INTERNATIONAL COLLABORATION ON CO₂ SEQUESTRATION

1st Annual Report
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The international project officially started December 4, 1998. This grant, which funds the US participation through MIT, officially started on August 23, 1998. Some pre-award money was used for Howard Herzog and Eric Adams to attend the first Technical Committee (TC) meeting on March 20-21, 1998 in Tokyo. Key personnel on the project include the Principal Investigators (Howard Herzog and Eric Adams) and the full time Research Assistants (Brian Crounse and Scott Socolofsky).

During this period, key events included:

- Second TC Meeting, August 27-28, 1998 in Bergen Norway. Attended by Howard Herzog, Eric Adams, and Brian Crounse.
- Third TC meeting, February 18-19, 1999 in Honolulu, HI. Attended by Howard Herzog, Eric Adams and Scott Socolofsky.
- The Fourth International Conference on Greenhouse Gas Control Technologies (GHGT-4) held August 30 - September 2, 1998 in Interlaken Switzerland. A paper on this project was presented.

This report is directed into three main components:

- Paper giving project overview (pages 2-8)
- Conceptual Design of Pipeline Operations and Control (pages 9-26)
- Design of the Field Experiment (pages 27-33).

AN INTERNATIONAL EXPERIMENT ON CO₂ OCEAN SEQUESTRATION¹

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ABSTRACT

The ocean represents the largest potential sink for anthropogenic CO₂. In order to better understand this potential, Japan, Norway, and the United States signed a Project Agreement for International Collaboration on CO₂ Ocean Sequestration in December 1997; since that time, Canada and ABB (Switzerland) have joined the project. The objective of the project is to investigate the technical feasibility of, and improve understanding of the environmental impacts from, CO₂ ocean sequestration in order to minimize the impacts associated with the eventual use of this technique to reduce greenhouse gas concentrations in the atmosphere. The project will continue through March 31, 2002, with a field experiment to take place in the summer of 2000 off the Kona Coast of Hawaii. The implementing research organizations are the Research Institute of Innovative Technology for the Earth (Japan), the Norwegian Institute for Water Research (Norway), and the Massachusetts Institute of Technology (USA). The general contractor for the project will be the Pacific International Center for High Technology Research in Hawaii. A Technical Committee has been formed to supervise the technical aspects and execution of this project. The members of this committee are the co-authors of this paper. In this paper we discuss key issues involved with the design, ocean engineering, measurements, siting, and costs of this experiment.

BACKGROUND AND MOTIVATION

One potential option to mitigate atmospheric CO₂ levels is to capture and sequester power plant CO₂. Commercial CO₂ capture technology, though expensive, exists today. However, the ability to sequester large quantities of CO₂ is uncertain. The deep ocean is one of only a few possible CO₂ disposal options (others include depleted oil and gas wells, coal beds, or deep saline aquifers), so it is important that we understand as much as possible about this strategy.

As indicated by recent international conferences on the subject (e.g., Handa and Ohsumi, 1995; Herzog, 1996; Ormerod, 1997), much has been learned about ocean CO₂ sequestration in the past half-dozen years. Of necessity, however, most of our knowledge has resulted from theoretical or laboratory studies. As we learn more, these studies must be validated and complemented with field studies.

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

We envision a series of three types of field experiments studying ocean sequestration at increasingly larger scales. The current project focuses on *pilot scale tests*. The primary objective of these experiments is to learn more about the physical-chemical processes which occur between seawater and CO₂ discharged as a buoyant liquid at ocean depths of order 1000 m in order to gain insights concerning the technical feasibility of this method and to better understand any associated environmental impacts. A number of tests will be performed at an open ocean site, over a

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

relatively short duration (one month), and at a significantly reduced scale (e.g., with a CO₂ loading of 0.1 to 1 kg/s). Possible follow-on experiments include:

- **Longer term tests of environmental impact.** The second type of experiment would focus on environmental impacts--both acute and chronic, including those expected in the water column and the seafloor--associated with the CO₂ discharge. In order to constrain the spatial dimensions of the experiment, tests could be conducted in a semi-enclosed body such as a fjord, as long as the hydrographic and biological conditions were similar to those of potential open ocean sites. However, the tests would need to be conducted over a sufficient time frame to be consistent with the lifetimes of impacted organisms (e.g., at least a year for many pelagic species). Extensive measurements would need to be taken before and after the release, as well as during the CO₂ release, in order to assess both change and recovery.
- **Full scale tests.** Before CO₂ ocean disposal can be accepted as a commercial technology, field tests will need to be conducted at full scale. Because of the substantial costs involved in producing large quantities of CO₂, a logical step in this direction would be to conduct an open ocean experiment using a "free" source of CO₂. Possible sites include the Norwegian Sea or the Gulf of Mexico, where CO₂ produced with natural gas is routinely vented to the atmosphere.

EXPERIMENTAL OBJECTIVES

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

- better understand the physical-chemical processes affecting the transport and fate of CO₂ released as buoyant liquid droplets at water depths of order 1000 m.
- evaluate the technical feasibility of this method.
- allow development and validation of transport and fate models, which are critical in predicting environmental impact.
- help establish CO₂ delivery techniques and field monitoring methodologies that will help in future experiments.

The physical-chemical interactions which need study are described below as a function of the scale of interaction. See also Figure 1. Note that while the experiment entails releasing the CO₂ droplets from a pipe on the ocean bottom, results should be applicable to the “moving ship” concept currently being investigated in Japan (Ohsumi, 1995).

CO₂ injection and droplet formation

The CO₂ will be injected through one or more nozzles and will form droplets upon its release. Important issues for nozzle design are the distribution of droplet sizes, interactions among droplets near the nozzle (e.g., aggregation/breakup), and the possibility of hydrate clogging at the nozzle. These characteristics will depend on nozzle design and, in particular, whether the design results in a jetting or atomization mode of droplet formation. Research on this topic is underway at several laboratories including the University of Hawaii (Masutani and Nihous, 1997), but field observations are needed for verification.

Droplet dynamics

Perhaps the most important technical uncertainty with the droplet plume option is whether or not hydrates will form on the rising droplets of a turbulent droplet plume. Hydrate “skins” will affect the rate of CO₂ dissolution and droplet rise velocity. The combined effects will influence the elevation within the water column at which the CO₂ ultimately comes to rest, and hence the efficiency of sequestration. Some experimental work on hydrate formation for individual, stationary droplets in a moving flow field has been conducted recently (e.g., Hirai *et al.*, 1996), and further laboratory experiments are planned at the University of Hawaii, but conditions may be different for a collection of free droplets in a highly turbulent plume. Field measurements to test the influence of hydrate formation will include direct observations of liquid CO₂ droplets at different elevations within the plume, and indirect measurements based on the vertical extent of pH perturbations and the concentration of tracers (e.g., fluorescent dye) injected with the CO₂.

Droplet/plume interaction

The behavior of a droplet plume in a stratified ambient is complicated by the fact that the core of the plume is positively buoyant, while the edge is negatively buoyant because the plume has entrained ambient water from lower depths and because a solution of CO₂ in seawater is denser than ambient water. The heavier solution tends to peel off as the plume rises. Model predictions suggest that the location and magnitude of the peeling affects the ultimate level and thickness of the CO₂ plume (Caulfield *et al.*, 1997; Thorkildsen and Alendal, 1997), but this effect needs more rigorous study, especially in the presence of ambient currents. Some understanding can be gleaned from experiments conducted in atmospheric pressure tanks (e.g., using air bubbles in salinity-stratified tanks), but a more complete confirmation requires field testing where the physical-chemical properties of CO₂ can be simulated at realistic pressures. Field tests will consist of observations of the plume flow field using video cameras, as well as 3-D velocity measurements. Additional measurements may be taken inside and outside the plume of other properties such as pH and the concentration of injected tracers (e.g., fluorescent dye).

Intrusion dynamics

Once CO₂-enriched water peels from the plume, it is expected to sink while intruding into the stratified ocean. Because of ambient density stratification, the CO₂-enriched seawater collapses vertically and spreads horizontally as it is advected by ocean currents. The intrusion is complicated by multiple peelings from the same plume, and multiple plumes from a multi-port injection. Theoretical and experimental data are available to describe

gravitational intrusion under idealized conditions (e.g., mass injected at a point in a linearly stratified, or a two-layer ambient; Akar and Jirka, 1995) but field validation is necessary. Properties to be measured include the width and thickness of the intrusion layer as a function of distance from the injection. These properties will be determined by measuring pH and the concentration of an injected tracer. Vertical profiles of velocity at various positions will also help establish the lateral extent of the intruded plume.

Ambient diffusion

At some distance from the point of injection, gravitational spreading will effectively cease, but the CO₂-enriched seawater will continue to diffuse due to passive ocean turbulence. Although much slower than plume-induced mixing near the point of injection, ambient diffusion is important for diluting plume contaminants and hence determining the distances required for plume concentrations and pH to return to background levels. Indeed, model sensitivity studies suggest that ambient diffusion is one of the most important variables affecting the impact on zooplankton passing through a CO₂-enriched plume (Adams *et al.*, 1997).

Many field experiments have been conducted to measure horizontal and vertical ambient diffusion in near surface waters (e.g., Okubo, 1971), but fewer data are available to describe such mixing at greater depths. Of particular importance would be measurements near the sea floor, where ambient turbulence (particularly in the vertical) may be considerably enhanced due to the proximity of the bottom boundary layer (Thorpe *et al.*, 1990). Several recent experiments with SF₆ have shown an influence of boundary mixing (Ledwell and Hickey, 1995; Ledwell and Bratkovich, 1995), and a recent near bottom tracer observation by CRIEPI has shown enhanced vertical mixing in very deep waters off the coast of Japan. However, additional measurements conducted near the bottom of the thermocline where we anticipate injecting the CO₂ would be helpful.

SITE SELECTION FOR PILOT SCALE EXPERIMENTS

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

- **Proximity to deep water.** The site needs to have relatively deep water (i.e., 1000 m depth) in close proximity to shore (i.e., <10 km) in order to minimize the costs of transporting CO₂ from shore.
- **Representative hydrography.** The vertical profile of temperature and density gradient should be representative of ocean sites where a “real” CO₂ injection might someday occur.
- **Shoreline support facilities.** The site should have the infrastructure to handle large CO₂ tanks, be near transportation facilities for emergency supplies, be able to house researchers, and, most importantly, have trained personnel to support the experiment.
- **Licensing considerations.** Although the environmental impacts of the pilot scale CO₂ experiment will be negligible, permission to conduct the experiment must be obtained from appropriate jurisdictions.

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

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

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

EXPERIMENTAL DESIGN

Scale of the experiment

The scale of the experiment refers to the duration of tests and the magnitude of the CO₂ loading. We envision a series of approximately 10 tests, each lasting from several hours to a day, performed over a period of several weeks.

The CO₂ loading should be sufficient for full scale simulation of a single nozzle; as such, loadings in the range of 0.1 to 1.0 kg/s are contemplated. The loading from a 500 MW_e coal-fired power plant is about 130 kg/s (Herzog *et al.*, 1996), so these tests will simulate the behavior from one nozzle out of an array of 100 to 1000 nozzles serving a large power plant.

CO₂ will be released from sufficient depth so that the liquid CO₂ droplets will dissolve before they rise to about 500 m, where they would flash into a vapor. To allow for the study of relatively large droplets with possible hydrate skins, a discharge depth of 700-1000 m is envisioned. It is desirable to discharge the CO₂ from at least two elevations above the ocean floor in order to observe the influence of the bottom boundary layer on plume transport and mixing.

While the CO₂ injection, droplet formation, and droplet dynamics will be simulated at full scale, the processes of droplet/plume interaction, intrusion dynamics and ambient diffusion will clearly be reduced in scale. The choice of CO₂ loading reflects a trade-off between measurement resolution (i.e., the ability to detect the CO₂ at various distances from the injection) and the cost of supplying CO₂. The cost of CO₂, including transportation and storage, could be as high as \$500 per tonne. At a loading of 1 kg/s, ten experiments, each lasting eight hours, would require about 300 tonnes of CO₂ costing \$150,000.

CO₂ Delivery

We considered the following options for discharging CO₂ at a depth of 1000 m.

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

A bottom pipeline was selected as the easiest option because the CO₂ would be handled on shore, and any troubleshooting of the delivery system could be conducted before the start of the experiments, minimizing interruptions to researchers and research vessels on site. In addition, the pipe will be semi-permanent, allowing follow-on tests to be conducted if desired. Electrical and fiber optic cables harnessed to the pipe will bring electricity to the terminus, and allow monitoring of the plume from shore.

The distance from shore to the pipe terminus at the Hawaiian site is about 3 km. A pipe designed to deliver CO₂ at a rate of 1 kg/s over this distance requires a diameter of about 3-5 cm and, in order to avoid phase changes, must withstand pressures as high as 170 bar. Steel pipe of the appropriate strength and flexibility is available commercially in lengths up to 10 km, coiled on large diameter reels. The typical cost of such a pipe is less than \$10,000 per km, but the larger cost comes in pipe deployment which requires the support of a pipe laying ship or barge and possibly a submersible to help anchor the pipe, attach risers, etc. Traditional pipe laying involves attaching straight pipe sections, but because of the small pipe diameter, the coiled pipe will simply be unreeled. We are currently comparing the various options which include:

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

To test the performance of different nozzles, and the effect of discharge at different heights above the bottom boundary layer, a riser system will be attached to the end of the pipe. A manifold will allow the nozzles to branch from the riser and be controlled remotely by solenoid valves. Anti-back flow valves installed near the nozzles and

an "electric blanket" will prevent seawater from intruding into the risers and potentially clogging the pipe with hydrates.

Measurements

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

- **Near field experiments** would be designed to test nozzle designs and observe droplet behavior. Observations will be made with a system of lights and tilt/pan video camera mounted on the seafloor near the diffuser section.
- **Intermediate field tests** will study droplet/plume interaction and intrusion dynamics at distances of order 100 m downstream from the discharge point. The principal measurement platform will be a remotely operated vehicle (ROV) which can maneuver precisely along a three-dimensional survey path measuring parameters such as pH, plume velocity, and concentrations of fluorescent dye. We will also collect discrete water samples which will be analyzed for temperature, salinity, and carbon chemistry aboard a supporting research vessel. Vertical arrays of pH sensors and an acoustic doppler current profiler will document ambient conditions.
- **Far field experiments** will measure ambient diffusivity. For the range of experimental release rates being considered, excess CO₂ concentrations, and hence perturbations in pH, will be too small to detect after several days. Hence, we plan to inject and measure a fluorescent tracer *in situ* with the aid of a sonar drifting buoy.

SCHEDULE

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

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CONCEPTUAL DESIGN OF PIPELINE OPERATIONS AND CONTROL

April 1999

Howard Herzog

This report summarizes work on the conceptual design of pipeline operations and control. In our investigation, we found no showstoppers. However, we have identified several potential problem areas that we will need to address. In this report, we discuss the three stages of operation, steady state, start-up, and shutdown.

In designing the pipeline system, a couple key criteria were developed:

- a. Keep the control system at the pipe exit as simple as possible. This is because any repairs or adjustments that may need to be made there could be very costly or even impossible.
- b. To enable accurate data collection, we want to be able to achieve a very steady flow rate for the CO₂ being injected. Therefore, we need to avoid regions of unsteady and/or oscillatory flow.

SPREADSHEET MODEL

To help design the pipeline control system, a simple spreadsheet was created (see attached). Key features of the spreadsheet include:

- Basis is a 2 km pipe going to a depth of 800 m.
- We approximated the slope in Hawaii as two segments of constant slope. The first 750 m drops to a depth of 160 m. The last 1.25 km drops at a steeper rate to cover remaining 640 m of depth.
- We used the summer temperature profile contained in the Site Selection Study.
- Pressure changes were calculated based on a loss due to friction and a gain due to the gravity head.
- Density was calculated as a function of temperature and pressure. A correlation was developed based on data from NIST (National Institute on Standards and Technology) over a temperature range of 5-27°C and a pressure range of 80-140 bar (see attached). Over this range of interest, correlated densities were within 1% of the NIST data. In much of the range, they were within 0.1%.
- Viscosity was calculated as a function of temperature based on a correlation provided by Gerard Nihous from Kreith and Bohn, *Principles of Heat Transfer*.

- The frictional pressure drop was calculated using the Fanning friction factor and standard calculations for flow in a pipe from Perry's *Chemical Engineers' Handbook*. We used the surface roughness given in Perry's for a commercial steel pipe. Indications from the pipe manufacture are that this is a conservative estimate (i.e., the manufacturer claims their pipe is smoother).

STEADY STATE OPERATION

Our initial analysis assumed the all flow control would be on the surface. We looked at two possible modes of operation:

First, one can operate with a small pressure drop at the pipe outlet. This means that two phase flow will result. If one assumes no frictional pressure losses, then the CO₂ will be vapor above a depth of approximately 350 m and a liquid below that depth. The pump outlet pressure will need to be about 45 bar. If frictional pressure losses exist, then the vapor-liquid transition will occur at a shallower depth and an inlet pressure greater than 45 bar will be required.

The other mode of operation is to force CO₂ to be in the liquid phase throughout. This means an inlet pressure above the critical point for CO₂ (73.843 bar). If we assume an inlet pressure of 80 bar and no frictional pressure losses, the bottom pressure will be about 146 bar. Frictional pressure losses will decrease the bottom pressure.

An advantage of method one is that the valving at the pipe exit can be quite simple because we have no excess pressure to dissipate. However, the exit flow rate may be difficult to control. Because the vapor portion is highly compressible and the exact height of the vapor-liquid interface may vary (due to pressure and heat transfer fluctuations), we may get unsteady flow at the outlet. In a worst case, the flow could oscillate, including significant periods of no flow. Because of the difficulty in controlling this flow rate, method two is the preferred method of operation if we control flow at the surface.

For method 2, a big challenge is how to dissipate the excess pressure in the bottom (see next paragraph). In other areas, this method offers advantages because it is a more predictable system. In addition, it may simplify the pump operation. We may be able to use a simple positive displacement pump (or, if necessary, a duplex or triplex). This will allow very accurate and easy metering of the flow. Depending on the exact pressure reduction valve chosen, any fluctuations caused by the pump may not affect the exit flow.

To dissipate the excess pressure, we will probably need 3 valves in series at the pipe exit. Starting at the exit and working back, they are:

- A check valve to stop any water from flowing into the pipe. It will be set at slightly above the ambient pressure of 80 bar. Important - we may need to build in a safety margin because of uncertainty in deploying to a precise depth. We also need to have a heating element starting at this valve through the diffuser to be able to melt any hydrates that may form.
- A block valve that is either on or off. This switch will be controlled from the surface.

- A pressure reduction valve to dissipate the excess pressure. Until we talk to vendors, it is uncertain whether one valve can handle all flows or whether we will need to put two valves in parallel, one for high flow and one for low flow. Also, it may be possible to eliminate this valve if this function can be combined with the check valve, but this approach is not recommended because it may be too risky.

Ideally, we would like to operate in the 0.1 – 1 kg/s range. We used the spreadsheet to calculate the bottom pressure (before the valves) for these flows for 3 different pipe sizes as shown in Table 1. Inlet pressures were set at 80 bar. Note that for the 1" pipe with a 1 kg/s flow, we will get boiling (i.e., 2, phase flow) in the pipe. We did not predict the bottom pressure for this case because the spreadsheet is valid for one phase liquid flow only.

Table 1. Bottom pressures.

Pipe OD	Pipe ID	Flow=1 kg/s	Flow=0.1 kg/s
1.5 inches	33.3 cm	136 bar	146 bar
1.25 inches	27.7 cm	119 bar	146 bar
1.0 inches	21.3 cm	boiling	145 bar

All 3 pipes show almost no pressure losses at 0.1 kg/s. The fastest flow we could use with a 1" pipe and an 80 bar inlet is about 0.75 kg/s. Note higher flows are obtainable if we boost inlet pressures. The spreadsheet model of the 1.5" pipe at 1 kg/s is attached. Graphs of the pressure profiles for the 1.25" pipe are also attached. Note the kink in these curves correspond to the change in the slope of the ocean floor.

Another consideration on choosing pipe diameters is the volume of CO₂ required to fill the pipe. This is shown in Table 2.

Table 2. Pipe volumes.

Pipe OD	Pipe ID	Volume	Amount CO ₂
1.5 inches	33.3 cm	1.74 m ³	1.54 tonnes
1.25 inches	27.7 cm	1.20 m ³	1.07 tonnes
1.0 inches	21.3 cm	0.71 m ³	0.63 tonnes

Currently, we are considering a 1.5" pipe. However, there seem to be advantages to getting a smaller pipe. Specifically, less CO₂ to manage during start-up and shut-down. Also, the smaller

pipe may be less expensive and easier to install. Possible disadvantages could be that a smaller pipe might be more easily kinked or damaged in some other way. Also, the 1" pipe may not be able to handle our fastest flow rate if we want a test at above 0.75 kg/s.

So, several things are all interconnected here and will need to be reconciled before final specifications are released. These are pipe diameter, experimental flow rates, pump size and type, and pipe control design. The next step is to find specific valves to finish the design of the piping system. Here is a summary of the current situation from the view of the piping system assuming we control flow at the surface:

- a. We will operate in the single phase region by keeping the CO₂ pressure above its critical point of 73.843 bar everywhere in the pipe. We call for a nominal inlet pressure of 80 bar.
- b. Baring other concerns, it seems we can reduce the pipe diameter (OD) from 1.5" to at least 1.25" and possibly 1".
- c. Depending on the pressure reduction valves chosen, we may be able to use a positive displacement pump and not be too concerned with its pulses affecting the exit flow.
- d. The critical task in finalizing the pipe design is to talk to vendors and identify the valves we will use at the pipe exit.

START-UP CONSIDERATIONS

There are two issues that must be addressed here. First, if one starts with a depressurized pipe that contains CO₂ vapor, the first step is to fill the pipe with liquid. This is accomplished by closing the block valve and adding CO₂ until the pressure in the top of the pipe hits 80 bar. Trying to fill the pipe with the block valve open will result in operating in the two phase regime, with crossing over to the single phase regime very difficult or maybe not even possible.

Once the pipe is filled with liquid, the block valve is open. What happens next will depend on the exact pressure reduction valves we purchase. We need to make sure that the pipe is not allowed to quickly depressurize and get us back in the two phase regime. This can be avoided by choosing the correct pressure reduction valves and/or overpressurizing the pipe before the block valve is opened.

SHUT-DOWN CONSIDERATIONS

Closing the block valve and shutting off the pump shuts down the operation. The exact order will vary depending on whether the system would be kept at pressure (close block valve first) or depressurized (close pump first).

The simplest procedure would be to keep the CO₂ locked in at high pressure. This means the pipe would remain filled with CO₂ for easy start-up. However, the system should be designed so the pipe can be depressurized and the resulting vapors returned to the CO₂ storage tank. Also, for safety, a return line with a pressure relief valve will also need to be included in the system.

ALTERNATIVE DESIGN

Upon completion of the initial conceptual design described above, we had it reviewed by Professor Peter Griffith, Professor of Mechanical Engineering at MIT and an expert on fluid flow in a pipe. Note that Professor Griffith also contributed to the development of the initial design. However, upon review, Professor Griffith raised concern of unstable flow. It is his experience that in compressible systems of this type, the exit flow will vary in an oscillatory manner. To confirm this suspicion, we will need to do detailed simulations.

To try to address this concern, we developed an alternate approach. This would involve controlling the flow at the exit. This was not considered originally because it was thought too risky, but we now believe we can minimize risks.

Our idea is to use the pipe as a CO₂ reservoir. At the outlet, we would put hydraulic motors. By setting the motor speed, we can accurately meter the flow. By choosing high speed motors and allowing 2-3 meters of pipe after the pump to act as a surge, we feel we can obtain a very steady flow.

In terms of flow rates, we can just change the motor speed. However, this may be risky at these depths, so we recommend 3 motors in parallel each preset at a given speed. This gives us both flexibility (we can operate motors in various combinations) and redundancy.

In summary, this alternative design has the following features:

- Since the pipe acts as just a CO₂ reservoir, we can operate in the 2-phase region. This eliminates large excess pressure at bottom and greatly simplifies requirements for the surface booster pump.
- We would want to stay with the 1.5" pipe (or maybe go slightly larger) to reduce vapor phase friction losses and to increase our reservoir volume.
- Start-up/Shut-down procedures simplified. All we need to do is to fill the pipe initially. Then it is a matter of turning the motors on and off.
- The next step is to verify that the type of motors we need are available for operation at 800m depth.

SUMMARY

The design of the piping system has turned out to be more challenging than originally anticipated. This is because of our need for a very steady exit flow combined with a desire for a simple, robust system at depth.

Our biggest obstacle is that the CO₂ system is compressible, making accurate control from the surface difficult. We have 2 conceptual designs we will continue to develop. We feel confident that a robust design will result, but more work is still required to work out the details.

ATTACHMENTS

- Spreadsheet model of stagnant liquid CO₂ (no flow).
- Spreadsheet model of 1 kg/s case for a 1.5" OD pipe (ID = 33.3 cm) with an 80 bar inlet pressure.
- Graphs of pressure profiles in a 1.25" pipe (ID=27.7 cm) for two different flows, 1 kg/s and 0.1 kg/s. Inlet pressure is 80 bars. Pressure is plotted against both pipe length and depth.
- NIST data used to develop the density versus temperature and pressure correlation.

No Flow

Pipe Diameter (m) 0.0333
 Flow Rate (kg/s) 0.00
 Roughness (m) 4.57E-05

X Pipe Length (m)	Z Depth (m)	T Temp (C)	P Pressure (bar)	p Density (kg/m3)	u Viscosity (Ns/m2)	v Velocity m/s	Re Reynolds Number Dvp/u	f Friction Factor	del Pf Friction Loss bar/m	del Pb Buoyancy Gain bar/m
0	0	26.7	80.00	762	5.82E-05	0.00	658	1.98E-02	0.000	0.069
10	2.1	26.7	80.15	763	5.82E-05	0.00	657	1.98E-02	0.000	0.069
20	4.3	26.6	80.30	763	5.83E-05	0.00	656	1.98E-02	0.000	0.069
30	6.4	26.6	80.44	764	5.83E-05	0.00	656	1.99E-02	0.000	0.069
40	8.5	26.5	80.59	765	5.84E-05	0.00	655	1.99E-02	0.000	0.070
50	10.7	26.5	80.74	766	5.85E-05	0.00	654	1.99E-02	0.000	0.070
60	12.8	26.5	80.89	767	5.85E-05	0.00	654	1.99E-02	0.000	0.070
70	15.0	26.4	81.04	768	5.86E-05	0.00	653	1.99E-02	0.000	0.070
80	17.1	26.4	81.19	769	5.87E-05	0.00	652	1.99E-02	0.000	0.070
90	19.2	26.3	81.34	769	5.87E-05	0.00	651	1.99E-02	0.000	0.070
100	21.4	26.3	81.49	770	5.87E-05	0.00	651	1.99E-02	0.000	0.070
110	23.5	26.3	81.64	770	5.88E-05	0.00	651	1.99E-02	0.000	0.070
120	25.6	26.3	81.79	771	5.88E-05	0.00	651	1.99E-02	0.000	0.070
130	27.8	26.3	81.94	771	5.88E-05	0.00	651	1.99E-02	0.000	0.070
140	29.9	26.3	82.09	772	5.88E-05	0.00	651	1.99E-02	0.000	0.070
150	32.1	26.2	82.23	772	5.88E-05	0.00	650	1.99E-02	0.000	0.070
160	34.2	26.2	82.38	773	5.88E-05	0.00	650	1.99E-02	0.000	0.070
170	36.3	26.2	82.53	773	5.88E-05	0.00	650	1.99E-02	0.000	0.070
180	38.5	26.2	82.68	773	5.89E-05	0.00	650	1.99E-02	0.000	0.070
190	40.6	26.2	82.84	774	5.89E-05	0.00	650	1.99E-02	0.000	0.070
200	42.7	26.2	82.99	774	5.89E-05	0.00	649	1.99E-02	0.000	0.070
210	44.9	26.2	83.14	775	5.89E-05	0.00	649	1.99E-02	0.000	0.070
220	47.0	26.1	83.29	775	5.90E-05	0.00	649	1.99E-02	0.000	0.070
230	49.2	26.1	83.44	776	5.90E-05	0.00	648	1.99E-02	0.000	0.071
240	51.3	26.1	83.59	777	5.90E-05	0.00	648	2.00E-02	0.000	0.071
250	53.4	26.1	83.74	777	5.91E-05	0.00	648	2.00E-02	0.000	0.071
260	55.6	26.0	83.89	778	5.91E-05	0.00	647	2.00E-02	0.000	0.071
270	57.7	26.0	84.04	779	5.92E-05	0.00	647	2.00E-02	0.000	0.071
280	59.8	26	84.19	779	5.92E-05	0.00	647	2.00E-02	0.000	0.071
290	62.0	26	84.34	779	5.92E-05	0.00	647	2.00E-02	0.000	0.071
300	64.1	26	84.49	779	5.92E-05	0.00	647	2.00E-02	0.000	0.071
310	66.2	26	84.65	780	5.92E-05	0.00	647	2.00E-02	0.000	0.071
320	68.4	26	84.80	780	5.92E-05	0.00	647	2.00E-02	0.000	0.071
330	70.5	26	84.95	780	5.92E-05	0.00	647	2.00E-02	0.000	0.071
340	72.7	26	85.10	781	5.92E-05	0.00	647	2.00E-02	0.000	0.071
350	74.8	26	85.25	781	5.92E-05	0.00	647	2.00E-02	0.000	0.071
360	76.9	26	85.40	781	5.92E-05	0.00	647	2.00E-02	0.000	0.071
370	79.1	26	85.55	782	5.92E-05	0.00	647	2.00E-02	0.000	0.071
380	81.2	26	85.71	782	5.92E-05	0.00	647	2.00E-02	0.000	0.071
390	83.3	26	85.86	782	5.92E-05	0.00	647	2.00E-02	0.000	0.071
400	85.5	26	86.01	782	5.92E-05	0.00	647	2.00E-02	0.000	0.071

X Pipe Length (m)	Z Depth (m)	T Temp (C)	P Pressure (bar)	p Density (kg/m3)	u Viscosity (Ns/m2)	v Velocity m/s	Re Reynolds Number Dvp/u	f Friction Factor	del Pf Friction Loss bar/m	del Pb Buoyancy Gain bar/m
410	87.6	26	86.16	783	5.92E-05	0.00	647	2.00E-02	0.000	0.071
420	89.8	26	86.31	783	5.92E-05	0.00	647	2.00E-02	0.000	0.071
430	91.9	26	86.47	783	5.92E-05	0.00	647	2.00E-02	0.000	0.071
440	94.0	26	86.62	784	5.92E-05	0.00	647	2.00E-02	0.000	0.071
450	96.2	26	86.77	784	5.92E-05	0.00	647	2.00E-02	0.000	0.071
460	98.3	26	86.92	784	5.92E-05	0.00	647	2.00E-02	0.000	0.071
470	100.4	26	87.08	785	5.92E-05	0.00	647	2.00E-02	0.000	0.071
480	102.6	25.9	87.23	786	5.93E-05	0.00	645	2.00E-02	0.000	0.071
490	104.7	25.7	87.38	788	5.95E-05	0.00	643	2.00E-02	0.000	0.072
500	106.8	25.6	87.53	790	5.97E-05	0.00	641	2.01E-02	0.000	0.072
510	109.0	25.5	87.69	791	5.99E-05	0.00	639	2.01E-02	0.000	0.072
520	111.1	25.4	87.84	793	6.01E-05	0.00	637	2.01E-02	0.000	0.072
530	113.3	25.2	87.99	795	6.03E-05	0.00	635	2.01E-02	0.000	0.072
540	115.4	25.1	88.15	796	6.04E-05	0.00	633	2.02E-02	0.000	0.072
550	117.5	25.0	88.30	798	6.06E-05	0.00	631	2.02E-02	0.000	0.072
560	119.7	24.8	88.46	799	6.08E-05	0.00	629	2.02E-02	0.000	0.073
570	121.8	24.7	88.61	801	6.10E-05	0.00	627	2.02E-02	0.000	0.073
580	123.9	24.4	88.77	804	6.15E-05	0.00	622	2.03E-02	0.000	0.073
590	126.1	24.0	88.93	808	6.20E-05	0.00	617	2.04E-02	0.000	0.073
600	128.2	23.7	89.08	811	6.24E-05	0.00	613	2.05E-02	0.000	0.074
610	130.4	23.4	89.24	815	6.29E-05	0.00	608	2.05E-02	0.000	0.074
620	132.5	23.0	89.40	818	6.34E-05	0.00	603	2.06E-02	0.000	0.074
630	134.6	22.7	89.56	821	6.39E-05	0.00	599	2.07E-02	0.000	0.075
640	136.8	22.4	89.72	824	6.44E-05	0.00	594	2.07E-02	0.000	0.075
650	138.9	22.0	89.88	828	6.49E-05	0.00	590	2.08E-02	0.000	0.075
660	141.0	21.7	90.04	831	6.54E-05	0.00	585	2.09E-02	0.000	0.075
670	143.2	21.5	90.20	833	6.57E-05	0.00	582	2.09E-02	0.000	0.076
680	145.3	21.3	90.36	835	6.61E-05	0.00	579	2.10E-02	0.000	0.076
690	147.5	21.5	90.52	833	6.57E-05	0.00	582	2.09E-02	0.000	0.076
700	149.6	21.0	90.68	837	6.64E-05	0.00	576	2.10E-02	0.000	0.076
710	151.7	20.8	90.85	839	6.67E-05	0.00	573	2.11E-02	0.000	0.076
720	153.9	20.6	91.01	841	6.71E-05	0.00	570	2.11E-02	0.000	0.076
730	156.0	20.4	91.17	843	6.74E-05	0.00	567	2.12E-02	0.000	0.077
740	158.1	20.1	91.34	845	6.78E-05	0.00	565	2.12E-02	0.000	0.077
750	160.3	19.7	91.50	849	6.84E-05	0.00	559	2.13E-02	0.000	0.077
760	165.4	19.2	91.89	853	6.92E-05	0.00	553	2.14E-02	0.000	0.077
770	170.5	18.8	92.29	857	6.99E-05	0.00	547	2.15E-02	0.000	0.078
780	175.5	18.3	92.68	861	7.07E-05	0.00	541	2.16E-02	0.000	0.078
790	180.6	17.8	93.08	865	7.14E-05	0.00	535	2.17E-02	0.000	0.079
800	185.7	17.1	93.48	870	7.26E-05	0.00	527	2.19E-02	0.000	0.079
810	190.8	16.4	93.89	875	7.37E-05	0.00	519	2.20E-02	0.000	0.080
820	195.9	15.7	94.29	880	7.49E-05	0.00	511	2.22E-02	0.000	0.080
830	201.0	15	94.70	885	7.60E-05	0.00	503	2.24E-02	0.000	0.080
840	206.1	14.5	95.11	889	7.68E-05	0.00	498	2.25E-02	0.000	0.081
850	211.2	14.1	95.52	892	7.76E-05	0.00	493	2.26E-02	0.000	0.081
860	216.3	13.6	95.93	896	7.84E-05	0.00	488	2.27E-02	0.000	0.081
870	221.4	13.1	96.35	899	7.92E-05	0.00	483	2.28E-02	0.000	0.082
880	226.5	13.0	96.76	900	7.95E-05	0.00	481	2.28E-02	0.000	0.082
890	231.6	12.8	97.18	902	7.98E-05	0.00	480	2.29E-02	0.000	0.082
900	236.7	12.7	97.60	903	8.00E-05	0.00	478	2.29E-02	0.000	0.082

X Pipe Length (m)	Z Depth (m)	T Temp (C)	P Pressure (bar)	p Density (kg/m3)	u Viscosity (Ns/m2)	v Velocity m/s	Re Reynolds Number Dvp/u	f Friction Factor	del Pf Friction Loss bar/m	del Pb Buoyancy Gain bar/m
910	241.7	12.5	98.01	904	8.03E-05	0.00	477	2.29E-02	0.000	0.082
920	246.8	12.3	98.43	906	8.06E-05	0.00	475	2.30E-02	0.000	0.082
930	251.9	12.1	98.85	908	8.10E-05	0.00	472	2.30E-02	0.000	0.082
940	257.0	11.9	99.27	909	8.13E-05	0.00	470	2.31E-02	0.000	0.083
950	262.1	11.7	99.69	911	8.17E-05	0.00	468	2.31E-02	0.000	0.083
960	267.2	11.6	100.11	912	8.19E-05	0.00	467	2.31E-02	0.000	0.083
970	272.3	11.4	100.54	913	8.22E-05	0.00	465	2.32E-02	0.000	0.083
980	277.4	11.3	100.96	914	8.25E-05	0.00	464	2.32E-02	0.000	0.083
990	282.5	11.1	101.38	916	8.27E-05	0.00	462	2.33E-02	0.000	0.083
1000	287.6	10.9	101.80	917	8.31E-05	0.00	460	2.33E-02	0.000	0.083
1010	292.7	10.7	102.23	919	8.34E-05	0.00	459	2.33E-02	0.000	0.083
1020	297.8	10.5	102.65	920	8.38E-05	0.00	457	2.34E-02	0.000	0.084
1030	302.9	10.3	103.08	922	8.41E-05	0.00	455	2.34E-02	0.000	0.084
1040	307.9	10.0	103.51	924	8.46E-05	0.00	452	2.35E-02	0.000	0.084
1050	313.0	9.8	103.93	925	8.51E-05	0.00	450	2.36E-02	0.000	0.084
1060	318.1	9.5	104.36	927	8.56E-05	0.00	447	2.36E-02	0.000	0.084
1070	323.2	9.4	104.79	928	8.58E-05	0.00	446	2.37E-02	0.000	0.084
1080	328.3	9.3	105.22	929	8.59E-05	0.00	445	2.37E-02	0.000	0.084
1090	333.4	9.2	105.65	930	8.61E-05	0.00	444	2.37E-02	0.000	0.085
1100	338.5	9.1	106.08	931	8.63E-05	0.00	443	2.37E-02	0.000	0.085
1110	343.6	9.0	106.51	932	8.65E-05	0.00	442	2.37E-02	0.000	0.085
1120	348.7	8.9	106.94	933	8.67E-05	0.00	441	2.38E-02	0.000	0.085
1130	353.8	8.8	107.37	934	8.69E-05	0.00	440	2.38E-02	0.000	0.085
1140	358.9	8.7	107.81	934	8.70E-05	0.00	440	2.38E-02	0.000	0.085
1150	364.0	8.6	108.24	935	8.72E-05	0.00	439	2.38E-02	0.000	0.085
1160	369.0	8.5	108.67	936	8.74E-05	0.00	438	2.39E-02	0.000	0.085
1170	374.1	8.4	109.10	937	8.76E-05	0.00	437	2.39E-02	0.000	0.085
1180	379.2	8.3	109.54	938	8.78E-05	0.00	436	2.39E-02	0.000	0.085
1190	384.3	8.3	109.97	938	8.79E-05	0.00	435	2.39E-02	0.000	0.085
1200	389.4	8.2	110.41	939	8.80E-05	0.00	435	2.39E-02	0.000	0.085
1210	394.5	8.2	110.84	940	8.80E-05	0.00	434	2.40E-02	0.000	0.085
1220	399.6	8.1	111.28	940	8.81E-05	0.00	434	2.40E-02	0.000	0.085
1230	404.7	8.1	111.71	941	8.82E-05	0.00	434	2.40E-02	0.000	0.085
1240	409.8	8.1	112.15	941	8.82E-05	0.00	434	2.40E-02	0.000	0.086
1250	414.9	8.0	112.58	941	8.83E-05	0.00	433	2.40E-02	0.000	0.086
1260	420.0	8	113.02	942	8.83E-05	0.00	433	2.40E-02	0.000	0.086
1270	425.1	7.9	113.45	943	8.85E-05	0.00	432	2.40E-02	0.000	0.086
1280	430.2	7.8	113.89	944	8.87E-05	0.00	431	2.40E-02	0.000	0.086
1290	435.2	7.7	114.33	944	8.89E-05	0.00	430	2.41E-02	0.000	0.086
1300	440.3	7.6	114.76	945	8.91E-05	0.00	430	2.41E-02	0.000	0.086
1310	445.4	7.6	115.20	946	8.92E-05	0.00	429	2.41E-02	0.000	0.086
1320	450.5	7.5	115.64	946	8.92E-05	0.00	429	2.41E-02	0.000	0.086
1330	455.6	7.5	116.08	947	8.93E-05	0.00	428	2.41E-02	0.000	0.086
1340	460.7	7.4	116.51	947	8.94E-05	0.00	428	2.41E-02	0.000	0.086
1350	465.8	7.3	116.95	948	8.96E-05	0.00	427	2.42E-02	0.000	0.086
1360	470.9	7.2	117.39	949	8.98E-05	0.00	426	2.42E-02	0.000	0.086
1370	476.0	7.1	117.83	950	9.00E-05	0.00	425	2.42E-02	0.000	0.086
1380	481.1	7	118.27	951	9.02E-05	0.00	424	2.42E-02	0.000	0.086
1390	486.2	7.0	118.71	951	9.03E-05	0.00	424	2.42E-02	0.000	0.086
1400	491.3	6.9	119.15	952	9.04E-05	0.00	423	2.43E-02	0.000	0.086

X Pipe Length (m)	Z Depth (m)	T Temp (C)	P Pressure (bar)	p Density (kg/m3)	u Viscosity (Ns/m2)	v Velocity m/s	Re Reynolds Number Dvp/u	f Friction Factor	del Pf Friction Loss bar/m	del Pb Buoyancy Gain bar/m
1410	496.4	6.9	119.59	952	9.05E-05	0.00	423	2.43E-02	0.000	0.087
1420	501.4	6.8	120.03	953	9.06E-05	0.00	422	2.43E-02	0.000	0.087
1430	506.5	6.8	120.47	953	9.06E-05	0.00	422	2.43E-02	0.000	0.087
1440	511.6	6.8	120.91	953	9.06E-05	0.00	422	2.43E-02	0.000	0.087
1450	516.7	6.7	121.35	954	9.07E-05	0.00	422	2.43E-02	0.000	0.087
1460	521.8	6.7	121.79	954	9.07E-05	0.00	422	2.43E-02	0.000	0.087
1470	526.9	6.6	122.24	955	9.09E-05	0.00	421	2.43E-02	0.000	0.087
1480	532.0	6.6	122.68	956	9.10E-05	0.00	420	2.43E-02	0.000	0.087
1490	537.1	6.5	123.12	956	9.12E-05	0.00	420	2.44E-02	0.000	0.087
1500	542.2	6.4	123.56	957	9.13E-05	0.00	419	2.44E-02	0.000	0.087
1510	547.3	6.4	124.01	957	9.14E-05	0.00	419	2.44E-02	0.000	0.087
1520	552.4	6.3	124.45	958	9.15E-05	0.00	418	2.44E-02	0.000	0.087
1530	557.5	6.3	124.89	958	9.16E-05	0.00	418	2.44E-02	0.000	0.087
1540	562.6	6.2	125.33	959	9.17E-05	0.00	417	2.44E-02	0.000	0.087
1550	567.6	6.1	125.78	959	9.18E-05	0.00	417	2.44E-02	0.000	0.087
1560	572.7	6.1	126.22	960	9.19E-05	0.00	416	2.45E-02	0.000	0.087
1570	577.8	6	126.67	961	9.21E-05	0.00	416	2.45E-02	0.000	0.087
1580	582.9	6.0	127.11	961	9.22E-05	0.00	415	2.45E-02	0.000	0.087
1590	588.0	5.9	127.56	962	9.23E-05	0.00	415	2.45E-02	0.000	0.087
1600	593.1	5.9	128.00	962	9.23E-05	0.00	414	2.45E-02	0.000	0.087
1610	598.2	5.8	128.45	963	9.24E-05	0.00	414	2.45E-02	0.000	0.087
1620	603.3	5.8	128.89	963	9.25E-05	0.00	414	2.45E-02	0.000	0.088
1630	608.4	5.8	129.34	963	9.25E-05	0.00	413	2.45E-02	0.000	0.088
1640	613.5	5.7	129.78	964	9.26E-05	0.00	413	2.45E-02	0.000	0.088
1650	618.6	5.7	130.23	964	9.26E-05	0.00	413	2.45E-02	0.000	0.088
1660	623.7	5.7	130.67	964	9.27E-05	0.00	413	2.45E-02	0.000	0.088
1670	628.7	5.7	131.12	965	9.27E-05	0.00	413	2.46E-02	0.000	0.088
1680	633.8	5.6	131.57	965	9.27E-05	0.00	412	2.46E-02	0.000	0.088
1690	638.9	5.6	132.01	965	9.28E-05	0.00	412	2.46E-02	0.000	0.088
1700	644.0	5.6	132.46	966	9.28E-05	0.00	412	2.46E-02	0.000	0.088
1710	649.1	5.6	132.91	966	9.29E-05	0.00	412	2.46E-02	0.000	0.088
1720	654.2	5.6	133.35	966	9.29E-05	0.00	412	2.46E-02	0.000	0.088
1730	659.3	5.6	133.80	967	9.29E-05	0.00	412	2.46E-02	0.000	0.088
1740	664.4	5.5	134.25	967	9.29E-05	0.00	412	2.46E-02	0.000	0.088
1750	669.5	5.5	134.70	967	9.30E-05	0.00	412	2.46E-02	0.000	0.088
1760	674.6	5.5	135.14	968	9.30E-05	0.00	411	2.46E-02	0.000	0.088
1770	679.7	5.5	135.59	968	9.30E-05	0.00	411	2.46E-02	0.000	0.088
1780	684.8	5.5	136.04	968	9.31E-05	0.00	411	2.46E-02	0.000	0.088
1790	689.9	5.5	136.49	969	9.31E-05	0.00	411	2.46E-02	0.000	0.088
1800	694.9	5.4	136.94	969	9.32E-05	0.00	411	2.46E-02	0.000	0.088
1810	700.0	5.4	137.38	969	9.32E-05	0.00	410	2.46E-02	0.000	0.088
1820	705.1	5.4	137.83	970	9.33E-05	0.00	410	2.46E-02	0.000	0.088
1830	710.2	5.4	138.28	970	9.33E-05	0.00	410	2.46E-02	0.000	0.088
1840	715.3	5.3	138.73	970	9.33E-05	0.00	410	2.46E-02	0.000	0.088
1850	720.4	5.3	139.18	971	9.34E-05	0.00	410	2.46E-02	0.000	0.088
1860	725.5	5.3	139.63	971	9.34E-05	0.00	409	2.46E-02	0.000	0.088
1870	730.6	5.3	140.08	971	9.35E-05	0.00	409	2.47E-02	0.000	0.088
1880	735.7	5.2	140.53	972	9.35E-05	0.00	409	2.47E-02	0.000	0.088
1890	740.8	5.2	140.98	972	9.36E-05	0.00	409	2.47E-02	0.000	0.088
1900	745.9	5.2	141.43	972	9.36E-05	0.00	409	2.47E-02	0.000	0.088

X Pipe Length (m)	Z Depth (m)	T Temp (C)	P Pressure (bar)	p Density (kg/m3)	u Viscosity (Ns/m2)	v Velocity m/s	Re Reynolds Number Dvp/u	f Friction Factor	del Pf Friction Loss bar/m	del Pb Buoyancy Gain bar/m
1910	751.0	5.2	141.88	973	9.36E-05	0.00	409	2.47E-02	0.000	0.088
1920	756.1	5.2	142.33	973	9.37E-05	0.00	408	2.47E-02	0.000	0.088
1930	761.1	5.2	142.78	973	9.37E-05	0.00	408	2.47E-02	0.000	0.088
1940	766.2	5.1	143.23	973	9.37E-05	0.00	408	2.47E-02	0.000	0.088
1950	771.3	5.1	143.68	974	9.37E-05	0.00	408	2.47E-02	0.000	0.088
1960	776.4	5.1	144.13	974	9.38E-05	0.00	408	2.47E-02	0.000	0.089
1970	781.5	5.1	144.58	974	9.38E-05	0.00	408	2.47E-02	0.000	0.089
1980	786.6	5.1	145.03	974	9.38E-05	0.00	408	2.47E-02	0.000	0.089
1990	791.7	5.1	145.48	975	9.38E-05	0.00	408	2.47E-02	0.000	0.089
2000	796.8	5.06	145.93	975	9.39E-05	0.00	408	2.47E-02	0.000	0.089

Flow = 1 kg/s, D = 33.3 cm

Pipe Diameter (m) 0.0333
Flow Rate (kg/s) 1.00
Roughness (m) 4.57E-05

X Pipe Length (m)	Z Depth (m)	T Temp (C)	P Pressure (bar)	p Density (kg/m3)	u Viscosity (Ns/m2)	v Velocity m/s	Re Reynolds Number Dvp/u	f Friction Factor	del Pf Friction Loss bar/m	del Pb Buoyancy Gain bar/m
0	0	26.7	80.00	762	5.82E-05	1.51	657513	5.40E-03	0.006	0.069
10	2.1	26.7	80.09	762	5.82E-05	1.51	656889	5.40E-03	0.006	0.069
20	4.3	26.6	80.18	763	5.83E-05	1.51	656266	5.40E-03	0.006	0.069
30	6.4	26.6	80.28	764	5.83E-05	1.50	655643	5.40E-03	0.006	0.069
40	8.5	26.5	80.37	765	5.84E-05	1.50	655021	5.40E-03	0.006	0.069
50	10.7	26.5	80.46	765	5.85E-05	1.50	654399	5.40E-03	0.006	0.070
60	12.8	26.5	80.55	766	5.85E-05	1.50	653624	5.40E-03	0.006	0.070
70	15.0	26.4	80.65	767	5.86E-05	1.50	652849	5.40E-03	0.006	0.070
80	17.1	26.4	80.74	768	5.87E-05	1.50	652076	5.40E-03	0.006	0.070
90	19.2	26.3	80.83	768	5.87E-05	1.50	651304	5.40E-03	0.006	0.070
100	21.4	26.3	80.93	769	5.87E-05	1.49	651150	5.40E-03	0.006	0.070
110	23.5	26.3	81.02	769	5.88E-05	1.49	650995	5.40E-03	0.006	0.070
120	25.6	26.3	81.11	769	5.88E-05	1.49	650841	5.40E-03	0.006	0.070
130	27.8	26.3	81.21	770	5.88E-05	1.49	650687	5.40E-03	0.006	0.070
140	29.9	26.3	81.30	770	5.88E-05	1.49	650533	5.40E-03	0.006	0.070
150	32.1	26.2	81.39	770	5.88E-05	1.49	650379	5.40E-03	0.006	0.070
160	34.2	26.2	81.49	771	5.88E-05	1.49	650225	5.40E-03	0.006	0.070
170	36.3	26.2	81.58	771	5.88E-05	1.49	650071	5.40E-03	0.006	0.070
180	38.5	26.2	81.68	771	5.89E-05	1.49	649917	5.40E-03	0.006	0.070
190	40.6	26.2	81.77	772	5.89E-05	1.49	649763	5.40E-03	0.006	0.070
200	42.7	26.2	81.87	772	5.89E-05	1.49	649421	5.40E-03	0.006	0.070
210	44.9	26.2	81.96	772	5.89E-05	1.49	649080	5.40E-03	0.006	0.070
220	47.0	26.1	82.05	773	5.90E-05	1.49	648739	5.40E-03	0.006	0.070
230	49.2	26.1	82.15	773	5.90E-05	1.49	648398	5.40E-03	0.006	0.070
240	51.3	26.1	82.24	774	5.90E-05	1.48	648057	5.40E-03	0.006	0.070
250	53.4	26.1	82.34	774	5.91E-05	1.48	647716	5.40E-03	0.006	0.070
260	55.6	26.0	82.43	775	5.91E-05	1.48	647036	5.40E-03	0.006	0.070
270	57.7	26.0	82.53	775	5.92E-05	1.48	646696	5.40E-03	0.006	0.070
280	59.8	26	82.62	776	5.92E-05	1.48	646696	5.40E-03	0.006	0.070
290	62.0	26	82.72	776	5.92E-05	1.48	646696	5.40E-03	0.006	0.071
300	64.1	26	82.82	776	5.92E-05	1.48	646696	5.40E-03	0.006	0.071
310	66.2	26	82.91	776	5.92E-05	1.48	646696	5.40E-03	0.006	0.071
320	68.4	26	83.01	776	5.92E-05	1.48	646696	5.40E-03	0.006	0.071
330	70.5	26	83.10	777	5.92E-05	1.48	646696	5.40E-03	0.006	0.071
340	72.7	26	83.20	777	5.92E-05	1.48	646696	5.40E-03	0.006	0.071
350	74.8	26	83.29	777	5.92E-05	1.48	646696	5.40E-03	0.006	0.071
360	76.9	26	83.39	777	5.92E-05	1.48	646696	5.40E-03	0.006	0.071
370	79.1	26	83.48	777	5.92E-05	1.48	646696	5.40E-03	0.006	0.071
380	81.2	26	83.58	778	5.92E-05	1.48	646696	5.40E-03	0.006	0.071
390	83.3	26	83.68	778	5.92E-05	1.48	646696	5.40E-03	0.006	0.071
400	85.5	26	83.77	778	5.92E-05	1.48	646696	5.40E-03	0.006	0.071
410	87.6	26	83.87	778	5.92E-05	1.48	646696	5.40E-03	0.006	0.071

X Pipe Length (m)	Z Depth (m)	T Temp (C)	P Pressure (bar)	p Density (kg/m3)	u Viscosity (Ns/m2)	v Velocity (m/s)	Re Reynolds Number Dvp/u	f Friction Factor	del Pf Friction Loss bar/m	del Pb Buoyancy Gain bar/m
420	89.8	26	83.96	778	5.92E-05	1.48	646696	5.40E-03	0.006	0.071
430	91.9	26	84.06	779	5.92E-05	1.48	646696	5.40E-03	0.006	0.071
440	94.0	26	84.16	779	5.92E-05	1.48	646696	5.40E-03	0.005	0.071
450	96.2	26	84.25	779	5.92E-05	1.47	646696	5.40E-03	0.005	0.071
460	98.3	26	84.35	779	5.92E-05	1.47	646696	5.40E-03	0.005	0.071
470	100.4	26	84.45	779	5.92E-05	1.47	646696	5.40E-03	0.005	0.071
480	102.6	25.9	84.54	781	5.93E-05	1.47	644712	5.40E-03	0.005	0.071
490	104.7	25.7	84.64	783	5.95E-05	1.47	642735	5.40E-03	0.005	0.071
500	106.8	25.6	84.74	784	5.97E-05	1.46	640767	5.40E-03	0.005	0.071
510	109.0	25.5	84.83	786	5.99E-05	1.46	638806	5.40E-03	0.005	0.071
520	111.1	25.4	84.93	787	6.01E-05	1.46	636853	5.40E-03	0.005	0.072
530	113.3	25.2	85.03	789	6.03E-05	1.46	634907	5.40E-03	0.005	0.072
540	115.4	25.1	85.13	791	6.04E-05	1.45	632969	5.40E-03	0.005	0.072
550	117.5	25.0	85.23	792	6.06E-05	1.45	631039	5.40E-03	0.005	0.072
560	119.7	24.8	85.33	794	6.08E-05	1.45	629116	5.41E-03	0.005	0.072
570	121.8	24.7	85.43	795	6.10E-05	1.44	627200	5.41E-03	0.005	0.072
580	123.9	24.4	85.53	799	6.15E-05	1.44	622323	5.41E-03	0.005	0.073
590	126.1	24.0	85.63	802	6.20E-05	1.43	617493	5.41E-03	0.005	0.073
600	128.2	23.7	85.73	806	6.24E-05	1.43	612712	5.41E-03	0.005	0.073
610	130.4	23.4	85.84	809	6.29E-05	1.42	607978	5.41E-03	0.005	0.074
620	132.5	23.0	85.94	812	6.34E-05	1.41	603291	5.41E-03	0.005	0.074
630	134.6	22.7	86.05	816	6.39E-05	1.41	598651	5.41E-03	0.005	0.074
640	136.8	22.4	86.15	819	6.44E-05	1.40	594056	5.41E-03	0.005	0.074
650	138.9	22.0	86.26	822	6.49E-05	1.40	589506	5.41E-03	0.005	0.075
660	141.0	21.7	86.37	825	6.54E-05	1.39	585001	5.41E-03	0.005	0.075
670	143.2	21.5	86.47	827	6.57E-05	1.39	582023	5.41E-03	0.005	0.075
680	145.3	21.3	86.58	829	6.61E-05	1.39	579064	5.41E-03	0.005	0.075
690	147.5	21.5	86.69	828	6.57E-05	1.39	582023	5.41E-03	0.005	0.075
700	149.6	21.0	86.80	831	6.64E-05	1.38	576124	5.41E-03	0.005	0.076
710	151.7	20.8	86.91	833	6.67E-05	1.38	573204	5.41E-03	0.005	0.076
720	153.9	20.6	87.02	835	6.71E-05	1.38	570303	5.41E-03	0.005	0.076
730	156.0	20.4	87.13	837	6.74E-05	1.37	567420	5.41E-03	0.005	0.076
740	158.1	20.1	87.24	839	6.78E-05	1.37	564557	5.41E-03	0.005	0.076
750	160.3	19.7	87.36	843	6.84E-05	1.36	558886	5.42E-03	0.005	0.077
760	165.4	19.2	87.69	847	6.92E-05	1.36	552906	5.42E-03	0.005	0.077
770	170.5	18.8	88.04	851	6.99E-05	1.35	547010	5.42E-03	0.005	0.077
780	175.5	18.3	88.38	855	7.07E-05	1.34	541195	5.42E-03	0.005	0.078
790	180.6	17.8	88.72	859	7.14E-05	1.34	535460	5.42E-03	0.005	0.078
800	185.7	17.1	89.07	865	7.26E-05	1.33	527152	5.42E-03	0.005	0.079
810	190.8	16.4	89.42	870	7.37E-05	1.32	519013	5.42E-03	0.005	0.079
820	195.9	15.7	89.78	875	7.49E-05	1.31	511037	5.42E-03	0.005	0.080
830	201.0	15	90.13	881	7.60E-05	1.30	503221	5.43E-03	0.005	0.080
840	206.1	14.5	90.49	884	7.68E-05	1.30	498007	5.43E-03	0.005	0.080
850	211.2	14.1	90.85	888	7.76E-05	1.29	492864	5.43E-03	0.005	0.081
860	216.3	13.6	91.21	891	7.84E-05	1.29	487791	5.43E-03	0.005	0.081
870	221.4	13.1	91.58	895	7.92E-05	1.28	482787	5.43E-03	0.005	0.081
880	226.5	13.0	91.94	896	7.95E-05	1.28	481220	5.43E-03	0.005	0.081
890	231.6	12.8	92.31	897	7.98E-05	1.28	479661	5.43E-03	0.005	0.082
900	236.7	12.7	92.68	898	8.00E-05	1.28	478108	5.43E-03	0.005	0.082
910	241.7	12.5	93.04	900	8.03E-05	1.28	476562	5.43E-03	0.005	0.082

X Pipe Length (m)	Z Depth (m)	T Temp (C)	P Pressure (bar)	p Density (kg/m3)	u Viscosity (Ns/m2)	v Velocity (m/s)	Re Reynolds Number Dvp/u	f Friction Factor	del Pf Friction Loss bar/m	del Pb Buoyancy Gain bar/m
920	246.8	12.3	93.41	901	8.06E-05	1.27	474511	5.43E-03	0.005	0.082
930	251.9	12.1	93.78	903	8.10E-05	1.27	472472	5.43E-03	0.005	0.082
940	257.0	11.9	94.15	905	8.13E-05	1.27	470444	5.43E-03	0.005	0.082
950	262.1	11.7	94.52	906	8.17E-05	1.27	468428	5.43E-03	0.005	0.082
960	267.2	11.6	94.90	907	8.19E-05	1.27	466923	5.43E-03	0.005	0.082
970	272.3	11.4	95.27	909	8.22E-05	1.26	465425	5.43E-03	0.005	0.083
980	277.4	11.3	95.64	910	8.25E-05	1.26	463933	5.43E-03	0.005	0.083
990	282.5	11.1	96.01	911	8.27E-05	1.26	462448	5.43E-03	0.005	0.083
1000	287.6	10.9	96.39	913	8.31E-05	1.26	460477	5.43E-03	0.005	0.083
1010	292.7	10.7	96.76	914	8.34E-05	1.26	458517	5.44E-03	0.005	0.083
1020	297.8	10.5	97.14	916	8.38E-05	1.25	456569	5.44E-03	0.005	0.083
1030	302.9	10.3	97.52	917	8.41E-05	1.25	454632	5.44E-03	0.005	0.083
1040	307.9	10.0	97.89	919	8.46E-05	1.25	452066	5.44E-03	0.005	0.084
1050	313.0	9.8	98.27	921	8.51E-05	1.25	449519	5.44E-03	0.005	0.084
1060	318.1	9.5	98.65	923	8.56E-05	1.24	446991	5.44E-03	0.005	0.084
1070	323.2	9.4	99.03	924	8.58E-05	1.24	446049	5.44E-03	0.005	0.084
1080	328.3	9.3	99.41	925	8.59E-05	1.24	445108	5.44E-03	0.005	0.084
1090	333.4	9.2	99.79	926	8.61E-05	1.24	444171	5.44E-03	0.005	0.084
1100	338.5	9.1	100.18	926	8.63E-05	1.24	443236	5.44E-03	0.005	0.084
1110	343.6	9.0	100.56	927	8.65E-05	1.24	442304	5.44E-03	0.005	0.084
1120	348.7	8.9	100.94	928	8.67E-05	1.24	441374	5.44E-03	0.005	0.084
1130	353.8	8.8	101.32	929	8.69E-05	1.24	440447	5.44E-03	0.005	0.084
1140	358.9	8.7	101.71	930	8.70E-05	1.24	439523	5.44E-03	0.005	0.085
1150	364.0	8.6	102.09	931	8.72E-05	1.23	438601	5.44E-03	0.005	0.085
1160	369.0	8.5	102.48	932	8.74E-05	1.23	437682	5.44E-03	0.005	0.085
1170	374.1	8.4	102.86	932	8.76E-05	1.23	436765	5.44E-03	0.005	0.085
1180	379.2	8.3	103.25	933	8.78E-05	1.23	435851	5.44E-03	0.005	0.085
1190	384.3	8.3	103.63	934	8.79E-05	1.23	435395	5.44E-03	0.005	0.085
1200	389.4	8.2	104.02	934	8.80E-05	1.23	434940	5.44E-03	0.005	0.085
1210	394.5	8.2	104.40	935	8.80E-05	1.23	434485	5.44E-03	0.005	0.085
1220	399.6	8.1	104.79	936	8.81E-05	1.23	434031	5.44E-03	0.005	0.085
1230	404.7	8.1	105.18	936	8.82E-05	1.23	433804	5.44E-03	0.005	0.085
1240	409.8	8.1	105.56	936	8.82E-05	1.23	433577	5.44E-03	0.005	0.085
1250	414.9	8.0	105.95	937	8.83E-05	1.23	433351	5.44E-03	0.005	0.085
1260	420.0	8	106.34	937	8.83E-05	1.23	433124	5.44E-03	0.005	0.085
1270	425.1	7.9	106.73	938	8.85E-05	1.22	432221	5.44E-03	0.005	0.085
1280	430.2	7.8	107.11	939	8.87E-05	1.22	431319	5.44E-03	0.005	0.085
1290	435.2	7.7	107.50	940	8.89E-05	1.22	430421	5.44E-03	0.005	0.085
1300	440.3	7.6	107.89	941	8.91E-05	1.22	429525	5.44E-03	0.005	0.085
1310	445.4	7.6	108.28	941	8.92E-05	1.22	429077	5.44E-03	0.005	0.086
1320	450.5	7.5	108.67	942	8.92E-05	1.22	428631	5.44E-03	0.005	0.086
1330	455.6	7.5	109.06	942	8.93E-05	1.22	428185	5.44E-03	0.005	0.086
1340	460.7	7.4	109.45	943	8.94E-05	1.22	427740	5.44E-03	0.005	0.086
1350	465.8	7.3	109.84	944	8.96E-05	1.22	426851	5.44E-03	0.005	0.086
1360	470.9	7.2	110.23	944	8.98E-05	1.22	425965	5.44E-03	0.005	0.086
1370	476.0	7.1	110.62	945	9.00E-05	1.22	425081	5.44E-03	0.005	0.086
1380	481.1	7	111.02	946	9.02E-05	1.21	424200	5.44E-03	0.005	0.086
1390	486.2	7.0	111.41	946	9.03E-05	1.21	423761	5.44E-03	0.005	0.086
1400	491.3	6.9	111.80	947	9.04E-05	1.21	423322	5.44E-03	0.005	0.086
1410	496.4	6.9	112.19	948	9.05E-05	1.21	422883	5.44E-03	0.005	0.086

X Pipe Length (m)	Z Depth (m)	T Temp (C)	P Pressure (bar)	p Density (kg/m3)	u Viscosity (Ns/m2)	v Velocity (m/s)	Re Reynolds Number Dvp/u	f Friction Factor	del Pf Friction Loss bar/m	del Pb Buoyancy Gain bar/m
1420	501.4	6.8	112.59	948	9.06E-05	1.21	422445	5.44E-03	0.005	0.086
1430	506.5	6.8	112.98	948	9.06E-05	1.21	422227	5.44E-03	0.005	0.086
1440	511.6	6.8	113.37	949	9.06E-05	1.21	422008	5.44E-03	0.005	0.086
1450	516.7	6.7	113.77	949	9.07E-05	1.21	421790	5.44E-03	0.005	0.086
1460	521.8	6.7	114.16	950	9.07E-05	1.21	421572	5.44E-03	0.005	0.086
1470	526.9	6.6	114.55	950	9.09E-05	1.21	420918	5.45E-03	0.005	0.086
1480	532.0	6.6	114.95	951	9.10E-05	1.21	420266	5.45E-03	0.005	0.086
1490	537.1	6.5	115.34	952	9.12E-05	1.21	419615	5.45E-03	0.005	0.086
1500	542.2	6.4	115.74	952	9.13E-05	1.21	418965	5.45E-03	0.005	0.087
1510	547.3	6.4	116.13	953	9.14E-05	1.21	418533	5.45E-03	0.005	0.087
1520	552.4	6.3	116.53	953	9.15E-05	1.21	418101	5.45E-03	0.005	0.087
1530	557.5	6.3	116.92	954	9.16E-05	1.20	417670	5.45E-03	0.005	0.087
1540	562.6	6.2	117.32	954	9.17E-05	1.20	417239	5.45E-03	0.005	0.087
1550	567.6	6.1	117.72	955	9.18E-05	1.20	416666	5.45E-03	0.005	0.087
1560	572.7	6.1	118.11	955	9.19E-05	1.20	416094	5.45E-03	0.005	0.087
1570	577.8	6	118.51	956	9.21E-05	1.20	415523	5.45E-03	0.005	0.087
1580	582.9	6.0	118.91	956	9.22E-05	1.20	415096	5.45E-03	0.005	0.087
1590	588.0	5.9	119.30	957	9.23E-05	1.20	414669	5.45E-03	0.005	0.087
1600	593.1	5.9	119.70	957	9.23E-05	1.20	414243	5.45E-03	0.005	0.087
1610	598.2	5.8	120.10	958	9.24E-05	1.20	413817	5.45E-03	0.005	0.087
1620	603.3	5.8	120.50	958	9.25E-05	1.20	413604	5.45E-03	0.005	0.087
1630	608.4	5.8	120.90	959	9.25E-05	1.20	413392	5.45E-03	0.005	0.087
1640	613.5	5.7	121.29	959	9.26E-05	1.20	413179	5.45E-03	0.005	0.087
1650	618.6	5.7	121.69	959	9.26E-05	1.20	412967	5.45E-03	0.005	0.087
1660	623.7	5.7	122.09	960	9.27E-05	1.20	412798	5.45E-03	0.004	0.087
1670	628.7	5.7	122.49	960	9.27E-05	1.20	412628	5.45E-03	0.004	0.087
1680	633.8	5.6	122.89	960	9.27E-05	1.20	412459	5.45E-03	0.004	0.087
1690	638.9	5.6	123.29	961	9.28E-05	1.20	412289	5.45E-03	0.004	0.087
1700	644.0	5.6	123.69	961	9.28E-05	1.20	412120	5.45E-03	0.004	0.087
1710	649.1	5.6	124.09	961	9.29E-05	1.20	411999	5.45E-03	0.004	0.087
1720	654.2	5.6	124.49	962	9.29E-05	1.19	411878	5.45E-03	0.004	0.087
1730	659.3	5.6	124.89	962	9.29E-05	1.19	411758	5.45E-03	0.004	0.087
1740	664.4	5.5	125.29	962	9.29E-05	1.19	411637	5.45E-03	0.004	0.087
1750	669.5	5.5	125.69	962	9.30E-05	1.19	411516	5.45E-03	0.004	0.087
1760	674.6	5.5	126.09	963	9.30E-05	1.19	411396	5.45E-03	0.004	0.087
1770	679.7	5.5	126.49	963	9.30E-05	1.19	411275	5.45E-03	0.004	0.088
1780	684.8	5.5	126.89	963	9.31E-05	1.19	411064	5.45E-03	0.004	0.088
1790	689.9	5.5	127.29	964	9.31E-05	1.19	410854	5.45E-03	0.004	0.088
1800	694.9	5.4	127.69	964	9.32E-05	1.19	410643	5.45E-03	0.004	0.088
1810	700.0	5.4	128.09	964	9.32E-05	1.19	410433	5.45E-03	0.004	0.088
1820	705.1	5.4	128.50	965	9.33E-05	1.19	410222	5.45E-03	0.004	0.088
1830	710.2	5.4	128.90	965	9.33E-05	1.19	410012	5.45E-03	0.004	0.088
1840	715.3	5.3	129.30	965	9.33E-05	1.19	409802	5.45E-03	0.004	0.088
1850	720.4	5.3	129.70	966	9.34E-05	1.19	409592	5.45E-03	0.004	0.088
1860	725.5	5.3	130.10	966	9.34E-05	1.19	409383	5.45E-03	0.004	0.088
1870	730.6	5.3	130.51	966	9.35E-05	1.19	409173	5.45E-03	0.004	0.088
1880	735.7	5.2	130.91	967	9.35E-05	1.19	408964	5.45E-03	0.004	0.088
1890	740.8	5.2	131.31	967	9.36E-05	1.19	408755	5.45E-03	0.004	0.088
1900	745.9	5.2	131.71	967	9.36E-05	1.19	408650	5.45E-03	0.004	0.088
1910	751.0	5.2	132.12	968	9.36E-05	1.19	408546	5.45E-03	0.004	0.088

X Pipe Length (m)	Z Depth (m)	T Temp (C)	P Pressure (bar)	p Density (kg/m3)	u Viscosity (Ns/m2)	v Velocity m/s	Re Reynolds Number Dvp/u	f Friction Factor	del Pf Friction Loss bar/m	del Pb Buoyancy Gain bar/m
1920	756.1	5.2	132.52	968	9.37E-05	1.19	408441	5.45E-03	0.004	0.088
1930	761.1	5.2	132.92	968	9.37E-05	1.19	408337	5.45E-03	0.004	0.088
1940	766.2	5.1	133.33	968	9.37E-05	1.19	408232	5.45E-03	0.004	0.088
1950	771.3	5.1	133.73	969	9.37E-05	1.19	408128	5.45E-03	0.004	0.088
1960	776.4	5.1	134.13	969	9.38E-05	1.19	408023	5.45E-03	0.004	0.088
1970	781.5	5.1	134.54	969	9.38E-05	1.19	407919	5.45E-03	0.004	0.088
1980	786.6	5.1	134.94	970	9.38E-05	1.18	407808	5.45E-03	0.004	0.088
1990	791.7	5.1	135.35	970	9.38E-05	1.18	407697	5.45E-03	0.004	0.088
2000	796.8	5.06	135.75	970	9.39E-05	1.18	407586	5.45E-03	0.004	0.088

Density of CO₂ (kg/m³) as a function of Temperature and Pressure

Pressure (bar)	Temperature (°C)				
	5	10	15	20	27
80	934.69	903.89	869.07	828.31	752.01
84	937.73	907.63	873.87	834.86	764.56
88	940.67	911.23	878.43	840.94	775.32
92	943.53	914.70	882.77	846.62	784.80
96	946.31	918.05	886.92	851.97	793.31
100	949.02	921.28	890.89	857.02	801.05
104	951.65	924.42	894.71	861.81	808.17
108	954.22	927.46	898.39	866.38	814.76
112	956.73	930.42	901.93	870.74	820.92
116	959.19	933.29	905.36	874.91	826.71
120	961.58	936.08	908.67	878.91	832.16
124	963.93	938.81	911.88	882.77	837.33
128	966.22	941.46	915.00	886.48	842.25
132	968.47	944.05	918.02	890.07	846.93
136	970.68	946.59	920.96	893.53	851.42
140	972.84	949.06	923.83	896.89	855.72

Source: National Institute on Standards and Technology (NIST) web site at
<<http://webbook.nist.gov>>

DESIGN OF THE FIELD EXPERIMENT

April 1999

E. Eric Adams

Introduction

Work has proceeded in five areas:

- detailed outline of measurements and supporting activities
- experimental matrix and diffuser design
- choice of tracers
- creation of a web site
- excess CO₂ concentration calculations.

This work has been done in collaboration with other members of the Technical Committee and in conjunction with the experimental study of two phase plumes being conducted in our laboratory.

I Outline of measurements and supporting activities

In preparation for the 2nd Technical Committee meeting (TC2) held in Bergen in August 1998, a compilation was made of possible measurements and supporting activities, identifying potential research groups that would be involved, priorities and estimated costs. Known as the “what/who/cost” matrix, this annotated list was used for discussion during the meeting and has been used for ongoing technical planning.

The experimental tasks are also discussed in the TC-authored paper (Adams et al., 1998) which we presented at GHGT-4 in Interlaken in September.

II Experimental matrix and diffuser design

In preparation for the 3rd Technical Committee meeting (TC3), held in Honolulu in February 1999, a matrix of experiments and a diffuser design were developed. These are discussed briefly below.

The primary objective of the experiments is to document the physical and chemical behavior of the plume within the near field region (approximately 100 m) surrounding the point of release. The goal is to better understand plume dynamics in order to develop, calibrate and verify mathematical models being developed in Norway, Japan, the U.S., and possibly elsewhere. These models, in turn, will be used to design prototype schemes that will minimize local impacts to the aquatic environment. A goal of the pilot scale study is to study a wide range of conditions in order to develop a robust data set.

2.1 Governing Variables

Four major factors determine the fate of CO₂:

- discharge buoyancy flux, given in kinematic units [L⁴/T³] as

$$B_o = Q_o g \Delta \rho / \rho$$

where Q_o is the volumetric discharge rate [L³/T] and $\Delta \rho / \rho$ is the normalized density difference of the CO₂ relative to ambient (about 0.1, depending on discharge depth).

- droplet size distribution, and hence distribution of droplet rise velocity
- ambient stratification, represented by the buoyancy frequency [T⁻¹]

$$N = [(g/\rho)(d\rho/dz)]^{0.5}$$

- ambient current speed, U .

The first two factors are primarily a function of the experimental design, while the last two factors are primarily a function of the site.

0.1 to 1.0 kg/s represents a realistic range of CO₂ discharge rates expected from individual risers of a long, bottom-mounted, multi-port diffuser designed for eventual full-scale ocean CO₂ sequestration. The range of 0.1 to 1.0 kg/s will result in a factor of 10 variation in discharge buoyancy flux.

Droplet size is a strong function of discharge velocity (Reynolds number). Experiments reported in Clift et al. (1978), and elsewhere, suggest that mean droplet size decreases as the discharge velocity increases. For example, Masutani et al. (1995) show results for CO₂ released at a simulated depth of about 500m through a 0.5 cm diameter orifice at exit velocities ranging from 6 to 300 cm/s. The smaller droplets obtained at higher exit velocities can be expected to rise more slowly and dissolve more rapidly than larger droplets, reducing both plume rise height and ultimate trap height, and restricting plume dilution. The nature of potential hydrate formation would also be different. It is therefore desirable to effect as wide a range in droplet sizes as possible in order to observe a wide range of plume behavior. The design of a suitable diffuser to do this is discussed further below.

Ambient stratification depends on the site and, hence, there is very little control. At the Keahole Pt. site, in water depths of 500 to 1000m, we can expect values of N ranging from 0.002 to 0.004 s^{-1} (Adams and Herzog, 1998).

Ambient currents at the site are expected to be primarily tidal with possible amplification of higher frequencies due to interaction of internal waves with the steep shoreline. Current speeds of 0 to 0.1 m/s or more can be expected (D. Luther, TC3 presentation). Current direction does not matter much to our experiments, as long as we are set up to survey both north and south of the discharge point, but we should try to sample as wide a range in speed as possible.

2.2 Diffuser design

It is desirable to maintain a simple design in order to facilitate deployment of the diffuser/pipeline system. In particular, earlier notions of a tall (~10m) riser to “keep the plume off the bottom” may be problematic. The simplest design is to have the delivery pipe terminate in a short tee-shaped manifold having two vertical risers at its ends. Each riser would have a diameter of about 20 cm and height of about 1 m. Flow rate would be adjusted by valves on shore, but each riser would be equipped with an additional on-off valve, an anti-backflow valve, and resistance heating to help prevent hydrate clogging. Each riser would terminate in a blind flange perforated with a uniform array of discharge ports. To promote standardization and allow comparison with detailed lab measurements of droplet size distribution, the ports should be circular and sharp-edged. An additional similar port would be located on each riser so that the behavior of individual droplets could be observed. These observations could be compared with those from other laboratory studies, such as those reported by M. Ozaki at TC3. The individual droplets would rise and eventually be incorporated into the plume created by droplets from the port array.

A spreadsheet was developed to help screen for suitable port arrays. In the spreadsheet Q is the flow total flow rate, N is the number of ports, D is the effective jet diameter (accounting for any nozzle contraction effects), U is the exit velocity, and ν is kinematic viscosity of CO_2 . Droplet size depends on Reynolds number,

$$Re = UD/\nu$$

which is proportional to Q/ND . In order to experience a wide range of droplet sizes, Re should vary by as much as possible. In addition, each port should “flow full”, meaning that sea water should not intrude. This requires that the densimetric Froude number

$$Fr = U/\sqrt{g(\Delta\rho/\rho)D}$$

exceed a critical value of approximately one (Wilkinson, 1988). Finally, in order to produce similar flow out of each port, the aggregate crosssectional area of the ports, $(\pi/4)ND^2$ should be small compared with the riser crosssectional area $(\pi/4)D_r^2$, such that the flow accelerate out of the ports. Thus,

$$ND^2/D_r^2 \ll 1$$

A number of different port arrays could satisfy the above objectives and constraints. One pair of possibilities includes

- ports, each with 0.5 cm diameter, which yields exit velocities of about 36 to 360 cm/s for mass flow rates of 0.1 to 1 kg/s
- 60 ports, each with 0.5 cm diameter, which yields exit velocities of about 9 to 90 cm/s.

An advantage of these particular combinations is that flow from such ports has already been studied in the University of Hawaii tank (Masutani, et al. 1995).

2.3 Experimental Matrix

We envision about 20 “experiments”, each defined by a different combination of the four factors listed under 2.1 above. This could be accomplished, for example, using three flow rates (0.1, 0.3 and 1.0 kg/s), two current speeds (relatively high and relatively low) and two nozzles, totaling 12 experiments. Another eight experiments could be devoted to replication. A key uncertainty here is the ambient current speed, so it is important that we obtain good site-specific measurements during this upcoming summer.

Assuming two hours per experiment (one hour to allow the flow field to adjust to quasi-steady state and to reposition survey vessels, and one hour for experimental measurements), four experiments per day, and a work schedule of 2 days on and one day off (as contingency and for interim evaluation of results), gives 5 survey days over a period of 7 actual days. This suggests that an ROV should be scheduled for a minimum duration of seven days of plume sampling. While two days of contingency are already built in to this schedule, discussion at TC3 suggested that four experiments per day might be tight, and hence that the scheduled ROV time should be increased somewhat--perhaps 10 days. Again, a major variable appears to be current velocity. (If we can experience the entire range of expected currents within a single tidal period of 12 hours, this would reduce the number of changes in riser and flow rate, and hence the time required for the flow field to adjust to a new quasi-steady state.)

Assuming seven of the experiments use a mass flow rate of 1 kg/s, six use a mass flow rate of 0.3 kg/s and seven use a mass flow rate of 0.1 kg/s, the CO₂ consumption for this scenario would be $(7*1 + 6*0.3 + 7*0.1)*7200/1000 = 68\text{T CO}_2$. Allowing for CO₂ losses in the system, an allotment of 100 T seems adequate. The maximum delivery per day would be less than 20 T.

2.4 ROV survey time requirements

The ROV would be used to survey the plume in three dimensions. Because vertical gradients are expected to be stronger than horizontal gradients, surveying is best done by traveling horizontally, then making a number of vertical ascents/descents through the plume. The time required for each survey would be

$$T = (NH + L) / U$$

where

T = time for survey
N = number of vertical profiles per survey
h = height of vertical profile
L = horizontal length of plume surveyed
U = velocity of ROV

We can get N = 17 profiles with height h = 30 m, U = 0.2 m/s, and L = 200 m in T = 3600 sec. The one hour survey is the approximate period of time during which a plume being advected in a tidal current can be approximated as steady.

III Tracer selection and use

One of the principal objectives of the field experiment is to understand plume dilution and hence the concentration of excess CO₂ and pH. Toward this objective, many tracers have been considered, including excess DIC, pH, fluorescent dye, SF₆, natural ¹³C and introduced ¹⁴C. The relative attributes of these tracers are summarized in a report which was circulated among the technical committee. This matrix is “work in progress” and we seek feedback from other TC members to help refine the various entries.

Nonetheless, it is clear at this point that there is no perfect tracer and, hence, that multiple tracers should be considered. As discussed briefly below, we are recommending three tracers (pH, DIC and labeled ¹⁴C) with the possibility of two more (natural ¹³C and dye).

pH is the only tracer that both directly follows the excess CO₂ and can be measured in-situ. pH can be measured with inexpensive, commercially available, glass electrodes. However, these are relatively slow and inaccurate, although their accuracy can be improved by periodic calibration against DIC measurements and against pH measurements made as the ROV travels “outside of the plume”. The pH signal can be transmitted in real time to ship for purposes of guiding the survey vessel (ROV). More accurate and rapid-response measurements can be obtained simultaneously with the solid state CRIEPI probe. The later measurements would be the ones most likely used for ultimate analysis of plume mixing.

DIC can be measured with somewhat greater resolution using standard shipboard analysis (coulometry). Because this requires bringing water samples to the surface, only a finite number of measurements can be made, so DIC measurements should be viewed as a complement to pH. The biggest limitation to the use of DIC to resolve excess CO₂ appears to be ambient variability, both vertically and potentially horizontally. This variability should be carefully assessed during this summer’s field survey.

¹⁴C can be added to the discharged CO₂ and measured in water samples by accelerated mass spectrometry. Although the precision (relative to ambient) of AMS is less than that for DIC, the lower ambient variability of ¹⁴C, coupled with the ability to adjust discharge tracer concentration allow for greater resolution of excess CO₂. Important considerations associated with ¹⁴C include

how to uniformly mix the labeled and unlabeled CO₂ prior to discharge, permitting and public perception concerning radioactivity.

It appears that the strong signature of ¹³C in fossil-fuel CO₂ compared with ambient seawater, coupled with the accuracy in measuring the ¹³C isotope fraction, allow estimates of excess CO₂ dilution that are comparable with those made from measurements of DIC. Hence this tracer should be considered if a participating scientist is interested. The actual concentration of ¹³C in the proposed CO₂ source should be ascertained first, however, since there is a wide range in commercial CO₂ sources (H. Herzog, personal communication).

Fluorescent dye, such as fluorescein or Rhodamine WT, though convenient and relatively accurate, is no longer being considered for direct plume tracking. This is because of concerns that dye will not be transported in exactly the same way as excess CO₂. For example, if introduced at the diffuser, dye will mark the entrained seawater and not necessarily the dissolved CO₂. Some of the entrained seawater may separate (peel) from the droplet plume before all of the CO₂ droplets dissolve, leaving subsequently dissolved CO₂ largely unmarked. Even if it were possible to dissolve dye within the CO₂ inside the delivery tank, there is concern that, outside the pipe, the dye would mix with the ambient seawater at a different rate than the CO₂. Dye is being considered for ancillary experiments to measure relatively near field ambient diffusivity and one or more of the experiments could be conducted in conjunction with the plume surveying to help discern differences in the transport characteristics of entrained water and CO₂ (T. Ohsumi, TC3).

SF₆ is similar to dye in that it won't truly mark excess CO₂ either. Compared with dye, it provides much greater resolution, in exchange for greater cost and effort, and the fact that it can not be measured in situ. It is really much more suitable for longer distance, far field studies, and is not being considered for this pilot scale study.

IV Project Web Site

We have developed a draft web site with a restricted-access URL. Discussion during TC3, and independently with J. Kildow, suggests that some of the information is too broad and that the focus of the site should be more project-specific. A revised, more concise, draft will be developed.

V Excess concentration and pH deficit calculations

As part of a presentation made to the NELHA board, PICHTR needed to estimate concentrations that might be experienced near the OTEC intake. We made such calculations using both base case and conservative assumptions, and transmitted the results in a memo of May 4, 1998 from E. Adams to S. Masutani.

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