. The important independent variables are the buoyancy flux, B, and the stratification frequency, $N = [-(g/\rho)(\partial\rho/\partial z)]^{1/2}$. We are interested in predicting the trap height, h_T. The characteristic plume length scale, l_C, is formed from B and N, yielding $l_C = (B/N^3)^{1/4}$. Normalizing h_T by l_C, we obtain the first non-dimensional group

$$\pi_1 = \frac{h_T}{(B/N^3)^{1/4}}. \tag{1}$$

Morton et al. (1956) reported the relationship $\pi_1 = 3.8$, and Turner (1986) verified its applicability from laboratory scales up to the scales of forest fires and volcanic eruptions.

Turning to the simplest multi-phase flow, consider an inverted, sediment plume where particle expansion and dissolution are negligible. This introduces two-phase plume physics without the complications of bubble expansion. Several sediment characteristics are important, including size, density, shape, and possibly cohesion. Since the slip velocity (or terminal fall velocity), u_s, is itself a function of these parameters, we assume that u_s incorporates the important two-phase characteristics affecting the plume. This is similar to the assumption as initiated by Kobus (1968). The characteristic plume fluid rise velocity, u_C, can be formed from B and N, yielding $u_C = (BN)^{1/4}$. Normalizing u_s by u_C provides a second non-dimensional group

$$\pi_2 = U_N = \frac{u_s}{(BN)^{1/4}}. \tag{2}$$

Since π_2 is a non-dimensional slip velocity, we define the new parameter $U_N = \pi_2$. The Buckingham Π theorem states that $\pi_1 = f(U_N)$; this hypothesis is tested in Section 5.

Completing the dimensional analysis, we add bubble expansion. For ideal gas behavior, the important parameter is H. Normalizing H by l_C gives

$$\pi_3 = \frac{H}{(B/N^3)^{1/4}}. \tag{3}$$

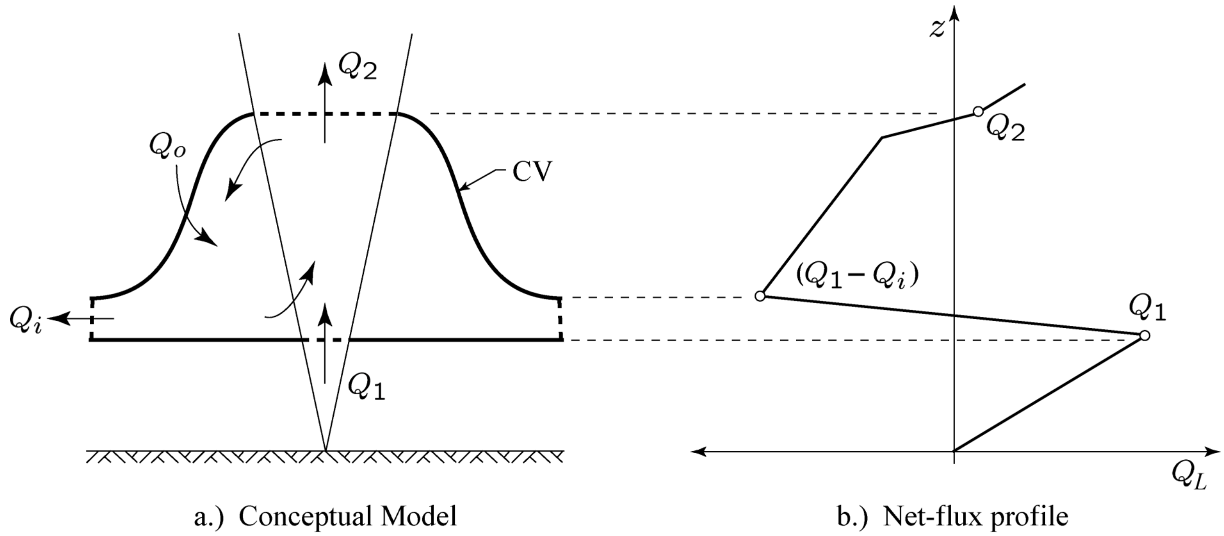

Figure 2. Schematic of a two-phase plume showing the control volume used to calculate the intrusion layer flux. Q_L is the net flux integrated across the plume; other variables are as defined in the figure.

The expression for π_3 indicates the length scale over which bubble expansion should be significant to impact the plume dynamics. Although H has always been included in correlation equations, most of the existing data for trap height do not have significant bubble expansion over the length scale l_C. As a result, the final relationship $\pi_1 = f(U_N, \pi_3)$ cannot be verified with existing data, and our continued analysis will correlate plume quantities with U_N alone.

4. Methods

Since the laboratory tank is only 2.4 m tall, bubble expansion was negligible in our lab as it is in the deep ocean. The tank was stratified with salt using the two-tank method, creating a linear density profile from 1027 Kg/m^3 on the bottom to 1003 Kg/m^3 at the surface (N = 0.3 s^{-1}). Salinity profiles were recorded using either a Head micro-scale conductivity and temperature (CT) probe or an Ocean Sensors OS300 CT probe, both mounted to a 2.8 m long linear actuator, allowing a resolution of less than 1 cm. Rhodamine 6G fluorescent dye tracer was injected at the base of the plume using a collar diffuser at a rate of about 0.1 mg/s. Dye profiles were recorded using a Chelsea in-situ field fluorometer connected to an Ocean Sensors OS200 conductivity, temperature and depth (CTD) probe. A 6 W argon-ion LASER connected by a fiber optic cable to a cylindrical lens illuminated a 1.5 cm-thick slice through the centerline of the plume. Images were captured at variable framing rates using a computer framegrabber and a 2.5" progressive-scanning CCD camera. Using cutoff filters on the camera, images could be obtained of just the dye, just the bubbles, or both.

The trap height of each distinct intrusion was measured directly from the dye profiles, taking the intrusion depth as the height of maximum dye concentration within each layer. Horizontal gradients of dye tracer were removed by diffusion within about 6 hours following an experiment. Horizontal homogeneity was guaranteed by comparing profiles from each corner and from the middle of the tank.

To quantify plume volume fluxes, salinity profiles before and after an experiment were analyzed. Internal waves prevented the analysis of salinity profiles taken during and immediately after the experiment. From the transport equation for salt in a closed container, Baines & Leitch (1992) show that the net flux integrated across the plume, Q_L, is given by

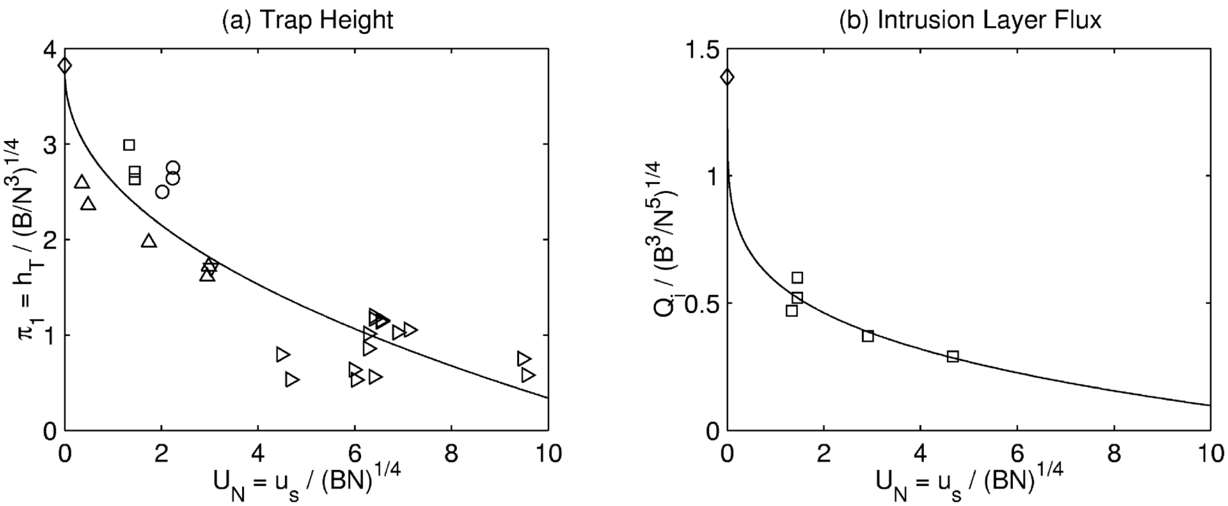

Figure 3. Dependence of trap height and intrusion layer flux on slip velocity plotted in non-dimensional space. Up and down triangles are from Reingold (1994), circles are from Asaeda & Imberger (1993), right-pointing triangles are from Lemckert & Imberger (1993), and squares are the authors' experiments.

$$Q_L = A \frac{\partial \rho / \partial t}{\partial \rho / \partial z} \tag{4}$$

where A is the cross-sectional area of the tank, ρ is the ambient density, and t and z are the time and space coordinates, respectively. To quantify the volume flux into the intrusion layer, the control volume (CV) defined in Figure 2 was used with the conservation of mass equation. From the figure we have

$$Q_i = Q_1 - (Q_1 - Q_i)\ . \tag{5}$$

Using this CV, the complicated interaction between the upward rising plume core and the downward flowing intrusion layer can be neglected. The numerical model presented in the companion paper discusses this interaction in more detail.

Plume type was evaluated from the flow visualization. Section 5 compares the results to the non-dimensional variables defined above.

5. Results

Figure 3a shows the dependence of trap height on slip velocity using our own laboratory data together with data from Reingold (1994), Asaeda & Imberger (1993), and Lemckert & Imberger (1993). The curve plotted in the figure is the least-squares fit of $\pi_1 = 3.8 - aU_N^b$, where $a = 1.2$ and $b = 0.5$. The data in Figure 3a span both laboratory and field-scale experiments and indicate that U_N explains the dominant variation in π_1. The intrusion depth is reduced in a multi-phase plume because the intruding water looses a significant amount of buoyancy when it separates from the bubbles or droplets.

Figure 3b shows the dependence of the intrusion layer flux for the first intrusion with slip velocity for our experimental data. Intrusion layer flux was non-dimensionalized following the procedure above with the characteristic fluid volume flux $Q_C = (B^3/N^5)^{1/4}$. The theoretical value of Q_i/Q_C in a single-phase plume is taken as the dilution at the trap height, or 1.4 (Fischer et al. 1979). The curve plotted in the figure represents the least-squares fit of $Q_i/Q_C = 1.4 - cU_N^d$, where $c = 0.8$ and $d = 0.2$. Because bubbles are less efficient pumps than single-phase plumes (Leitch & Baines 1989) and because the intrusion depth is lower, the dilution is reduced from the single-phase value.

Since U_N appears to be the dominant variable for describing the effect of the dispersed phase, the available data from Asaeda & Imberger (1993) for plume type along with our own observations were compared to values for U_N. Type 1 plumes cannot be predicted without reference to *H*; hence, U_N does not predict them. The transition from Type 2 to Type 3 behavior, however, is predicted and occurs at U_N = 2.4. As the slip velocity becomes large compared to the plume velocity, the bubbles and fluid become more independent and fluid would be expected to detrain more frequently. Thus, U_N suggests a physical basis for the difference between Types 2 and 3.

Our experiments also identified a new plume type, Type 1*, that occurs for small U_N (see Figure 1). In the Type 2 region, the bubbles stay in a tight core and are unaffected by peeling. As U_N decreases below about 1.4, however, u_s becomes small compared to the plume fluid velocity and the bubbles are deflected toward the intrusion layer by the detraining fluid. Above the first detrainment point the plume structure becomes diffuse and behaves similarly to the Type 3 plume: the spread out bubbles are ineffective at lifting fluid and the fluid and bubbles become more independent. Hence, three plume types applicable to the deep ocean are fully predicted by the parameter U_N: Type 1 plumes for U_N below about 1.4, Type 2 plumes for U_N between about 1.4 and 2.4, and Type 3 plumes for U_N above about 2.4 (Socolofsky in prep).

6. Discussion

Base case scenarios for a small, medium, and large oil-well blowout illustrate these results at the field scale (the companion paper addresses CO_2). Assume a plume origin at 1000 m into water characterized by N = 0.0034 s^{-1}. Oil-well blowouts often eject both oil and gas; assuming a gas-oil ration (GOR) at depth of one, we have the characteristics reported in Table 1.

Variable	Units	Small Spill	Medium Spill	Large Spill
B	m^4/s^3	0.01	0.1	1
Gas: u_s	cm/s	35	40	40
Oil: u_s	cm/s	35	30	20

Table 1. Characteristic of base-case oil-well blowouts.

Taking the medium spill as an example, the curve in Figure 3a predicts the first intrusion of the oil and gas plume at 77 m. Assuming a uniform distance between intrusions, as in Asaeda & Imberger (1993), the oil and gas plume has 12 intrusions. The curve in Figure 3b provides an estimate of the intrusion layer flux: 100 m^3/s for the medium spill.

It is commonly assumed that the oil would leave the gas plume and intrude with the detrained fluid in the first intrusion. This corresponds to our Type 1* plume. Taking u_s for the oil and computing U_N from Table 1, we get 4.4, 2.1, and 0.8 for the small, medium and large spills, respectively. Only the large spill falls in the Type 1* range, indicating that the oil would trap for a large spill, but follow the gas for any other spill.

7. Summary

The dimensional analysis and related experiments have allowed us to remove the *H*-dependence from correlations for plume trap height, intrusion layer flux, and characteristic type. The new correlations use *B* and *N* to non-dimensionalize the dependent variables and the variation in the resulting non-dimensional variable depends on U_N. Since U_N is the ratio of the slip velocity to the plume fluid velocity, a physical mechanism can be inferred: as the slip velocity increases relative to the plume fluid velocity, the bubbles become more independent of the plume fluid and the behavior tends toward that of a non-entraining bubble column.

8. Acknowledgements

This work was supported by the MIT Sea Grant College Program, the National Energy Technology Laboratory of the U.S. Department of Energy, and the Deep Spills Task Force, comprised of the Minerals Management Service of the U.S. Department of Interior and a consortium of 13 member oil companies of the Offshore Operations Committee.

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Bubble and Droplet Plumes in Stratification 2: Numerical Studies

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1. Abstract

This paper describes a numerical model of a steady-state plume in linear stratification driven by a buoyant dispersed phase, such as bubbles or droplets. The model was developed specifically to simulate CO_2 sequestration plumes. It extends the hybrid double-plume model of Asaeda & Imberger (1993) by incorporating droplet dynamics (dissolution, hydrate formation, and phase changes), by introducing a self-regulating detrainment criterion, and by allowing multiple intrusions to overlap. The model is calibrated to data from the literature and from the companion paper and is applied to study the sensitivity of a CO_2 plume to ambient stratification.

2. Introduction

Several techniques for transferring CO_2 to the deep ocean have been proposed; however, buoyant droplet plumes injected around 1000 m depth are the simplest and least costly (Adams & Herzog 1996). Although the oceans and atmosphere will eventually equilibrate (on the order of 1000 years), the intent of such a sequestration strategy is to minimize atmospheric CO_2 concentrations over the next few hundred years, by which point CO_2 emissions will have significantly decreased (Adams & Herzog 1996). This and the companion paper explore the design of such a CO_2 injection.

This paper presents a numerical model for a two-phase plume in stratification that extends the hybrid double-plume model of Asaeda & Imberger (1993). The model currently neglects the effects of a crossflow in order to minimize the number of dynamic processes involved. This is deemed acceptable since the no-current case probably represents a worst-case scenario in terms of dilution of the dissolved CO_2. Because the dissolution of CO_2 increases the density of the seawater, there is a feedback on the plume dynamics. After presenting the model, this paper explores the relative importance of stratification and CO_2 dissolution for controlling the resultant plume structure.

3. Model Formulation

The spatial evolution of a two-phase plume in stratification is controlled by four primary processes: buoyant forces acting upon the droplets and plume water, dissolution of the droplets, turbulent entrainment of ambient water into the plume, and buoyant detrainment, called peeling.

Integral models reduce the three-dimensional plume flow to a one-dimensional problem by assuming a profile shape independent of height for each flux variable. Although this similarity assumption is not strictly valid for a two-phase plume in stratification, models based on similarity have been successful (Asaeda & Imberger 1993, Wüest et al. 1992, Turner 1986, McDougall 1978). Here, we choose top-height profiles (variables are assumed constant over the plume width) for both the inner, rising plume of water and droplets, and for the outer, falling annular plume of water only. Asaeda & Imberger (1993) introduced this type of double plume.

We formulate the model in terms of the governing flux variables. The mass flux of bubbles, W_b, is given by their number flux, N_b, their nominal diameter, d_b, and their density, ρ_b, yielding

$$W_b(z) = \frac{1}{6}\pi d_b^3(z) N_b \rho_b(z) = Q_b(z)\rho_b(z) . \tag{1}$$

The size and density of bubbles are tracked in a bubble sub-model that accounts for dissolution, hydrate formation and phase changes. Denoting X as the cross-sectional fraction of the inner plume occupied by bubbles, we define the volume flux, Q, of plume water as

$$Q_i(z) = \int_0^{b_i} (1 - X(z)) u_i(z) 2\pi r dr = \pi b_i^2 u_i \tag{2}$$

where u is the average water velocity and b is the plume width. The subscript i indicates an inner-plume value. The momentum flux, M, includes the momentum of both the bubbles and the droplets

$$M_i(z) = \gamma \int_0^{b_i} (1 - X(z)) u_i^{\,2}(z) \rho_i(z) 2\pi r dr + \gamma \int_0^{b_i} X(z)(u_i(z) + u_b(z))^2 \rho_b 2\pi r dr \tag{3}$$

where u_b is the bubble slip velocity and γ is a momentum amplification term, first introduced by Milgram (1983), that accounts for the fact that the model formulation implicitly ignores turbulent momentum transport. Because $X \ll 1$ and $u_b = O(u_i)$, the second term in (3) can be ignored giving $M_i = \gamma\rho_i\pi b_i^2 u_i^2 = \gamma\rho_i Q_i u_i$.

The buoyant forces generating the plume result from changes in density. For this model, density is tracked through changes in salinity flux, S, heat flux, J, and the dissolved CO_2 flux, C. The salinity flux is defined from the local plume salinity, s, such that

$$S_i(z) = Q_i(z) s_i(z) . \tag{4}$$

The heat flux of the plume is defined from the local water temperature, T, yielding

$$J_i(z) = Q_i(z) \rho_i c_p(z) T_i(z) \tag{5}$$

where c_p is the heat capacity of the fluid. Finally, the dissolved CO_2 flux is defined from the local dissolved CO_2 concentration, c,

$$C_i(z) = Q_i(z) c_i(z) . \tag{6}$$

Thus, (1) through (6) define the model state variables for the inner plume.

The state variables for the outer plume are nearly identical. The primary difference is that, because the outer plume is assumed to be annular, the volume flux of the outer plumes is defined as

$$Q_o(z) = \pi(b_o^2 - b_i^2) u_o \tag{7}$$

where the subscript, o, indicates an outer plume value. Defining z as the upward spatial coordinate and specifying that the outer plume flow downward, the velocity u_o is negative and u_i is positive. Using (7) and changing the subscripts in (1) to (6) from i to o yield the flux equations for the outer plume.

The plume develops by exchanging fluid with the ambient and by exchanging fluid between the inner and outer plumes. The entrainment hypothesis, introduced by Morton et at. (1956), states that the entrainment flux across a turbulent shear boundary is proportional to a characteristic velocity in the turbulent layer. In this model, we have defined three entrainment fluxes: E_i entrains from the ambient or from the outer plume into the inner plume, E_o entrains from the inner plume into the outer plume, and E_a entrains from the ambient into the outer plume. The entrainment relationship for counterflows is not well known. Here, we adopt the relationship used by Asaeda & Imberger (1993):

$$E_i(z) = 2\pi b_i \alpha_i (u_i - u_o) \tag{8}$$

$$E_o(z) = 2\pi b_i \alpha_o u_o \tag{9}$$

$$E_a(z) = 2\pi b_o \alpha_a u_o \tag{10}$$

where the α's are entrainment coefficients.

The final exchange equation accounts for buoyant detrainment, which has been modeled in a variety of ways. Liro (1992) assumed that a fixed fraction of plume fluid was ejected when the net buoyancy flux across the plume approached zero. Asaeda & Imberger (1993) assumed that all of the plume fluid detrained when the net momentum approached zero. Based on experiments, peeling is better predicted when the net momentum approaches zero. For this model, a self-regulating peeling criterion is introduced. We know that peeling occurs when the drag from the bubbles can no longer support the negative buoyancy of the fluid. The simplest parameterization that behaves similarly to experiments gives the peeling flux as

$$E_p(z) = \varepsilon \left(\frac{u_b(z)}{u_i(z)} \right)^2 \left(\frac{B_i(z)}{u_i^2(z)} \right) \tag{11}$$

where ε is a non-dimensional fitting parameter of order 0.01, and B is the buoyancy flux, defined as

$$B_i(z) = gQ_i(z)\frac{\rho_a(z) - \rho_i(z)}{\rho_i} \tag{12}$$

where ρ_a is the ambient density. The relationship in (11) makes it easier for outer plumes to overlap and makes it possible to simulate the continuous peeling nature of Type 3 plumes, which are described in the companion paper (Socolofsky et al. 2000). Based on velocity ratios, (11) reflects the local value of U_N.

With these definitions, the plume conservation equations can be readily defined. From mass conservation, we have:

$$\frac{dQ_i}{dz} = E_i + E_o + E_p \tag{13}$$

$$\frac{dQ_o}{dz} = E_i + E_o + E_p + E_a\,. \tag{14}$$

Momentum conservation states that the momentum changes in response to the applied forces, which gives the following equations

$$\frac{dM_i}{dz} = g\left(\frac{Q_b}{(u_i + u_b)}(\rho_a - \rho_b) + \pi b_i^2(\rho_a - \rho_i) \right) + E_i\rho_o u_o + E_o\rho_i u_i + E_p\rho_i u_i \tag{15}$$

$$\frac{dM_o}{dz} = -g\pi(b_o^2 - b_i^2)(\rho_a - \rho_o) + E_i\rho_o u_o + E_o\rho_i u_i + E_p\rho_i u_i + E_a\rho_a u_a\,. \tag{16}$$

The conservation of salt, heat and dissolved CO_2 flux follow from the mass conservation equation, yielding for the inner plume:

$$\frac{dS_i}{dz} = E_i s_o + E_o s_i + E_p s_i \tag{17}$$

$$\frac{dJ_i}{dz} = c_p\rho_r(E_i T_o + E_o T_i + E_p T_i) + \frac{dW_b}{dz}\Delta H_{diss} \tag{18}$$

$$\frac{dC_i}{dz} = E_i c_o + E_o c_i + E_p c_i \tag{19}$$

and for the outer plume:

$$\frac{dS_o}{dz} = E_i s_o + E_o s_i + E_p s_i + E_a s_a \tag{20}$$

$$\frac{dJ_o}{dz} = c_p\rho_r(E_i T_o + E_o T_i + E_p T_i + E_a T_a) \tag{21}$$

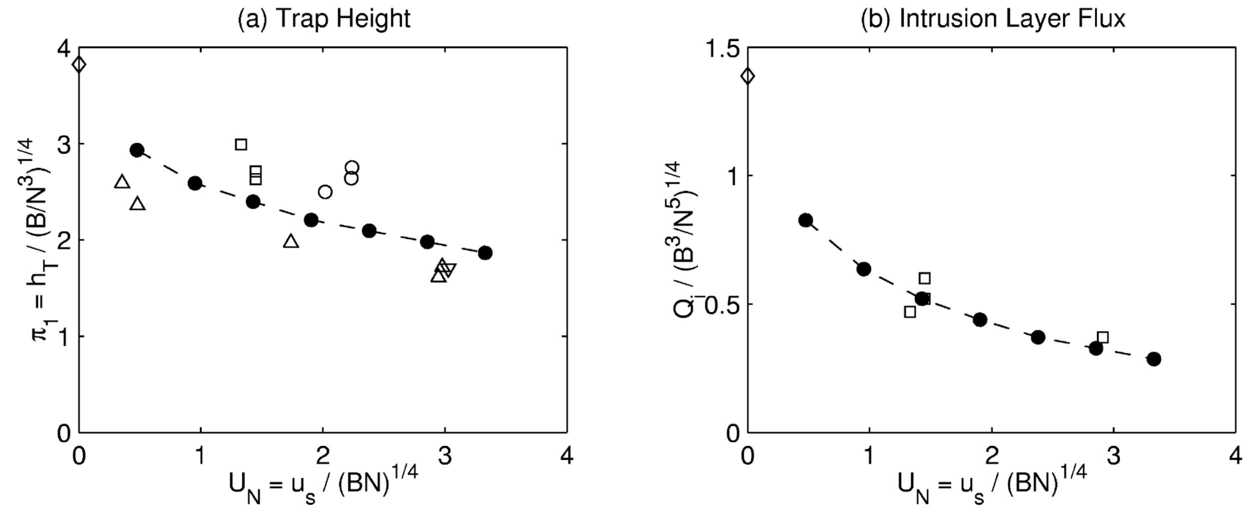

Figure 1. Model predicted (a) trap height and (b) intrusion layer volume flux versus experimental data described in the companion paper. Model predictions are represented by the filled circles.

$$\frac{dC_o}{dz} = E_i c_o + E_o c_i + E_p c_i + E_a c_a \tag{22}$$

The last term in (18) accounts for the energy released by dissolving CO_2. The densities ρ_i *and* ρ_o are determined by an equation of state which is a function of *s*, *T*, and *c*. dW_b/dz is calculated by the bubble sub-model.

The model begins with integration of the inner plume from the point of release to the point where the droplets disappear or the water surface is reached. Once the inner plume integration is complete, the outer plume segments are integrated. The integration of each outer plume section continues until the momentum flux approaches zero. Then, the next outer plume section is initialized and integrated. This cycle repeats until the solution converges to a steady result (typically 10 iterations).

4. Calibration

Literature data were available for an unstratified bubble plume and for a single-phase plume (u_b=0) in stratification. For both these cases the outer plume did not develop, so only values for α_i could be calibrated. Data for the unstratified case were from Milgram (1983) for a 50 m deep spring. The model matched the trend and magnitude of the measured plume velocities for a value of α_i = 0.12. In the stratified case, the trap height relationship $h_T = 3.8(B/N^3)^{1/4}$ was tested. The model reproduced the scale-dependence of h_T on B and N for α_i = 0.11.

Additional calibration data for two-phase plumes in stratification were available from Socolofsky (in prep.). Our companion paper shows the dependence of trap-height and intrusion flux on slip velocity. Calibrating to the trap-height relationship gives values of α_i = 0.07, α_o = 0.11, and α_a = 0.11. Figure 1 shows the model predictions for trap height and intrusion layer flux, compared to comparison to the data and correlations described in the companion paper.

5. Sensitivity to Stratification

The ambient density gradient, characterized by the buoyancy frequency, varies somewhat with geographic location and strongly with depth. To investigate the model sensitivity to stratification, a base-case CO_2

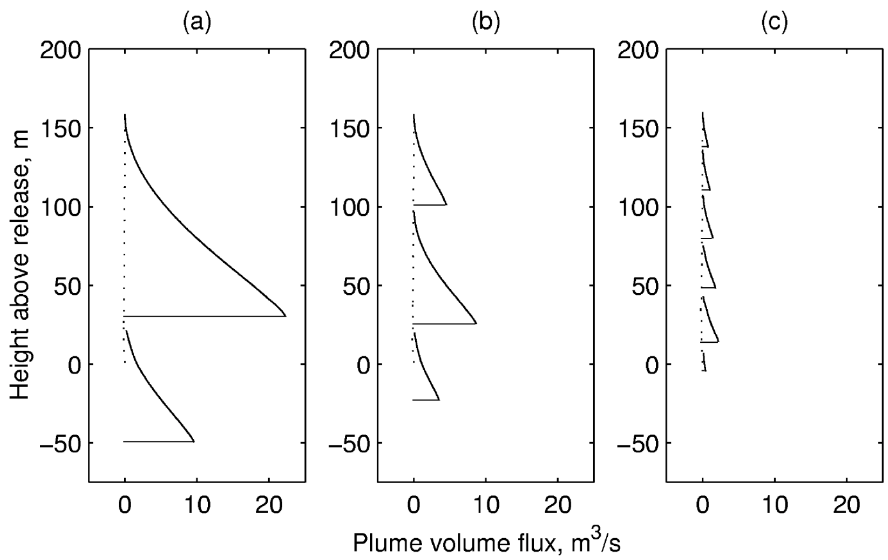

Figure 2. Sensitivity of plume structure to ambient stratification. The solid lines represent the volume flux profiles of the outer plume sections; the dotted lines represent the volume flux profiles of the inner plume sections.

injection scenario was defined. Table 1 summarizes the base case along with scenarios featuring decreased and increased stratification.

Variable	(a) Decreased Stratification	(b) Base Case	(c) Increased Stratification
Release Depth	800 m	800 m	800 m
Droplet Diameter	0.5 cm	0.5 cm	0.5 cm
Droplet Density	940 Kg/m^3	940 Kg/m^3	940 Kg/m^3
Flow rate	1.1 L/s	1.1 L/s	1.1 L/s
Buoyancy Frequency	0.0016 s^{-1}	0.0032 s^{-1}	0.0064 s^{-1}

Table 1. Simulation scenarios for CO_2 sequestration sensitivity analysis.

Figure 2 shows the model results for the three sequestration scenarios in Table 1. Although the total plume rise heights are about the same (the bubbles completely dissolve at the same height), the intrusion levels and fluxes differ. The volume flux to the intrusion layers decreases with increasing stratification because their descent is arrested more quickly in higher stratification, which leads to less cumulative entrainment and less total dilution. The mean concentration of excess CO_2 and the resulting change in pH in the intrusions are summarized in Table 2.

Case	Intrusion excess CO_2
(a) Decreased stratification	0.03 Kg/m^3
(b) Base case	0.06 Kg/m^3
(c) Increased stratification	0.13 Kg/m^3

Table 2. Intrusion excess CO_2 concentration for the three cases simulated.

The near-field dilution of the CO_2 reported in Table 2 is controlled by the competition between the stratification and the solution density effect of the CO_2. Over the range of buoyancy frequencies sampled, the concentration of CO_2 in the intrusion layers is nearly proportional to the buoyancy frequency.

6. Summary

A numerical model has been presented that extends our modeling abilities for a buoyant CO_2 plume in the deep ocean. The newly introduced detrainment relationship (11) provides a convenient numerical solution for downdraught flows that overlap, as is the case for CO_2 plumes. Although the entrainment relationship for the resulting counterflow is not well understood, the density feedback of the CO_2 dissolution provides a large enough driving force that the outer plume dominates the structure, and the dilution in the outer plume becomes insensitive to reasonable values for the entrainment coefficients. Thus, the near-field dilution of a CO_2 plume is controlled by the balance between the negative buoyancy of the dissolving CO_2 and the stratification, rather than by the buoyancy of the bubbles.

7. Acknowledgements

This work was supported by the MIT Sea Grant College Program, the National Energy Technology Laboratory of the U.S. Department of Energy, and the Deep Spills Task Force, comprised of the Minerals Management Service of the U.S. Department of Interior and a consortium of 13 member oil companies of the Offshore Operations Committee.

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Preliminary Design for Injection of CO_2 from a Ship

April 2000

Howard Herzog

This report summarizes our work in helping develop a preliminary design for injection of CO_2 from a ship for the International Experiment. The first use of this information was as input to the Technical Committee (TC) in making the decision of a land-based versus ship-based system for injection. Now that the decision to use a ship-based system has been made, it will also be used as input to the more detailed design of this system.

The report is divided into two parts. The first part documents input from a Norwegian group (SINTEF) that will attempt a similar experiment this June in the North Sea. They will inject oil and gas, not CO_2, but the type of injection, injection depth, measurements, etc. are very similar to us. Part A reports on a meeting I had with SINTEF. Part B is the analysis of the Hawaii situation based on the SINTEF information. Finally, Part C is an update on SINTEF's plans.

The second part is a preliminary design for our injection. This was done with the aid of a consultant, JM Consult of Stavanger Norway, who is also working with SINTEF. Part A is my problem definition and instructions to JM Consult. Part B is the report produced by JM Consult, including cost estimates. Finally, Part C is a series of follow-up questions and answers to the report.

I. SINTEF Project

A. Report on SINTEF meeting, January 13, 2000

On Thursday, January 13, Howard Herzog visited Oinstein Johansen and Per Daling at SINTEF in Trondheim Norway. Overall, the meeting was very productive and we should stay in close contact with this project. Not only do they face similar technical challenges, they also have some of the same political and financial challenges.

The meeting reinforced our feeling that the barge option is the best way to go. Some key points from the meeting are listed below:

1. The project is going ahead for June. June is the best weather month. The need winds less than 12 m/s because of small ships sampling the oil slick on the surface. In June, they only exceed this 7.7% of time for a duration of 13.7 hours.

2. They will use a drill ship as the supply vessel (see updated information in Section I.C, below). This means the pumps and the pipe will be on this vessel. The oil will go down the drill pipe. During drilling, mud is pumped down the pipe. For this experiment, they will use same pumps, substituting oil for mud. The drill pipe will go all the way to ocean floor to fix the release point and make sure it does not sway. Otherwise, measurements (i.e., sonic image) will be fuzzy. Nozzle will be inserted in pipe above ocean floor to release the oil.

3. A second pipe, coiled tubing, will be used. It will be bundled to the drill pipe. They need 2 pipes, one for oil (drill pipe), one for gas (coiled tubing). This is to better simulate a blowout, where there are 2 distinct phases. If they were injected in the same pipe, the gas may dissolve in the oil before release. The drill pipe is standard diameter (Oistein thought 4 inch) and the coiled tubing is 2 in (I think, I can't find in my notes, but that is what I recollect).

4. Note that while the pipe is directly above and below the nozzle, ROV entanglement is NOT a major concern. When specifically asked about this, he said they have checked it out and got a green light from ROV operators. In fact, they want to use 2 ROVs, one in close to the nozzle and the other out in the plume. This suggests that we are way too conservative in our ROV entanglement concerns.

5. The drill ship has DP, the ROV ship does NOT.

6. They went to use the drill ship because of costs. They can rent coiled tubing setup (roll, gooseneck, injector) for 30,000 NOK/day each (1$ = 8 NOK). The supply ship would cost 100,000 NOK/day. However, they would need to spend 2,500,000 NOK to build a system to lay pipe from back of supply ship and keep proper angle. This was a budget buster. Therefore, they will spend more on supply ship (i.e. drill vessel) at 280,000 NOK/day and save money overall. They also like the simplicity of the design better.

7. They identified a consultant to design pipe system. It is JM Consult in Norway <http://www.jmc.no>. Since they never went ahead with 2 coiled tube system, they never

needed him to do a design. However, they did have discussions with him at no charge. A rough design would have cost $10,000. We may want to consider using him.

8. Originally, they were going to permit 2 sites, so they could have a contingency in case of bad weather. However, now they will do only one. They dropped one site because it was more environmentally sensitive. Even though that site had several advantages (closer to shore, steadier currents). They thought the advantages not worth the risk (sounds familiar, doesn't it).

9. They will map the plume using sonar, UV fluorescence (the oil will act as the UV tracer), and measuring dissolved methane (using real time sensors). They will also use video and ADCPs. The ADCPs will be mounted on the drill pipe.

10. Surface temps about 10 C in summer, -1 C at depth.

11. Their consultant on pumping methane is Marintek. I asked if they looked into flow instabilities, and he said no, but will ask consultant to investigate. They did pump compressed air in 1996 and did not have oscillatory flow, but depth was only 100 m. However, still a good sign. They are looking at possibility of rubber tubing to replace coiled tubing, but Oistein does not think rubber tubing will be acceptable.

12. They will mix gas and oil in nozzle just before release. Oil rate is one cubic meter per minute. Gas to oil ratio in SCM is 60 to 1. He was positive, but thought the nozzle opening was about 10 cm. He was sure on criteria of exit velocity of 2 m/s. This will yield oil droplets between 0.5 and 5 mm.

13. The only valve they contemplate on nozzle assembly is a one-way valve to block water ingress (one on each line). They though about a solenoid, but decided no. They will NOT have power on nozzle assembly. If flow instability is not a problem, we can also have a simple system. If it is, we will need to be more complex.

14. As requested, Oinstein was invited to the March TC meeting. He will consider.

B. Follow-up Memo to SINTEF Meeting, January 26, 2000

Below is some further analysis as a follow-up to the SINTEF meeting. It results from a brain-storming session held with Eric, Scott, and Brian here at MIT.

We think that the barge options can be classified as follows:

Option A - Go vertical. Just as SINTEF is doing, we can go vertical -- that is hanging the pipe straight down from the "supply" ship. Unfortunately, I do not think there are any drilling ships available in Hawaii to help us. Therefore, a big concern is keeping the pipe rigid. First, the pipe cannot hang freely, but must be attached to the ocean bottom so we can fix the release point. Secondly, choosing a pipe that has some inherent rigidity is essential. Third, if we want to bring the diffuser up and down several times, the pipe we choose must accommodate this task. Also, the ship must have DP. This means that our RV (monitoring ship) will not have DP. This is doable, but means that we cannot use JASON as the ROV if we can only afford one DP vessel.

Option B - Single supply ship set back 100-300 m. This is similar to Gerard's options 1 and 2. The supply ship would maintain a position throughout the experiment. Up to 300 m of pipe would lay on the ocean floor to provide a set-back for ROV operations. This option assumes that the single ship can lay the pipe and the pipe can support the weight of the diffuser during deployment and recovery. A pipe that can do this needs to be identified. Assuming we can find such a pipe, we feel that this may be the simplest approach. Of course, Gerard's concerns about using a non-DP ship must be addressed.

Option C - Option B with a cable. In the raising and lowering of the pipe and diffuser, a second ship with DP would be used (note that this DP ship would also serve as the mother ship for the ROV). The second ship would use a cable to raise and lower the diffuser assembly. This is similar to Gerard's option 4, except we use a ship instead of a barge. Following diffuser deployment, some of the cable would be laid on the bottom to achieve a set-back similar to the pipe to avoid ROV interference. While this option may be more robust in raising and lowering the diffuser and pipe, we now have to worry about the cable getting entangled with either the pipe or ROV.

As you can see, we need to work out the details of above options to see the best approach. We are extremely confident that we can make one of these options (or a variation) work, but are worried about budgets. For example, certain pipes may be cheap, but may require expensive equipment to keep them from kinking. On the other hand, we can buy very flexible pipe to avoid this problem, but it may be very expensive. We need to understand these trade-offs ASAP, perhaps with the aid of a consultant.

To try to keep in budget, we need to be able to be creative. We can play with the type of pipe, type of ship (DP vs. non-DP), cable vs. no cable, vertical vs. set-back. In addition, we can also consider ROVs that do not require DP if we need DP for supply ship. We also need to look at experimental design -- if we simplify there, we maybe can simplify infrastructure (note that we already have simplified the design and if we simplify too much, we will not collect all the critical data we need). Finally, we should compact the experimental duration to as short a time as possible, thereby keeping ship costs to a minimum.

We also feel that we should have as a goal of testing our proposed technique in this summer's cruise. This should be the number one priority of the cruise. Of course, that means we have lots of details to work out in a short time. It is unclear whether we can meet such tight deadlines, but we should try.

Finally, while we are not making any recommendations, but want to point out that part of our troubles come from working in Hawaii, especially away from Honolulu. Hawaii does not have the infrastructure of the Gulf Coast or the North Sea. Therefore, costs are high and some of our options are limited (e.g., going vertical, finding DP ships). In laying pipe from shore, this disadvantage was made up for by the short distances and the support from NELHA. In going from the barge, we free ourselves to go anywhere. We should not lose sight of this fact, especially if all our options start breaking the budget.

C. Update on SINTEF Plans, February 9, 2000

The following is an e-mail sent to us by Oinstein Johansen:

Concerning the choice of discharge arrangement - we have been forced to drop the drilling vessel due to unforeseen postponements of other planned commissions of the vessel (with higher priority). This implies that we had to return to original CST-based arrangement. Presently, we are working with a solution based on the use of a supply vessel with a so-called moon-pool located amidships. The moon-pool is a kind of "well" with a square opening of about 4x4 m. We plan to mount the injector heads above the moon-pool and guide the CST's and the discharge platform down through the well. Jens Myklebust [JM Consult] is presently working with technical details, which will later be used to apply for approval at DnV (safety aspects). This solution is in theory much simpler than the previous one suggested by JM Consult with the injector heads mounted on a kind of sledge that would be moved behind the stern of the vessel during the field experiment. So, this is where we are at present.

II. Preliminary Design for Injection Technique

A. Problem Definition

Below are the instructions sent JM Consult:

Our ultimate goal is to inject liquid CO_2 into the ocean at a depth of about 800 m. We expect flowrates between 0.1 and 1.0 kg/s. This means we will need a pipe diameter of 1 to 2 inches. The experiment will take place in the summer of 2001, but we are hopeful we may be able to test out key components this summer.

We would like your advice on the type of delivery system needed for injecting the CO_2. Originally, we thought of using a pipeline from shore (probably coiled tubing). Since the slope in Hawaii is very steep, a 2 km pipeline would get us to the required depth. However, deployment costs from shore may be high, so we want to also consider delivery from a surface ship. We have a Technical Committee meeting in Japan the first week in March to try to make some decisions. We hope you can provide some guidance on making this decision.

First, here is some background on conditions in Hawaii:

Currents: off of Keahole Point (West coast of the Big Island of Hawaii), currents can be strong and are driven by large leeward cyclonic eddies; consequently, they are less predictable than tidal currents. For design purposes, I would assume a surface current of 1.5 m/s (3 knots) flowing along the coast, with a 400 m e-folding depth to approximate a typical profile: thus, current at depth z (m, positive) would be 1.5 exp(-z/400). In reality, there may be some shear (current direction reversal in deep water), and fairly strong internal waves occur near the steep deep seafloor. The seafloor slope is steep (25 to 30 degrees) from the nozzle toward the shoreline, and the bottom basaltic with a patchy cover of silt. The area is very well protected from the brisk Trade winds, and typical wind-driven seas are mild (sea breezes): 1 m height, 4 to 6 s periods.

Being in Hawaii, the probability of large swells cannot be ruled out, even in the summer time, though we would be far away from the surf zone. A typical large swell could have a height of 2 m and period of 18 s. We are considering 3 options for injecting from a barge. I summarize these below with some comments. Since we are not experts, you may disagree with some of our assumptions. Please let us know where our logic may be faulty:

Option A - Go vertical. Just as SINTEF is doing, we can go vertical --that is hanging the pipe straight down from the "supply" ship. Unfortunately, I do not think there are any drilling ships available in Hawaii to help us. Therefore, a big concern is keeping the pipe rigid. First, the pipe cannot hang freely, but must be attached to the ocean bottom so we can fix the release point. Secondly, choosing a pipe that has some inherent rigidity is essential. Third, if we want to bring the diffuser up and down several times, the pipe we choose must accommodate this task. Also, the ship must have DP (dynamic positioning).

Option B - Single supply ship set back 100-300 m. The supply ship would maintain a position throughout the experiment. Up to 300 m of pipe would lay on the ocean floor to provide a set-back to stay clear of ROV operations. This option assumes that the single ship can lay the pipe and the pipe can support the weight of the diffuser during deployment and recovery. A pipe that can do this needs to be identified.

Option C - Option B with a cable. In the raising and lowering of the pipe and diffuser, a second ship would be used. The second ship would use a cable to raise and lower the diffuser assembly. Following diffuser deployment, some of the cable would be laid on the bottom to achieve a set-back similar to the pipe to avoid ROV interference. While this option may be more robust in raising and lowering the diffuser and pipe, we now have to worry about the cable getting entangled with either the pipe or ROV.

As you can see, we need to work out the details of above options to see the best approach. We are worried about budgets. For example, certain pipes may be cheap, but may require expensive equipment to keep them from kinking. On the other hand, we can buy very flexible pipe to avoid this problem, but it may be very expensive. We need to understand these trade-offs, such as the type of pipe, type of ship (DP vs. non-DP), cable vs. no cable, vertical vs. set-back.

We have considered 2 types of pipe. First is coiled tubing. The second is a more flexible pipe from a company called DUCO. I will try to get some additional information on the DUCO pipe for you soon.

Our 2 major concerns are budget and risk. To minimize risk, we want to be able to raise and lower our pipe (with a diffuser unit on the end) about 4-6 times during the experiment, which may take place over 5-7 days. Of course, during the raising and lowering of the pipe, we want to minimize risk of damaging the pipe itself (that is why we are considering very flexible pipe).

Key items to consider for budget are cost of pipe, cost of auxilliary equipment for pipe (winch, etc. that allows us to raise/lower), and cost of "supply ship". The supply ship will have the CO_2, pimps, and one end of the pipeline. We will use a second ship as a research vessel to take measurements during the experiment. This second ship can also help raise and lower the pipe.

Some of our questions we need to answer are:

What is the best strategy (option A, B, C, from shore, or other) for injecting the CO_2?

What type pipe is required?

How wo be deployed and recovered?

What type ship is required? Does ship need DP?

What are the costs involved?

Your input into helping us resolve these questions will be greatly appreciated.

Two final points. First, the equipment available to us in Hawaii is much more limited than that in the North Sea. Second, you may want to check the experiment web site for more information at: <http://www.co2experiment.org/>

After you have had a chance to review and think about this information, we can talk on the phone. At that time, I can answer additional questions you may have. Also, you can let me know your initial thoughts and how you would like to proceed.

B. Report from JM Consult

DEEP WATER CO_2 TEST IN HAWAII

PRESTUDY REPORT RELATED TO METHODS AND EQUIPMENT FOR INJECTION OF CO_2

prepared by JM Consult

1.0 INTRODUCTION

This report deals with the feasibility and costs related to the use of Coiled Tubing (CT) equipment or other methods for pumping liquid CO_2 down to the seabed at 800m depth. Layouts for the CT alternative are proposed, and the alternative solutions (see Section II.A.) are discussed.

2.0 CONCLUSION

We will recommend the use of CT equipment which is found to be feasible with the following advantages:

High mechanical strength will avoid fracture/bursting and kinking of tubing during deployment / recovery and testing.

1. High pullforce will eliminate the need for additional winch assistance.

2. Pullforce and tubing length are monitored by the injector.

3. The tubing weight will reduce horizontal drifting due to currents.

4. Preliminary calculations show, however, that the tubing still may drift downstream by high currents, and such make it difficult to lay down tubing upstream from the Discharge Platform. This has to be analyzed early in the detail engineering phase. Also possible dynamical behavior due to currents should be checked out. MIT possesses competence in this field of the upper world class. Maybe MIT experts like J. Kim Vandiver in Dept. of Ocean Eng. should take a look into this?

5. Low cost, as most of the equipment and trained personnel can be rented. (Depend on transport costs for the various alternatives).

3.0 ALTERNATIVE SOLUTIONS

We have evaluated the options with the following comments:

1. Option A – Go vertical.
This alternative will require a drillship, and it seems to result in a comprehensive and expensive operation if the pipe must be attached to the seabed. We consider this alternative to be the less cost efficient, unless a very good price for the drillship is obtained.

2. Option B – Supply ship and pipe.
This alternative is described more in detail for a steel pipe (CT) in the following:

A flexible hose will require a reel with sufficient capacity, and the hose will require sufficient strength to hold its own weight in addition to the 5 ton Discharge Platform. The impact from currents is expected to be more severe by this alternative. Also kinking may be a problem. If a suitable reel is available for rental, then this may be cheaper alternative than the CT alternative.

3. Option C – Option B with a cable.
A cable may easily get entangled into the flexible hose and ROV equipment. This operation will also require a coordinated operation from a second ship which is not necessary by the CT alternative.

3.0 SYSTEM DESCRIPTION WHEN USING CT.

The CT package is shown on the enclosed illustrations and consists of the following:

1. One CT injector w/gooseneck. Pulling capacity approx. 30 tons.
2. One CT reel with approx. 1200m of OD 1 1/2”- 2” (ID 1.15”-1,6”) tubing.
3. One Control Cabin w/hydraulic powerpack.
4. One Workshop Container.
5. High pressure piping w/flexible couplings (chicksan) to connect the reel and pump. As there should be no need for spooling in or out during the test, the high pressure piping may bypass the swivel and be connected direct to the reel drum.

Dowell Schlumberger in Ventura CA which seems to be the CT company closest to Hawaii may provide all this equipment.

3.1 The Discharge Platform

The Discharge Platform is shown on the enclosed illustrations, and consists of the following:

1. A flat steel structure to provide sufficient tension to the tubing during deployment and to minimize drifting due to currents. The platform has four sharp steel spears to avoid horizontal movements on the hard seabed.

2. Steel piping to give a vertical outlet. The connection to the CT end will be made by a short flexible hose secured by chains. This is to avoid kinking of the CT if the platform should be hanging out of level during deployment/ recovery, or when the CT is laid down on the seabed. Also a swivel joint will be installed to prevent torsion forces in the tubing. A flapper valve will be installed close to the outlet to avoid seawater to enter the tubing between the tests.

3. One trumped shaped guide to ensure that the flexible pipe is not getting kinked.

3.2 Proposed Layout

The enclosed illustrations present a layout based on that the boat has no cargo rail in the stern, or is equipped with a moonpool.

The stern alternative is based on a skidding frame cantilevered over the stern. The injector and the Dischange Platform (ref. 3.1) are positioned inside the deck area during transit to the test site, and they are skidded outside by means of a winch prior to deployment.

A boat with moonpool would simplify the arrangement as shown on the illustrations. (No skidding required).

4.0 INSTALLATION WORK / SEAFASTENING

1. Injector skidbeams to be prefabricated and welded to the deck structure.

2. Injector and Discharge Platform to be positioned and connected. Additional seafastening chains to be rigged.

3. CT reel to be positioned on deck and seafastened by welding to deck structures.

4. Control Cab and Workshop container to be positioned and seafastened.

5. CT to be hooked up to Discharge Platform. All hydraulics to be connected and tested. The complete CT arrangement to be tested by lowering the Discharge Platform down to the seabed at the quayside or in the harbor area prior to going offshore.

5.0 OPERATIONAL PROCEDURES

1. Injector to lift the Discharge Platform free from the deck.

2. Injector to be skidded to the end of the cantilevered beams by means of a winch on deck, and secured.
   The CT reel to release tubing during skidding.

3. Injector to lower the Discharge Platform down to the seabed.

4. When the Discharge Platform hits the seabed, then the injector must continue to pay out tubing to allow for heave motions. Approximately 200 – 300m of additional tubing to be laid on the seabed to ensure a distance between the vertical tubing and outlet point. (Due to ROV maneuvering.)

5. A ROV should inspect that the Discharge Platform is OK.

6. The high pressure piping is then to be connected and the test can start. The tubing may be paid out at a speed of 25 m/min. The deployment activities should then be possible to be performed within 1 hour if everything work as planned.

7. The recovery is basically performed in the reversed manner. The total pull capacity is approx. 30 tons, which should be more than sufficient.

6.0 COST ESTIMATES

6.1 Detail Engineering

Scope: Prepare drawings and calculations for the prefabrication and installation of: Discharge Platform, Injector support beams, seafastening. Prepare detailed installation and operational procedures. Follow up.

6.1.2	Cost Estimate	NOK 180.000,- ($ 22.500,-)

6.2 Prefabrication

6.2.1	Discharge Platform:	NOK 160.000,- ($ 20.000,-)
6.2.2	Skid beams (Alt.1)	NOK 210.000,- ($ 26.250,-)
6.2.3	Seafastening equipm.: NOK	15.000,- ($1.875,-)

6.3 Installation / removal

6.3.1	Discharge Platform:	NOK 10.000,- ($ 1.250,-)
6.3.2	Skid beams (Alt.1)	NOK 40.000,- ($ 5000,-)
6.3.3	Seafastening	NOK 10.000,- ($ 1.250,-)

	Total Eng. Prefab., Inst:	NOK 625.000,- ($ 78.125,-)

6.4 Coiled tubing Equipment and Operations

Schlumberger

Dowell

Bartlet J. Patton
Steve Emerick
3530 Arundell Circle
Ventura, Ca. 93003
(805) 644-8160
(805) 644-2682 (fax)

Jens Myklebust
JM Consult
Injection of CO_2 in Hawaii

This bid is estimated on 10 days boat of travel to and fromHawaii and 10 days of operating time on location. The bid does not include cost of loading equipment onto boat

Cost Estimate:

ITEM	VOLUME	UNIT	UNIT PRICE	DISC	TOTAL PRICE
1.5" Coiled Tubing-12 hrs	10	ea	$2 900,00	0 %	$29 000,00
1.5" Coiled Tubing	120	hrs	$230,00	0 %	$27 600,00
Coiled Tubing Standby Charges	10	day	$1 800,00	0 %	$18 000,00
Service Tech	240	hrs	$66,00	0 %	$15 840,00
Pipe Charges	10	day	$1 600,00	0 %	$16 000,00
CT Connector	10	day	$70,00	0 %	$700,00
Disconnect	10	day	$300,00	0 %	$3 000,00
Hydraulic Energizer	1	ea	$170,00	0 %	$170,00
Stripper Element	1	ea	$170,00	0 %	$170,00
Check Valve	10	day	$95,00	0 %	$950,00
Tree Connection	10	day	$45,00	0 %	$450,00
Convertion Charge	2	ea	$2 010,00	0 %	$4 020,00
Mobilization Charge	4	ea	$400,00	0 %	$1 600,00
Pick-Up Charge	150	mi	$2,15	0 %	$322,50
Crew Travel Air Fare	4	ea	$650,00	0 %	$2 600,00
Crew Subsistance per person per day	40	day	$165,00	0 %	$6 600,00
					$127 022,50

All costs are estimates only. Actual costs will be determined by time,material, and equipment used during treatment.

Grand total 6.1 to 6.4: NOK 1.641.126,-
($ 205.147,-)

C. Questions and Answers

Q1. What are the requirements of the mother ship (assuming no moonpool)? Specifically, do we need a ship with dynamic positioning (DP)?
A1. If the ship does not have a moonpool, then it should be open at the stern. If not we will have to elevate the injector above the railing which will be more expensive. The deck must have sufficient space and strength (the heaviest item will be the reel approx 25 tons). It may not be necessary with a DP ship if the testing periods only will be a couple of hours each time, and the tubing is recovered between each test, provided that the ship is equipped with thrusters which make it possible to stay within a 50 to 100 meters circle. But for a continuous operation 24 hours a day I think a DP system will be a must.

Q2. We plan to deploy the setup at the start of a day and bring it up at the end of a day. A typical day for deployment may be anywhere from 6 to 12 hours. Would we need DP for this scenario?
A2. Up to 12 hours is a long time to hold a ship manually based on GPS navigation, but I will check with a ship owner tomorrow. The response from the shipowner company was positive. They did not see any problems in staying within 50- 100m for 12 hours without a DP system , based on proper thrusters and navigation system.

Q3. Could you estimate the deck space requirements?
A3. Estimated deck space requirement is approx 5m x 17m.

Q4. You recommend a deck space of 5 m x 17 m; we assume that this is only to satisfy the requirements of the coiled tubing and nozzle deployment hardware; we would need extra space for CO_2 storage and pumps. Is our assumption correct?
A4. Yes, 5m x 17m is only for the CT equipment.

Q5. We are concerned about torsion - or twisting - while the nozzle assembly is lowered to the seafloor. Can a connection between the nozzle assembly and the tube be such that no auxiliary wire is needed to control twisting?
A5. We have considered to use a standard high pressure swivel joint between the tubing and the nozzle assembly, as twisting may be a problem if the shape of the nozzle assembly (Discharge Platform) makes it rotate during deployment and recovery.

Q6. Our independent information about coiled tubing from Quality Tubing (QTI) was that we would need a coating to protect from corrosion. What is your opinion on what is needed for corrosion prevention? Would the same corrosion control processes be available from Schlumberger if they were to be the suppliers instead of QTI?
A6. We do not see any major problems with corrosion by such a short duration of seawater exposure. Seawater are normally present during offshore operations, and the only thing they do is to apply a liquid corrosion inhibitor inside and outside the tubing after the operations for protection during storage. One alternative to coating is to choose a tubing with heavy wall thickness to obtain some corrosion allowance, as weight will also be beneficial to reduce impacts from currents. Anyway, I think a simple zink primer should be sufficient for this period if this is shown to be of concern.

Q7. Option A - Go vertical: Please clarify the statement in your report that this would require a drillship. Isn't SINTEF "going vertical" without a drillship?
A7. Sintef had a plan to go vertical with jointed drillpipes by using a drillship. As the drillship would not be available in the testing period, they now want to go for the CT alternative. i.e. similar to the system we propose for you, but they have two CT lines (one for oil and one for gas).

Q8. What is the diameter of the reel and pipe?
A8. The max reel diameter is approx. 3.5m to 4m , tubing dia. 1.5"- 2" (OD) depending on necessary flow area. Wall thickness is approx. 0.175".

Q9. There is a concern that repeated deployment and retrieval of pipe would cause plastic deformation and warping. Can you address these concerns?
A9. We do not see any problems with repeated recovery with regard to plastic deformation, as most of the deformation will probably be in the gooseneck (on top the injector) as during normal CT operations. We will install a swivel joint at the Discharge platform to avoid build up of torsional forces in the tubing. However, the tubing will have internal bending forces from being spooled onto the reel. The tubing may therefore get a spiral shaped configuration on the seabed. We believe this spiral will have long radius sweeps, and should then not represent problems during recovery, unless the tubing is laid out with too much slack in one area. The layout on the seabed should therefore be surveyed by a ROV camera prior to recovery. The impact from currents are important to evaluate by analyses, hereunder possible wear to the tubing due to possible rubbing towards the sharp? seabed.

Q10. The platform will sit a steep slope. How will the design take this into account? Will the platform be at an angle or can we compensate for the slope?
A10. It will be a bit difficult to compensate the platform slope. Is it important that the outlet is vertical?

Q11. If the pipe gets damaged (like a small hole or a short section gets kinked), is it easy to repair? Does the workshop container have repair equipment? I think I remember that coiled tubing can use couplers to splice together 2 pieces of pipe, so welding is not required. Is this true?
A11. Yes, it is possible to splice the tubing mechanically or by welding, but it will be difficult to do this below the injector.(A hole can be repaired between the injector and the reel.) As back up for a kinked tubing we think it would be better to have a back up reel complete with tubing on the boat deck.

Q12. Do you need to know the exact characteristics of the mother ship in order to do the detailed design?
A12. Approximate characteristics should be sufficient, at least length, width and drawings of the relevant deck areas.

Q13. What are the approximate dimensions of the Discharge Platform?
A13. The discharge platform would have approx. size of 2m x 3-4m width (6ft x 9 - 12ft).

Field Experiment Design

April 2000

Eric Adams

I Tracer Intercomparison for Y2K+1 Experiment

We have updated our spreadsheet (attached), which intercompares tracers for potential use during the field experiment.

Brief conclusions regarding this intercomparison:

- Dye and (particularly) SF_6 can be measured with high resolution, and dye can be measured in situ. However, neither are true tracers of excess CO_2, because of the phenomenon of plume peeling, in which CO_2 droplets and CO_2-enriched seawater (the latter carrying the dye or SF_6) separate. However, CRIEPI has proposed to use dye (as measured with a fluorometer), along with DIC (as inferred from pH) as part of a "dual tracer" experiment to help determine the rate of CO_2 dissolution. Prior to the first plume "peel", the flux of dye injected near the nozzle should be conserved along the plume trajectory, while the flux of DIC should increase with height as more of the CO_2 dissolves. We might also be able to use the dye measurements to quantify actual droplet/plume separation process (i.e., determine how much of the water peels).
- Of the other tracers, only pH can be measured in situ with inexpensive, readily available, instruments, and it appears that the time constant for the CRIEPI pH probe is acceptable. However, IOS may wish to measure p CO_2, as a back-up tracer, using an in situ photometric method.
- The sensitivity of DIC appears greater than it did before, because the ambient variability is less. Based on the IOS data collected during the Y2K-1 cruise, it appears that the vertical gradient at depths of 600 to 900 m, is about 0.1 micromol/L-m which, if multiplied by an uncertainty of 10-20 m in the weighted average elevation of entrained plume water, gives an ambient uncertainty of 1-2 micromol/L, which is comparable with the measurement uncertainty. The maximum resolvable dilution increases by a factor of about 3 above what we had previously concluded.
- The sensitivity of using the C13 signal from the discharged carbon dioxide appears to be about the same as we had concluded previously.
- This leaves excess DIC and pH as the primary tracers, with C13 a close second (maximum resolvable dilution within one half order of magnitude). There has also been discussion about using deliberately labeled C13.
- Despite its high level of sensitivity, we have abandoned the idea of using deliberately labeled C14 as a tracer. This is largely based on the substantial time required for permitting, and the fact that this permitting would be tied to the project at large, hence placing the entire project at risk of further delays.

II Nozzle/diffuser design for Y2K+1 Experiment

We have had extensive discussions with PICHTR and UH regarding the nozzle/diffuser design and the experiment parameters as a function of the method of pipeline deployment. In summary, for deployment from a barge (as was agreed upon at TC5), such that the diffuser assembly can be regularly brought up to the surface, the diffuser design can be made as simple as possible, with interchangeable diffusers/risers to be connected onboard. In such a scenario, only a single diffuser, operated with a single flow rate, and at a single elevation would be needed for a given deployment. The set of experiments for each deployment would then consist of different sets of measurements/observations/sample collections and different ambient conditions--principally currents. Altogether, we would anticipate two or three diffusers (with designs similar to those presented during TC3--e.g., arrays of 15 and 60 ports with 0.5 cm diameter), operated at perhaps two mass flow rates (0.1 and 1.0 kg/s) and perhaps two elevations above the water surface. Not all combinations would be required, so we might expect about six deployments, give or take. The number of experiments/conditions to be tested and their duration will depend on the period of time for plume adjustment after a new diffuser is deployed and the time during which the plume can be considered in steady state. This second time is very important and reflects the period of time over which the current remains reasonably steady in both speed and (especially) direction. Based on current measurements collected during the Y2K-1 cruise, each of these periods of time is estimated to be about an hour. Because an ROV and RV would be on site for 24 hours a day, we would want to be able to deploy/haul up diffusers and initiate experiments at any hour of the day.

III Planning and scientific coordination of Y2K-1 ocean field survey.

This task included organizing individuals from six participating institutions via email and conference calls, planning/scheduling the experimental components, and serving as chief scientist onboard the R/V KOK.

The cruise itself (August 3-7, 1999) went very well. The scientific party consisted of 16 individuals who:

- deployed two current meter moorings (the NIVA rig with ADCP and ADV, and the CRIEPI rig with ADV and pH sensors)
- took CTD (plus pH) casts and water samples (for dissolved oxygen, salinity, carbon chemistry, bacterial production rate and efficiency, nutrients, ambient C-13 and C-14) at over 30 stations, including: i) a 25-hour time series off Keahole Pt (primary site), ii) 5 stations within a 10 km radius of the site, iii) 3 stations along a transect from Kahe Pt (alternate site) to Keahole and iv) 4 stations from Keahole to the Loihi Seamount.
- obtained video footage of the bottom area from an ROV
- obtained two small samples of benthic sediments

- obtained bathymetric data near the site (600 -1000m; extending existing data which followed the pipelines to about 700m)

Three videos were prepared from the cruise: i) a general summary, ii) observations of the bottom from the ROV, and iii) a condensation of iii). These videos have been used for various purposes including public outreach.

We have also helped summarize the cruise on the project web site.

IV Planning and scientific coordination of Y2K ocean field survey

At TC-4 in Boston I introduced the concept of a microexperiment to be conducted during the summer of 2000 (now possibly October). The experiment would entail the release of a modest quantity of CO_2 (perhaps 1 tonne) with the goals of

- testing CO_2 delivery/diffuser systems which might be used during the summer of 2001.
- observing fauna (including possible attraction to a CO_2 release)
- observing droplet dynamics (at a scale one step larger than previous tests at MBARI)
- testing tracers/measurement systems

At the same time we could supplement some of the measurements collected during this past summer's background survey and begin the planning for possible additional (biological) components of the experiment.

At TC5 it was determined that it is not practical to use the Y2K cruise to test the Y2K+1 deployment system(s), but it should be feasible to purchase off the shelf a number of 30 gallon accumulators (perhaps 60 kg each of actively-available CO_2) which could be deployed from a vessel, either onto the seabed or suspended above the bed from a cable. A sub-committee has been corresponding by email and conference call concerning plans for this survey. The RV KOK with the submersible Pisces is available to use during October 2000, which may afford the best option.