SERI/TP-252-2149
UC Categories: 62e, 64
DE84000086

An Artificial Upwelling Driven by Salinity Differences in the Ocean

D. H. Johnson
J. Decicco

December 1983

To be presented at the ASME
7th Annual Energy Sources
Technology Conference and Exhibition
New Orleans, Louisiana
12–16 February 1984

Prepared under Task No. 1390.21
FTP No. 415

Solar Energy Research Institute
A Division of Midwest Research Institute

1617 Cole Boulevard
Golden, Colorado 80401

Prepared for the
U.S. Department of Energy
Contract No. DE-AC02-83CH10093

Printed in the United States of America
Available from:
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price:
Microfiche A01
Printed Copy A02

AN ARTIFICIAL UPWELLING DRIVEN BY SALINITY DIFFERENCES IN THE OCEAN

D. H. Johnson
J. Decicco

Solar Energy Research Institute
1617 Cole Boulevard
Golden, Colorado 80401

ABSTRACT

A concept for an artificial upwelling driven by salinity differences in the ocean to supply nutrients to a mariculture farm is described and analyzed. A long shell-and-tube counterflow heat exchanger built of inexpensive plastic and concrete is suspended vertically in the ocean. Cold, nutrient rich, but relatively fresh water from deep in the ocean flows up the shell side of the heat exchanger, and warm but relatively saline water from the surface flows down the tube side. The two flows exchange heat across the thin plastic walls of the tubes, maintaining a constant temperature difference along the heat exchanger. The plastic tubes are protected by the concrete outer shell of the heat exchanger. The flow is maintained by the difference in density between the deep and surface water due to their difference in salinity. This phenomenon was first recognized by the oceanographer Stommel, who termed it "The Perpetual Salt Fountain." The heat transfer and flow rate as a function of tube number and diameter is analyzed and the size of the heat exchanger optimized for cost is determined for a given flow of nutrients for various locations. Reasonable sizes (outer diameter on the order of 5 m) are obtained. The incremental capital cost of the salinity-driven artificial upwelling is compared to the incremental capital cost and present value of the operating cost of an artificial upwell fueled by liquid hydrocarbons. The salinity-driven upwelling is generally cheaper.

1.0 BACKGROUND

One of the major factors inhibiting implementation of mariculture farms in the ocean is a cost-effective way of fertilizing the mariculture. The deep ocean contains inorganic material that could fertilize the mariculture if brought to the surface. Present methods of doing this are too expensive to make mariculture farms commercially feasible. The deep water in the ocean is usually less saline and colder than the surface water. In 1956, the oceanographer Stommel (1) noted that if a long vertical pipe were lowered into the ocean in such a manner that its bottom was exposed to cold, relatively fresh water and its top to warm saline water, a continuous flow up the pipe could be maintained after priming the fountain. His explanation was that the ascending water in a pipe suitable for heat exchange would exchange heat but not salinity with the ambient ocean and would be accelerated due to its deficiency in salt (and thus density) relative to fluid at the same level outside the pipe. Stommel also attempted an experiment in the ocean to demonstrate this effect, but the results were inconclusive. The small boat he used to suspend his pipe from was strongly affected by waves, so he could not separate the effects of wave pumping from a flow caused by salinity differences.

Since Stommel's 1956 article, most of the effort related to this phenomenon has been to understand naturally occurring "salt fingers" in the ocean as described in Stern (2). This work has recently been summarized by Huppert and Turner (3). Our search of the literature since Stommel's original paper in 1956 found only one discussion of the engineering aspects of using the salinity difference in the ocean to drive an artificial upwelling (4). Groves estimated flow rates and diameters for a single pipe exchanging heat with the ambient ocean as originally described by Stommel. It was found that a 600-m- long, 20-cm-diameter copper pipe installed at an angle so its bottom is 300 m below the surface might produce a flow rate of 5.5 L/s. This upwelling was assumed to supply phosphorus for fish. It was estimated that it would produce 54 kg/yr of edible nutrients for fish. The same amount of phosphorus could be added by dumping in 290 kg/yr of Peruvian guano, whose phosphorus content is 4.6%. Thus, Groves (4) concluded that the artificial upwelling is not likely to be worth the effort. However, there are several reasons to reexamine the practicability of an artificial upwelling driven by salinity differences.

Commercially viable mariculture is likely to be on a large scale (much greater than 10 acres). If an effective upwelling system can be constructed that does not run on fuel shipped to the site, then at some

size the upwelling may become cheaper than shipping fertilizer. There are also other mariculture products besides fish that may be commercially viable. For example, kelp for use as a feedstock to produce synthetic natural gas has been proposed as a mariculture product. Nitrogen is not present in sufficient quantities in surface water to provide a commercially viable kelp yield. A recent study (5) concluded that commercial nitrogen fertilizer would be too expensive to use as a nitrogen source even when considering only the energy required to produce it. Deep ocean water is typically rich in nitrogen. The commercial viability of a kelp farm depends on finding an economical way of getting this deep water to the surface. The concept presented in this paper holds potential for building such a cost-effective artificial upwelling.

2.0 THE SERI ARTIFICIAL UPWELLING CONCEPT

The SERI concept is essentially a large shell-and-tube counterflow heat exchanger (Fig. 1). Structural support is provided by the outer shell of diameter D_s. This shell would be constructed in a manner similar to an Ocean Thermal Energy Conversion (OTEC) cold water pipe (6). It might be made of concrete, plastic, or some other inexpensive material. No significant heat transfer occurs across the shell.

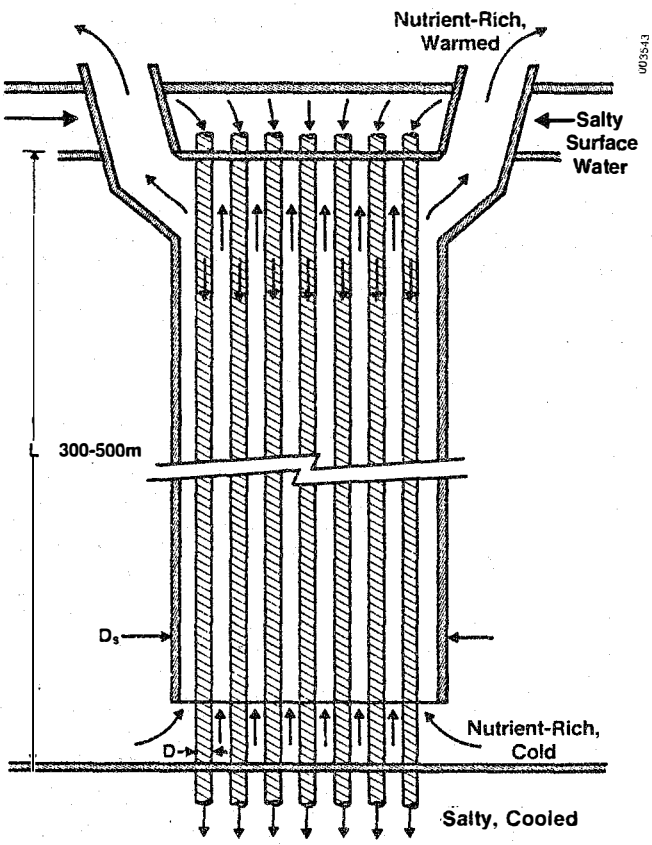

Figure 1. Sea Upwelling Pump for Mariculture

The shell is connected to manifolds at the top and bottom, which direct the flow of water from the surface and the depths. Once initiated by pumps, the flow of water from the surface and from the depths is maintained by Stommel's salt fountain effect. Warm salty surface water is drawn from just above the bottom of the surface mixed layer (typically at a depth of 50 m) and flows down the tubes inside the shell. These tubes are supported at stations along the length of the shell so they do not bear a significant load. They are constructed of very thin (a few tenths of millimeters thick) extruded plastic. Cold, relatively fresh, nutrient rich water from 300 m to 500 m below the surface is drawn into the shell side of the heat exchanger and flows towards the surface. The deep water and surface water flow counter to each other and maintain an approximately equal temperature difference throughout the length of the heat exchanger. This is the most efficient arrangement for heat transfer and is the major difference between our concept and Stommels' original idea.

When the deep water reaches the top of the heat exchanger it has been warmed to a temperature slightly less than the temperature of the surface water but is more bouyant than the ambient surface water because of lower salinity. The warmed, nutrient-rich deep water is directed towards the surface by the upper manifold. It rises and floats on the surface due to its buoyancy. The streams of water entering and exiting the top of the heat exchanger are kept separate by the stratification set up by their density differences. When the surface water reaches the bottom of the heat exchanger, it has been cooled to a temperature slightly higher than the deep water but is heavier than the ambient deep water because of higher salinity. It is discharged directly downward through the lower manifold and sinks below the depth from which deep water is being withdrawn until it reaches a depth where the surrounding water has the same density. The two streams of water are kept separate by the natural stratification that exists in the ocean at these depths.

Once a flow has been established through the heat exchanger it will be maintained by the buoyancy difference between the warmed deep water and the cooled surface water due to their difference in salinity. However, since this natural pump must first be primed, mechanical pumps will be required to initiate the flow.

Any artificial upwelling operating far from land will have to provide a method of keeping the nutrient-rich deep water on the surface once it is brought there from the depths. The present method accomplishes this by warming the deep water until it is buoyant compared to the surface water during the pumping process. No other action is needed. An upwelling continuously driven by mechanical pumps would need to take further steps to keep the deep water on the surface. This point will be discussed further in Section 5.0.

3.0 ANALYSIS

Suppose a tube of diameter D surrounded by a shell extends vertically downward from the surface of the ocean to a depth L. Deep water rises through the shell side and exchanges heat with a counterflow of surface water flowing down the tubes. Let S_o, T_o denote the salinity and temperature of the surface water, and T_l that of the water at depth L, with $T_o > T_l$ and $> S_l$. Approximating the difference in density ρ of seawater inside the tubes and outside the tubes but within the shell (ignoring compressibility due to pressure) by

$$\Delta\rho = \rho(\beta\Delta - \alpha\Delta T) ,$$

where

$$\Delta S = S_o - S_1$$

and

$$\alpha = -\frac{1}{\rho}\frac{d\rho}{dT} \text{ and } \beta = \frac{1}{\rho}\frac{d\rho}{dS} ,$$

then the pressure head due to density difference between the rising water in the tube and the counterflow is

$$\Delta P_\rho = -\int_{-L}^{0} \Delta\rho g \, dy = -\rho g L(\beta\Delta S - \alpha\Delta T) . \quad (1)$$

This assumes a constant temperature difference ΔT between the upwelling and counterflow. The pressure drop due to friction is

$$\Delta P_f = \frac{1}{2} f\rho v^2 \, L/D \quad (2)$$

where f is the Darcy friction factor and v, the flow velocity. For a steady flow, $\Delta P_\rho + \Delta P_f = 0$, so the equation describing the upwelling flow is

$$-g(\beta\Delta S - \alpha\Delta T) + \frac{v^2 f}{2D} = 0 , \quad (3)$$

or

$$v^2 = [2gD/f(v)] \, (\beta\Delta S - \alpha\Delta T) . \quad (4)$$

We can find an expression for ΔT by considering an energy balance on a control volume of fluid in a counterflow tube; the resulting energy equation is

$$\frac{\pi}{4} D^2\rho v \, (C_p dT + g dy) = \pi D U \Delta T \, dy , \quad (5)$$

where the conductance through the tube from the counterflow to the upwelling is

$$U = \frac{1}{(2D/Nuk) + R_w} , \quad (6)$$

with Nu being the Nusselt number for the flow, k the thermal conductivity of seawater, and R_w the thermal resistance of the tube wall. Simplification yields

$$C_p dT = \left(\frac{4U\Delta T}{\rho v D} - g\right) dy , \quad (7)$$

which we can integrate from depth L to surface (y = 0) to obtain

$$T_o' - T_1 = \frac{4UL\Delta T}{\rho C_p v D} - \frac{gL}{C_p} . \quad (8)$$

The tube outlet temperature T_o' is also

$$T_o' = T_o - \Delta T . \quad (9)$$

Therefore we can solve for Δ as

$$\Delta T = \Delta T^*\left(1 + \frac{4UL}{\rho C_p v D}\right)^{-1} , \quad (10)$$

where

$$\Delta T^* = (T_o - T_1) + gL/C_p . \quad (11)$$

Note that $T_o - T_1$ is the maximum temperature difference in the system, and gL/C_p corresponds to the potential energy change of the upwelled seawater. $T_o - T_1$ might be 10 - 15°C; for a depth L of 500 meters, gL/C_p is 1.2°C.

Substituting for ΔT in Eq. 4 gives

$$v^2 = \frac{2gD}{f(v)} \left[\beta\Delta S - \alpha\Delta T^*\left(1 + \frac{4UL}{\rho C_p v D}\right)^{-1}\right] . \quad (12)$$

For a given diameter D, this equation implicitly determines the velocity v of the upwelling flow, and therefore the volume flow capacity $Q = (\pi/4) D^2 v$ of a tube. The friction factor f in this equation depends on v; for turbulent flow, U also depends on v due to the nonconstant Nusselt number. As we shall see, the flow may be either laminar or turbulent.

Our assumption of constant ΔT corresponds to an assumption of constant heat flux through the tube wall, which for laminar flow gives a constant Nu = 4.36.

For laminar flow (i.e., Re < 2300), Eq. 12 reduces to a quadratic:

$$v^2 + bv + c = 0 , \quad (13)$$

where

$$b = C_1 + C_2 (A - B)$$
$$c = -C_1 C_2 B$$
$$A = \alpha\Delta T^*$$
$$B = \beta\Delta S$$
$$C_1 = 4UL/\rho C_p D$$
$$C_2 = gD^2/32\nu$$

using f = 64/Re and Re = vD/ν.

The solution is

$$v = \frac{1}{2}\left[-b + (b^2 - 4c)^{1/2}\right] . \quad (14)$$

A real solution is assured when c < 0; i.e., when $\Delta S > 0$ ($S_o > S_1$). The other root gives a negative velocity that is not meaningful.

Once flow velocity is known, the flow per tube is given by $Q = \frac{\pi}{4} D^2 v$. Given a total flow requirement Q_T to supply a sea farm, the number of tubes can be computed as $n = Q_T/Q$. From this the shell inside diameter D_s can be calculated, completing the basic design.

4.0 COST ESTIMATION

An upwelling pump/heat exchanger could be constructed in the form of a large shell-and-tube heat exchanger. The outer shell is of a size similar to that needed for the cold water pipe of an OTEC plant. Designs for OTEC cold water pipes have been performed by others (6,7,8) with the conclusion that the most promising design would be a fiber-reinforced plastic (FRP) sandwich construction. An estimated total cost for design, fabrication, and deployment for a 30-ft-diameter, 3280-ft-long cold water pipe is $21,500,000 (7). This is equivalent to a cost per unit volume times shell thickness, $C_s t_s$, of $900/m^2 ($84/ft^2) after increasing costs by 20% to scale from 1980 to 1983.

Tubes could be made from thin polyethylene. A nominal 5-cm (2-in.)-diameter tube costs $2.00/ft. This is equivalent to a cost per unit volume times tube thickness, $C_t t_t$, of $40/m^2 ($4/ft^2). Standard engineering approaches to estimating costs of shell-and-tube heat exchangers indicate that as the number of tubes and their length become large, then the dominant tube-related cost becomes the cost of the tube material (9). We will neglect the cost of support plates, baffles, etc., compared to tube material since we anticipate a heat exchanger with many very long tubes.

Also, we do not need to estimate the costs of the rest of the mariculture system or the costs of installing the system in the ocean. This information is not required to optimize the size of the counterflow heat exchanger or to compare its cost with the cost of an upwelling driven by a mechanical pump. this latter point will be discussed further in Section 5.0.

If we consider that the shell diamter D_s is such that the cross-sectional area for shellside flow equals the cross-sectional area for tubeside flow then

$$D_s = D(2n)^{1/2} \ . \qquad (15)$$

The cost C for the shell-and-tube heat exchanger will be given by

$$C = nC_t t_t \pi DL + C_s t_s \pi D_s L$$

$$= \left[\left(\frac{n}{2}\right)^{1/2} C_t t_t + C_s t_s\right]\pi L D_s$$

$$= \left[\left(28.3(n)^{1/2} + 900\right) \$/m^2\right]\pi L D_s \qquad (16)$$

where n is the number of tubes, L the length (depth), and D_s the shell diameter.

Costs for a 10-acre kelp farm are evaluated as a function of tube diameter; the diameter for which cost is minimum is selected as the best design. The total volumetric flow required for a 10-acre kelp farm is 1.32 m^3/s (5). Calculations were made for two locations; the Gulf of Mexico off Florida and the Pacific Ocean off Chile. The Florida site was chosen because it is a good site for a continental U.S.-based mariculture and because it has one of the best set of conditions for a salinity-driven upwelling of those locations we surveyed. The Chile site was chosen because there is already an active commercial fishing industry off Chile with which we can eventually compare the upwelling to and because it has one of the least favorable set of conditions for a salinity-driven upwelling of those locations we surveyed. Of course, there are locations in the ocean at which the salinity-driven upwelling will not work.

We consider that for the purposes of this initial exploratory investigation of the concept calculations for favorable and unfavorable but not impossible locations are adequate. Future studies should identify the distribution of oceanographic conditions that favor the concept, and the potential worldwide capacity of mariculture fertilized by the concept. Costs were reevaluated using different cost per unit area figures, we found the optimum diameter was not sensitive to this parameter, although total costs certainly are. It was found that total system cost depends more strongly on tube costs than shell costs. These results are shown in Figures 2 and 3 for the two sites considered. Parameters and cost data for the shell-and-tube heat exchanger for these two locations are summarized in Table 1.

5.0 COST COMPARISONS WITH AN ARTIFICIAL UPWELLING DRIVEN BY LIQUID HYDROCARBON FUEL

Consider an artificial upwelling that uses a liquid-hydrocarbon-fueled pump to bring cold, nutrient-rich water from deep in the ocean to the surface. Once brought to the surface, the cold water cannot simply

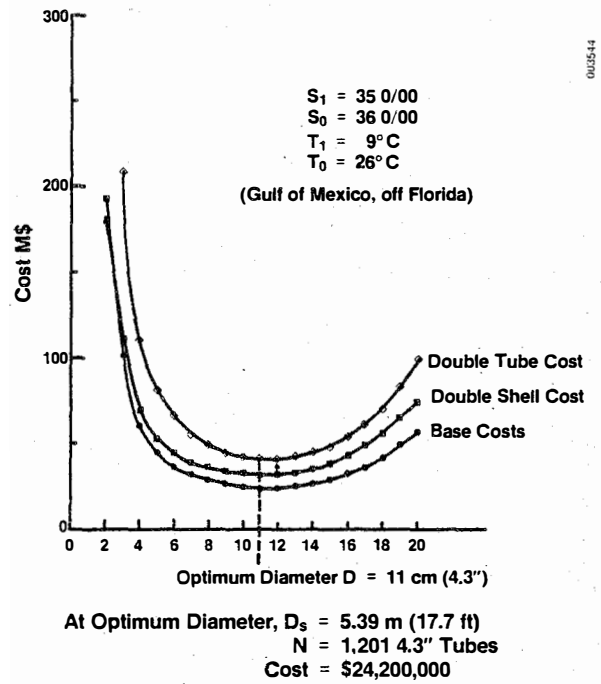

Figure 2. Cost vs. Tube Diameter, Gulf of Mexico off Florida

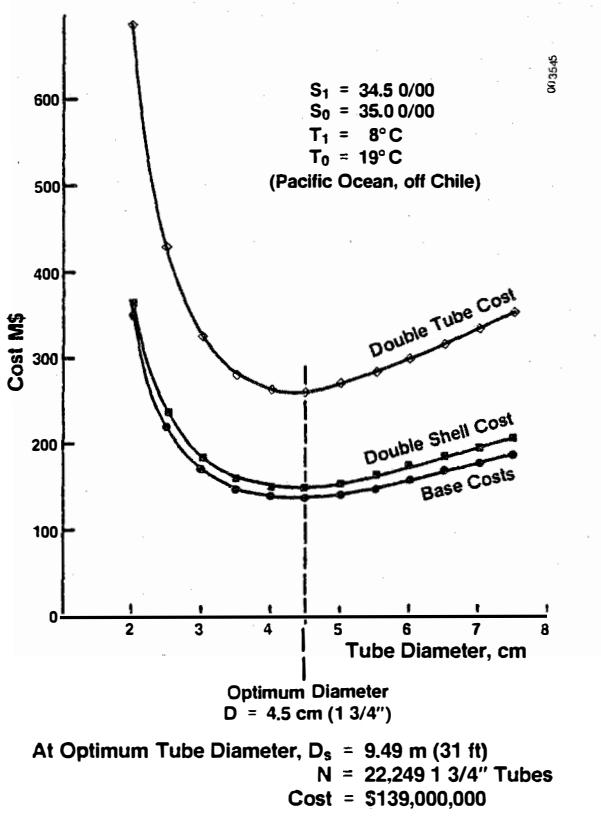

Figure 3. Cost vs. Tube Diameter, Pacific Ocean off Chile

Table 1

Heat Exchanger Parameters	Gulf of Mexico off Florida	Pacific Ocean off Chile
S_o	36 0/00	35 0/00
S_1	35 0/00	34.5 0/00
T_o	26°C	19°C
T_1	9°C	8°C
Q_T	1.32 m^3/s	1.32 m^3/s
L	500 m	500 m
$D_{optimum}$	11 cm	4.5 cm
n	1201	22,249
D_S	5.39 m	9.49 m
v	11.6 cm/s	3.7 cm/s
C	$24,200,000	$139,200,000
ΔT	2.36°C	1.51°C
Re	11,360	1,342

be released or it would sink. The cold water could be kept on the surface by impounding it in a container or bringing it to the same density as the surface water by heating it or mixing it with a larger quantity of surface water. Commercial mariculture farms will be large (greater than 10 acres). Even if the capital costs of a 10 acre or larger container were economic, maintaining it in good repair in the ocean environment would be prohibitively expensive. Thus, we will not consider the containment method.

We estimated the cost of heating the deep water versus mixing it with the surface water, and found that heating is much more expensive than mixing. Thus, we will not consider the heating method.

The water from the depths could be mixed with the surface water. This could be done by injecting the deep water into the surface at a high Froude number F, where

$$F = \frac{u_o}{\left(\frac{g\Delta\rho_o h}{\rho}\right)^{1/2}} , \tag{17}$$

and

$\Delta\rho_o$ = initial density difference
u_o = speed of injection
h = nozzle diameter.

Experiments (10) indicate that for good mixing, F = 10 to 100. We will use F = 20 because at this value there is considerable data. Injection could be accomplished at low speed through many small nozzles spread out over the farm or at high speed through a few centralized large nozzles. In either case the turbulent jet exits the nozzle with a horizontal speed u_o and begins to curve downward due to its negative buoyancy compared to the water in the surface mixed layer. As it curves downward it grows in diameter and slows down due to the entrainment of the surrounding fluid.

The following relationships from Abraham (10) describe the geometry of the jet for a Froude number of 20 and using y and x as the vertical and horizontal coordinates.

The jet has become approximately vertical when it has sunk to a depth of

$$\frac{y}{h} = .10F = 200 . \tag{18}$$

The center line at the jet when it is vertical is a distance x from the nozzle of

$$x/h = 100 . \tag{19}$$

The path length s along the trajectory of the jet from the nozzle to a point 100h in the horizontal and 200h in the vertical is

$$\frac{s}{h} = 240 . \tag{20}$$

The radius of the jet at this point is

$$\frac{r}{h} = \frac{1}{8.43}\frac{s}{h} = 28.5 . \tag{21}$$

At this point the center line velocity of the jet has slowed to

$$\frac{u}{u_o} = \frac{1}{10} , \tag{22}$$

and the density difference between water in the jet and the water outside the jet has decreased to

$$\frac{\Delta\rho}{\Delta\rho_o} = 7.5 \times 10^{-3} . \tag{23}$$

Now consider a single central injection nozzle. The requirement of continuity of mass places the following restriction on u_o and h:

$$u_o \frac{\pi h^2}{4} = Q_T . \tag{24}$$

This together with the Froude number requirement determines u_o and h. Typical numbers are

$$Q_T = 1.32 \frac{m^3}{s} \text{ (for a 10-acre farm)} ,$$

and

$$\frac{\Delta\rho_o}{\rho} = 3.16 \times 10^{-3} \text{ (for the Gulf of Mexico off Florida)},$$

so

$$u_o = 4.37 \text{ m/s}$$

and

$$h = 0.620 \text{ m} .$$

According to the discussion of the preceeding paragraph, the trajectory of this jet becomes approximately vertical at a horizontal distance of 62 m from the nozzle and a depth of 124 m below the nozzle, where its diameter is 17.7 m. Typical mixed-layer depths are 50 m, so this implies that the jet has impacted the bottom of the mixed layer rather than mixing with the surface waters. The conclusion is that a single central jet is too large a mass of water to mix with the surface water given typical depths of the mixed layer. Of course, background turbulence in the mixed layer will help to ameliorate this problem, but not to a significant extent. Typical turbulence levels in jets are perhaps a tenth of the center line speed. According to the correlations of Abraham (10), this jet has a center line speed of 0.5 m/s at a depth of 50 m below the nozzle. This means that the root mean square turbulence (rms) levels in the jet are ~5 cm/s. Typical mixed-layer levels of turbulence are the same order of magnitude. It appears that to mix the deep and surface waters, the deep waters must be dispersed over the area of the farm.

Consider a network of distribution pipes and manifolds that deliver the water from the upwelling pipe to nozzles uniformly dispersed over the area of the farm. Each nozzle produces a jet that occupies a horizontal area of

$$2r(x + r) = 37 \times 128h^2 \ . \qquad (25)$$

The total area to be covered by these dispersed jets is 10 acres (4.05×10^4 m^2), so the total number of jets N_j is

$$N_j = \frac{(4.05 \times 10^4)m^2}{(7.8 \times 10^3)h^2} = \frac{5.19}{h^2} \ . \qquad (26)$$

From continuity of mass we see that

$$N_j u_o \frac{\pi h^2}{4} = Q_T \ , \qquad (27)$$

so

$$u_o = 0.324 \text{ m/s} \ .$$

The Froude number criterion then gives

$$h = 8.47 \times 10^{-3} \text{ m.}$$

We will consider a network of distribution pipes and manifolds consisting of two 100-m-long manifolds leading in opposite horizontal directions from the upwelling pipe connected to 100-m-long horizontal distribution pipes that branch at right angles in both directions from the manifolds. The pipes will be separated by a horizontal distance of 2x, and there will be pairs of nozzles (actually simple holes) spaced a distance 2r from each other along each pipe. Thus, the number of pipes per header is

$$n_p = \frac{2 \times 100 \text{ m}}{2x} = 90 \ , \qquad (28)$$

and the number of holes per pipe is

$$n_j = \frac{2 \times 100 \text{ m}}{x} = 394 \ . \qquad (29)$$

To avoid excessive pressure drop the total area of the holes in a pipe should be no more than the cross-sectional area of the pipe. Thus, the diameter of the pipe is

$$D_p = (n_j)^{1/2} \ h = 0.168 \text{ m} \ . \qquad (30)$$

For the same reason the diameter of the manifold is given by

$$D_m = (n_p)^{1/2} \ D_p = 1.60 \text{ m} \ . \qquad (31)$$

To summarize, the distribution network is composed of two 100-m-long, 1.6-m-diameter manifolds that feed 182, 100-m-long, 0.168-m-diameter pipes each of which has 394 pairs of 8.47-mm-diameter holes spaced 0.5 m apart. This network must float on or near the surface and withstand the action of the waves. We will assume that it is made of an almost-neutrally buoyant, flexible, cheap material such as polyethylene. It is very difficult to determine a thickness for the manifolds and pipes that ensures protection from wave action for the lifetime of the plant. We will arbitrarily take 1 cm as the thickness. The total volume of material is then

$$\begin{aligned} &(182 \times 100)\text{m} \times \pi \times (0.168 \times 10^{-2})\text{m} \\ &+ (2 \times 100)\text{m} \times \pi \times (1.6 \times 10^{-2})\text{m}^3 \\ &\pi \ [(182 \times 0.168) + (2 \times 1.6) \ \text{m}^3] \\ &= 106 \ \text{m}^3 \ . \end{aligned}$$

Using the same price for polyethylene as before, the total cost of the distribution network is

$$\begin{aligned} C_n &= (2 \times 10^5) \ \frac{\$}{\text{m}^3} \times 106 \ \text{m}^3 \\ &= 21.2 \times 10^6 \ . \end{aligned} \qquad (32)$$

To this must be added the cost of the cold water pipe and the present value of the fuel used to pump water up the pipe. When this cost is optimized for cold water pipe diameter, we find that

$$D_s = 0.842 \text{ m}$$

and that the cost of the cold water pipe plus present value of fuel is

$$C_p = \$1.4 \times 10^6 \ .$$

Thus, the total cost of the liquid-hydrocarbon-fueled upwelling and water distribution system is

$$C = \$22.6 \times 10^6 \ .$$

This is to be compared to the cost for the salinity-driven upwelling in the Gulf of Mexico off Florida determined in Section 4.0, which was

$$C = \$24.2 \times 10^6 \ .$$

6.0 CONCLUSIONS

The concept of an artificial upwelling driven by salinity differences in the ocean is based upon a physical phenomenon (double diffusive convection) that has been well characterized in the laboratory and shown to be active in the ocean. The concept involves using a highly effective, counterflow heat exchanger to exploit this phenomenon to drive an artificial upwelling to fertilize a mariculture farm. The heat exchanger is designed to separate the functions of heat exchange and mechanical support. This results in a reasonable size for the heat exchanger. The outer load bearing shell of the heat exchanger is approximately the size of an OTEC cold water pipe. Construction and deployment of such a pipe has been studied extensively by the U.S. DOE OTEC program. The tubes of the heat exchanger are constructed of thin-walled polyethylene. This concept appears to be technically feasible, although many questions remain about the actual construction and maintenance of the pipe.

The optimum size of the upwelling pipe (the size that results in minimum cost) has been determined for two locations (one favorable, one not so favorable). The cost of the salinity-driven artificial upwelling is compared to one driven by liquid hydrocarbon fuel. The greatest cost in this plant is the cost of manifolds and pipes to distribute the deep water over the farm so it will mix with the surface water and not sink. The salinity-driven upwelling accomplishes this by heating with a counterflow of warm surface water. The favorable site for the salinity-driven upwelling results in an upwelling plant for which the capital cost is the same order of magnitude as the present value of the fuel cost over the lifetime of a liquid-hydrocarbon-fueled plant plus the capital cost of the cold water pipe and distribution network. This analysis does not address total costs of either plant, but the conclusion is that the salinity-driven upwelling is not significantly more expensive than a hydrocarbon-fueled upwelling. Further detailed analysis is required to determine which is actually cheaper. Note that the greatest cost in the hydrocarbon-fueled plant is the horizontal distribution network that is exposed

to the action of waves and may have a limited life.

7.0 RECOMMENDATIONS

This preliminary analysis indicates that the concept of an artificial upwelling driven by salinity differences in the ocean is worth further development. A product for the mariculture farm should be chosen and a complete system laid out and costed. This would include specifying a method of construction. The purpose of this study would be to identify technical problems and the potential for producing an economically competitive product. Several research efforts are needed to support this systems study. A laboratory scale test of the upwelling pipe concept is needed to determine the effectiveness and pressure drop of a shell-and-tube heat exchanger using thin-walled flexible plastic tubing. Laboratory tests are also needed to determine the best manifold arrangement at the top and bottom of the pipe.

8.0 REFERENCES

1. Stommel H., Arons, A. B., and Blanchard, D., "An Oceanographical Curiosity; the Perpetual Salt Fountain," Deep Sea Research, Vol. 3, pp. 152-153 (1955)

2. Stern, M. E., "The Salt-Fountain and Thermohaline Convection," Tellus, Vol. 12, pp. 172-175 (1960).

3. Huppert, H. E. and J. S. Turner, "Double Diffusive Convection," J. Fluid Mech, Vol. 106, pp. 299-329 (1981).

4. Groves, G. W., "Flow Estimates for the Perpetual Salt Fountain," Deep Sea Research, Vol. 5, pp. 209-214 (1959).

5. Sullivan, McGinn, Jain, and Engel, Systems Analysis Studies on Marine Biomass Commercial Application, General Electric Corp., (Dec. 1981).

6. Griffin and Mortaloni, "Baseline Designs for Three OTEC Cold Water Pipes," Proc. 7th Ocean Energy Conf. (June 1980).

7. TRW, Inc., OTEC Cold Water Pipe Preliminary Design Project: Final Report, 00275 (Nov. 1979).

8. Hove and Grote, "OTEC CWP Baseline Designs," Proc. 7th Ocean Energy Conf. (June 1980).

9. Pikulik, A. and H. E. Diaz, "Cost Estimating for Major Process Equipment," Chemical Engineering, Oct. 10, 1977.

10. Abraham, G., "Horizontal Jets in Stagnant Fluid of Other Density," Proc. of the ASCE, J. Hydraulics Division, Vol. 4, pp. 139-154 (July 1965).

11. Johnston Engineering Data, Johnston Pump Co., Glendora, CA.